Programa de Doctorado de Ingeniería de la Construcción y Gestión Ambiental

Departamento de Ingeniería de la Construcción y de Proyectos de Ingeniería Civil
Department of Construction Engineering and Civil Engineering Projects
Departamento de Ciencia Animal
Department of Animal Science

Ph.D. Thesis

OPTIMIZACIÓN DE DISEÑO DE GRANJAS AVÍCOLAS DE POLLOS
OPTIMISATION OF DESIGN FOR BROILER POULTRY FARMS

Eliseo Bustamante García
Supervisors:
Dr. Antonio Hospitaler Pérez
Dr. Antonio Germán Torres Salvador

Valencia (Spain), October 2015

Resumen (en español)

La avicultura intensiva del pollo de carne (broiler) es un sector estratégico en la economía y desarrollo de muchos países y regiones, entre ellos España y la Comunidad Valenciana. La producción intensiva del broiler se da confinando al animal en edificios específicos (granjas de pollos) bajo un microclima interno controlado. Tiene dos variantes fundamentales en función de su sistema de ventilación: producción en granjas con ventilación natural y producción en granjas con ventilación mecánica (generalmente por depresión negativa mediante ventiladores de extracción). Un inadecuado diseño de la ventilación es la causa principal del estrés térmico y de la mortalidad de los pollos. En este sentido, una solución para disminuir el estrés térmico por calor y la mortalidad de los pollos es ayudar en su termorregulación biológica mediante un aumento de la velocidad del aire sobre ellos.

En esta tesis doctoral, se ha caracterizado y analizado la ventilación (rangos de velocidad del aire y su distribución, especialmente al nivel de presencia del pollo) en los principales sistemas de ventilación mecánicos instalados en las granjas de pollos. Pese a la envergadura de la actual problemática (estrés térmico y mortalidad de los pollos) y la sensibilidad de la sociedad hacia los aspectos del bienestar animal, hasta la fecha no se han caracterizado y analizado con rigurosidad científica los diferentes sistemas de ventilación mecánicos en las diferentes tipologías de granjas de pollos. En esta tesis doctoral se han estudiado los tres más relevantes: cruzado, túnel y de pared única.

El enfoque metodológico en todos los casos de estudio ha sido muy similar: se han realizado unas mediciones mediante un sistema multisensor de registro isotemporal (de diseño y fabricación propios), se han realizado las correspondientes simulaciones Computational Fluid Dynamics (CFD) y finalmente se han validado estas simulaciones. Estas validaciones se han llevado a cabo mediante dos técnicas estadísticas: mediante técnicas de regresión lineal y mediante el estudio de la significatividad (en un análisis de la varianza) de la metodología utilizada (sensores o CFD) en sendos modelos de validación propuestos. Una vez validadas estas simulaciones CFD, se tiene la seguridad de poder utilizarlas para caracterizar y analizar la ventilación en todo el espacio interior de las granjas (los sensores sólo permiten caracterizarla en las localizaciones físicas de los mismos).

El primer caso de estudio es el de una granja que tiene instalado un sistema de ventilación mecánico cruzado (habitual en el clima Mediterráneo). Las conclusiones de este estudio demuestran que este sistema de ventilación es adecuado para la crianza del pollo para casi todo el año en localizaciones climáticas templadas (por ejemplo, el clima Mediterráneo). Sin embargo, en días o periodos de calor (verano), no será adecuado porque no se pueden

alcanzar valores de velocidad del aire grandes que permiten disminuir el estrés por calor de los pollos.

El segundo caso de estudio es el de una granja que instala el sistema de ventilación mecánico túnel. Las conclusiones de este estudio demuestran que es menos apropiado que el anterior (sistema de ventilación mecánico cruzado) para la crianza del pollo durante todo el año en localizaciones climáticas templadas. Sin embargo, en días o periodos de calor (verano), será muy adecuado porque se pueden alcanzar valores de velocidad del aire grandes que permiten disminuir el estrés por calor de los pollos.

El tercer caso de estudio es el de una granja que instala el sistema de ventilación mecánico de pared única. Las conclusiones de este estudio demuestran que este sistema de ventilación es adecuado para la crianza del pollo para casi todo el año en localizaciones climáticas templadas. Sin embargo, en días o periodos de calor (verano), no será adecuado porque no se pueden alcanzar valores de velocidad del aire grandes que permitan disminuir el estrés por calor de los pollos. Los valores de velocidad del aire son discretamente superiores a los obtenidos con el sistema de ventilación mecánico cruzado.

Con estos análisis y caracterizaciones, se concluye que la granja óptima de pollos para zonas geográficas con incertidumbre climática (incrementando su extensión por el efecto del cambio climático y el calentamiento global) y para localizaciones climáticas templadas (por ejemplo, el clima Mediterráneo) tiene que tener instalado un sistema mecánico híbrido de ventilación (transversal y túnel). En algunos casos, este sistema híbrido de ventilación será antieconómico pero respetuoso con el bienestar animal porque el sistema de ventilación tipo túnel sólo se utilizará ocasionalmente para pocos días o para la estación calurosa (verano).

Además, como la caracterización de la ventilación es la clave para el diseño óptimo del sistema de refrigeración de un sistema por nebulización, se ha incluido un capítulo que optimiza la localización de las tuberías de distribución de agua y la orientación de las boquillas de pulverización del agua. El enfoque metodológico ha sido muy similar al de los otros capítulos de la tesis doctoral (uso de CFD, mediciones con sensores y validación).

La presente tesis doctoral avala el uso de las técnicas CFD como herramienta poderosa para la búsqueda de modelos óptimos de granjas de pollos y de sus sistemas de ventilación instalados a través de concepciones de diseño y de funcionamiento “virtuales” desarrollados fácilmente en gabinete mediante el software CFD.

Summary (in English)

Intensive (broiler) poultry farming is a strategic sector for the economy and development of many countries and regions, including Spain and the Valencian Community region. Intensive production consists of keeping the animals in specific buildings (broiler buildings) under a controlled indoor microclimate. Two main options are found regarding the ventilation systems: production in broiler buildings with natural ventilation and production in broiler buildings with mechanical ventilation (commonly with negative depression by exhaust fans). Inadequate design is the main cause of thermal stress and the mortality of broilers. In this sense, one solution to decrease the broilers' heat stress and mortality consists of assisting in their biological thermoregulation by increasing the air velocity over them.

In this PhD dissertation, the ventilation (ranges of the air velocity and its distribution, mainly at the level and plane where the broilers are located) in the main mechanical ventilation systems installed in the broiler buildings is characterised and analysed. Despite the magnitude of the current difficulties (broilers' thermal stress and mortality) and society's sensitivity regarding aspects of animal welfare, to date, the different mechanical ventilation systems in the different types of broiler building have not been characterised and analysed with scientific scrupulousness. In this PhD dissertation, the three most relevant types have been studied: cross, tunnel and single-sided.

The methodological approach has been very similar in all the cases of study: some measurements by means a multi-sensor system (with our own original design and building) has been used for isotemporal recordings, the corresponding Computational Fluid Dynamics (CFD) simulations have been carried out and finally these simulations have been validated. These validations were carried out by means of two statistical techniques: by means of linear regression techniques and by means of a study of the significance (in an analysis of the variance) for the method used (sensors or CFD) in each different proposed validation model. Having validated these CFD results, CFD techniques can safely be used to characterise and analyse the ventilation in all the indoor space of the broiler buildings (sensors only allow it to be characterised in their physical locations).

The first case studied involves a broiler building which has a cross mechanical ventilation system (commonplace in Mediterranean climates) installed. The conclusions from this study show that this ventilation system is adequate for broiler rearing during nearly the whole year in mild climatic locations (e.g. Mediterranean climate). However, on certain days or in periods of heat (summer), it would not be adequate because it cannot reach high enough air velocity values to reduce the heat stress on the broilers.

The second case studied is a broiler building with tunnel mechanical ventilation installed. The conclusions from this study show that it is less suitable than the first one analysed (cross mechanical ventilation) for broiler rearing over nearly the whole year in mild climatic locations. However, on certain days or in periods of heat (summer), it is very suitable because it can reach higher air velocity values to reduce the heat stress on the broilers.

The third case studied is a broiler building with single-sided mechanical ventilation installed. The conclusions from this study show that this ventilation system is suitable for broiler rearing almost throughout the year in mild climatic locations. However, on certain days or in periods of heat (summer), it would be not adequate because it cannot reach high enough air velocity values to reduce the heat stress on the broilers. The air velocity values are slightly higher than those obtained in the cross mechanical ventilation system.

Given these analyses and characterisations, it is concluded that the optimum broiler building for geographical areas with meteorological uncertainty (increasing in size as a consequence of the effects of climate change and global warming) and for milder climatic locations (e.g. Mediterranean climate) must have a hybrid mechanical ventilation system installed (transversal and tunnel). In some cases, this hybrid ventilation system may be uneconomical, but it promotes animal welfare because the tunnel type ventilation system will only be used occasionally for a few days or for the hot season (summer).

Moreover, as the characterisation of the ventilation is essential for the optimal design of a spray or misting type cooling system, a chapter has been included that optimises the location of the pipes for water distribution and the orientation of the high pressure nozzles. The methodological approach has been very similar to the other chapters in the PhD dissertation (use of CFD, measurements by means of sensors and validation).

The present PhD dissertation supports the use of CFD techniques as a powerful tool in the search for optimum models of broiler buildings and the ventilation systems installed in them, via "virtual" design and management conceptions developed easily in the office using the CFD software.

Resum (en valencià)

L'avicultura intensiva del pollastre de carn (broiler) és un sector estratègic en l'economia i desenvolupament de molts països i regions, entre ells Espanya i la Comunitat Valenciana. La producció intensiva del broiler es dóna confinant a l'animal en edificis específics (granges de pollastres) sota un microclima intern controlat. Té dues variants fonamentals en funció del seu sistema de ventilació: producció en granges amb ventilació natural i producció en granges amb ventilació mecànica (generalment per depressió negativa mitjançant ventiladors d'extracció). Un inadequat disseny de la ventilació és la causa principal de l'estrés tèrmic i de la mortalitat dels pollastres. En aquest sentit, una solució per disminuir l'estrés tèrmic per calor i la mortalitat dels pollastres és ajudar en la seua termoregulació biològica mitjançant un augment de la velocitat damunt d'ells.

En aquesta tesi doctoral, s'ha caracteritzat i analitzat la ventilació (rangs de velocitat de l'aire i la seua distribució, especialment al nivell de presència del pollastre) en els principals sistemes de ventilació mecànics instal·lats a les granges de pollastres. Malgrat l'envergadura de l'actual problemàtica (estrés tèrmic i mortalitat dels pollastres) i la sensibilitat de la societat envers els aspectes del benestar animal, fins aquesta data no s'han caracteritzat i analitzat amb rigor científic els diferents sistemes de ventilació mecànics a les diferents tipologies de granges de pollastres. En aquesta tesi doctoral han sigut estudiats els tres més rellevants: creuat, túnel i de paret única.

L'enfocament metodològic en tots els casos d'estudi ha sigut molt similar: han sigut realitzats uns mesuraments mitjançat us sistema multisensor de registre isotemporal (de disseny i fabricació propis), han sigut realitzades les corresponents simulacions Computational Fluid Dynamics (CFD) i finalment han sigut validades aquestes simulacions. Aquestes validacions s'han dut a terme mitjançant dues tècniques estadístiques: mitjançant tècniques de regressió lineal i mitjançant l'estudi de la significativitat (en una anàlisi de la variància) de la metodologia utilitzada (sensors o CFD) en sengles models de validació proposats. Una vegada validades aquestes simulacions CFD, es té la seguretat de poder utilitzar-les per a caracteritzar i analitzar la ventilació en tot l'espai interior de les granges (els sensors només permeten caracteritzar-la en les localitzacions físiques dels mateixos).

El primer cas d'estudi és el d'una granja que té instal·lat un sistema de ventilació mecànic creuat (habitual en el clima Mediterrani). Les conclusions d'aquest estudi demostren que aquest sistema és adequat per a la criança del pollastre durant quasi tot l'any en localitzacions climàtiques moderades (per exemple, el clima Mediterrani). Tanmateix, en

dies o períodes de calor (estiu), no serà adequat perquè no es poden obtenir valors de velocitat de l'aire grans que permeten disminuir l'estrés per calor dels pollastres.

El segon cas d'estudi és el d'una granja que instal·la el sistema de ventilació mecànic túnel. Les conclusions d'aquest estudi demostren que és menys adequat que l'anterior (sistema de ventilació mecànic creuat) per a la criança del pollastre durant tot l'any en localitzacions climàtiques moderades. Tanmateix, en dies o períodes de calor (estiu), serà molt adequat perquè es poden obtenir valors de velocitat de l'aire grans que permeten disminuir l'estrés per calor dels pollastres.

El tercer cas d'estudi és el d'una granja que instal·la el sistema de ventilació mecànic de paret única. Les conclusions d'aquest estudi demostren que aquest sistema és adequat per a la criança del pollastre durant quasi tot l'any en localitzacions climàtiques moderades. Tanmateix, en dies o períodes de calor (estiu), no serà adequat perquè no es poden obtenir valors de velocitat de l'aire grans que permeten disminuir l'estrés per calor dels pollastres. Els valors de velocitat de l'aire són discretament superiors als obtinguts amb el sistema de ventilació mecànic creuat.

Amb aquests anàlisis i caracteritzacions, es conclou que la granja òptima de pollastres per àrees geogràfiques amb incertesa climàtica (incrementant la seua extensió per l'efecte del canvi climàtic i el calfament global) i per a localitzacions climàtiques moderades ha de tindre instal·lat un sistema mecànic híbrid de ventilació (transversal i túnel). En alguns casos, aquest sistema híbrid serà antieconòmic però respectuós envers el benestar animal perquè el sistema de ventilació tipus túnel només s'utilitzarà ocasionalment per a pocs dies o per a l'estació calorosa (estiu).

A més a més, com la caracterització de la velocitat és la clau pel disseny òptim del sistema de refrigeració d'un sistema per nebulització, ha sigut inclós un capítol que optimitza la localització de les canonades de distribució de l'aigua i l'orientació dels broquets de polvorització de l'aigua. L'enfocament metodològic ha sigut molt similar al dels altres capítols de la tesi doctoral (ús de CFD, mesuraments amb sensors i validació).

La present tesi doctoral avala l'ús de les tècniques CFD com a ferramenta poderosa per a la recerca de models òptims de granges de pollastres i dels seus sistemes de ventilació instal·lats mitjançant concepcions de disseny i de funcionament "virtuals" desenvolupats fàcilment en gabinet amb el software CFD.

Acknowledgements

This PhD thesis was funded in part by the project GV04B-511 (Generalitat Valenciana, Spain) and by the Vicerrectorado of Investigación de la Universitat Politècnica de València (Programa de Apoyo a la Investigación y Desarrollo Multidisciplinar Project PAID register 2614).

In the first place, I would like to express my deep gratitude to my supervisors, Dr. Antonio Hospitaler and Dr. Antonio G. Torres. Both supervisors believed in me and in this work. It is obvious that without their implication beyond strictly academic matters, it would not have been possible to accomplish this PhD thesis.

Three years ago, one of my supervisors retired (Dr. Antonio Torres). However, he has continued to guide me without any need to do so or compensation, simply to finish his “last academic commitment,” as he puts it. In addition to my thanks to Dr. Antonio Torres for assuming “this last commitment”, I also thank Dr. Antonio Hospitaler who, again under no obligation, also provided more help and guidance after Dr. Torres’ retirement. I have been fortunate to find the best supervisors in the world.

I wish to thank Dr. Fernando J. García-Diego for his wisdom in the field of sensors; I have learnt a lot about sensors and I have been able to apply this knowledge in this PhD thesis. Special thanks to him because his contributions and advice were key to finishing this PhD thesis.

I also wish to thank the coauthors, professors and friends at the Universitat Politècnica de València for making this work easier and for the moments of amusement: Salvador Calvet, Fernando Estellés, Enrique Guijarro, Sebastian Balasch, Pedro Beltrán, María Cambra, Elisa Adell, Milagros Borrás, Elena Sanchís, Jose Vicente Martí, Mª Carmen Beltrán, Pau Ferrer, Nemesio Fernández, Cristòfol Peris, Paloma Merello and Claudia Scatigno, to mention a few.

Also, special thanks to Victor Rosa for his expert opinions and for allowing to me gain experience in his broiler building.

Finally, I would like to give special thanks to my mother for my happy life, her continuous support and understanding. Special thanks to my father who died 19 years ago but is always present. Thanks in his name to Dr. Antonio Torres, because he commented to me that if I needed some advice or suchlike from the University, I should ask for him.

Eliseo Bustamante García
Valencia, October 2015

Index

Index of Figures

Index of Tables

List of abbreviations

The following list contains the main abbreviations used in this thesis.

ANOVA Analysis of Variance

ASABE American Society of Agricultural and Biological Engineers

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers.

BC Boundary Condition.

BS British Standard

CFD Computational Fluid Dynamics

DEFRA Department for Environment, Food and Rural Affairs

DIN Deutsches Institut für Normung

EU European Union

FAO Faostat Agriculture

GAMBIT Geometry and Mesh Building Intelligent Toolkit.

GLM Generalized Linear Model

LES Large Eddy Simulation

Max Maximum

Min Minimum

MV Mechanical Ventilation

MVAC	Mechanical Ventilation and Air Conditioning
PC	Personal Computer
PDEs	Partial Differential Equations
RAM	Random Access Memory
RANS	Reynolds Averaged Navier-Stokes
RSM	Reynolds Stress Model
RH	Relative Humidity
RTD	Resistance Temperature Detector
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations.
TFD	Thin Film Detector
UNE	Una Norma de España.
UPV	Universitat Politècnica de València
USA	United States of America
V&V	Verification and Validation
VOF	Volume Finites
3D	Three Dimensional.

Chapter 1

Introduction, objectives and structure of the thesis

This chapter presents:
- The interdepartmental approach and motivation.
- An introductory overview.
- The general context and the initial reviews (state of the art).
- The general aim and specific objectives of this PhD dissertation.
- The scope of this PhD dissertation.
- The structure of this PhD dissertation.
- The published and submitted articles/conferences derived from this PhD dissertation.

1.1. Interdepartmental approach and motivation

This doctoral thesis “Optimisation of design for broiler poultry farms” depends on the Department of Construction Engineering and Civil Engineering Projects of the Universitat Politècnica de València (Spain). However, this doctoral thesis is also developed in the Department of Animal Science of the same University. Therefore, this PhD dissertation opens a new research line that involves two vital departments of this University. Multidisciplinary approaches, creativity and originality among other characteristics are crucial in modern PhD dissertations in a globalised world. Science merges disciplines, cultures, points of view and methodologies creating enthusiasm. “Inter” and “multi” are key prefixes that enrich.

Under the supervision of Dr. Hospitaler (Department of Construction Engineering and Civil Engineering Projects) and Dr. Torres (Department of Animal Science), we hope to create interests and relevant results and conclusions through the contribution and integration of different points of view, methodologies and strategies. On one hand, from the general basis of construction and Computational Fluid Dynamics techniques (CFD) and on the other, in terms of the biological issues of the animals and the peculiarities of animal houses. The synergy of both extraordinary contributions in these two important sides of knowledge creates great initial motivation and interest. Thus, I hope that this interdepartmental line of research will continue in further studies in other livestock buildings.

Among other important objectives and motivations explained through the formal corpus of the doctoral thesis, I wish to outline here one important paragraph on motivation of this type of work, with special relevance for the whole of society and raising awareness of the problem:

“Planet Earth is overpopulated and a large percentage of its inhabitants suffer from famine or are not properly fed. For the future, biological, agricultural, industrial and civil engineers face a great challenge: to provide the necessary food knowing that the land is limited, and supply it at a reasonable price-quality ratio to achieve food supplies for all social strata, considering the rapid increase in population. At this point, intensive production (not exempt from controversy) in agriculture, livestock and fisheries is crucial to provide food to the Earth’s population. This PhD, entitled «Optimisation of design for broiler poultry farms», may form a modest part of the contribution to intensive livestock or “livestock industrialisation” and particularly focuses on intensive poultry production for meat (broilers) in this great challenge, which the scientific community must address and resolve.”

Every day, adults and children alike die from the simple lack of food or water. Production of the necessary food, ethical prices for the producers (farmers), absence of speculation on essential foodstuffs and their ethical distribution in an overpopulated world with limited land and resources are compulsory and highly motivating for the whole of society. We think that the primary needs (justice, food, water, work...) of our society come before anything else.

1.2. Introductory overview

Intensive poultry production for meat (broilers) generally involves confining the animals in specific buildings, which are generally mechanically ventilated. Ventilation is a key variable to optimise their indoor environments and find the optimal designs for these buildings. Surprisingly, there is currently no optimum model for broiler buildings with mechanical ventilation, either in terms of dimensions and/or design or from the point of view of the ventilation system. The absence of this precise guideline in broiler house design gives rise to uncertainty in the building design. Empiricism or intuition is not the way to build animal houses in the third millennium.

For these reasons, it is necessary to characterise and analyse the air velocity distribution and the associated values to discover the deficiencies of the different ventilation systems in the different typologies of these specific buildings. In fact, broilers suffer from great episodes of thermal stress and mortality in different typologies of broiler buildings in some climatic events. These fatal episodes are especially relevant in the hot seasons of the Mediterranean climate, where an important number of broiler buildings are concentrated. Proper air velocity values around the birds are crucial to assist in their biological thermoregulation and to diminish or eliminate the negative effect on the birds of the adverse climatic events. Unfortunately, climate change and global warming increase the areas of climatic uncertainty and occasional unexpected extreme weather (heat or cold waves).

To characterise these air velocity values and their distribution:

(i) We conceived and built **the electronic instrumentation**, i.e., suitable sensors (a multi-sensor system composed of a large number of air velocity, air temperature and differential pressure sensors) able to operate in the tough conditions of broiler buildings, receiving isotemporal signals.

(ii) We carried out **the field experiments** using this original instrumentation system, experimenting in the three main mechanical ventilation systems: **cross, tunnel and single-sided**.

(iii) We performed **the Computational Fluid Dynamics (CFD)** simulations in the same scenarios of the aforementioned field experiments using the appropriate computational settings and the best CFD protocols (most approximate CFD-geometry of the building, better mesh, test convergence studies...).

(iv) We **validated the CFD** results by means of regression lines and validation models, concluding that the CFD tools are fully valid to explore "virtual" geometries of broiler buildings in order to find the optimum broiler buildings and the most suitable ventilation system.

(v) The **results** show that cross and single-sided ventilation systems cannot achieve high enough air velocity values to decrease the excess heat of the broilers and reduce the mortality and heat stress in hot seasons of the Mediterranean climate. On the contrary, tunnel ventilation can achieve these high air velocity values, although it is less appropriate for the cold seasons in Mediterranean climate.

(vi) CFD techniques can also serve to optimise other relevant devices installed in broiler buildings. This way, the indoor air velocity characterisation is the main variable in the best design of a **fogging system** and the orientation of the fog spray nozzles. For this reason, this study is also included in this PhD dissertation.

According to the results, **the optimum broiler building** for the Mediterranean climate or areas with climatic uncertainty will install a hybrid mechanical ventilation system consisting of a transversal mechanical system (cross or single-sided) and a longitudinal mechanical ventilation system (tunnel). In the majority of cases, installing this hybrid mechanical ventilation system will be uneconomical, as the tunnel ventilation system will only be valid for occasional hot days or hot seasons, but entirely respectful with animal welfare issues.

1.3. General context and initial reviews

1.3.1. General context: types of poultry farm, amount and location of broiler production and comparison to other animal meat production

There are currently two major groups of poultry farms: for laying hens and for meat production (broilers). Poultry production for meat (broilers) is one of the most important food industries, with a 633.34 % increase in world production in the period from 1972 to 2012 (FAO, 2015). This percentage increase is the highest compared to the five main types of meat animal production: broiler (633.34 %), turkey (399.18 %), swine (268.61 %), cattle (164.22 %) and sheep (149.62 %). Table 1.1 shows the world production of these five sectors in tonnes. Table 1.1 shows that swine is the main important food production, although the highest percentage increase is in broiler production.

Table 1.1. *Meat animal production in tones (FAO, 2015).*

Type of meat	***1972***	***1982***	***1992***	***2002***	***2012***
Pig	40624567	53198527	72166373	88780643	109122261
Broiler	14653581	25184501	39017741	63581332	92812054
Cattle	38539081	45915112	52741876	56822921	63288605
Sheep	5660347	5887957	7026158	7770001	8470307
Turkey	1405256	2174970	4043669	5417422	5609529

In this huge increase for broiler meat, three issues are key:

(i) The high quality of the meat and the reasonable price to consumers (Slingenbergh *et al.*, 2007).

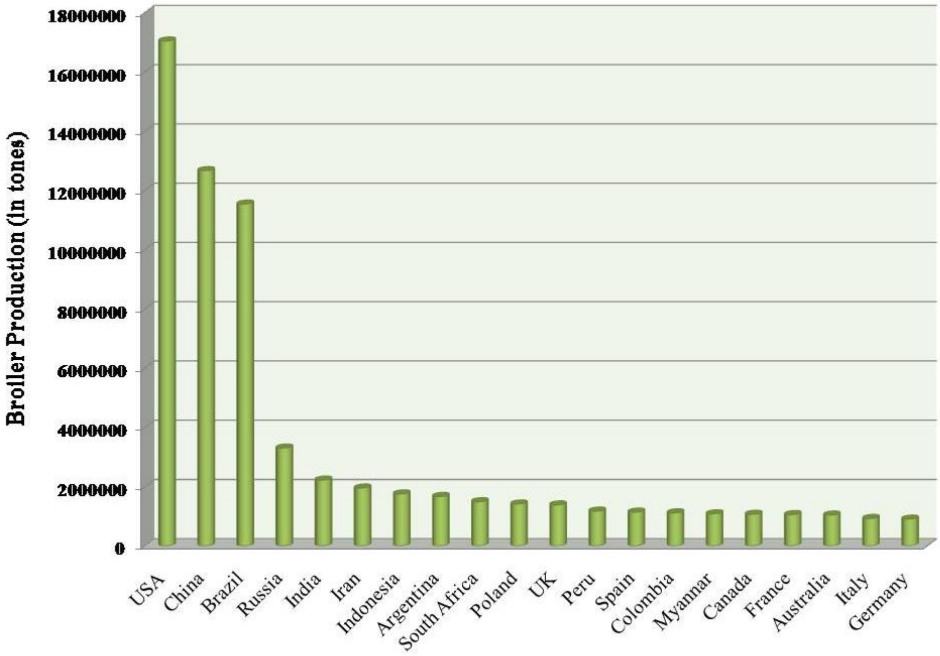
(ii) Poultry meat is accepted by almost all cultural and religious groups, whereas pig, cattle or rabbit meet with acceptance issues in some cultures or religions.

(iii) Among all types of intensive livestock production, broiler production is the most efficient in terms of feed conversion (Steinfeld *et al.*, 2006).

Moreover, broiler production has developed genetic improvements, better and concentrated feed, an improvement in preventive disease controls and biosecurity measures, and the use of technology to exhaustively control in-house environmental conditions (Havenstein *et al.*, 2003).

In the context of production by countries, the USA is the main producer (18.35 % of total world production), China is the second (13.64 %), Brazil is the third (12.43 %) and Russia comes fourth (3.56 %) (FAO, 2015). These four countries concentrate nearly half of all world production. Spain is the thirteenth broiler meat producing country worldwide and an important amount of this broiler production is concentrated in the Valencian Community (Martínez *et al.*, 2008). Figure 1.1 shows the twenty main broiler meat producing countries (FAO, 2015).

Figure 1.1. *Twenty main broiler meat producer countries. Production in tonnes.*



According to the colossal volume of this production (Figure 1.1), intensive poultry farming for meat is a strategic sector in the economy of many countries and regions.

1.3.2. Poultry housing for broilers

Modern intensive broiler production consists of confining the birds in animal houses and has two fundamental variants: production in animal houses with natural ventilation and production in animal houses with mechanical ventilation. On the other hand, there is also an emergent variety of poultry meat in developed countries known as ecological/organic production for the type of consumer who does not mind paying a much higher price for the product compared to that obtained in intensive production. This type of production takes place in open air, yards or rooms rather than specific buildings and is usually very limited. Of course, another type of minority production is non-commercial or for family consumption, typical of primitive societies, developing countries or rural settings.

Intensive production (not exempt from controversy) takes place in modern buildings that resemble factories and the animal production process has several analogies with an industrial process in the whole sense. Thus, we can incorporate new terms: the terms "livestock industrialisation" to describe the progress and industrialisation of the livestock sector and the terms "factory farms" to speak about modern animal houses.

In broiler buildings, the most prominent ventilation system uses mechanical or forced ventilation, mainly through negative-pressure systems (ASAE, 1986; MWPS, 1990; Pedersen, 1999). In these broiler buildings, energy savings have become increasingly important due to climate change and rising energy prices (Rajaniemi *et al.*, 2012). Lighting, ventilation and fans are shown to account for over 80% of the total electrical consumption (Corkery *et al.*, 2013; Teagasc, 2011). Of course, the energy consumption depends on many factors: climate, season, building type, management, age of the broilers… In cold-temperate weather, in the broiler buildings of Ireland, heating the indoor environment represents 84 % of the total direct energy consumption (mainly by using fuel) and the ventilation issues represent 7 % of the total direct energy consumption and the main spend in total electricity consumption (45 %). The outlay on lighting is slightly lower (37 % of total electricity consumption) (Corkery *et al.*, 2013; Teagasc, 2011). Evidently, in countries with hot weather the ventilation needs will be greater and the expenditure on electricity consumption will be higher. Of course, the greatest energy input (indirect energy consumption) in broiler production is in the feed (Baughman *et al.*, 1977).

In intensive poultry housing for broilers, it is necessary to control different key variables that strongly affect the bird: ventilation, lighting, stocking density, feed supply, health, nutrition, temperature, water supply and vaccinal status (Ross, 1996).

Mechanical ventilation systems allow a high density of broilers and more thermal comfort compared to naturally ventilated broiler buildings (Charles *et al.*, 2002). According to Dawkins *et al.*, 2004, housing conditions are acknowledged as having greater impact than animal density on broiler welfare. Surprisingly, there is currently no optimum model for broiler buildings with mechanical ventilation, either in terms of dimensions and/or design or from the point of view of the ventilation system. The absence of this precise guideline in broiler house design leads to uncertainty in the building design. Thus, several retrofits were found after the first functional conception of the broiler building.

Empiricism or intuition is not the way to build animal houses in the third millennium. Broiler production in the third millennium needs to be revised, incorporating recent technological advances and scientific approaches.

1.3.3. Hot weather and cold weather. Climate change and uncertainty

According to the climatic conditions, broiler building conceptions are different and the problems are different. In cold or temperate weather, the building will need more specific designs and strategies to heat the indoor space to achieve the proper temperature for the birds. On the contrary, in hot weather, the building will need more specific designs and strategies to decrease the indoor temperature and the excess heat on the birds.

In Mediterranean climate, the weather is not constant; the seasonal changes can be greater. Evidently, broiler buildings must be designed taking each climatic season into account. Thus, both functional conceptions in design (for hot and cold weather) need to be present in the broiler building model in Mediterranean climate.

As in any building, each broiler building needs to be designed according to the requirements for the entire period of its useful life. However, climate change and global warming cause climatic uncertainty in the designs of any building (Holmes *et al.*, 2007) and evidently in livestock systems (Nardone *et al.*, 2010). For these effects, some constructed broiler buildings require adaptation after their initial design and conception. Of course, new broiler buildings must take into account in their functional conception the possible effects of climate change and unexpected periods of hot weather (e.g. heat waves) or cold weather (e.g. cold waves).

In the short/mid-term, the status of some climatic areas will change. Moreover, a high percentage of broiler buildings will need to be designed to solve both extreme climatic conditions (cold and hot weather).

1.3.4. Effects of cold temperatures and hot temperatures on broilers

Temperatures cause a great range of effects on broilers. Cold broilers are less active, so do not eat and do not gain weight. During winter or cold weather, birds exposed to lower temperatures suffer cold stress. The cold stress significantly affects broiler health, welfare and performance (Blahova *et al.*, 2007; Yang *et al.*, 1999). In cold weather, broiler buildings must be heated to increase the indoor temperature. Broilers need to increase their metabolism levels through an increase in this indoor temperature and feed. In this sense, the indoor oxygen requirements are greater on one hand to contribute to devices that heat the building (heating systems) and on the other, to help in the feed consumption of the animals. Of course, the rearing phase of the birds is an important factor, because if the broilers are younger or featherless it is necessary to heat the building more than if the birds are older. On the other hand, older broilers need to breathe greater amounts of oxygen than younger ones (Czarich *et al.*, 2003).

Hot temperatures also affect broiler health, welfare and performance by causing heat stress (Daghir, 2001; Deaton *et al.*, 1997; DEFRA, 2008; Sohail *et al.*, 2012; Yanagi *et al.*, 2002; Yavah *et al.*, 2004). During this heat stress, broilers are less active, panting or breathing with difficulty, and the blood parameters are altered, especially the stress hormones (corticosteroid, adrenocorticotrophic and glucocorticoid hormones) (Altan *et al.*, 2000; Edens *et al.*, 1975). Thus, corticosteroid concentrations are used to measure the environmental stress in broilers (Altan *et al.*, 2000; Siegel, 1975). DEFRA, 2008 refers to the changes in the broiler metabolism and the need for thermoregulation to reduce the internal heat of the animals. In this thermoregulation, broiler housing ventilation (by means of high air velocity values) can help by increasing the convective flux heat of broilers and therefore decrease their heat stress and associated mortality.

In both extreme cases (very high or low temperature), the fatal consequences will be thermal stress (heat or cold stress) and, in some cases, mortality of the broilers. In the Mediterranean summer climate, the episodes of mortality by heat stress are repetitive, with several mortality rates (El País, 2003). The economic losses due to heat stress are huge; in the US poultry industry alone, the total annual estimated losses range from $128 to $165 million (St-Pierre *et al.*, 2003).

1.3.5. Broiler housing ventilation: the main problem in Mediterranean climate and areas with climatic uncertainty. Introductory overview of cross and tunnel mechanical ventilation

Ventilation plays a critical role in ensuring appropriate indoor conditions to achieve high broiler productivity (growth and food conversion) and low mortality (Charles *et al.*, 2002; Lott *et al.*, 1998). Ventilation design is based on three basic principles: the rate of air exchange, air distribution and air velocity range at the animal level (ASAE, 1986; MWPS, 1990; Pedersen, 1999). In this context, the dominant intensive production system for broilers takes place in buildings with mechanical ventilation, mainly by negative pressure by means of exhaust fans. These mechanically ventilated broiler buildings allow higher broiler density and independence from the outdoor weather, thereby improving the internal microclimate and increasing the animals' comfort.

In cold, temperate and Mediterranean climate (where an important part of broiler production is concentrated), cross-mechanical ventilation is the most widespread ventilation system in broiler production (Blanes-Vidal *et al.*, 2008).

In hot or tropical climates, the principal ventilation system is mechanical tunnel ventilation (Daghir, 2001). In tunnel mechanical ventilation, it is possible to achieve air velocities in a wide range from ~0.5 $m\ s^{-1}$ to ~3 $m\ s^{-1}$. These high velocities can help in the aforementioned process of thermoregulation of broilers in hot weather (DEFRA, 2008, Simmons *et al.*, 2003). It is essential to differentiate the needs of air velocity and the needs of oxygen. Using only a small number of fans, the renewals of air and the quantity of oxygen (approximate a 20% of air is oxygen) are considerably lower than when using a greater number of fans (independently of the ventilation system used). Controlling both crucial variables of broiler building management (air velocity and demands of oxygen) is key. It is also crucial to control the level of pollutants (the maximum ammonia concentration levels for broilers must be around 20 ppm, while for carbon dioxide, about 5,000 ppm (Carvalho *et al.*, 2012).

In addition, heterogeneity of air velocity distribution is undesirable, as it causes indoor migration of broilers and higher concentrations of birds in some areas of the building. An excess of density or birds is adverse (Dawkins *et al.*, 2004) and the same indoor migration can cause stress (Blanes-Vidal *et al.*, 2008).

Nowadays, broiler buildings equipped with these mechanical ventilation systems (cross and tunnel) have thermal problems. These thermal problems are frequently described by the farmers interviewed and objectively verified by the high number of deaths and blood stress parameters of the broilers (Altan *et al.*, 2000; Siegel, 1975). Higher or lower concentrations of the birds are also observed in some specific areas of the broiler buildings. For these reasons, new mechanical ventilation systems have been introduced, with new disposition of fans, the use of heat exchangers and cones at fans among other strategies. These new ventilation systems and strategies are especially experienced in Mediterranean climate, where the heat stress on broilers in hot seasons is an important and cyclic problem.

1.3.6. (State of the art) Review of the literature, publications, main contributions and current methodologies to characterise indoor environments and ventilation patterns in broiler buildings. CFD, electronic instrumentation (sensors) and validation

There is an important lack of publications and specific literature about the characterisation of indoor environments and ventilation in broiler buildings. Despite the sector's economic importance, the colossal production volume and the huge increase in confined intensive broiler production shown in Table 1.1, it is very difficult to find an important review of the microclimate characteristics of the buildings. The importance of broiler production does not entail the supposed equivalent amount of specific scientific literature, precise values, references, contributions or guidelines. The constant complaints of the producers (farmers) and news of massive deaths of broilers in national newspapers (El País, 2003) and in specific websites of the sector (World Poultry, 2012) merely confirm and outline the big thermal problem in a non-scientific way or approach. However, it is possible to find a lot of published scientific literature, contributions and proposed methodologies for studying the indoor environments in other important agricultural buildings, such as greenhouses. Of course, taking into account their peculiarities, it is possible to apply all the equivalent published scientific literature on buildings for human activities (houses, flats, museums, stadiums...) and for plants (greenhouses) to broiler buildings. Besides, the influence of indoor environment of broiler buildings on humans (farmers, vets...) who work in them must be considered in some specific branches of research.

According to the current state of the art, the trends to characterise indoor environments of agricultural buildings (greenhouses and livestock buildings) and also for buildings for human activities have two major methodologies: direct measurements with the appropriate electronic instrumentation (sensors) and indirect methods such as Computational Fluid Dynamics (CFD) techniques. The use of these CFD techniques applied to agricultural buildings such as greenhouses (Bartzanas *et al.*, 2004; Boulard *et al.*, 2002; Bournet *et al.*, 2010; Campen *et al.*, 2003; Fatnassi *et al.*, 2006; Mistriotis *et al.*, 1997; Molina-Aiz *et al.*, 2004; Norton *et al.*, 2007; Valera *et al.*, 2006) and livestock buildings (Bartzanas *et al.*, 2007; Bjerg *et al.*, 2002; Blanes-Vidal *et al.*, 2008; Lee *et al.*, 2007; Norton *et al.*, 2007; Pawar *et al.*, 2007; Xia *et al.*, 2002) has exponentially increased in recent years. On the other hand, the use of CFD in buildings for human occupation is much more developed, with more years of experience leading to an immense body of published literature.

In all cases, a key point in the use of CFD techniques is the need for validation of the numerical simulations (Oberkampf *et al.*, 2002) by means of suitable instrumentation. To this end, interesting instrumentation and data acquisition systems have been developed to validate these CFD simulations applied in agricultural buildings: in greenhouses (Boulard *et al.*, 1995; López *et al.*, 2011; Pawlowsky *et al.*, 2009; Shilo *et al.*, 2004) and in livestock buildings (Berckmans *et al.*, 1991; Blanes-Vidal *et al.*, 2010; van Wagenberg *et al.*, 2003; Wilhelm *et al.*, 2001; Zhang *et al.*, 1996). It should be noted that the use of CFD techniques and associated instrumentation for validation is widespread in other engineering fields (e.g. aerodynamic, automotive, spatial, chemistry, nuclear, fire simulation...), but in agricultural engineering they are less developed, particularly in the study of indoor livestock building environments.

Focusing on broiler buildings, the published literature is very scarce and the points of departure and the necessary references of this PhD dissertation are two articles: the article focused on CFD applications in broiler buildings by Blanes-Vidal *et al.*, 2008 and the article on electronic instrumentation for validation of these CFD simulations of air velocity (Blanes-Vidal *et al.*, 2010). Unfortunately, these two articles only analyse one mechanical ventilation system (cross) and the number of sensors used to validate the CFD simulations is very limited (3 sensors). In the CFD article of necessary reference for this PhD dissertation (Blanes-Vidal *et al.*, 2008): CFD Fluent (Fluent, 2001) was used to perform the numerical simulations and Gambit (Gambit, 2001), the pre-processor of Fluent, was also used to create the geometry of the broiler building and the mesh. This commercial CFD software is widely used in different fields of engineering, such as in greenhouses or in buildings for human occupation. CFD Fluent (Fluent, 2001) is powerful commercial CFD software and a guarantee of good numerical results.

On the other hand, as in all building types, there is a strong relation between the nature and characteristics of the buildings (geometry, doors, windows, building materials...) with the resulting indoor environments. Unfortunately, from the point of view of construction, geometry and facilities, it is necessary to indicate that livestock buildings are usually very heterogeneous in terms of building materials, geometry, dimensions, location of windows, doors and ventilation systems, etc. Likewise, broiler buildings are even more heterogeneous, as there is currently no optimum model for broiler buildings. Consequently, a great variety of broiler building typologies and installed ventilation systems are found. A repertory or catalogue of broiler buildings by categories (building typology and installed ventilation system) is the first step to begin the case studies in this PhD dissertation. In the case of the Valencian Community (Spain), a database collated by Martinez *et al.*, 2008 was the initial reference. From this database and from new inspections of broiler buildings, we found three major cases for study: broiler buildings equipped with cross-mechanical ventilation, with tunnel mechanical ventilation and with single-sided mechanical ventilation. Cross and tunnel are commonly installed in broiler buildings (traditional ventilation systems), whereas single-sided is an emergent and experimental ventilation system.

To sum up in a single sentence, the uncertainty and anarchy in broiler building design and the ventilation systems installed is the current essence of the nature of broiler buildings. However, we find three important cases to study: broiler buildings equipped with cross-mechanical ventilation, with tunnel mechanical ventilation and with single-sided mechanical ventilation. Therefore, the indoor microclimate trends and characterisation of the indoor ventilation will depend on the typology of the building and the ventilation system installed.

1.4. General aim and specific objectives of this PhD dissertation

This section describes the general aim of this PhD dissertation, as well as the specific objectives set for its consecution.

1.4.1 General aim

There is a huge lack of previous studies and specific literature on the characteristics of indoor environments and characterisation of the ventilation in the different broiler buildings. Surprisingly, there are currently no optimum models for broiler buildings, either in typologies or the ventilation systems installed. The absence of this precise guideline in design causes uncertainty in the building design, in the ventilation system and in other key devices installed, such as the cooling system. Thus, several retrofits were found after the first functional conception. Empiricism or intuition is not the way to build animal houses in the third millennium. In recent decades, the "livestock industrialisation" process characterised by a huge increase in the number of livestock buildings with operational and automation procedures similar to those of factories has led to broiler buildings being designed with several deficiencies. Among these defects, the main problem is the ventilation and the consequent thermal problems on the broilers, especially relevant in the hot days of the Mediterranean climate. Optimising all the colossal variables of design and functioning of these complex buildings is an immense work. Moreover, it is necessary to take into account the interaction with the birds and their biological performance, which can change depending on the type, genetics, age or weather conditions... Thus, this PhD dissertation strikes a necessary balance between the "agricultural and biological surroundings and conception" and "industrial sense".

Therefore, the general aim of this PhD dissertation is to characterise the ventilation and indoor air velocities (ranges and distribution) of the main mechanical ventilation systems in different broiler building typologies, in order to outline an optimum general model. As mentioned previously, the air velocity issue is the key variable to solve the current problems of mortality and thermal stress on the animals in broiler buildings in the Mediterranean climate. Through these analyses, we shall discuss and draw conclusions on the advantages or disadvantages of each type of ventilation system installed and building architecture, establishing future trends and design protocols for new broiler buildings and retrofits of the broiler buildings already constructed, under the premise of efficiency and optimisation in the fullest sense of the words. To perform these analyses, we used powerful methodologies: the CFD techniques and the suitable electronic instrumentation. CFD simulations are validated using an original multi-sensor system specifically designed and conceived for this PhD dissertation. Validation of the numerical results is carried out through statistical approaches: regression lines and validation models. From this dissertation, CFD techniques can be used to explore broiler building architectures that install "virtual" ventilation systems in order to find the optimum broiler building geometry and the best ventilation system.

On the other hand, as the key variable in designing the cooling system (in this case, a fogging system) is full knowledge of the indoor air velocity characterisation, this PhD dissertation also includes a chapter on the design of a fogging system for the tunnel mechanically ventilated broiler building in chapter 6.

Finally, taking into account the results of the different air velocity characterisations in the case studies, the general optimum models for broiler houses are proposed. In this way, and in the case of Mediterranean climate or areas with climatic uncertainty, the optimum broiler building will have a hybrid mechanical ventilation system installed, consisting of a transversal mechanical system (cross or single-sided) and a longitudinal mechanical ventilation system (tunnel).

1.4.2. Specific objectives

To achieve the general aim of this PhD dissertation, the following specific objectives must be covered:

1. Initial reviews of the introductory items, the context and the state of the art on beginning the research for this thesis.

2. To conceive and build the electronic instrumentation (sensors) to measure environmental parameters in broiler buildings. For this PhD dissertation, a multi-sensor system has been conceived and built with 24 air velocity sensors, 24 air temperature sensors, 2 differential pressure sensors and 7 multiplexers able to receive isotemporal signals. This multi-sensor system designed will be able to verify and validate (V&V) the CFD simulations developed for broiler buildings and able to work perfectly under the tough conditions in which the field measurements will be taken.

3. To characterise and analyse cross mechanical ventilation experimenting in the corresponding broiler building by using current scientific methodologies (the multi-sensor system designed and CFD simulations). By means of this characterisation and analysis, some possible deficiencies in the ventilation system will be detected, as well as in the geometry of the broiler building, the thermal problems in the broilers, the suitability of this ventilation system for rearing broilers throughout the year, and the methodologies and strategies to optimise the ventilation system, proposing future corrective management and actions.

4. To characterise and analyse the tunnel mechanical ventilation experimenting in the corresponding broiler building by using current scientific methodologies (the multi-sensor system designed and CFD simulations). By means of this characterisation and analysis, some possible deficiencies will be detected in the ventilation system as well as in the geometry of the broiler building, the thermal problems in the broilers, the suitability of this ventilation system for rearing broilers throughout the year, and the methodologies and strategies to optimise the ventilation system, proposing future corrective management and actions.

5. To characterise and analyse single-sided mechanical ventilation experimenting in the corresponding broiler building by using current scientific methodologies (the multi-sensor system designed and CFD simulations). By means of this characterisation and analysis, some possible deficiencies will be detected in the ventilation system and in the geometry of the broiler building, the thermal problems in the broilers, the suitability of this ventilation system for rearing broilers throughout the year, and the methodologies and strategies to optimise the ventilation system, proposing future corrective management and actions.

6. To design a cooling system (a fogging system) based on the characterisation of the ventilation of a broiler building. This cooling design will focus mainly on the location of the pipes, the orientation of the fog spray nozzles and the easy calculation of the amount of water used during the cooling period. Design strategies in case of failures and methodologies for maintenance will be also proposed.

7. To propose general optimum broiler buildings for climatic areas with constant cold weather, constant hot weather and areas of Mediterranean climate or areas of climatic uncertainty (the main cases).

> **7.1.** To propose protocols to achieve specific optimum broiler buildings under the requirements of the building, customers, investment, etc.
>
> **7.2.** To introduce heuristic procedures in order to achieve these specific optimum broiler buildings.

These specific objectives are structured and numbered by this procedure so that they will be achieved in the corresponding chapters of the doctoral thesis (e.g. specific objective 7.X will be achieved in chapter 7). This structuring of the specific objectives enables better coherence and gradation of the doctoral thesis.

1.5. Scope of the PhD dissertation

The scope of this thesis is limited to experiments in empty broiler buildings and to analysing the air velocity characterisation in the main mechanical ventilation systems in different broiler building typologies. However, the multi-sensor system designed and conceived is able to work with birds and the CFD techniques can easily be implemented in the presence of the broilers and the emitted heat source.

The scope of this thesis was broad because the thresholds were very low in all spheres from the outset: we needed to conceive and build all the electronic instrumentation; databases and cataloguing of the broiler buildings were obsolete; the field experiments involved a lot of time and resources without specific previous guidelines; CFD simulations took up a lot of time, improving the numerical results in this dissertation because we adopted more accurate boundary conditions and better computational settings and options (turbulence models, better geometry, better quality of the mesh...).

We have opened a strong line of research, with solid fundamentals to enable us to analyse other design variables, to easily include the presence of birds in CFD, to also perform the field experiments with birds using this instrumentation and, finally, to extrapolate these protocols and methodology to other livestock buildings.

1.6. PhD dissertation structure

In this PhD dissertation, eight chapters are developed. These chapters are organised in the most suitable order for better coherence and comprehension for the readers, resulting in a monographic work. Development of the instrumentation is dealt with first, before going on to develop the chapters that analyse and characterise the indoor air velocity of the three main mechanical ventilation systems (cross, tunnel and single-sided) in different broiler building typologies. Then, a chapter related to the design of a fogging system in the tunnel broiler building of chapter 4 is also included, as the main variable in their optimal design is characterisation of the ventilation.

Some chapters have been published (chapter 2, 3 and 4) in or submitted (chapter 5 and 6) to an international journal indexed in Journal Citations Report. Miscellaneous excepts and outlines of chapters have been presented at conferences (obtaining an award at the International Conference of Évora (Portugal)) and a brief summary of the state of the art and future perspectives on ventilation in intensive broiler production has also been submitted as a letter to an international journal indexed in Journal Citations Report.

The chapters are structured as follows:

- An initial chapter for the introduction, objectives and structure of the thesis.
- A second chapter on the instrumentation used to measure indoor broiler house environments.
- A third chapter to study cross mechanical ventilation in broiler houses.
- A fourth chapter to study tunnel mechanical ventilation in broiler houses.
- A fifth chapter to study single-sided mechanical ventilation in broiler houses.
- A sixth chapter to analyse the CFD possibilities in the cooling and heating systems of broiler houses, focusing on fogging systems.
- A seventh chapter with general results and discussion.
- An eight chapter with the conclusions.

1.7. Published articles/conferences derived from this PhD dissertation. Awards

Some articles have been published in an international journal indexed in Journal Citations Report and some conference articles were derived from the present PhD dissertation. In addition, an award was granted. These published articles and conferences are as follows:

Refereed journal articles

Bustamante E., Guijarro E., García-Diego F.J., Balasch S., Hospitaler A., Torres A.G. (2012). Multisensor system for isotemporal measurements to assess indoor climatic conditions in poultry farms. *Sensors* 2012, 12, 5752-5774. **(Q1)**

Bustamante E., García-Diego F.J., Calvet S., Estellés F., Beltrán P., Hospitaler A., Torres A.G. Exploring Ventilation Efficiency in Poultry Buildings: The Validation of Computational Fluid Dynamics (CFD) in a Cross-Mechanically Ventilated Broiler Farm. *Energies* 2013, 6, 2605-2623. **(Q2)**

Bustamante E., García-Diego F.J., Calvet S., Torres A.G., Hospitaler A. Measurement and numerical simulation of air velocity in a tunnel-ventilated broiler house. *Sustainability* 2015, 7, 2066-2085. **(Q3)**

Conference articles

National Conferences

Bustamante E., Montero M., Alós M., Guijarro E., Estellés F., Calvet S., Cambra M., Hospitaler A., Torres A.G. (2009). Diseño prévio de un protocolo para medir el caudal de los ventiladores en granjas mediante técnicas CFD. Proceedings of the V Congreso Nacional y II Congreso Ibérico AGROINGENIERÍA 2009, September 28-30, Lugo, Spain.

Bustamante E., Montero M., Alós M., Guijarro E., Estellés F., Calvet S., Cambra M., Fernández N., Hospitaler A., Torres A.G. (2009). Ensayos preliminares mediante la utilización de técnicas CFD para la optimización del diseño de granjas avícolas de pollos. Proceedings of the V Congreso Nacional y II Congreso Ibérico AGROINGENIERÍA 2009, September 28-30, Lugo, Spain.

International Conferences

Estellés F., Montero M., **Bustamante E.**, Torres A.G., Calvet S. (2010). Effect of distance and number of measurement points when determining airflow rates in a conducted fan. Proceedings of the ASABE 2010 Annual International Meeting, June 20-23, Pittsburgh, USA.

Bustamante E., F.J. García-Diego, Estellés F., Calvet S., Hospitaler A., Torres A.G. (2011). Influencia de las condiciones de entrada y salida del aire sobre los parámetros ambientales en granjas avícolas de pollos (Premio a la mejor comunicación en el área temática de Tecnología de la Producción Animal). Proceedings of the VI Congreso Ibérico AGROINGENIERÍA 2011, September 5-7, Évora, Portugal.

Estellés, F.; **Bustamante, E.**; Torres, A.G.; Calvet, S. Evaluation of climate control strategies in rabbit houses. Proceedings of 10th World Rabbit Congress, September 3-6, Sharm El Sheikh, Egypt, 2012.

Awards

Premio a la mejor comunicación del VI Congreso Ibérico AGROINGENIERÍA 2011, September 5-7, Évora, Portugal, 2011 en la temática de producción animal a:

Bustamante, E.; García-Diego, F.J.; Calvet, S.; Estellés, F.; Hospitaler, A.; Torres, A.G. Influencia de las condiciones geométricas de la entrada y salida de aire sobre los parámetros ambientales en granjas avícolas de pollos. Proceedings of the VI Congreso Ibérico AGROINGENIERÍA 2011, September 5-7, Évora, Portugal, 2011.

1.8. References

Altan, Ö.; Altan, A.; Çabuk, M.; Bayraktar, H. Effects of heat stress on some blood parameters in broilers. *Turk J Vet Anim Sci* 2000, 24, 145-148.

ASAE EP270.5. Design of Ventilation Systems for Poultry and Livestock Shelters. In ASABE Standards 2009; American Society of Agricultural and Biological Engineers (ASABE): St. Joseph, MI, USA, 1986; pp. 1–19.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). ASHRAE Fundamentals Handbook; American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.: Atlanta, GA, USA, 2001.

Baughman, G.R.; Parkhurst, C.R. Energy consumption in broiler production. *T ASAE* 1977, 20, 341-344.

Bartzanas, T.; C. Kittas, T. Boulard. Effect of vent arrangement on windward ventilation of a tunnel greenhouse. *Biosyst. Eng.* 2004, 88, 479-490.

Bartzanas, T.; Kittas, C.; Sapounas, A.A.; Nikita-Martzopoulou, C. Analysis of airflow through experimental rural buildings: Sensitivity to turbulence models. *Biosyst. Eng.* 2007, 97, 229–239.

Berckmans, D.; Vandenbroeck, P.; Goedseels, V. Sensor for continuous measurement of the ventilation rate in livestock building. *Indoor Air* 1991, 1, 323–336.

Bjerg, B.; Svidt, K.; Zhang, G.; Morsing, S.; Johnsen, J.O. Modeling of air inlets in CFD prediction of airflow in ventilated animal houses. *Comput. Electron. Agr.* 2002, 34, 223–235.

Blahova, J.; Dobsikova, R.; Strakova, E.; Suchy, P. Effect of low environmental temperature on performance and blood system in broiler chickens (Gallus domesticus). *Acta Vet. (Brno)* 2007, 76, 17-23.

Blanes-Vidal, V.; Guijarro, E.; Balasch, S.; Torres, A.G. Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. *Biosyst. Eng.* 2008, 100, 105–116.

Blanes-Vidal, V.; Guijarro, E.; Nadimi, E.S.; Torres, A.G. Development and field test of an on-line computerized instrumentation system for air velocity, temperature and differential pressure measurements in poultry houses. *Span. J. Agric. Res.* 2010, 8, 570–579.

Boulard, T.; Draoui, B. Natural Ventilation of a Greenhouse with continuous roof vents: Measurements and data analysis. *J. Agr. Eng. Res.* 1995, 61, 27-36.

Boulard, T.; Kittas, C.; Roy, J.C.; Wang, S. Convective and Ventilation Transfers in Greenhouses, Part 2: Determination of the Distributed Greenhouse Climate. *Biosyst. Eng.* 2002, 83, 129-147.

Bournet. P.E.; Boulard, T. Effect of ventilator configuration on the distributed climate of greenhouses: *Comput. Electron. Agr.* 2010, 74, 195–217.

Calvet, S.; Cambra-López, M.; Blanes-Vidal, V.; Estellés, F.; Torres, A.G. Ventilation rates in mechanically ventilated commercial poultry buildings in Southern Europe: Measurement system development and uncertainty analysis. *Biosyst. Eng.* 2010, 106, 423–432.

Campen, J.B.; Bot, G.P.A. Determination of Greenhouse-specific Aspects of Ventilation using three-dimensional Computational Fluid Dynamics. *Biosyst. Eng.* 2003, 84, 66-77.

Carvalho, T.M.R.; Moura, D.J.; Souza, Z.M.; Souza, G.S.; Freitas, L.G.; Lima, K.A.O. Use of geostatistics on broiler production for evaluation of different minimum ventilation systems during brooding phase. *R. Bras. Zootec.* 2012, 41, 194-202.

Czarick, M.; Fairchild, B. Poultry housing tips. Oxygen. Technical Bulletin, December 2003, Vol. 15, number 11. Athens: University of Georgia, USA, 2003.

Charles, D.; Walker, A. Poultry Environment Problems: A Guide to Solutions, 1st ed.; Charles, D., Walker, A., Eds.; Nottingham University Press: Nottingham, UK, 2002.

Corkery, G.; Ward, S.; Kenny, C.; Hemmingway, P. Monitoring environmental parameters in poultry production facilities. Institute for Process and Particle Engineering. Graz University of Technology, Graz, Austria, 2013.

Daghir, N.C. Poultry Production in Hot Climates; CAB International: Wallingford, UK, 2001.

Dawkins, M.S.; Donnelly, C.A.; Jones, T.A. Chicken welfare is influenced more by housing conditions than stocking density. *Nature* 2004, 427, 342–344.

Deaton, J.W.; Reece, F.N.; Mcnaughton, N. The effect of temperature during the growing period on broiler performance. *Poult. Sci.* 1997, 57, 1070-1074.

DEFRA (Department for Environment, Food and Rural Affairs). Heat Stress in Poultry. Solving the Problem; DEFRA: London, UK, 2008.

Edens, F.W.; Siegel, H.S. Modification of corticosterone and glucose responses by sympathologic agents in young chickens during acute heat exposure. *Poult. Sci.* 1976, 55, 1704-1712.

El País, Anonymous. Medio millón de pollos mueren fuerte calor últimos días. Available online:
http://www.elpais.com/articulo/Comunidad/Valenciana/Medio/millon/pollos/mueren/

fuerte/calor/ultimos/dias/elpepiespval/20030617elpval_4/Tes (accessed on 14 June 2015).

FAO. **Faostat-Agriculture.** Available online: http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor (accesed on 14 June 2015).

Fatnassi, H.; Boulard, T.; Poncet, C.; Chave, M. Optimisation of Greenhouse Insect Screening with Computational Fluid Dynamics. *Biosyst. Eng.* 2006, 93, 301-312.

Fluent. Fluent User's Guide, version 6.0; Fluent Inc.: Lebanon, NH, USA, 2001.

Gambit. Gambit User's Guide, version 2.0; Fluent Inc.: Lebanon, NH, USA, 2001.

Havenstein, G.B.; Ferket, P.R.; Qureshi, M.A. Growth, livability and feed conversion of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. *Poultry Sci.* 2003, 82, 1500–1508.

Holmes, M.J.; Hacker, J.N. Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century. *Energ. Build.* 2007, 39, 802–814.

Lee, I.B.; Sase, S.; Sung, S.H. Evaluation of CFD accuracy for the ventilation study of a naturally ventilated broiler house. *Jpn. Agric. Res. Q.* 2007, 41, 53–64.

López, A.; Valera, D.L.; Molina-Aiz, F.D. Sonic Anemometry to Measure Natural Ventilation in Greenhouses. *Sensors* 2011, 11, 9820–9838.

Lott, B.D.; Simmons, J.D.; May, J.D. Air velocity and high temperature effects on broiler performance. *Poultry Sci.* 1998, 77, 391–393.

Martínez, M.; Marín, C.; Torres, A.; Laínez, M. Characterization of chicken farm of the Valencian Community (In Spanish); Fundación Agroalimed, Conselleria d´Agricultura, Pesca i Alimentació. Generalitat Valenciana: Valencia, Spain, 2008; pp. 93–97.

Mistriotis, A.; de Jong, T.; Wagemans, M.J.M.; Bot, G.P.A. Computational fluid dynamics as a tool for the analysis of ventilation and indoor microclimate in agriculture buildings. *Neth. J. Agr. Sci.* 1997, 45, 81–96.

Molina-Aiz, F.D.; Valera, D.L.; Álvarez, J.A. Measurements and simulation of climate inside Almería-type greenhouses using computational fluid dynamics. *Agr. Forest. Meteorol.* 2004, 125, 33-51.

MWPS. Mechanical Ventilating Systems for Livestock Housing, 1st ed.; Midwest Plan Service, Iowa State University: Ames, IA, USA, 1990.

Nardone, A.; Ronchi, B.; Lacetera, N.; Ranieri, M.S.; Bernabucci. U. Effects of climate changes on animal production and sustainability of livestock systems. *Livest. Sci.* 2010, 130, 57–69.

Norton, T.; Sun, D.; Grant, J.; Fallon, R.; Dodd, V. Applications of computational fluid dynamics (CFD) in the modeling and design of ventilation systems in the agricultural industry: A review. *Bioresour. Technol.* 2007, 98, 2386–2414.

Oberkampf, W.L.; Trucano, T.G. Verification and validation in computational fluid dynamics. *Progr. Aerosp. Sci.* 2002, 38, 209–272.

Pawar, S.R.; Cimbala, J.M.; Wheeler, E.F.; Lindberg, D.V. Analysis of poultry house ventilation using computational fluid dynamics. *Trans. ASABE* 2007, 50, 1373–1382.

Pawlowski, A.; Guzman, J.L.; Rodríguez, F.; Berenguel, M.; Sánchez, J.; Dormido, S. Simulation of greenhouse climate monitoring and control with wireless sensor network and event-based control. *Sensors* 2009, 9, 232–252.

Pedersen, S. Forced Ventilation. In CIGR Handbook of Agricultural Engineering: Animal Production & Aquacultural Engineering; American Society of Agricultural Engineers (ASAE):St. Joseph, MI, USA, 1999; pp. 68–87.

Rajaniemi, M.; Ahokas, J. A case study of energy consumption measurement system in broiler production. *Agronomy Research* 2012, 1, 195-204.

Ross Breeders, 1996. Producing quality broiler meat. Ross broiler management manual. Ross Breeders Limited, Midlothian, UK.

Shilo, E.; Teitel, M.; Mahrer, Y; Boulard, T. Air-flow patterns and heat fluxes in roof-ventilated multi-span greenhouse with insect-proof screens. *Agr. Forest. Meteorol* 2004, 122, 3–20.

Siegel. H.S. Physiological stress in birds. *Bio Science* 1980, 301, 529-533.

Simmons, J.D.; Lott, B.D.; Miles, D.M. The effects of high-air velocity on broiler performance. *Poult. Sci.* 2003, 82, 232–234.

Slingenbergh, J.; Gilbert, M. Do Old and New Forms of Poultry Go Together? In Proceedings of the International Poultry Conference, Bangkok, Tailand, 5–7 November 2007. Available online:

http://www.fao.org/ag/againfo/home/events/bangkok2007/docs/part2/2_3.pdf (accessed on 14 June 2015).

Sohail, M.U.; Hume, M.E.; Byrd, J.A.; Nisbet, D.J.; Ijaz, A.; Sohail, A.; Shabbir, M.Z.; Rehman, H. Effect of supplementation of prebiotic manan-oligosaccharides and probiotic mixture on growth performance of broilers subjected to chronic heat stress. *Poult. Sci.* 2012, 91, 2235–2240.

Steinfeld, H., Gerber, P.; Wassenaar, T.; Castel, V.; Rosales, M.; de Haan, C. Livestock's long shadow environmental issues and options. FAO, 2006.

St-Pierre, N.R.; Cobanov, B.; Schnitkey, G. Economic losses from heat stress by US livestock industries. J Dairy Sci 2003, 83 (E. Suppl.), E52-E77.

Teagasc. Energy use in agriculture. Oak Park, Carlow, Ireland, 2011.

Testo Inc. Homepage. Available online: http://www.testo.com (accessed on 19 March 2013).

Valera, D.L.; Alvarez, A.J.; Molina, F.D. Aerodynamic analysis of several insectproof screens used in greenhouses. *Span. J. Agric. Res.* 2006, 4, 273–279.

Van Wagenberg, A.V.; de Leeuw, M.T.J. Measurement of air velocity in animal occupied zones using an ultrasonic anemometer. *Appl. Eng. Agric.* 2003, 19, 499–508.

Wilhelm, L.R.; Milner, J.M.; Snyder, S.D.; McKinney, D.B. An instrumentation system for environmental measurements in broiler and swine housing. *Appl. Eng. Agric.* 2001, 17, 677–681.

WorldPoultry. Korea heat wave kills off 830,000 chickens (in August 2012). Available online: http://www.worldpoultry.net/Broilers/Health/2012/8/S-Korean-heat-wave-kills-off-830000-chickens-WP010736W/ (accessed on 14 June 2015).

Xia, B.; Sun, D.-W. Applications of computational fluid dynamics (CFD) in the food industry:A review. *Comput. Electron. Agric.* 2002, 34, 5–24.

Yanagi, T.; Xin, H.; Gates, R.S. A research facility for studying poultry responses to heat stress and its relief. *Appl. Eng. Agric.* 2002, 18, 255–260.

Yang, H.M.; Lee, S.Z. Research progress of cold stress in animals. *Heilomgjiang Anim. Sci. Vet. Med.* 1999, 3, 42-44.

Yavah, S.; Straschnow, A.; Luger, D.; Shinder, D.; Tanny, J.; Cohen, S. Ventilation, sensible heat loss, broiler energy and water balance under harsh environmental conditions. *Poult. Sci.* 2004, 83, 253–258.

Zhang, G.; Strøm, J.S.; Morsing, M. A Computerized Multi-point Temperature and Velocity Measurement System. In Proceedings of the Fifth International Conference on Air Distribution in Rooms (RoomVent'96), Yokohama, Japan, 17–19 July 1996; pp. 531–538.

Chapter 2

Instrumentation to measure indoor environments at broiler houses

An adapted version is published in:

Multisensor System for Isotemporal Measurements to Assess Indoor Climatic Conditions in Poultry Farms. Eliseo Bustamante, Enrique Guijarro, Fernando-Juan García-Diego, Sebastian Balasch, Antonio Hospitaler and Antonio G. Torres. *Sensors* 12 (2012), 5752-5774.

Abstract: The rearing of poultry for meat production (broilers) is an agricultural food industry with high relevance to the economy and development of some countries. Periodic episodes of extreme climatic conditions during the summer season can cause high mortality among birds, resulting in economic losses. In this context, ventilation systems within poultry houses play a critical role to ensure appropriate indoor climatic conditions. The objective of this study was to develop a multisensor system to evaluate the design of the ventilation system in broiler houses. A measurement system equipped with three types of sensors: air velocity, temperature and differential pressure was designed and built. The system consisted in a laptop, a data acquisition card, a multiplexor module and a set of 24 air temperature, 24 air velocity and two differential pressure sensors. The system was able to acquire up to a maximum of 128 signals simultaneously at 5 second intervals. The multisensor system was calibrated under laboratory conditions and it was then tested in field tests. Field tests were conducted in a commercial broiler farm under four different pressure and ventilation scenarios in two sections within the building. The calibration curves obtained under laboratory conditions showed similar regression coefficients among temperature, air velocity and pressure sensors and a high goodness fit (R^2 = 0.99) with the reference. Under field test conditions, the multisensor system showed a high number of input signals from different locations with minimum internal delay in acquiring signals. The variation among air velocity sensors was not significant. The developed multisensor system was able to integrate calibrated sensors of temperature, air velocity and differential pressure and operated succesfully under different conditions in a mechanically-ventilated broiler farm. This system can be used to obtain quasi-instantaneous fields of the air velocity and temperature, as well as differential pressure maps to assess the design and functioning of ventilation system and as a verification and validation (V&V) system of Computational Fluid Dynamics (CFD) simulations in poultry farms.

Keywords: poultry building; sensors; air velocity; isotemporal measurements; multipoint measurements; troubleshooting.

2.1. Introduction

Broiler production is an essential food industry in many countries. Currently, modern poultry production chains supply safe, nutritious and relatively cheap high-quality protein; for this reason, large-scale commercial poultry production plays nowadays an essential role supplying food to a rapidly growing, urban middle class worldwide (Slingenbergh *et al.*, 2007). From 2000 to 2010, the production of the poultry meat sector has increased more than 4% per year, compared to 2.1% for pig and 1.1% for beef. As a result, its share in global meat production has increased from 15% in the 1970 decade to 33.5% at present 2010 (FAO, 2010). This growth has been accompanied and supported by rapid technological, scientific and industrial changes associated with the development of highly industrialized landless intensive systems. Recent developments of poultry meat production have consisted in huge genetic improvements, the use of concentrated feed, an improvement of preventive disease controls and biosecurity measures, and the use of technology to exhaustively control in-house environmental conditions (Havenstein *et al.*, 2003). In this context, ventilation of poultry houses plays a critical role to ensure appropriate indoor conditions for achieving a high animal productivity (growth and food conversion) and a low mortality (Bartzanas *et al.*, 2007; Lee *et al.*, 2003; Lott *et al.*, 1998).

The dominant ventilation system in modern broiler houses uses forced ventilation, mainly through negative-pressure systems. Ventilation design is based in three basic principles: the rate of air exchange, air distribution and air velocity range at the animal level (MWPS, 1990; ASAE, 1986; Pedersen, 1999). However, the design of ventilation systems for poultry housing has seen a certain amount of development by trial and error in the absence of precise guidelines (Charles *et al.*, 2002). Therefore, it seems that further research is necessary to establish standardised protocols to design ventilation systems for poultry houses. The air exchange rate is calculated according to animal age and number in the building and is achieved with exhaust fans. The number of fans installed and operated will depend on ventilation needs and the performance of each fan. The air exchange rate must ensure a proper control of indoor temperature as well as an effective evacuation of air moisture and air pollutants (ASAE, 1986). On the contrary, the uniform distribution of air inside the house and the air velocity at animal level depend mainly on farm design and operation factors which interact in a complex way. Design factors (building geometry and location) and also operational factors (fan operation, adjustment of air inlet openings and pressure drop) become essential to define an optimal ventilation system (ASAE, 1986; MWPS, 1990; Pedersen, 1999). However, the distribution of air may be affected under field conditions by unplanned openings (open doors and windows as well as cracks in walls or ceilings), bad adjustment of openings or impaired performance of exhaust fans caused by equipment ageing, bad maintenance or changes in electricity supply (Boon *et al.*, 1988; MWPS, 1990).

Tao *et al.*, 2003 have indicated that poultry farms with inadequate ventilation systems suffer from higher mortality rates when the indoor air is hot, humid and still in the zones occupied by animals. Even more, it has been reported that chicken's welfare is more influenced by the ventilation system than by the animal stocking density (Dawkins *et al.*, 2004). For this reason, the inappropriate design or malfunctioning of ventilation systems can enhance the occurrence of lethal environmental conditions within production buildings, thus leading to significant economic losses. Moreover, even well designed and operated buildings may be insufficient to cope with extreme circumstances. In this context, massive deaths of approximately 500,000 birds occurred in 2003 because of heat stress in the Valencian Community (Spain), a region with an approximate stock of 9,000,000 birds (El País, 2003).

To assess the design and operation of ventilation systems in livestock houses direct measurements with appropriate instrumentation and measurement protocols are required. Alternatively, there is an increasing use of computational fluid dynamics (CFD) to indirectly evaluate ventilation systems in agricultural systems (Bartzanas *et al.*, 2007; Blanes-Vidal *et al.*, 2008; Mistriotis *et al.*, 1997; Norton *et al.*, 2007; Pawar *et al.*, 2007; Xia *et al.*, 2002). However, this indirect method also needs verification and validation (V&V), and thus using adequate instrumentation is also necessary. This instrumentation must allow simultaneous measurement of air velocity at different locations inside the house, but at the same time must be precise enough in the usual range of air velocity in broiler houses, which is normally lower than 3 m s^{-1}. Current commercial instrumentation systems, however, are not thought to evaluate ventilation systems of commercial farms because they normally measure only point values and their measurement thresholds are higher than the usual air velocity found in the farms. Furthermore, complex measurement systems should be avoided. Wheeler *et al.*, 2003 indicated that an instrumentation operator may produce distortions in the airflow inside the farm and its use may be unpractical under field conditions.

Recent studies have focused on the use of electronic instrumentation and sensors in farms. Some authors have developed systems to measure ventilation rates in livestock buildings, which are based on different sensors. So, turbinemeters have been used to determine the ventilation rate in livestock buildings (Berckmans *et al.*, 1991) or a portable anemometer to determine the fan performance curve (Simmons *et al.*, 1998). Wilhelm *et al.*, 2001 implemented an instrumentation system for performing environmental measurements in broiler and swine housing, whereas Van Wagenberg *et al.*, 2003 used an ultrasonic anemometer to measure the air velocity in animal-occupied zones in a swine farms. Another interesting study used hot-wire anemometry to measure the air velocity based on monitoring thermal losses in a heated measuring element (Ligęza *et al.*, 2008). However, in all cases, research until now has recorded only measurements taken at one or a few points and not addressed long term measurements using a large number of sensors.

Recently, a basic system for measuring temperature and air velocity in poultry houses was described (Blanes-Vidal *et al.*, 2010), which has been used in later experiments (Blanes-Vidal *et al.*, 2008). The same authors suggested that the described measurement system could be used as a basis to develop a measurement system equipped with a larger number of sensors fulfilling the essential premise of simultaneous measurement at multiple points. To achieve this premise, the time delay between two consecutive acquisitions needs to be minimized and a multiplexing system arises as an essential element in the design of this ideal measurement system. A multiplexer allows for data acquisition in a quasi-simultaneous regime at different locations including animal level and other heights, minimising potential distortions of airflow inside the farm.

It must be considered that the airflow inside a mechanically ventilated building is turbulent by nature. The presence of animals intensifies this internal turbulent atmosphere, creating sudden changes of environmental parameters both in time and space. An instrumentation to evaluate the indoor climate of a livestock building must therefore receive as many input signals per time unit as possible, from a large number of widely distributed measuring locations, particularly from zones occupied by animals (Blanes-Vidal *et al.*, 2010; Strøm *et al.*, 2002; Wheeler *et al.*, 2003). As indicated above, it is also necessary to measure differential pressure because of its critical influence on ventilation performance of a mechanically ventilated farm.

The main objective of this study was to develop a multisensor system to evaluate the design of the ventilation system in broiler houses. The system was designed to measure simultaneously air velocity, temperature and differential pressure with different sensors. This system was calibrated and then tested under farm conditions and may serve as a useful tool to evaluate the indoor environment of poultry farms, as affected by farm design, for troubleshooting, and as a V&V system of CFD simulations.

2.2. Materials and Methods

In this section, the developed measurement system, as well as the methodology followed for its field validation, will be described.

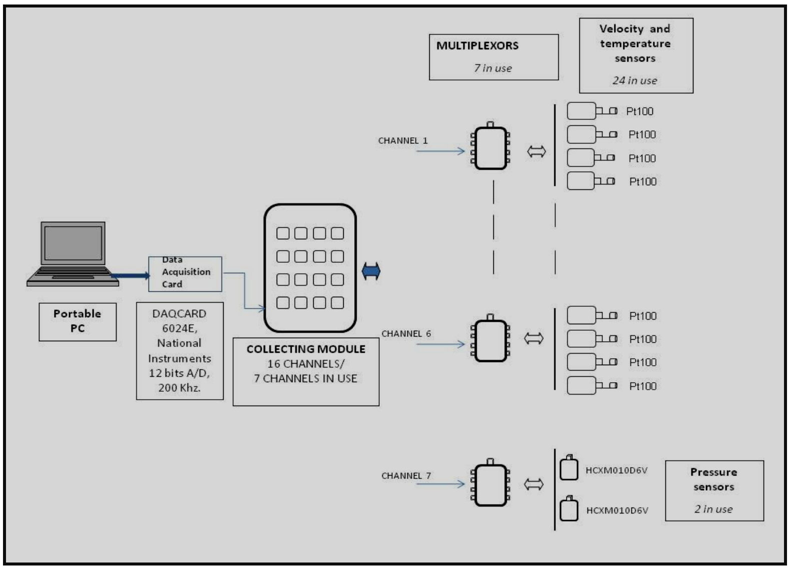
2.2.1. Measurement System Development

2.2.1.1. General Description

A configurable multi-sensor device aimed at measuring air velocity, temperature and differential pressure in multiple locations at the same time was designed and built. The system consisted in a portable PC (Pentium III, 64 Mb RAM) and a National Instruments Corporation (Austin, TX, USA) DAQCARD 6024E data acquisition card with 16 analogue inputs and a maximum sampling rate of 200 kS/s. Its absolute accuracy at full scale was 10.568 mV. As 16 channels were less than those needed, a central multiplexor data collection module was designed. The multiplexing modules were able to concentrate eight signals into a single channel. Therefore, the system extended the 16 channels of the acquisition card to a maximum of 128 signals. To reduce interferences, all information was sent in current mode instead of voltage mode. The card also had eight digital input-output channels, which were used to control multiplexing units.

In this paper, we describe a system adapted to operate with 24 air velocity sensors, 24 temperature sensors, two differential pressure modules and seven multiplexers. A schematic of the system is shown in Figure 2.1.

Figure 2.1. *Scheme of the measurement system.*



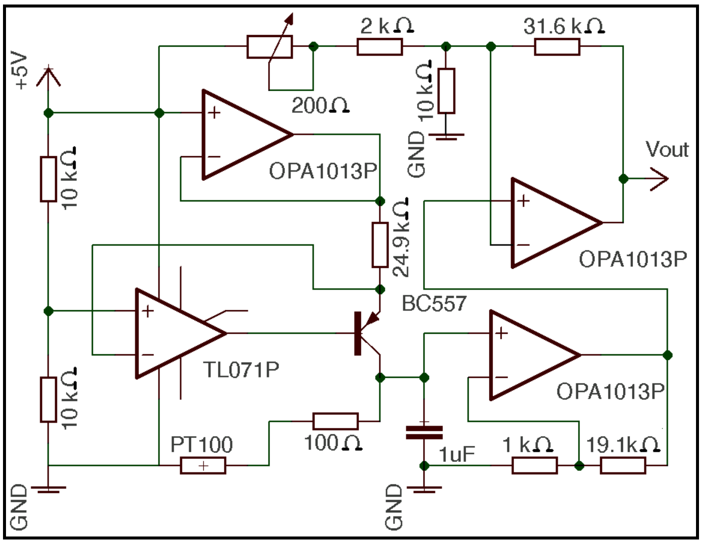
Data was acquired in the PC by using specifically developed software. This software was based on the National Instruments Corporation LabVIEW 8.2 platform (National Instruments, LabView). The software was able to acquire and monitor signals from sensors, as well as control the multiplexing and demultiplexing functions.

Two programs were developed in LabVIEW. One to monitor all the sensors used in the installation at real time, and another one that shows on the screen the time evolution of the sensors and can record data on the PC at the programmed rate. In this experiment, data of all sensors is taken every five seconds and kept for an average of 120 readings (every ten minutes).

2.2.1.2. Temperature Material and Circuit

A platinum resistance temperature detector (RTD) thin film detector Pt100 (Omega, Inc., Stamford, CT, USA) printed on a ceramic substrate (TFD, Omega Engineering) was chosen as the temperature sensor; the technical characteristics of the device are consistent with Deutsches Institut für Normung (DIN)-43760 and British Standard (BS)1904. Figure 2.2 shows the circuit of the temperature sensor. It is used to linearise the response of the Pt100 and to regulate the zero offset by the variable resistor of 200 Ω.

Figure 2.2. *Circuit of the temperature sensor.*



2.2.1.3. Temperature Calibration

In order to calibrate temperature sensors, a Fluke Corporation (Everett, WA, USA) temperature calibrator Fluke-724 that simulates a Pt100 was used. The sensor was disconnected from the electronic circuit and connected to the simulator. It was also connected to the acquisition system in the temperature module to measure the output voltage from the different temperatures simulated using the Fluke-724. Calibration temperature ranged from 0 °C to 44 °C. This range is found within the common range of temperatures in commercial poultry farms. For each of the 24 sensors, two consecutive calibrations were conducted to study potential hysteresis. The first calibration lay between 0 °C and 44 °C, whereas the second lay between 44 °C to 0 °C. Each calibration was performed at 2 °C intervals within each range. Therefore, a total of forty six temperature values were used to calibrate each sensor.

For each calibration, the output potential (U_t) was measured as a linear function of temperature, including a quadratic term following Equation (2.1). The quadratic term was used to account for those cases where the linear effect varied with increases in temperature:

$$U_t = \alpha + \beta \times T + \gamma \times T^2 \tag{2.1}$$

To detect differences between sensors a unique regression analysis integrating all sensors with dummy variables was used following the model:

$$\begin{aligned} E(U_t) &= \alpha_0 + \beta_0 \times T + \gamma_0 \times T^2 + \\ &+ \sum_{i=1}^{i=n-1} \alpha_i \times S_i + \sum_{i=1}^{i=n-1} \beta_i \times S_i \times T + \sum_{i=1}^{i=n-1} \gamma_i \times S_i \times T^2 \end{aligned} \tag{2.2}$$

where:

$E(U_t)$: Mean value of the measured potential U_t (volts) in both calibrations with the multimeter.

T: Air temperature (°C).

S_i: Sensor i (dummy variable) that takes 0 and 1 values; for any specific sensor, the variable takes a value of 1 and 0 in all cases (1 for the sensor that corresponds to the observation and 0 for the rest of the sensors).

α_0: Independent coefficient of regression.

β_0: Regression coefficient of variable temperature (T) simulated at calibrator "Fluke 724" (in °C).

β_i : Regression coefficient of the interaction between variables T and S_i.

γ_0: Regression coefficient of the variable for the square of the temperature (T^2).

α_i: Regression coefficient of the variable sensor (S_i).
γ_i: Regression coefficient of the interaction between variables T^2 and S_i.
The dummy variables (S_i) had to be created so that they assume a value equal to the number of variables minus 1; thus, a reference sensor was used to determine all variables. If the sensor assumes a value of 0, the rest assume a value 1 with respect to one of these variables (Kutman *et al.*, 2005). Differences between sensors in the model were detected in three ways: changes in the intercept (α coefficients), changes in the slope (β coefficients) and the square coefficients (γ).
The model in Equation (2.2) provided the equation of the reference sensor (Equation (2.3)) and the coefficients of the other sensors (Equation (2.4)):

$$E(U_t) = \alpha_0 + \beta_0 \times T + \gamma_0 \times T^2 \tag{2.3}$$

$$E(U_t) = (\alpha_0 + \alpha_i) + (\beta_0 + \beta_i) \times T + (\gamma_0 + \gamma_i) \times T^2 \tag{2.4}$$

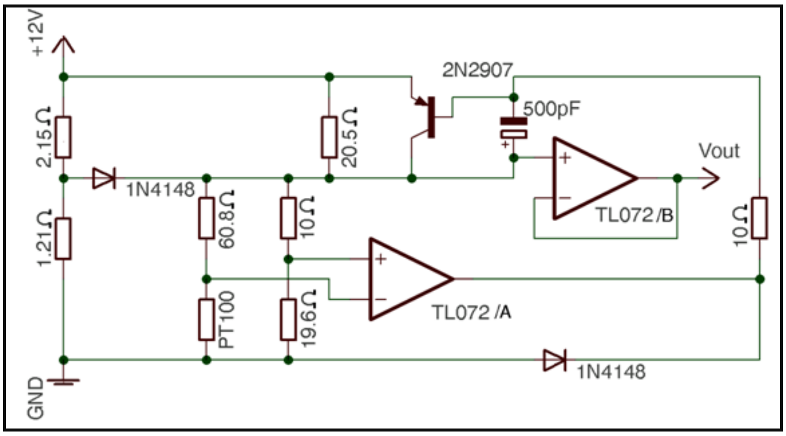
This analysis was performed with the PROC REG procedure of SAS (SAS, 1998). Maximum and minimum differences between measures and estimated observations were taken as a practical criterion of the accuracy of the model.

2.2.1.4. Air Velocity Material and Circuit

Among the different available technologies used to measure air velocity (Glaninger *et al.*, 2000), hot-wire anemometry was chosen because of its various advantages. The basic principle of hot-wire anemometry is very simple: a fluid (in this case air) crosses an (electrically) heated wire at a constant temperature; thus, an energy balance can be established between the power supply to the heated wire and the dissipation, which is proportional to the air velocity.
Based on hot-wire anemometry, an RTD was chosen as air velocity sensor. An RTD consists of a thin wire, sheet or metallic component that is generally supported by a ceramic. In this case, the RTD featured a thin platinum piece, whose processing offered a resistance of 100 Ω at 0 °C; thus, the RTD was referred to as Pt100. In fact, Pt100 has great advantages: minimal thermal mass, the ability to detect small mass velocity, mechanical robustness and no moving components, easy mounting, very fast response time, ability to perform a simple electronic analysis, the best price-performance ratio, good repeatability and great stability over time (Ibrahim, 2002). For these reasons, the same sensor as in temperature determinations (platinum resistor Pt100, printed on a ceramic substrate, thin film detector (TFD), Omega Inc. (TFD, Omega Engineering)) was chosen for the velocity measurements. The electronic circuit of the air velocity sensor is shown in Figure 2.3.

The circuit operates as follows: the resistors of 10 Ω, 60.18 Ω and 19.6 Ω and the Pt100 form a Wheatstone bridge. To make this bridge balanced, the resistance of the Pt100 should be 119.168 Ω which is equivalent to a temperature of 49.41 °C. If the bridge becomes unbalanced, the operational amplifier TL072/A and the transistor 2N2907 act until the bridge is balanced again.

Figure 2.3. *Circuit of the air velocity sensor.*



2.2.1.5. Air Velocity Calibration

The equation governing the thermal equilibrium between the heating of the sensor to a constant temperature and the dissipation of the air is:

$$\frac{dE}{dt} = W - H \tag{2.5}$$

where E is the thermal energy stored in the sensor, W is the electrical power applied to it and H is the energy dissipated to the surroundings.

Under quasi-stationary conditions, the thermal energy stored is constant, so:

$$0 = W - H \tag{2.6}$$

$$W = U^2 / R(T_W) \tag{2.7}$$

where $R(T_w)$ is the resistance of the Pt100 at a constant temperature (T_W = 49.41 °C), and U is the voltage applied to the Pt100.

Assuming convection is the main mode of heat transmission (neglecting radiation and conducting losses):

$$H = h \cdot A \cdot (T_W - T_f) \tag{2.8}$$

where h is the film coefficient of heat transfer, A is the sensor surface and T_f is the temperature of fluid. In a forced convection regime, coefficient ($h \cdot A$) may be expressed as:

$$h \cdot A = a + b \cdot V_f^n \tag{2.9}$$

where a and b are constants dependent on the fluid, in this case air, and V_f is the velocity of the fluid. Replacing and rearranging Equation (2.6) produces an expression that relates voltage U, the fluid velocity V_f, the wire temperature T_W and the fluid temperature T_f, resulting in:

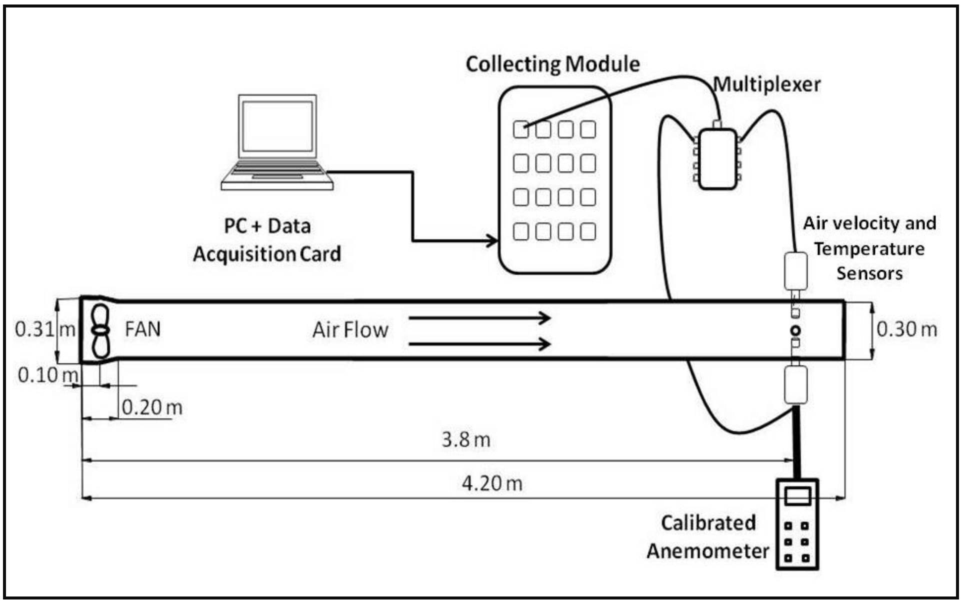
$$U^2 / R(T_W) = (T_w - T_f) \cdot (a + b \cdot V_f^n) \tag{2.10}$$

In this paper, n is assumed to be 0.5 (Champagne *et al.*, 1967; Martin *et al.*, 2002; Morrison *et al.*, 1972; Sherif *et al.*, 1998). Grouping and transforming the constants (a, b, $R(T_W)$), results in Equation (2.11), known as King's Law:

$$\frac{U^2}{T_W - T_f} = \delta + \lambda V_f^{0.5} \tag{2.11}$$

A wind tunnel was designed to calibrate the velocity sensors (Figure 2.4).

Figure 2.4. *A scheme of the wind tunnel showing the position of the air velocity and temperature sensors.*



Fifteen velocity values were measured in the wind tunnel within the range from 0.1 to 4.5 m s^{-1}. These velocities were obtained varying the fan power. A calibrated Testo 425 hot-wire anemometer was used to obtain reference values (Testo Inc., Sparta, NJ, USA; error 0.03 m/s + 5% of the measured value) (Testo Inc., 2004).

The calibration procedure was performed as follows (Zhang *et al.*, 1996) according to the designed circuit

(Figures 2.2 and 2.3) and from Equation (2.11). So, if we called:

$$y = \frac{U_v^2}{T_W - T_f} \tag{2.12}$$

$$x = \sqrt{V_f} \tag{2.13}$$

The follow Equation (2.14) results:

$$y = \delta + \lambda \cdot x \tag{2.14}$$

A least-square algorithm is used to obtain the coefficients of the linear regression (δ, λ) between the reference air velocity (V_f) measured with the reference anemometer and the terms included in y (Equation (2.12)), so that T_W, the temperature of the wire that is fixed by the electronic circuit (T_W= 49.41 °C), the output voltage of the velocity (U_v) and temperature (U_t) sensors was measured; in turn, the output voltage of the temperature it used to calculated the sensor temperature (T_f) through its corresponding calibration, as explained before. In conclusion, a collection of values (U_v, V_f, T_a) was measured simultaneously while controlling the fan power.

MATLAB software (Matlab Central, The MathWorks, Inc.) was used to create a program to sum up the whole process, and then calculate the regression coefficients δ and λ of the Equation (2.14) by the PROC REG procedure of the SAS program (SAS, 1998). A curve of specific calibration was obtained for every module sensor.

Once all regressions were obtained for the different sensors, in order to ascertain the validity of the calibrations a linear regression analysis between the velocity measured by the anemometer ($V_{f(real)}$) and the estimated velocity ($V_{f(e)}$) by the calibration procedure described, done as (Zhang *et al.*, 1996). The statistical model used in order to compare calibration curves was a linear regression using the PROC REG procedure of SAS (SAS, 1998) too:

$$E(V_{f(real)}) = \alpha_0 + \beta_0 \times V_{f(e)} + \sum_{i=1}^{i=n-1} \alpha_i \times S_i + \sum_{i=1}^{i=n-1} \beta_i \times S_i \times V_f \tag{2.15}$$

where:

$E(V_{f(real)})$: Mean air velocity measured with the hot-wire anemometer (m/s).
$V_{f(e)}$: Estimated velocity determined by the calibration procedure for the sensors.
S_i: Sensor i (dummy variable) that take 0 and 1 values; for a specific sensor, the variable takes a value of 1 and 0 in all cases (1 for the sensor that corresponds to the observation and 0 for the rest of the sensors).
α_0: Independent coefficient of regression.
β_0: Regression coefficient of the $V_{f(e)}$ variable.
α_i: Regression coefficient of the variable S_i.
β_i: The regression coefficient of the interaction S_i by $V_{f(e)}$.
The model provided differences for the reference sensor (Equation (2.16)) and the others sensors (Equation (2.17)):

$$E(V_{f(real)}) = \alpha_0 + \beta_0 \times V_{f(e)} \tag{2.16}$$

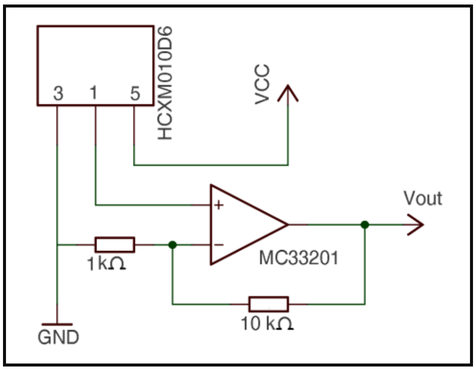
$$E(V_{f(real)}) = (\alpha_0 + \alpha_i) + (\beta_0 + \beta_i) \times V_{f(e)} \tag{2.17}$$

Maximum and minimum differences between measures and estimated observations were taken as a practical criterion of the accuracy of the model.

2.2.1.6. Differential Pressure Module

A sensor with a range between 0 and 100 Pa was selected as the operating conditions rarely exceed 60 Pa. A HCXM010D6V differential pressure-sensing module based on a pre-amplified silicon gauge pressure sensor (Sensortechnics Inc., Puchheim, Germany); nonlinear and hysteretic error <0.5% (Sensortechnics Inc.) was used. This module has previously been used in mechanically ventilated poultry farms (Blanes-Vidal *et al.*, 2008). An electronic circuit was designed to obtain a range between 0 and 100 Pa by a non-inverting, operational amplifier with a gain of 11, as shown in Figure 2.5.

Figure 2.5. *Differential pressure electronic circuit.*



The differential pressure modules were calibrated using a differential manometer (U-shaped tube filled with distilled water), a dropper and the data acquisition system. The calibration was performed with water at 4 °C because, at this temperature, the water density is 1 g/mL. Different output voltages related to the displacements of the liquid column were measured. These displacements were observed along a vertical ruler using a magnifying glass. Moreover, in order to improve the precision, the volume of water injected was registered and counted drop by drop. The maximum range of calibration (100 Pa) corresponded to one centimetre of displacement and 13 drops of 100 µL. The calibration equation was as follows:

$$U = \alpha_0 + \beta_1 \times dP \tag{2.18}$$

where:
U: Measured voltage (in volts).
α_0: Independent coefficient of regression.
β_1: Regression coefficient of independent variables.
P: Pressure (in Pa) calculated from the displacement of the water column.
Through a regression analysis using SAS (SAS, 1998), the regression coefficients were estimated.
A regression equation was developed for each of the two sensors. As with air temperature and air velocity sensors, maximum and minimum differences between measures and estimated observations were taken as a practical criterion of the accuracy of the model.

2.2.2. Field Experiments

2.2.2.1. Assay Building

The system was tested in a commercial broiler farm which was selected for its location (Villarreal, Castellón, Spain) and climatic conditions that are representative of the Mediterranean region. These climatic conditions are characterized by high temperatures and high relative humidity (e.g., >30 °C, >70% RH).
The farm featured a mechanical cross-ventilation system. The dimensions of the building were: length, 110 metres; width, 12.60 metres; sidewall height, 2.6 metres; slope cover, 21.53%. Sixteen exhaust fans were installed: nine large fans with a diameter of 1.28 m (Gigola & Riccardi, Cazzago San Martino, Italy, model Gigola ES-140, with a power consumption of 0.74 kW and a nominal ventilation flow of 34,956 $m^3 \cdot h^{-1}$ to $\Delta P = 0$ Pa) and seven 0.68 m diameter small ones (Ziehl-Abegg A.G., Küzelsau, Germany, model FC063-6D, power consumption 0.58 kW and nominal ventilation flow 12,750 $m^3 \cdot h^{-1}$ to $\Delta P = 0$

Pa). The farm was equipped with 66 Tuffigo© air inlets (Quimper, France, model Kan'Air, 0.795 × 0.24 metres placed at 1.51 metres height) controlled by an automatic system for automatically management in three groups of 22 inlets. The building was empty during the experiments to avoid possible interference due to the presence of animals.

2.2.2.2. Measurement Conditions (Scenarios)

To test the measurement system, four different boundary conditions were established: (I) 30 Pa using only large fans, (II) 38 Pa working all fans, (III) 50 Pa working large fans and (IV) 50 Pa working all fans. Two sections were studied, one (Section A) was located near one extreme of the building, whereas the second (Section B) was in the centre. Table 2.1 shows trial scenarios.

Table 2.1. *Trial scenarios.*

Assay Section	Differential Pressure (Pa)	Ventilation Rate [1] $m^3\ h^{-1}$	Operating Fans	Boundary Condition
Section A	30	233,163	Large	*I*
	38	276,204	Large + Small	*II*
	50	193,518	Large	*III*
	50	250,472	Large + Small	*IV*
Section B	30	233,163	Large	*I*
	38	276,204	Large + Small	*II*
	50	193,518	Large	*III*
	50	250,472	Large + Small	*IV*

[1] Ventilation rates were measured in each scenario as indicated by Calvet *et al.*, 2010.

For each scenario, all 24 air velocity and temperature sensors, two differential pressure sensors and seven multiplexers were placed on 12 tripods; two sensors were placed on each tripod: one of them at the level of the birds (0.25 metres) and the other at a height of 1.75 metres. A detail of a tripod when measuring in the building is shown in the photograph, Figure 2.6.

To sum up, eight trials were conducted (two sections with four boundaries) with 12 measurement positions as indicated in Figure 2.7. The location of the sensors was chosen according the situation of inlets and fans and considering where the farmer had observed any anomaly such as a greater or lesser concentrations of chicken or increased mortality. Acquisition time for each trial was 10 minutes. As the system was programmed for measuring each 5 seconds, each value was the mean of 120 data.

For all tests, the two differential pressure sensors were used to control the opening of the inlets and performance of the fans precisely.

Figure 2.6. *Tripod with a multiplexer at its centre and two air velocity and temperature sensors at the level of the birds (0.25 metres) and at 1.75 metres.*

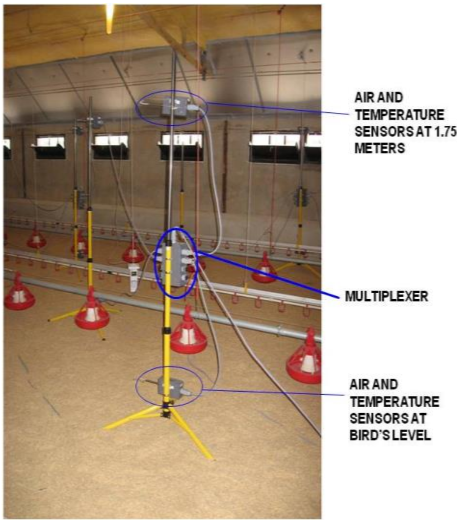
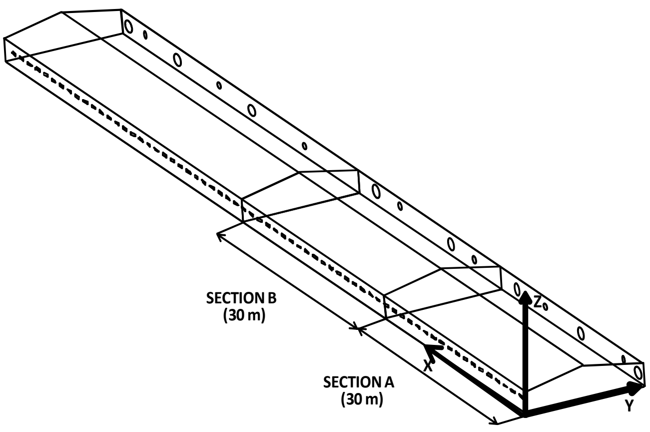


Figure 2.7. *Location of the measurements in the two sections of the poultry farm.*



	Section A		Section B	
Sensor number*	X-Coordinate *(m).*	Y-Coordinate *(m).*	X-Coordinate *(m).*	Y-Coordinate *(m).*
1-2	22.45	0.30	35.90	0.05
3-4	19.50	12.00	31.50	11.80
5-6	18.00	11.95	32.80	11.95
7-8	9.30	12.00	41.80	7.15
9-10	5.70	12.05	40.70	6.80
11-12	0.60	12.00	45.85	11.35
13-14	0.55	6.30	47.35	4.50
15-16	0.50	7.60	46.95	5.35
17-18	0.55	2.15	44.05	0.80
19-20	8.70	6.70	48.50	3.15
21-22	24.85	7.10	47.70	1.10
23-24	23.60	7.15	47.70	0.65

*: The first sensors at animal level, the second at 1.75 m

2.2.2.3. Statistical Procedures

In order to study the effect of factors involved in the performance of the system under field conditions, an analysis of variance following the next model was developed:

$$Y_{ijkl} = \mu + Z_i + B_j + H_k + S_{l(k)} + (Z \times B)_{ij} + (B \times H)_{jk} + (Z \times B \times H)_{ijk} + \\ + (Z \times S)_{il(k)} + (B \times S)_{jl(k)} + (Z \times B \times S)_{ijl(k)} \quad (2.19)$$

where:

Y_{ijkl}: Air velocity measured in the Section *i* at conditions *j* at *k* height by sensor *l*.
μ: Overall mean.
Z_i: Measurement Section (2).
B_j: Boundary conditions (4).
H_k: Height of sensor (2).
$S_{l(k)}$: Sensor (24) hierarchical to height.
$(Z \times B)_{ij}$: Interaction Section-Boundary (8).
$(Z \times H)_{ik}$: Interaction Section-Height (8).
$(B \times H)_{jk}$: Interaction Boundary-Height (8).
$(Z \times B \times H)_{ijk}$: Triple interaction Section-Boundary-Height (16).
$(Z \times S)_{il(k)}$: Interaction Section-Sensor (48).
$(B \times S)_{jl(k)}$: Interaction Boundary-Sensor (96).
$(Z \times B \times S)_{ijl(k)}$: Triple interaction Section-Boundary-Sensor (residual term of the model).
Numbers in parentheses indicate number of factors. To study these effects, all factors were considered to be at random. The model was analysed by the GLM procedure of SAS systems (SAS, 1998).

2.3. Results and Discussion

2.3.1. Sensor Calibration

2.3.1.1. Temperature Calibration

Table 2.2 presents the regression coefficients resulting from applying the regression model in Equation (2.2). Five regression equations were obtained for different groups of sensors according to the nature of the calibration curves (Equations (20) to (24)). In all cases the regressions showed high significance ($P < 0.001$) and goodness fit ($R^2 = 0.99$). The first line in Table 2.2 (Equation (2.20)), represents the reference sensor's regression coefficients after applying Equation (2.3), i.e., α_0 = 2.00, β_0 = 0.152 and γ_0 = 0, and thirteen other sensors that were not significantly different from it, i.e., α_i = 0, β_i = 0 and γ_i = 0, after applying Equation (2.4).

Table 2.2. *Results of regressions of temperature calibrations.*

Numbers of Sensors	**N (Data Number)**	**Regression Estimated Coefficient**			**Equation**
		Intercept $(\alpha_0+\alpha_i)$	**Temperature Coefficient** $(\beta_0+\beta_i)$	**Square Temperature Coefficient** $(\gamma_0+\gamma_i)$	
14	644	2.00	0.152	0	(2.20)
4	184	2.00	0.148	0	(2.21)
4	184	1.98	0.154	−0.000053	(2.22)
1	46	2.00	0.154	0	(2.23)
1	46	1.98	0.152	0	(2.24)
14	644	2.00	0.152	0	(2.20)

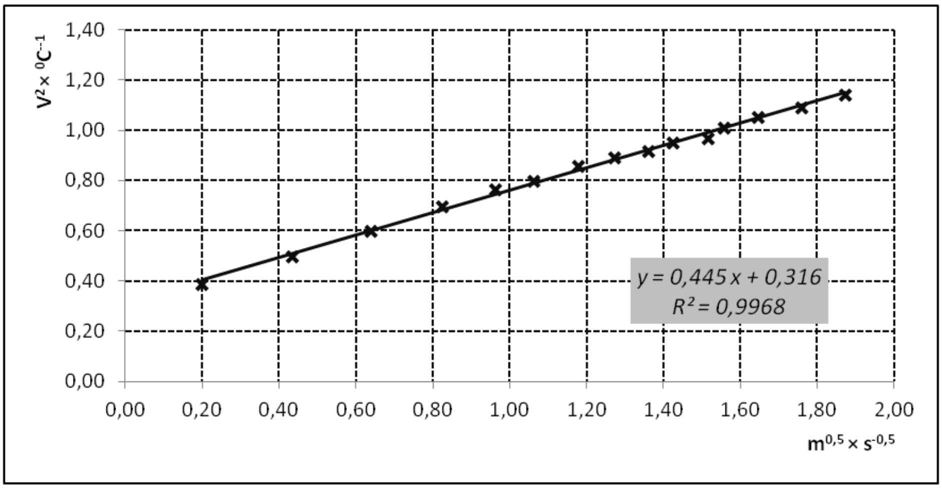
The difference between Equations (2.20) and (2.21) was the temperature coefficient, representing the slope of the regression line. The four sensors grouped in Equation (2.21) showed a slightly lower slope than sensors grouped in Equation (2.20). Equations (2.23) and (2.24) only grouped one sensor each and showed a higher temperature coefficient (slope) (Equation (2.23)) or lower intercept (Equation (2.24)) than sensors grouped in Equation (2.20). Equation (2.22) grouped four sensors and showed the most different coefficients. Equation (2.23) showed a lower intercept and a higher slope than sensors grouped in Equation (2.20), but a negative quadratic term. The effect of the quadratic term indicated that an increase in the temperature reduced the slope of the regression equation. In this case, clearing the temperature produced a second-degree polynomial equation.

For Equations (2.20) and (2.24) the maximum error measured was 0.33 °C and the minimum was<0.01 °C, for Equation (2.21) the maximum error measured was 0.07 °C and the minimum was<0.01 °C, for Equation (2.22) the maximum error measured was 0.05 °C and the minimum was <0.01 °C and finally for Equation (2.23) the maximum error measured was 0.32 °C and the minimum was<0.01 °C. As in all cases the minimum error was lower than the reading of the simulator (0.01 °C), we used these minimum errors for estimations. In all cases a very low error hysteresis value was obtained (±0.0227%).

2.3.1.2. Air Velocity Calibration

Figure 2.8 shows an example of the result of the calibration of an air velocity sensor, where the regression parameters of Equation (2.11) are shown.

Figure 2.8. *Regression curve of a velocity sensor calibration.*



The estimated velocities (Vf(e)) (m s^{-1}) were obtained from the regression of each sensor. Comparing these estimated velocities with real velocities V_f(real) (m s^{-1}), using the model of Equation (2.15), we obtained a high significance ($P < 0.001$) with a high goodness of fit (R^2= 0.99), but no differences between sensors were detected. Consequently, only one calibration curve was obtained for all velocity sensors:

$$E(V_{f\,(real)}) = -0.01431 + 0.9956 V_{f\,(e)} \tag{2.25}$$

The maximum error measured was 0.018 m s^{-1}, and the minimum was 0.002 m s^{-1}. Since these errors were smaller than the error of the anemometer (0.03 m s^{-1} + 5% of the reading), we used the anemometer error for calculations.

2.3.1.3. Differential Pressure Calibration

The calibration results for the differential pressure sensors shows two similar calibration curves:

Sensor 1: $$U = 5.6911 + 0.045 dP (R^2 = 0.99; p < 0.001) \tag{2.26}$$

Sensor 2: $$U = 5.6381 + 0.0465 dP (R^2 = 0.99; p < 0.001) \tag{2.27}$$

The regressions were similar with respect to their intercepts and slopes. To obtain dP from the measured voltage (U), only Equations (2.26) and (2.27) had to be changed. The maximum error measured was 0.41 Pa, and the minimum was 0.22 Pa for differential pressure sensor 1 and the maximum error measured was 0.29 Pa, and the minimum was 0.20 Pa for differential pressure sensor 2.

2.3.2. Field Experiment

Considering all scenarios and sensors, 23,040 data values of air velocity were measured with the designed system. Table 2.3 shows the results of the ANOVA analysis. The variable sensor resulted not significant, as section, boundary and height and some interactions. Only the interactions “Section by Sensor (Height)” and “Boundary by Sensor (Height)” were significant.

Table 2.3. *ANOVA of the air velocity scenarios.*

	DF	Sum of Squares	Mean Square	F-Ratio	P-Value
Section	1	0.37	0.37	3.06	0.7935
Boundary	3	1.41	0.47	12.19	0.9051
Height	1	>0.00	>0.00	0.00	0.9909
Sensor(Height)	22	16.82	0.76	1.05	0.4428
Section × Boundary	3	0.10	0.03	0.11	0.9471
Section × Height	1	0.35	0.35	0.46	0.5076
Boundary × Height	3	0.82	0.27	0.72	0.5760
Section×Boundary×Height	3	0.79	0.26	2.46	0.0700
Section × Sensor(Height)	22	13.46	0.61	5.71	<0.0001
Boundary × Sensor(Height)	66	14.69	0.22	2.08	0.0017
Residual	66	7.08	0.11	-	-
Total (corrected)	191	55.88			

Table 2.4. *Air velocities in m s^{-1} (average ± standard deviation) in the field experiment. The number of data is indicated in parenthesis.*

Boundary Conditions	Height	Section A	Section B	All
	0.25 m	0.62 ± 0.86 (12)	0.37 ± 0.30 (12)	0.50 ± 0.65 (24)
I	1.75 m	0.37 ± 0.39 (12)	0.66 ± 1.00 (12)	0.52 ± 0.76 (24)
	All	0.50 ± 0.67 (24)	0.53 ± 0.74 (24)	0.51 ± 0.70 (48)
	0.25 m	0.70 ± 0.35 (12)	0.71 ± 0.29 (12)	0.71 ± 0.33 (24)
II	1.75 m	0.47 ± 0.32 (12)	0.68 ± 0.47 (12)	0.58 ± 0.41 (24)
	All	0.59 ± 0.35 (24)	0.70 ± 0.38 (24)	0.64 ± 0.37 (48)
	0.25 m	0.78 ± 0.41 (12)	0.80 ± 0.31 (12)	0.79 ± 0.35 (24)
III	1.75 m	0.63 ± 0.34 (12)	0.77 ± 0.50 (12)	0.70 ± 0.42 (24)
	All	0.71 ± 0.37 (24)	0.79 ± 0.41 (24)	0.75 ± 0.39 (48)
	0.25 m	0.42 ± 0.26 (12)	0.65 ± 0.59 (12)	0.54 ± 0.46 (24)
IV	1.75 m	0.72 ± 0.69 (12)	0.77 ± 0.87 (12)	0.74 ± 0.75 (24)
	All	0.57 ± 0.53 (24)	0.71 ± 0.71 (24)	0.64 ± 0.62 (48)
	0.25 m	0.63 ± 0.53 (48)	0.63 ± 0.41 (48)	0.63 ± 0.47 (96)
All	1.75 m	0.55 ± 0.47 (48)	0.72 ± 0.71 (48)	0.63 ± 0.61 (96)
	All	0.59 ± 0.50 (96)	0.68 ± 0.58 (96)	0.63 ± 0.54 (192)

Table 2.4 shows the obtained air velocity values according the different variables (Section, Boundary and Height) and some interactions. These values shows that the air velocities achieved in all boundaries are very homogeneous, the minimum value is 0.37 ± 0.30 m s^{-1} (Section B, Boundary I) and the maximum value is 0.80 ± 0.31 m s^{-1} (Section B, Boundary III) although there are peak measurements (not reflected in Table 2.4) between 0.06 m s^{-1} to 3.52 m s^{-1}.

2.3.3. Discussion

2.3.3.1. Measurement System Development

The measurement system developed in this study was able to integrate calibrated sensors of temperature, air velocity and differential pressure and operated succesfully in different conditions in a mechanically-ventilated poultry farm.

It is currently accepted that wireless sensor networks can be applied to monitor environmental parameters in agricultural systems (Hwang *et al.*, 2010; Ruiz-García *et al.*, 2009). However, wired sensors were used because they were considered more appropriate for our measurement needs than wireless sensors. In this sense, hot-wire air velocity sensors operated with a frequent data collection interval (10 minutes in this work) which imply a high energy consumption. Therefore the batteries required for a wireless system are not able to guarantee energy supply for long-term measurements. This wired acquisition system can operate during one whole rearing cycle of broilers (6 to 7 weeks) with minimum maintenance, which avoids disturbing the normal operation in the farm. Similar wired systems to measure environmental parameters have also been used recently (Zarzo *et al.*, 2011) obtaining succesful results.

In addition, this measurement system can receive the environmental signals without the physical presence of a technician (avoiding then the interference on measured values). This is due to its large data storing and adquisition capacity as well as its autonomy in terms of energy consumption (Wheeler *et al.*, 2003).

Regarding to sensors nature, air velocity and temperature are hot-wire type sensors and RTDs, respectively. They were chosen based on their advantages, such as their robustness observed for similar uses (Blanes-Vidal *et al.*, 2010). On the other hand, there is still a need to test differential pressure sensors in mechanically ventilated poultry farms (Blanes-Vidal *et al.*, 2008).

According to the results of this work, a single calibration curve was obtained for all velocity sensors. The error of the calibration curve was lower than the measurement error of the anemometer used for the calibration (±5% of reading) which indicates a good agreement among all sensors. On the contrary, several calibration curves were required for different temperature sensors. The results indicated that the sensors in this study could be classified into five statistically different groups, but differences between the five calibration equations were irrelevant in practical terms. This indicates that slight differences among sensors could arise from differences in the fabrication process or components. Regarding the calibration of differential pressure sensors, similar calibration curves were obtained, as expected considering the nature of these sensors.

The use of dummy variables for sensor calibration has been an innovative method for this purpose. So, using this tool allows obtaining optimum number of calibration curves according to statistical criteria. Ideally, a single calibration curve should be used, nevertheless a variety of factors including differences in fabrication, components or welds, make it not always possible in practice. Moreover, the precision required for measurement systems plays a crucial role, and using this methodology sensors can be grouped in homogeneous groups when small differences are observed. As indicated above, this is the case of temperature sensors in this study.

2.3.3.2. Field Experiments

The sensors and the measurement system were tested in a commercial farm located in Eastern Spain. It is important to remark that despite commercial broiler farms do not follow any standard in terms of geometry or construction design, according to a wide knowledge base regarding the general construction characteristics of poultry farms in the region (Martínez *et al.*, 2008), this farm had typical dimensions and can therefore be considered representative of typical mediterranean broiler buildings.

Although the tests conducted in this study were performed in an empty broiler house, the configuration of the system and materials used, make the system robust enough to resist the aggressive environmental conditions (e.g., dust, high relative humidity, and gas concentration), occurring in buildings during animal rearing. Nevertheless, air velocity changes when psychometric conditions are modified by fluctuations of temperature or air density must be kept in mind. In this sense, in occupied farms, indoor environmental boundary conditions are more complex than in an empty farm. The reasons for this difference are the influence of broiler heat, chemical reactions of litter, as well as the cooling or heating systems. In any case, when using this system in occupied building, some improvements are recommendable. First, sensors placed at animal level must be protected (e.g., using a mesh) to avoid access by the animals. Second, it is also recommendable to include more sensors at a different level above the birds' heads in order to reduce the effect of the animals on measurements. Other practices such as frequent revisions and cleaning of sensors are also recommendable. Nevertheless, it would be necessary to test the system with animals to study the system's reliability.

In this paper, only air velocity data were presented and discussed since temperature and differential pressure conditions were similar for all situations investigated. In this regard, despite the fact that in this work only air velocity data were presented, in the case of occupied farms, when cooling and heating systems are operating or when significative differences between exterior and internal temperatures occur, additional studies on the results of temperature should be developed. Moreover, additional sensors (*i.e.*, humidity sensors, *etc.*) can be implemented at the other channels of the collecting module for wider studies, for example when measurement conditions take place under different environmental conditions.

According to the evaluation of the effects in the air velocity records, the results obtained show that the variation between sensors was not significant, as expected according to the information obtained in the calibration procedure. Moreover, the interactions “Section by Sensor (Height)” and “Boundary by Sensor (Height)” were the only significant interactions. The lack of statistical significance of the variable “Sensor” in this simple effect indicates a homogeneous behaviour for all the sensors on average for the different sections and boundaries studied. However, the interaction “Boundary by Sensor (Height)” indicates that the effects of the air velocity changing the boundaries are not identical in all of the sensors, *i.e.*, this interaction indicates that the differences between the boundary conditions do not appear in the average because this factor is not significant (boundaries). In the same way, the interaction “Section by Sensor (Height)” indicates that the air velocity changes at each section are not identical in all the sensors; *i.e.*, this interaction indicates the differences between sections do not appear in the average because this factor is not significant (sections). These results are in accordance with the continuity equation for the case of infinite points (Benedict, 1984), and they have important consequences in determining the locations of the sensors.

Regarding the performance of the ventilation system, when the best scenarios under which high mortality would be prevented during summer months was explored and a high value of the air velocity was not obtained at the level of the birds (a maximum of 0.80 ± 0.31 m s^{-1} in Section B, Boundary *III*). For this reason, it can be concluded that cross-mechanical ventilation is a good system for mild weather, but it is neccessary to explore other conditions of the ventilation system to prevent episodes of high mortality during summer months because this mechanical system of ventilation does not offer high air velocities at the level of the birds.

Moreover, it was interesting to note the great fluctuation in the values of air velocity in a mechanically ventilated poultry farm. As observed in the Table 2.4, the overall mean is 0.63 ± 0.54 m/s, the means by section are 0.59 ± 0.50 m s^{-1} (Section A) and 0.68 ± 0.58 m s^{-1} (Section B) and 0.51 ± 0.70 m s^{-1} (Boundary *I*), 0.64 ± 0.37 m s^{-1} (Boundary *II*), 0.75 ± 0.39 m s^{-1} (Boundary *III*) and 0.64 ± 0.62 m s^{-1} (Boundary *IV*). This variability is due air turbulence in farm building (Heber *et al.*, 1996) and the location of sensors (Blanes-Vidal *et al.*, 2010; Wheeler *et al.*, 2003). Environmental parameters values obtained through this measurement system can be utilised for V&V procedures (Oberkampf *et al.*, 2002) of CFD works and futures studies.

2.4. Conclusions

An on-line computerized multisensor system for measuring air velocities, temperatures and differential pressure in multiple locations in poultry houses at the same time was designed and built. The system consisted in a laptop, a data acquisition card, a multiplexor module and a set of 24 air temperature, 24 air velocity and two differential pressure sensors. The system was able to acquire up to a maximum of 128 signals simultaneously at 5 second intervals.

The statistical procedures used to obtain calibration curves demonstrate the robustness of the system regarding temperature sensors. A single regression curve was obtained for 14 sensors, two curves for four sensors, and only two individual curves. Moreover, for air velocity sensors a single calibration curve was obtained. The regression error was smaller than the error of the reference anemometer.

Under field tests in a commercial broiler farm, the multipoint sensor system allowed for the measurement of a high number of input signals from different locations with minimum internal delay in acquiring signals. In terms of air velocity, the results allow to conclude that the variation among sensors was not significant. It also demonstrated to be robust and portable and could be used without presence of any operator which could disturb air velocity profiles.

The developed multisensor system can be used to obtain quasi-instantaneous fields of the air velocity and temperature, as well as differential pressure maps to assess the design and functioning of ventilation system and as a V&V system of CFD simulations.

2.5. References

ASAE EP270.5. Design of Ventilation Systems for Poultry and Livestock Shelters. In ASABE Standards 2009; American Society of Agricultural and Biological Engineers (ASABE): St. Joseph, MI, USA, 1986; pp. 1–19.

Bartzanas, T.; Kittas, C.; Sapounas, A.A.; Nikita-Martzopoulou, C. Analysis of airflow through experimental rural buildings: Sensitivity to turbulence models. *Biosyst. Eng.* 2007, 97, 229–239.

Benedict, R.P. Fundamentals of Temperature, Pressure, and Flow Measurements; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 1984.

Berckmans, D.; Vandenbroeck, P.; Goedseels, V. Sensor for continuous measurement of the ventilation rate in livestock building. *Indoor Air* 1991, 1, 323–336.

Blanes-Vidal, V.; Guijarro, E.; Balasch, S.; Torres, A.G. Application of Computational Fluid Dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. *Biosyst. Eng.* 2008, 100, 105–116.

Blanes-Vidal, V.; Guijarro, E.; Nadimi, E.S.; Torres, A.G. Development and field test of an on-line computerized instrumentation system for air velocity, temperature and differential pressure measurements in poultry houses. *Span. J. Agric. Res.* 2010, 8, 570–579.

Boon, C.R.; Battams, V.A. Air mixing fans in a broiler building-their use and efficiency. *J. Agric. Eng. Res.* 1988, 39, 137–147.

Calvet, S.; Cambra-López, M.; Blanes-Vidal, V.; Estellés, F.; Torres, A.G. Ventilation rates in mechanically ventilated commercial poultry buildings in Southern Europe: Measurement system development and uncertainty analysis. *Biosyst. Eng.* 2010, 106, 423–432.

Champagne, F.H.; Sleicher, C.A.; Wehrmann, O.H. Turbulence measurements with inclined hot-wires. *J. Fluid Mech.* 1967, 28, 153–175.

Charles, D.R.; Clark, J.A.; Tucker, S.A. Ventilation Rate Requirements and Principles of air Movement. In Poultry Environment Problems. A Guide to Solutions, 1st ed.; Charles, D.,Walker, A., Eds.; Nottingham University Press: Nottingham, UK, 2002; pp. 17–46.

Dawkins, M.S.; Donnelly, C.A.; Jones, T.A. Chicken welfare is influenced more by housing conditions than stocking density. *Nature* 2004, 427, 342–344.

El País, Anonymous. Medio millón de pollos mueren fuerte calor últimos días. Available online: http://www.elpais.com/articulo/Comunidad/Valenciana/Medio/millon/pollos/mueren/fuerte/calor/ultimos/dias/elpepiespval/20030617elpval_4/Tes (accessed on 15 December 2011).

FAO. Faostat-Agriculture. Available online: http://faostat.fao.org/site/569/default.aspx#ancor (accessed on 15 January 2012).

Glaninger, A.; Jachimowicz, A.; Kohl, F.; Chabicovsky, R.; Urban, G. Wide range semiconductor flow sensors. *Sens. Actuators A* 2000, 85, 139–146.

Havenstein, G.B.; Ferket, P.R.; Qureshi, M.A. Growth, livability and feed conversion of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. *Poultry Sci.* 2003, 82, 1500–1508.

Heber, A.J.; Boon, C.R.; Peugh, M.W. Air patterns and turbulence in an experimental livestock building. *J. Agric. Eng. Res.* 1996, 64, 209–226.

Hwang, J.; Yoe, H. Study of the ubiquitous hog farm system using wireless sensors networks for environmental monitoring and facilities control. *Sensors* 2010, 10, 10752–10777.

Ibrahim, D. RTD Temperature Sensors. Microcontroller Based Temperature and Control; Newnes: Oxford, UK, 2002.

Kutman, M.H.; Nachtsheim, J.; Nefer, J.; Li, W. Applied Linear Statistical Models; McGraw Hill: New York, NY, USA, 2005.

Lee, I.B.; You, B. K.; Choi, K.H.; Jeun, J.G.; Kim, G.W. Study of Internal Climate of Naturally and Mechanically Ventilated Broiler Houses. In Proceedings of the ASAE Meeting, Las Vegas, NV, USA, 28–31 July 2003; Paper No. 034060.

Ligęza, P. Optimization of single-sensor two-state hot-wire anemometer transmission bandwidth. *Sensors* 2008, 10, 6747–6760.

Lott, B.D.; Simmons, J.D.; May, J.D. Air velocity and high temperature effects on broiler performance. *Poultry Sci.* 1998, 77, 391–393**.**

Matlab Central. The MathWorks, Inc.: Natick, MA, USA. Available online: http://www.mathworks.es/
matlabcentral/index.html (accessed on 15 December 2011).

Martin, D.P.; Grant, J.J.; Ringwood, J.V. Evaluation of a prototype thermal anemometer for use in low airspeed drying measure calculations. *Flow Meas. Instrum.* 2002, 12, 385–396.

Martínez, M.; Marín, C.; Torres, A.; Láinez, M. Characterization of chicken farm of the Valencian Community (In Spanish); Fundación Agroalimed, Conselleria d´Agricultura, Pesca i Alimentació. Generalitat Valenciana: Valencia, Spain, 2008; pp. 93–97.

Mistriotis, A.; de Jong, T.; Wagemans, M.J.M.; Bot, G.P.A. Computational fluid dynamics as a tool for the analysis of ventilation and indoor microclimate in agriculture buildings. *Neth. J. Agric. Sci.* 1997, 45, 81–96.

Morrison, G.L.; Perry, A.E.; Samuel, A.E. Dynamic calibration of inclined and crossed hot wires. *J. Fluid Mech.* 1972, 52, 465–474.

MWPS. Mechanical Ventilating Systems for Livestock Housing, 1st ed.; Midwest Plan Service, Iowa State University: Ames, IA, USA, 1990.

National Instruments. LabView. Available online: http://www.ni.com/labview (accessed on 15 December 2011).

Norton, T.; Sun, D.; Grant, J.; Fallon, R.; Dodd, V. Applications of computational fluid dynamics (CFD) in the modelling and design of ventilation systems in the agricultural industry: A review. *Bioresour. Technol.* 2007, 98, 2386–2414.

Oberkampf, W.L.; Trucano, T.G. Verification and validation in computational fluid dynamics. *Prog. Aerosp. Sci.* 2002, 38, 209–272.

Pawar, S.R.; Cimbala, J.M.; Wheeler, E.F.; Lindberg, D.V. Analysis of poultry house ventilation using computational fluid dynamics. *Trans. ASABE* 2007, 50, 1373–1382**.**

Pedersen, S. Forced Ventilation. In CIGR Handbook of Agricultural Engineering: Animal Production & Aquacultural Engineering; American Society of Agricultural Engineers (ASAE):St. Joseph, MI, USA, 1999; pp. 68–87.

Ruiz-García, L.; Lunadei, L.; Barreiro, P.; Robla, I. A review of wireless sensor technologies and applications in agriculture and food industry: State of the art and current trends. *Sensors* 2009, 9, 4728–4750.

SAS. SAS User's Guide: Statistics, version 6.12; SAS Inst. Inc.: Cary, NC, USA, 1998.

Sensortechnics Inc. Available on line: http://www.sensortechnics.com (accessed on 15 December 2011).

Sherif, S.A.; Pletcher, R.H. An analytical procedure for predicting the response of constant temperature hot-wire and film anemometers. *Measurement* 1999, 25, 193–201.

Simmons, J.D.; Hannigan, T.E.; Lott, B.D. A portable anemometer to determine the output of large in-place ventilation fans. *Appl. Eng. Agric.* 1998, 14, 649–653.

Slingenbergh, J.; Gilbert, M. Do Old and New Forms of Poultry Go Together? In Proceedings of the International Poultry Conference, Bangkok, Tailand, 5–7 November 2007. Available online:

http://www.fao.org/ag/againfo/home/events/bangkok2007/docs/part2/2_3.pdf (accessed on 15 December 2011).

Strøm, J.S.; Zhang, G.; Morsing, S. Predicting near-floor air velocities for a slot-inlet ventilated building by jet velocity decay principles. *Trans. ASAE* 2002, 45, 1559–1568.

Tao, X.; Xin, H. Acute synergistic effects of air temperature, humidity and velocity on homeostasis of market-size broilers. *Trans. ASAE* 2003, 46, 491–497.

Testo Inc. 2004. Available online: http://www.testo.com (accessed on 15 December 2011).

TFD. Omega Engineering, Inc. Available online: http://www.omega.com/Temperature/pdf/TFD_RTD.pdf (accessed on 15 December 2011).

Van Wagenberg, A.V.; de Leeuw, M.T.J. Measurement of air velocity in animal occupied zones using an ultrasonic anemometer. *Appl. Eng. Agric.* 2003, 19, 499–508.

Wheeler, E.F.; Zajaczkowski, J.L; Saheb, N.C. Field evaluation of temperature and velocity uniformity in tunnel and conventional ventilation broiler houses. *Appl. Eng. Agric.* 2003, 19, 367–377.

Wilhelm, L.R.; Milner, J.M.; Snyder, S.D.; McKinney, D.B. An instrumentation system for environmental measurements in broiler and swine housing. *Appl. Eng. Agric.* 2001, 17, 677–681.

Xia, B.; Sun, D.-W. Applications of computational fluid dynamics (CFD) in the food industry:A review. *Comput. Electron. Agric.* 2002, 34, 5–24.

Zarzo, M.; Fernández-Navajas, A.; García-Diego, F.J. Long-term monitoring of fresco paintings in the cathedral of Valencia (Spain) through humidity and temperature sensors in various locations for preventive conservation. *Sensors* 2011, 11, 8685–8710.

Zhang, G.; Strøm, J.S.; Morsing, M. A Computerized Multi-point Temperature and Velocity Measurement System. In Proceedings of the Fifth International Conference on Air Distribution in Rooms (RoomVent'96), Yokohama, Japan, 17–19 July 1996; pp. 531–538.

Chapter 3

Cross mechanical ventilation in broiler houses

An adapted version is published in:

Exploring Ventilation Efficiency in Poultry Buildings: The Validation of Computational Fluid Dynamics (CFD) in a Cross-Mechanically Ventilated Broiler Farm. Eliseo Bustamante, Fernando-Juan García-Diego, Salvador Calvet, Fernando Estellés, Pedro Beltrán, Antonio Hospitaler and Antonio G. Torres. *Energies* 6 (2013), 2605-2623.

Abstract: Broiler production in modern poultry farms commonly uses mechanical ventilation systems. This mechanical ventilation requires an amount of electric energy and a high level of investment in technology. Nevertheless, broiler production is affected by periodic problems of mortality because of thermal stress, thus being crucial to explore the ventilation efficiency. In this article, we analyse a cross-mechanical ventilation system focusing on air velocity distribution. In this way, two methodologies were used to explore indoor environment in livestock buildings: Computational Fluid Dynamics (CFD) simulations and direct measurements for verification and validation (V&V) of CFD. In this study, a validation model using a Generalized Linear Model (GLM) was conducted to compare these methodologies. The results showed that both methodologies were similar in results: the average of air velocities values were 0.60 ± 0.56 m s^{-1} for CFD and 0.64 ± 0.54 m s^{-1} for direct measurements. In conclusion, the air velocity was not affected by the methodology (CFD or direct measurements), and the CFD simulations were therefore validated to analyze indoor environment of poultry farms and its operations. A better knowledge of the indoor environment may contribute to reduce the demand of electric energy, increasing benefits and improving the thermal comfort of broilers.

Keywords: livestock building; design; efficiency; ventilation; cross-mechanical ventilation; poultry farm; broilers.

3.1. Introduction

In many areas, broiler production is affected every year by several episodes of massive bird mortality because of the confluence of high temperature and humidity values during summer seasons. This problem causes great economical losses and animal suffering, which is inconceivable in a modern society, which uses a high technological investment at these poultry farms and establishes regulations to ensure animal welfare. In the last decades, mechanical ventilation was incorporated at intensive poultry farms to improve the thermal comfort of the animals (Charles *et al.*, 2002; MWPS, 1990), but the problems related with heat stress have not been solved yet (El País, 2003; WorldPoultry, 2012). Cross-mechanical ventilation is widely used in poultry farms but the problems of mortality and broiler stress appears more frequently in hot and humid climates, especially in summer. For this reason, it is crucial to explore thoroughly the efficiency of these ventilation systems in order to improve the whole livestock building design and to improve their indoor environment. Whereas natural ventilation does not consume electric energy to force air exchange, mechanical ventilation requires a certain amount of energy to activate the fans, the automation of inlets and other electric/electronic facilities. Obviously, an optimization of energy consumption is desired to reduce farm costs and to reduce the demand of electric energy. A great percentage of electric energy is provided by fossil fuels, nuclear or other non renewable sources. A reduction of electric energy consumption in livestock farms can be achieved by optimizing livestock building design and improving ventilation efficiency by an appropriate management. This may contribute to reduce costs for farmers, and indirectly may reduce the consumption of fossil fuel or other non-renewable sources contributing to the control of the global warming. In agricultural systems such as greenhouses or farms, two methodologies are used to analyze problems related to the indoor environment: direct measurements by the suitable electronic instrumentation and Computational Fluid Dynamics (CFD) techniques. The CFD procedures are very emergent techniques in many fields of science and engineering. However, it is necessary a suitable instrumentation system to validate the simulations. Whereas CFD techniques and associate instrumentation are widely developed in other fields of engineering (e.g., aerodynamic, automotive, spatial, chemistry, nuclear, simulation of fire...), in agricultural engineering they are less developed, particularly in the study of indoor environments of farms. A possible reason for this fact is that direct measurements by means of multi-sensor systems for poultry farms are complex and they have not been tested with great success yet (Bustamante *et al.*, 2012). Previous research has focused on the design of sensors and data acquisition systems to measure the environmental parameters according with the ranges and particularities of these complex buildings (large dimensions, automatisms of fans and air-inlets, feeding and watering equipment, refrigerating and heating systems…), which is essential to carry out the validation. A robust measurement system adapted to the hard environmental conditions at poultry farms was designed, which allowed data acquisition at conditions of isotemporality at multiple points (Bustamante *et al.*, 2012). Such a system is necessary to validate CFD measurements due to the great sudden fluctuations of air velocity in time and space generated at mechanical ventilation.

Broiler production offers meat at reasonable price to the consumers and in the current context of economic crisis the consumption of broiler meat is increasing due to its price-quality relation. In this sense, poultry meat must maintain its quality, reducing mortality and other costs. Intensive production normally takes place at mechanically ventilated farms that with a high level of investment which allows a high density of animals and more thermal comfort in comparison with naturally ventilated farms. In this way, housing conditions is acknowledged to influence animal welfare more than animal density (Dawkins *et al.*, 2004). In the European Union (EU), a specific regulation related to intensive production and welfare of broilers has been developed (EU Council Directive 2007/43/EC) (European Union, 2007). According to this Directive, the countries of EU must ensure that broiler facilities are constructed and operated to provide the animals with a proper environment in terms of temperature, relative humidity and gases (ammonia and carbon dioxide). Several studies have demonstrated the influence of thermal effects on the broiler performance: Lott *et al.*, 1998 studied the effects of air and temperature on broiler performance; May *et al.*, 2000 studied the effect of air velocity on broiler performance and feed and water consumption; Yavah *et al.*, 2001 affirmed that the air velocity alters the broiler performance under harsh environmental conditions; Yanagi *et al.*, 2002 studied the poultry responses to heat stress; Simmons *et al.*, 2003 studied the effects of high-air velocity on broiler performance; Yavah *et al.*, 2004 studied the ventilation, sensible heat loss, broiler energy and water balance under harsh environmental conditions.

In mechanically ventilated broiler buildings, farmers usually control the indoor environment by changing the geometry of inlets and the activity of fans. These changes are carried out by automatisms that cause changes in the differential pressure and as a consequence, fluctuations in the air velocity values and directions are originated. These changes of air velocity are used to regulate the heat exchange of the broilers with their environment. For the farmers, modifying animal housing conditions is relatively simple using pressure difference, but normally, the farmer experience is a key factor to provide the animals with proper ventilation. However, to the moment very scarce information is available on how to optimize ventilation, not only in terms of air exchange, but also of velocity distribution. As a consequence, massive deaths due to thermal stress still occur in hot conditions. For this reason, the CFD techniques will not be only used to find optimal design for poultry buildings and improve their thermal comfort; they will also be used to analyze the best poultry farms operations under the strong premise that economizes electric energy.

In a general context of livestock buildings, CFD techniques have been already applied (Bartzanas *et al.*, 2007; Mistriotis *et al.*, 1997; Norton *et al.*, 2007; Norton *et al.*, 2009). Furthermore, it can found some applications of CFD simulations applied specifically at poultry farms (Blanes-Vidal *et al.*, 2008; Lee *et al.*, 2007; Pawar *et al.*, 2007).

The validation of CFD simulations is an important rule (Oberkampf *et al.*, 2002). In this sense, it is essential to ensure that CFD can be used to explore trends of poultry farm design and its optimal operations in practice. For laying hens, Pawar *et al.*, 2007 studied a mechanical ventilated building using the commercial code CFD FLUENT (Fluent Inc., 2001). Similarly, Blanes-Vidal *et al.*, 2008 studied a transversal, mechanically ventilated broiler farm with the same commercial code. However, they only used three measurement points in a single mobile support that had to be changed by an operator. In their experiment, the number of measurement points was reduced and the presence of an operator to change the mobile post could distort the airflow and air velocity values and trajectories (Wheeler *et al.*, 2003).

This study aims to validate CFD simulations of air velocity with direct measurements of a multi-sensor system. As the fluctuations of values and trajectories of air velocity is the most expanded method to control thermal comfort at poultry farms with forced ventilation systems, this paper focuses on the validation of the CFD-air velocity results with the direct measurements performed in a broiler farm located in the Valencia Community (Spain).

3.2. Materials and Methods

3.2.1. Experimental Poultry Farm

Measurements and simulations were carried out at a commercial broiler farm located in Villarreal (Northern Hemisphere, Latitude 39°56’, Longitude 0°6’; 43 m above sea level) in Eastern Spain. The poultry building used forced ventilation by negative-pressure systems, in particular, a mechanical cross-ventilation system. Dimensions were: length, 110 m; width, 12.60 m; sidewall height 2.6 m; roof 21.53%, total height of the building 4 m. There were nine large exhaust fans (diameter 1.28 m) and seven small exhaust fans (diameter 0.68

m) installed, described in Bustamante *et al.*, 2012. The building was empty during the experimentation to avoid the possible interferences due to the presence of the animals in the airflow circuit and to prevent the inconveniences that the measuring system could cause in animal performance.

3.2.2. Test Sections and Multisensor System for Direct Measurements

Field experiments were conducted in two sections of the poultry farm of similar length (30 m). As shown in Figure 3.1, the first section was located near one extreme of the building (Section A), whereas the second corresponded to the center of the building (Section B). A multisensor system for isotemporal measurements to assess indoor climatic conditions in poultry farms was used to measure air velocity. The measurement system was composed by 24 air velocity sensors, 24 temperature sensors and 2 differential pressure sensors (Bustamante *et al.*, 2012) and was able to acquire up to a maximum of 128 signals simultaneously at 5 s intervals obtaining one data of each sensor at a frequency of this 5 s (10 min in each section and in each Boundary Condition). In the two studied sections measurements were taken at two heights (0.25 m—birds' level—and 1.75 m) using 12 tripods. The location of the sensors was chosen according to the situation of inlets and fans and the sensor's coordinates are shown in Table 3.1. During the field experiment, a total of 23,040 measurements were taken in the same day at four scenarios and two sections of the poultry farm in 24 points of each section and eight CFD simulations for the same scenario and section where done.

Figure 3.1. *Test sections in the experimental poultry farm.*

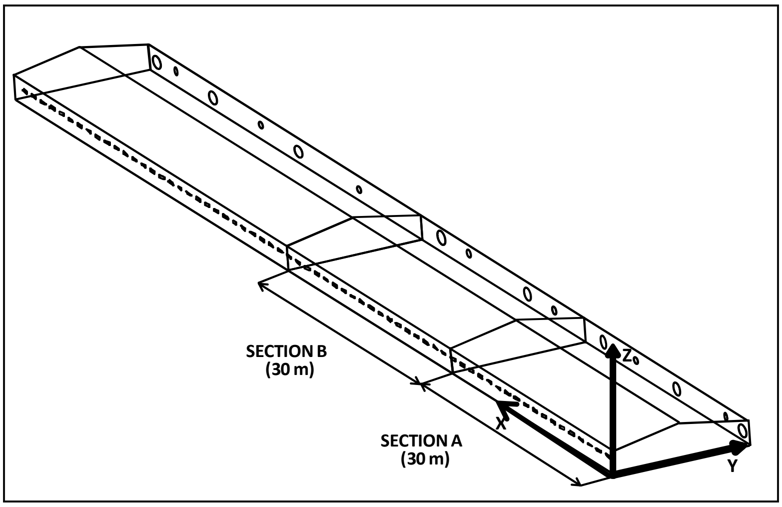


Table 3.1. *Coordinates of sensors.*

Sensor number *	Section A		Section B	
	***X*-coordinate (*m*)**	***Y*-coordinate (*m*)**	***X*-coordinate (*m*)**	***Y*-coordinate (*m*)**
1–2	22.45	0.30	35.90	0.05
3–4	19.50	12.00	31.50	11.80
5–6	18.00	11.95	32.80	11.95
7–8	9.30	12.00	41.80	7.15
9–10	5.70	12.05	40.70	6.80
11–12	0.60	12.00	45.85	11.35
13–14	0.55	6.30	47.35	4.50
15–16	0.50	7.60	46.95	5.35
17–18	0.55	2.15	44.05	0.80
19–20	8.70	6.70	48.50	3.15
21–22	24.85	7.10	47.70	1.10
23–24	23.60	7.15	47.70	0.65

*****: The first sensors at animal level, the second at 1.75 m.

3.2.3. CFD Background

The commercial software FLUENT (Fluent Inc., 2001) was used to realize all the CFD simulations. The geometry model and mesh were developed using the pre-processor Gambit (Geometry and Mesh Building Intelligent Toolkit) of FLUENT (Gambit, Fluent Inc., 2001). CFD FLUENT was used at previous CFD simulations of poultry farms as mentioned before (Blanes-Vidal *et al.*, 2008; Lee *et al.*, 2007; Pawar *et al.*, 2007).

The basic idea of all CFD techniques is the resolution of a set of partial differential Equations (PDE's) (Norton *et al.*, 2007; Patankar *et al.*, 1980) that corresponded to Equations of continuity [Equation (3.1)], conservation of momentum (Navier-Stokes's law) [Equation (3.2)] and Equation of the energy [Equation (3.3)].

Those Equations for an uncompressible fluid with isothermal properties are:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{3.1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i \tag{3.2}$$

$$\frac{\partial}{\partial t}(\rho cT) + \frac{\partial}{\partial x_j}(\rho u_j cT) - \frac{\partial}{\partial x_j}\left(K \frac{\partial T}{\partial x_j}\right) = S_T \tag{3.3}$$

where ρ: fluid density (kg m^{-3}); t: time (s); x, x_i, x_j: length components (m); u_i, u_j: velocity component (m s^{-1}); p: pressure (Pa); τ_{ij}: stress tensor (Pa); g_i: gravitational acceleration (m s^{-2}); F_i: external body forces in the i direction (N m^{-3}); c: specific heat (W kg^{-1} K^{-1}); T: temperature (K); K: thermal conductivity (W m^{-1} K^{-1}); S_T: thermal source term (W m^{-3}).

3.2.4. Turbulence Models and Boundary Conditions (BC)

CFD FLUENT (Fluent Inc., 2001) has various available turbulence models: Inviscid, laminar, Spallard-Allmaras, standard k-ε, k-ε RNG, k-ε realizable, Reynolds Stress Model (RSM), standard k-ω, SST k-ω and Large Eddy Simulation (LES). Reynolds averaged Navier-Stokes Equations (RANS) determine the effect of turbulence on the mean flow field through time averaging (Norton *et al.*, 2007); LES forms a solution given the fact that large turbulent eddies are highly anisotropic on both the mean velocity gradients and geometry of the flow domain (Norton *et al.*, 2007). LES needs higher computing time and powerful computers and it is used for specific purposes when extreme accuracy is required. It should be noted that none of the existing turbulence models are complete, *i.e.*, their prediction performance is highly reliant on turbulent flow and geometry (Norton *et al.*, 2007). Traditionally, in agricultural engineering, (greenhouses and livestock buildings), the turbulence models commonly used were: standard k-ε, k-ε RNG, k-ε realizable and Reynolds Stress Model (RSM). In this paper, the standard k-ε model described by (Launder & Spalding, 1974) was used, also considering that (Blanes-Vidal *et al.*, 2008) also used it in their CFD simulations in a cross-mechanical ventilated poultry farm. This model is widely used in engineering for agricultural applications such as the modeling of poultry farms (Blanes-Vidal *et al.*, 2008; Lee *et al.*, 2007; Pawar *et al.*, 2007), because it is considered robust and reasonably accurate. The Equations of transport of this turbulence model were (3.4) and (3.5) (Fluent Inc., 2001):

$$\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\varepsilon - Y_M \tag{3.4}$$

$$\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{3.5}$$

where k: turbulent kinetic energy (m^2 s^{-2}); μ: fluid viscosity (m^2 s); μ_t: turbulent viscosity (m^2 s); σ_k: turbulent Prandtl number for k; G_k: the generation of kinetic energy due to the variations of the components of the average velocity of the flow (kg m^{-1} s^{-2}); G_b: the generation of kinetic energy by boundary push (kg m^{-1} s^{-2}); ε: turbulent dissipation rate (m^2 s^{-3}); Y_M: contribution of the pulsatile expansion associated to the compressible turbulence (kg m^{-1} s^{-2}); σ_ε: turbulent Prandtl number for ε; $C_{1\varepsilon}$: constant; $C_{2\varepsilon}$: constant; $C_{3\varepsilon}= tanh[u_1/u_2]$; u_1: velocity of flow parallel to g_i (gravitational vector); u_2: velocity of flow perpendicular to g_i. Moreover, the constant values were $C_{1\varepsilon}$ = 1.44, $C_{2\varepsilon}$ = 1.92, σ_k = 1.0 and σ_ε = 1.3 (Fluent Inc., 2001; Launder & Spalding, 1974).

In this paper, we carried out eight final three-dimensional CFD simulations that corresponded with the four scenarios tested (four typical conditions of operation at two sections of the poultry farm). Each scenario was mainly characterized by the number of fans operating and the different opening of inlets, the differential pressure (Bustamante *et al.*, 2012) and the ventilation rate was measured (Calvet *et al.*, 2010) in each trial scenario. From these scenarios were obtained the BC to introduce at CFD software.

Each final simulation was adopted when the numerical solutions were stabilized through successive numerical simulations increasing the density and refinement of the mesh (grid independence). As we have indicated above, the pre-processor GAMBIT (Gambit, Fluent Inc., 2001) was used to build the computational domain with these meshes assigning (without the numerical value) the BC's at each surface and volume. To assure a good quality of the mesh (mainly composed by tetrahedral cells), the equiangular skewness of GAMBIT (Gambit, Fluent Inc., 2001) was used. For a good quality of the mesh, this value must be less than 0.8 (Gambit, Fluent Inc., 2001):

$$Skewness = \max\left[\frac{\theta_{\max} - \theta_e}{180 - \theta_e}, \frac{\theta_e - \theta_{\min}}{\theta_e}\right] \tag{3.6}$$

where θ_{max}= Largest angle in face or cell; θ_{min}= Smallest angle in face or cell; θ_e= Angle for equiangular face or cell.

The mesh domain built in GAMBIT (Gambit, Fluent Inc., 2001) was exported to the CFD-solver FLUENT (Fluent Inc., 2001), which solved the above mentioned governing partial differential Equations of continuity [Equation (3.1)], of momentum [Equation (3.2)] and energy [Equation (3.3)] in each mesh of the computational domain. The pressure and velocity coupling is solved by the SIMPLE algorithm (Patankar, 1980) with the second order upwind scheme (Patankar, 1980). The k-ε standard turbulence model and wall functions (Fluent Inc., 2001) were used in the CFD simulations.

It was assumed that the flow is steady, three-dimensional, viscous, turbulent, incompressible and isothermal. The properties of the fluid (air in this case) are considered constants and their values were shown in Table 3.2. Gravitational acceleration was also considered.

Table 3.2. *Main inputs and BC at CFD simulations.*

(i) Constant and computational settings
3D double precision Segregated Steady Turbulence model: Standard k-ε Wall treatment: Standard Wall Functions Pressure-velocity coupling: SIMPLE algorithm Discretization scheme: Pressure: standard; Momentum: Second order upwind; Turbulence kinetic energy: Second order upwind; Turbulence dissipation rate: Second order upwind; Energy: Second order upwind. Air properties: Density: 1.225 Kg m^{-3}; C_p: 1006.43 J kg^{-1} K^{-1}; Thermal conductivity: 0.0242 W m^{-1} K^{-1}; Viscosity: $1.789 \cdot 10^{-5}$ kg $m^{-1}s^{-1}$. Wall material: Density: 2400 Kg m^{-3}; C_p= 1125 J kg^{-1} K^{-1}; Thermal conductivity: 1.2 W m^{-1} K^{-1}. Atmospheric pressure: 101,325 Pa. Gravitational acceleration: 9.81 m s^{-2}.

(ii) Boundary Conditions					
CFD Simulation	Assay Section	Scenario	Outlets (Fans) Mass Flux rate at each outlet (in kg s^{-1}) Air temperature at each outlet (in K)	Inlet Air (10% Turbulence Intensity (1)) Air velocity (in m s^{-1}) Air temperature (in K)	Temperature at solid elements (in K) Floor North-Wall (2) South-Wall (2) East-Wall (2) West-Wall (2) East-Cover (2) West-Cover (2)
I	Section A	I	Large = 9.60 Kg s^{-1} 303.7 K Small = 0	6.62 m s^{-1} 304.5 K	303.0 K 303.4 K 304.7 K 305.1 K 304.1 K

					305.5 K
					305.0 K
II	Section A	II	Large = 9.03 Kg	7.70 m s^{-1}	303.0 K
			s^{-1} 301.9 K	303.3 K	302.5 K
			Small = 3.2 Kg		303.0 K
			s^{-1} 301.9 K		303.5 K
					302.0 K
					303.5 K
					302.0 K
III	Section A	III	Large = 8.17 Kg	9.01 m s^{-1}	302.0 K
			s^{-1} 303.7 K	304.5 K	303.4 K
			Small = 0		304.6 K
					306.6 K
					303.1 K
					305.7 K
					305.0 K
IV	Section A	IV	Large = 7.82 Kg	10.67 m s^{-1}	303.0 K
			s^{-1} 301.9 K	303 K	302.5 K
			Small = 2.78 Kg		303.0 K
			s^{-1} 301.9 K		304.0 K
					302.0 K
					303.5 K
					302.0 K
V	Section B	I	Large = 9.60 Kg	4.66 m s^{-1}	305.0 K
			s^{-1} 304.8 K	305.6 K	305.0 K
			Small = 0		306.0 K
					307.0 K
					303.0 K
					305.0 K
					304.0 K
VI	Section B	II	Large = 9.03 Kg	5.93 m s^{-1}	304.0 K
			s^{-1} 305.1 K	305.8 K	304.0 K
			Small = 3.2 Kg s^{-1}		306.0 K
			305.1 K		307.3 K
					303.5 K

					305.7 K 304.6 K
VII	Section B	III	Large = 8.17 Kg s^{-1} 304.9 K Small = 0	6.35 m s^{-1} 305.8 K	304.0 K 304.5 K 306.0 K 307.2 K 303.2 K 305.5 K 304.3 K
VIII	Section B	IV	Large = 7.89 Kg s^{-1} 305.1 K Small = 2.78 Kg s^{-1} 305.1 K	8.23 m s^{-1} 306.2 K	304.0 K 304.0 K 306.0 K 307.5 K 303.5 K 305.3 K 304.7 K

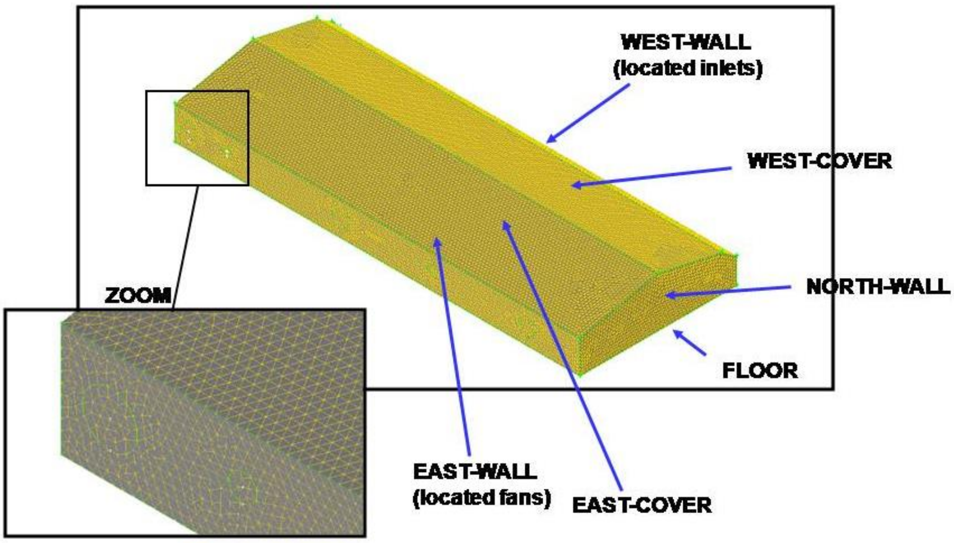
(1) Turbulence intensity is defined by (Fluent Inc., 2001) as the ratio of the root-mean-square of the velocity fluctuations, u_{fluct} , to the mean flow velocity, u_{aver}

(2) According to the main orientation reached by the walls and covers.

Mass flux rate (in kg s^{-1}) of each outlet (fan), air velocity at inlets and temperature at solid elements were BC used to carry out the CFD simulations. The air temperature was also measured at inlets and at outlets, as the temperature fluctuations at inlets and at outlets were negligible in each scenario (operation), one average from air temperature at inlets and another average from air temperature at outlets was introduced as indicates in Table 3.2. In the same way, two averages of mass flux rate (one average from each type of fans) and another average of air velocity at inlets from each scenario were introduced at CFD software as indicated in Table 3.2. These air velocity at inlets (m s^{-1}) were obtained from thirty measurements (thirty seconds) at each inlet by means of a calibrated Testo 425 hot-wire anemometer (Testo Inc., 2013); then, the average of all inlets was calculated and introduced in CFD software. Introducing these single values reduces time consumption of CFD calculations; in this sense, some authors have calculated and assumed uniform velocities and airflow rates for inlets or outlets in their CFD simulations (Bjerg *et al.*, 2002; Blanes-Vidal *et al.*, 2008; Davidson *et al.*, 1989). In this paper, the individual ventilation rate of each outlet was measured by Calvet *et al.*, 2010. This protocol of measurement (Calvet *et al.*, 2010) consist of ducted the exhaust air 50 cm from the fan and then by means

of a hot wire anemometer measuring at 24 different locations in the section (ASHRAE, 2001). On the other hand, the surface temperature of internal solid elements (wall, floor or covers) was measured by means of a portable model Optex PT-3LF non-contact (infrared) thermometer and the measured values were indicated in the same Table 3.2. Evidently, the specifications of a correct functioning of this model of thermometer were according to the range of values reached of any poultry farm from broiler production (an accuracy ±1 of the reading value or ±2 °C ±1 digit in an ambient temperature 0 °C to 50 °C, ambient humidity 35% to 85% RH). The temperatures reached at solid elements were another BC requires by CFD program. Table 3.2 summarizes the main inputs and BC at CFD simulations.
Geometry and mesh were developed using GAMBIT (Gambit, Fluent Inc., 2001). The CFD models were discretized in finite volumes in unstructured meshes as shown in Figure 3.2. For practical reasons of nomenclature expression of some BC (temperature at walls and covers), the terms North-Wall, South-Wall, East-Wall, West-Wall, East-Cover, West-Cover and floor will be used, according to the physical orientation as seen in Figure 3.2.

Figure 3.2. *Screen of geometry and meshed of poultry farm at GAMBIT (FLUENT). Orientation of walls and covers.*



The big exhaust fans and the small exhaust fans were modeled as circles of diameter 1.28 m and 0.68 m respectively (its real dimensions). The inlets were modeled for each scenario following the actual geometry adopted by the inlet windows. As the poultry farm was empty during the scenarios, the broiler metabolism and other elements such feeding and watering equipment were not modeled.

Model CFD locations with special interest were those corresponding to the location of the sensors, which coordinates were specified in the Table 3.1.

3.2.5. Statistical Validation Model

The validation consisted of a statistical treatment between CFD-air velocity results and the direct measurements with the multi-sensor system, by means of an analysis of variance (ANOVA).

The model used to do this validation was:

$$Y_{ijk\ln} = \mu + Z_i + B_j + H_k + SN_l + M_n + (Z \times B)_{ij} + (Z \times H)_{ik} + (Z \times M)_{in} + \\ + (Z \times SN)_{il} + (B \times H)_{jk} + (B \times SN)_{jl} + (B \times M)_{jn} + (H \times M)_{kn} + \\ + (SN \times H)_{lk} + (Z \times B \times H)_{ijk} + (Z \times SN \times M)_{i\ln} + +(B \times SN \times M)_{j\ln} + \\ + (Z \times B \times H \times M)_{ijkn} + \varepsilon_{ijk\ln} \quad (3.7)$$

where the different variables are explained below, and in brackets the number of levels within each variable is indicated:

Y_{ijk}: Air velocity in the section *i* at boundary conditions *j* at height *k* by the sensor *l* and by methodology *n*;

Z_i: Measurement section (2);

B_j: Boundary conditions (4);

H_k: Height of the sensor (2);

SN_l: Sensor *l* (24);

M_n: Methodology: CFD *vs.* direct measurements using the multisensor system (2);

$(Z\ X\ B)_{ij}$: Interaction between Section-Boundary (8);

$(Z\ X\ H)_{ik}$: Interaction between Section-Height (4);

$(Z\ X\ M)_{in}$: Interaction between Section-Methodology (4);

$(Z\ X\ SN)_{il}$: Interaction between Section-Sensor (48);

$(B\ X\ H)_{jk}$: Interaction between Boundary-Height (8);

$(B\ X\ SN)_{jl}$: Interaction between Boundary-Sensor (96);

$(B\ X\ M)_{jn}$: Interaction between Boundary-Methodology (8);

$(H\ X\ M)_{lk}$: Interaction between Height-Methodology (4);

$(SN\ X\ H)_{lk}$: Interaction between Sensor-Height (48);

$(Z\ X\ B\ X\ H)_{ijk}$: Triple interaction between Section-Boundary-Height (16);

$(Z\ X\ SN\ X\ M)_{iln}$: Triple interaction between Section-Sensor-Methodology (96);

$(B\ X\ SN\ X\ M)_{jln}$: Triple interaction between Boundary-Sensor-Methodology (192);

***(Z X B X H X M)**$_{ijkn}$*: Four interaction between Section-Boundary-Height-Methodology (384);

ε_{ijkln}: Error of the model

For observing the effect of the methodology (CFD or direct measurements) all factors are considered random, the model was analyzed by the GLM procedure of SAS Systems (SAS, 1998). It was considered that a factor has a statistically significant influence on a variable when the p-value obtained for this valor in the analysis of variance is equal or lower than 0.05. On the contrary, higher *p*-values indicate that a factor has no significant influence.

3.3. Results and Discussion

3.3.1. CFD vs. Direct Measurements

CFD-air velocity results and its direct measurements using the multisensor system are shown in Table 3.3.

As shown in Table 3.3 minor differences were found between CFD results and direct measurements using the multi-sensor system. It has not appreciated any significant tendency in the results using both methodologies. The more discrepant case (CFD *vs.* direct measurements) was in scenario II at 0.25 m (broiler's level) obtaining 0.70 ± 0.35 m s^{-1} from measurements and 0.60 ± 0.30 m s^{-1} from CFD.

Table 3.3. *Air velocity in m s^{-1} (average ± standard deviation) in the field experiment by direct measurements and by CFD simulations. The number of data is indicated in parenthesis.*

Scenario	Height	Methodology	Section A	Section B	Mean
I	0.25 m	Measured	0.62 ± 0.86 (12)	0.37 ± 0.30 (12)	0.50 ± 0.65 (24)
		CFD	0.52 ± 0.68 (12)	0.34 ± 0.29 (12)	0.43 ± 0.52 (24)
	1.75 m	Measured	0.37 ± 0.39 (12)	0.66 ± 1.00 (12)	0.52 ± 0.76 (24)
		CFD	0.35 ± 0.40 (12)	0.62 ± 0.97 (12)	0.49 ± 0.74 (24)
	Mean	Measured	0.50 ± 0.67 (24)	0.53 ± 0.74 (24)	0.51 ± 0.70 (48)
		CFD	0.43 ± 0.55 (24)	0.48 ± 0.71 (24)	0.46 ± 0.63 (48)
II	0.25 m	Measured	0.70 ± 0.35 (12)	0.71 ± 0.29 (12)	0.71 ± 0.33 (24)
		CFD	0.60 ± 0.30 (12)	0.74 ± 0.36 (12)	0.67 ± 0.33 (24)
	1.75	Measured	0.47 ± 0.32 (12)	0.68 ± 0.47 (12)	0.58 ± 0.41 (24)
		CFD	0.41 ± 0.34 (12)	0.68 ± 0.50 (12)	0.55 ± 0.44 (24)

	Mean	Measured	0.59 ± 0.35 (24)	0.70 ± 0.38 (24)	0.64 ± 0.37 (48)
		CFD	0.60 ± 0.30 (24)	0.71 ± 0.43 (24)	0.61 ± 0.39 (48)
III	0.25 m	Measured	0.78 ± 0.41 (12)	0.80 ± 0.31 (12)	0.79 ± 0.35 (24)
		CFD	0.73 ± 0.36 (12)	0.89 ± 0.43 (12)	0.75 ± 0.36 (24)
	1.75 m	Measured	0.63 ± 0.34 (12)	0.77 ± 0.50 (12)	0.70 ± 0.42 (24)
		CFD	0.50 ± 0.32 (12)	0.79 ± 0.55 (12)	0.65 ± 0.47 (24)
	Mean	Measured	0.71 ± 0.37 (24)	0.79 ± 0.41 (24)	0.75 ± 0.39 (48)
		CFD	0.62 ± 0.35 (24)	0.84 ± 0.49 (24)	0.73 ± 0.44 (48)
IV	0.25 m	Measured	0.42 ± 0.26 (12)	0.65 ± 0.59 (12)	0.54 ± 0.46 (24)
		CFD	0.37 ± 0.27 (12)	0.54 ± 0.38 (12)	0.46 ± 0.34 (24)
	1.75 m	Measured	0.72 ± 0.69 (12)	0.77 ± 0.87 (12)	0.74 ± 0.75 (24)
		CFD	0.72 ± 0.87 (12)	0.80 ± 1.04 (12)	0.76 ± 0.94 (24)
	Mean	Measured	0.57 ± 0.53 (24)	0.71 ± 0.71 (24)	0.64 ± 0.62 (48)
		CFD	0.54 ± 0.65 (24)	0.67 ± 0.78 (24)	0.61 ± 0.71(48)
All	0.25 m	Measured	0.63 ± 0.53 (48)	0.63 ± 0.41 (48)	0.63 ± 0.47 (96)
		CFD	0.55 ± 0.44 (48)	0.63 ± 0.41 (48)	0.59 ± 0.43 (96)
	1.75 m	Measured	0.55 ± 0.47 (48)	0.72 ± 0.71 (48)	0.63 ± 0.61 (96)
		CFD	0.50 ± 0.53 (48)	0.72 ± 0.78 (48)	0.61 ± 0.67 (96)
	Mean	Measured	0.59 ± 0.50 (96)	0.68 ± 0.58 (96)	0.63 ± 0.54 (192)
		CFD	0.52 ± 0.49 (96)	0.68 ± 0.62 (96)	0.60 ± 0.56 (192)

3.3.2. CFD-Air Velocity Results

An advantage of CFD simulations is that they offer a visual representation which gives a comprehensive idea of the trends of airflow in which parameters are represented by colors or vectors at different trial scenarios (operations). Examples of some graphical outputs of CFD simulations are shown in Figures 3.3 and 3.4. Figure 3.3 shows air velocity fields in two vertical planes (Planes 1 and 2) of the section A at Scenario II. Plane 1 was placed in the same center of a fan and inlet and Plane 2 was placed between fans. According to this location, these two planes showed different air velocity distribution as seen in Figure 3.3.

CFD also provides interesting knowledge of the trajectories of airflow using vectors as shows the Figure 3.4.

Figure 3.3. *Contours of air velocity in Planes 1 and 2 of the Section A in a trial scenario (Scenario II). Air velocity is expressed in m* s^{-1}.

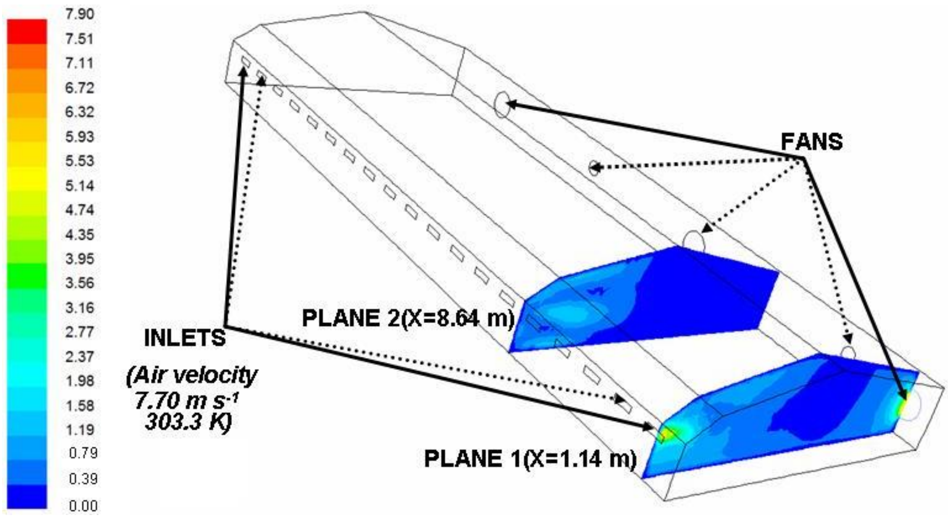
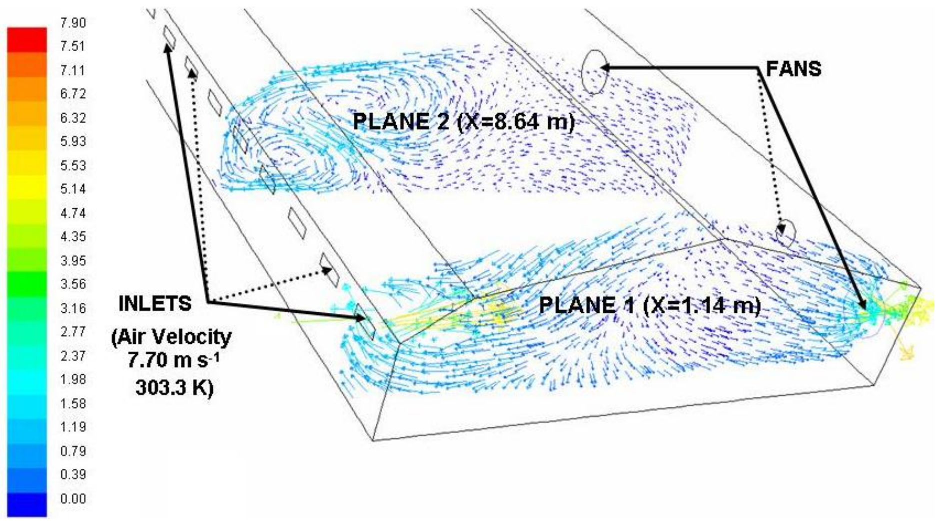


Figure 3.4. *Vectors of air velocity showing trajectories in Planes 1 and 2 of the Figure 3.3. Air velocity is expressed in m* s^{-1}.



3.3.3. Results of the Validation Model

Table 3.4 shows the results of the ANOVA. In this table, the main result is that the variable "Methodology" was not significant (p-value < 0.5271); *i.e.*, it is indifferent using the CFD techniques or the direct measurements using the multisensor system. Using this model, it can be affirmed that the CFD results of air velocity are validated.

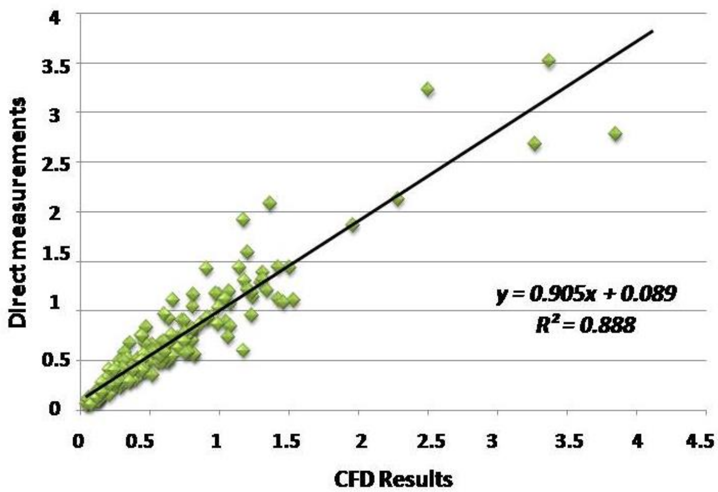
Table 3.4. *ANOVA of air velocity at different scenarios.*

Parameter	DF	Sum of squares	Mean square	F-ratio	*p*-value
Section	1	1.31	1.32	2.94	0.4895
Boundary	3	3.16	1.05	1.87	0.4551
Height	1	0.01	0.01	0.02	0.9184
Sensor	22	34.83	1.58	0.89	0.6041
Methodology	1	0.11	0.11	0.46	0.5271
Section × Boundary	3	0.24	0.08	0.20	0.8884
Section × Height	1	0.59	0.59	0.36	0.5574
Section × Methodology	1	0.11	0.11	–1.92	-
Section × Sensor	22	30.31	1.38	51.55	<0.0001
Boundary × Height	3	2.41	0.80	1.15	0.3829
Boundary × Sensor	66	26.77	0.40	33.98	<0.0001
Boundary × Methodology	3	0.01	0.003	–0.05	-
Height × Methodology	1	0.01	0.01	–0.07	-
Sensor × Height	22	0.66	0.03	–0.47	-
Section × Boundary × Height	3	1.20	0.40	22.12	0.0012
Section × Sensor × Methodology	22	0.59	0.03	0.26	0.9997
Boundary × Sensor × Methodology	66	0.79	0.01	0.12	1.0000
Section × Boundary × Height × Methodology	6	0.11	0.02	0.17	0.9833
Error	132	13.68	0.10		

Besides the mean of air velocities values using CFD techniques were 0.60 ± 0.56 m s^{-1} and using the direct measurements using the multisensor system were 0.64 ± 0.54 m s^{-1}. For comparing both data a linear regression in the 192 studied points of the poultry building of the measured air velocity and the calculated by CFD was done. As expected, in this regression the slope was near one and the independent term near zero. The coefficient of determination of the linear regression was 0.888 (Figure 3.5).

The proposed statistical procedure for the validation of the CFD simulations concluded that the results by CFD procedures or direct measurements using the multisensor system (variable "Methodology") was not significant, and the same was found for its interactions. Therefore, according to these results it was concluded that the use of these direct measurements or its correspondents CFD simulations is indifferent to explore indoor air velocity in a poultry farm. Nevertheless, little differences were found between CFD results and direct measurements as indicated in Table 3.3. The air velocity values obtained at animal level was very similar to those previously obtained for a poultry farm with cross mechanical ventilation (Blanes-Vidal *et al.*, 2008), and therefore the ranges of air velocity were considered representative of a real situation.

Figure 3.5. *Regression curve of CFD results vs. direct measurements in the studied points.*



The ranges of air velocity values were small in all scenarios and very homogeneous in average. At broiler level, the maximum air velocity was 0.89 ± 0.43 m s^{-1} (CFD) and 0.80 ± 0.31 m s^{-1} (measured). This was obtained for section B in scenario III. On the contrary, the minimum velocity was 0.34 ± 0.29 m s^{-1} (CFD) and 0.37 ± 0.31 m s^{-1} (measured) in the section B, scenario I. As indicated in literature, fluctuations of air velocity may have crucial effects on broiler rearing and performance (Lott *et al.*, 1998; May *et al.*, 2000; Simmons *et al.*, 2003; Yanagi *et al.*, 2002; Yavah *et al.*, 2001; Yavah *et al.*, 2004). Considering that determining and evaluating this velocity pattern may help the climate control of farms, we have achieved a validation of CFD to determine this pattern of broiler buildings.

Apart from obtaining accurate values of air velocity at certain locations, a visual representation of them can be obtained as well. This graphic representation also provides additional information on airflow characteristics and patterns, which may contribute to a more effective design of ventilation.

The validation of CFD simulations is an important rule (Oberkampf *et al.,* 2002) and we have corroborated it by means of the proposed model of validation, which results are shown in Table 3.4. The proposed model has included a large amount of input data of measured and modeled air velocity and has needed large field experiments and simulations to develop the analyzed variables. Simulations using CFD were used previously to study indoor environment of animal houses (Bartzanas *et al.*, 2007; Mistriotis *et al.*, 1997 ; Norton *et al.*, 2007 ; Norton *et al.*, 2009) and also in poultry farms (Blanes-Vidal *et al.*, 2008; Lee *et al.*, 2007; Pawar *et al.*, 2007) using a similar methodology to that used in this paper showing that our results are mostly in agreement with their results. According to the results at this conventional geometry of poultry farm, we can affirm that cross mechanical ventilation systems was appropriate in terms of air velocity distribution under the most common weather conditions in mild climates. However, it does not prevent from episodes of thermal stress summer seasons because the air velocity values were too low for animal requirements. As remarked by Dawkins *et al.*, 2004: "the housing conditions influenced more than the bird's density in the animal welfare", and therefore it is essential to find an optimal poultry building model and the best operations. New ventilation systems, other poultry farm geometries and effective climate control strategies must be explored in order to overcome this problem. To do this, CFD techniques may be very effective to identify potential solutions. It must be considered that CFD simulations can provide air velocity and direction, which would be probably time-consuming and costly if directly measured. Next designs of air velocity sensors must be guided to obtain direct measurements of air velocity components. Unfortunately, at this moment no research has been conducted to evaluate the biological response (heat) of broilers as influenced by air velocity directionality. However, some farmers and technicians tend to apply gradual changes in the operation of their poultry farms, in order to change the directionality and values of air velocity because they observe alterations in the animal behavior and performance. To avoid the critical effects of heat stress, it would be interesting to investigate from a biological and engineering point how changes in building design and boundary conditions affect the welfare of animals and their performance.

Future works in instrumentation must focus on multi-sensor systems with isotemporal measurements obtaining air velocity components. The thermal comfort of animals must be also considered to explore the building characterization and elements that have relevance in the optimal poultry farm design, such length *vs.* width, slopes of the roof, number of fans and inlets, their types and dimensions, geometrical location to the floor, among others. All above mentioned factors must be evaluated to find optimal poultry farms and the best operations by means of CFD techniques and associate instrumentation. A main issue of study should be how to obtain a homogeneous distribution of increased air velocity at animal's level to reduce broiler stress and the associated mortality in summer seasons, and at the same time to keep an acceptable level of energy consumption.

3.4. Conclusions

Two methodologies were used to explore ventilation efficiency in a modern poultry farm with cross-mechanical ventilation: CFD techniques and direct measurements by instrumentation. In this paper, commercial CFD FLUENT was used to conduct the numerical simulations, whereas direct measurements were obtained using a multisensor system for poultry farms. To analyze this input data obtained were used the GLM procedure of SAS Systems. This model showed that both methodologies were similar in results: the mean of air velocity values were 0.60 ± 0.56 m s^{-1} for CFD techniques and 0.64 ± 0.54 m s^{-1} for direct measurements using the multisensor system. The "methodology" variable was not significant (p-value < 0.5271), and the same was found for its interactions. Accordingly, it is indifferent using the CFD techniques or the direct measurements with the multisensor system used here. Then, CFD techniques have been validated by multisensor isotemporal direct measurements and they can be used to explore ventilation efficiency and to identify optimal poultry farm designs, as well as to assess their optimal management. On the other hand, from this work and the analysis of this typical geometry model of poultry farm, we can affirm that mechanical cross ventilation system is adequate under the most common weather conditions, but they do no prevent from episodes of mortality caused by heat stress, because they provide lower velocity values than those required by animals in these conditions. According to the results of this paper, new forced ventilation systems and other livestock buildings designs could be evaluated using both developed methodologies in order to improve the thermal comfort and diminish mortality of animals. In this way forced ventilation systems require electric energy to activate the fans and automatisms, which are not required in naturally ventilated livestock buildings. Finally, it must be noted that from the two analyzed methodologies to explore the ventilation efficiency in livestock buildings, CFD techniques provide more points of knowledge and a more general view of indoor climatic conditions of poultry farms through the graphics than direct measurements.

3.5. References

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). ASHRAE Fundamentals Handbook; American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.: Atlanta, GA, USA, 2001.

Bartzanas, T.; Kittas, C.; Sapounas, A.A.; Nikita-Martzopoulou, C. Analysis of airflow through experimental rural buildings: Sensitivity to turbulence models. *Biosyst. Eng.* 2007, 97, 229–239.

Bjerg, B.; Svidt, K.; Zhang, G.; Morsing, S.; Johnsen, J.O. Modeling of air inlets in CFD prediction of airflow in ventilated animal houses. *Comput. Electron. Agr.* 2002, 34, 223–235.

Blanes-Vidal, V.; Guijarro, E.; Balasch, S.; Torres, A.G. Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. *Biosyst. Eng.* 2008, 100, 105–116.

Bustamante, E.; Guijarro, E.; García-Diego, F.J.; Balasch, S.; Torres, A.G. Multisensor system for isotemporal measurements to assess indoor climatic conditions in poultry farms. *Sensors* 2012, 12, 5752–5774.

Calvet, S.; Cambra-López, M.; Blanes-Vidal, V.; Estellés, F.; Torres, A.G. Ventilation rates in mechanically ventilated commercial poultry buildings in Southern Europe: Measurement system development and uncertainty analysis. *Biosyst. Eng.* 2010, 106, 423–432.

Charles, D.; Walker, A. Poultry Environment Problems: A Guide to Solutions, 1st ed.; Charles, D., Walker, A., Eds.; Nottingham University Press: Nottingham, UK, 2002.

Davidson, L. Ventilation by displacement in a three-dimensional room: A numerical study. *Build. Environ.* 1989, 24, 363–372.

Dawkins, M.S.; Donnelly, C.A.; Jones, T.A. Chicken welfare is influenced more by housing conditions than stocking density. *Nature* 2004, 427, 342–344.

El País, Anonymous. Medio millón de pollos mueren por el fuerte calor de los últimos días. Available online:

http://elpais.com/diario/2003/06/17/cvalenciana/1055877480_850215.html (accessed on 14 November 2012).

European Union (EU). Laying down Minimum Rules for the Protection of Chickens Kept for Meat Production; EU Council Directive 2007/43/EC; European Union: Brussels, Belgium, 2007.

Fluent User's Guide, version 6.0; Fluent Inc.: Lebanon, NH, USA, 2001.

Gambit User's Guide, version 2.0; Fluent Inc.: Lebanon, NH, USA, 2001.

Launder, B.E.; Spalding, D.B. The numerical computation of turbulent flows. *Comput. Method. Appl. M.* 1974, 3, 269–289.

Lee, I.B.; Sase, S.; Sung, S.H. Evaluation of CFD accuracy for the ventilation study of a naturally ventilated broiler house. *Jpn. Agric. Res. Q.* 2007, 41, 53–64.

Lott, B.D.; Simmons, J.D.; May, J.D. Air velocity and high temperature effects on broiler performance. *Poult. Sci.* 1998, 77, 391–393.

May, J.D.; Lott, B.D.; Simmons, J.D. The effect of air velocity on broiler performance and feed and water consumption. *Poult. Sci.* 2000, 79, 1396–1400.

Mistriotis, A.; de Jong, T.; Wagemans, M.J.M.; Bot, G.P.A. Computational fluid dynamics as a tool for the analysis of ventilation and indoor microclimate in agriculture buildings. *Neth. J. Agr. Sci.* 1997, 45, 81–96.

MWPS (Midwest Plan Service). Mechanical Ventilating Systems for Livestock Housing, 1st ed.; Midwest Plan Service, Iowa State University: Ames, IA, USA, 1990.

Norton, T.; Sun, D.; Grant, J.; Fallon, R.; Dodd, V. Applications of computational fluid dynamics (CFD) in the modeling and design of ventilation systems in the agricultural industry: A review. *Bioresour. Technol.* 2007, 98, 2386–2414.

Norton, T.; Grant, J.; Fallon, R.; Sun, D.-W. Assessing the ventilation effectiveness of naturally ventilated livestock buildings under wind dominated conditions using computational fluid dynamics. *Biosyst. Eng.* 2009, 103, 78–99.

Patankar, S.V. Numerical Heat Transfer and Fluid Flow; Hemisphere Publishing Corporation: Washington, WA, USA, 1980.

Pawar, S.R.; Cimbala, J.M.; Wheeler, E.F.; Lindberg, D.V. Analysis of poultry house ventilation using computational fluid dynamics. *Trans. ASABE* 2007, 50, 1373–1382.

Oberkampf, W.L.; Trucano, T.G. Verification and validation in computational fluid dynamics. *Progr. Aerosp. Sci.* 2002, 38, 209–272.

SAS. SAS User's Guide: Statistics, version 6.12; SAS Institute Inc.: Cary, NC, USA, 1998.

Simmons, J.D.; Lott, B.D.; Miles, D.M. The effects of high-air velocity on broiler performance. *Poult. Sci.* 2003, 82, 232–234.

Testo Inc. Homepage. Available online: http://www.testo.com (accessed on 19 March 2013).

Wheeler, E.F.; Zajaczkowski, J.L.; Saheb, N.C. Field evaluation of temperature and velocity uniformity in tunnel and conventional ventilation broiler houses. *Appl. Eng. Agric.* 2003, 19, 367–377.

WorldPoultry. Korea heat wave kills off 830,000 chickens (in August 2012). Available online: http://www.worldpoultry.net/Broilers/Health/2012/8/S-Korean-heat-wave-kills-off-830000-chickens-WP010736W/ (accessed on 7 May 2013).

Yanagi, T.; Xin, H.; Gates, R.S. A research facility for studying poultry responses to heat stress and its relief. *Appl. Eng. Agric.* 2002, 18, 255–260.

Yavah, S.; Straschnow, A.; Luger, D.; Shinder, D.; Tanny, J.; Cohen, S. Ventilation, sensible heat loss, broiler energy and water balance under harsh environmental conditions. *Poult. Sci.* 2004, 83, 253–258.

Yavah, S.; Straschnow, A.; Vax, E.; Razpakovski, V.; Shinder, D. Air velocity alters broiler performance under harsh environmental conditions. *Poult. Sci.* 2001, 80, 724–726.

Chapter 4

Tunnel mechanical ventilation in broiler houses

An adapted version is published in:

Measurement and numerical simulation of air velocity in a tunnel-ventilated broiler house. Eliseo Bustamante, Fernando-Juan García-Diego, Salvador Calvet, Antonio G. Torres and Antonio Hospitaler. *Sustainability* 7 (2015), 2066-2085.

Abstract: A building needs to be designed for the whole period of its useful life according to its requirements. However, future climate predictions involve some uncertainty. Thus, several sustainable strategies of adaptation need to be incorporated after the initial design. In this sense, tunnel ventilation in broiler houses provides high air velocity values (2–3 $m \cdot s^{-1}$) at animal level to diminish their thermal stress and associated mortality. This ventilation system was experimentally incorporated into a Mediterranean climate. The aim was to resolve these thermal problems in hot seasons, as (traditional) cross-mechanical ventilation does not provide enough air velocity values. Surprisingly, very little information on tunnel ventilation systems is available, especially in terms of air velocity. Using Computational Fluid Dynamics (CFD) and a multi-sensor system, the average results are similar (at animal level: 1.59 ± 0.68 $m \cdot s^{-1}$ for CFD and 1.55 ± 0.66 $m \cdot s^{-1}$ for measurements). The ANOVA for validation concluded that the use of CFD or measurements is not significant (p-value=0.1155). Nevertheless, some problems with air velocity distribution were found and need to be solved. To this end, CFD techniques can help by means of virtual designs and scenarios providing information for the whole indoor space.

Keywords: poultry building; sensors; air velocity; isotemporal measurements; multipoint measurements; troubleshooting.

4.1. Introduction

A building needs to be designed according to its requirements for the entire period of its useful life. Among these requisites, the geographical location and the climatic situation are prominent design features. Thus, the indoor environments of broiler house building are strongly conditioned by the climatology. Unfortunately, the uncertainty arising from climate change and global warming also causes uncertainty in the building design and the facilities installed (Holmes *et al.*, 2007; Nardone *et al.*, 2010). For these reasons, farms in areas of climatic uncertainty (e.g., Mediterranean climate) need to adapt their designs by means of sustainable strategies. To this end, new models of ventilation systems were incorporated after the initial conception of the building-farm design. Obviously, these experimental design adaptations and experimental ventilation systems must be analysed using scientific procedures (CFD techniques and direct measurements).

Nowadays, broiler rearing involves the use of highly developed technology. In fact, modern broiler buildings can be considered intelligent buildings in the fullest sense (Clements-Croome *et al.*, 1997). In these buildings, forced ventilation is the most commonly-used ventilation system (Bustamante *et al.*, 2012; 2013; Charles *et al.*, 2002; MWPS; 1990), mainly through negative pressure-systems (Bustamante *et al.*, 2012; 2013). Mechanical ventilation allows higher density of the broilers than natural ventilation. Moreover, mechanical ventilation diminishes the thermal stress and mortality of the birds in summer seasons or extreme climate, as it improves the control and values of the ventilation rates. Recently, Dawkins *et al.*, 2004 affirmed that housing conditions had more impact than flock density on animal welfare. Despite the technical complexity of broiler buildings, discrete and repetitive episodes of high mortality occur every year in summer (El País, 2003; WorldPoultry, 2012). In the Mediterranean climate, these fatal episodes of thermal stress and broiler mortality have been accentuated under the effects of global warming and climate change. In this climate, cross-mechanical ventilation is the most widespread ventilation system in broiler production (Blanes-Vidal *et al.*, 2008).

There are some important studies on the influence of excessively hot climate on broilers. Mitchell *et al.*, 1998 describe its influence on high mortality rates, a decrease in meat quality and reduced welfare; Sohail *et al.*, 2012 refer to the losses in feed intake (−16.4%), losses in body weight (−32.6%) and higher feed conversation ratio (25.6%) when a broiler reaches an age of 42 days. DEFRA, 2008 refers to the changes in the metabolism of the broilers and the need for thermoregulation to reduce the internal heat of the animals. In this thermoregulation, high air velocity values (~2 $m \cdot s^{-1}$) can help by increasing the convective flux heat of broilers and therefore decrease their thermal stress and associated mortality.

DEFRA, 2008 reports the effects on welfare of these high air velocities over the birds: they remove the hot air around the birds, adding to conventional heat loss, and they remove humid air from around the broiler's head, making panting more efficient and imparting a sense of wind chill. To meet these high air velocity needs, tunnel ventilation has been experimentally incorporated in some Mediterranean climate areas. Moreover, it is also crucial to relate the number of fans in action with the associated air velocity values at broiler level. This is essential to determine the optimal programming of the fans and/or inlet automatisms of these tunnel broiler buildings.

Mediterranean climate refers to the weather typical of the Mediterranean area (Spain, France, Italy, etc.), although it is also found in other geographic areas worldwide: sections of Central Asia, Western and South Australia, South Africa, central Chile, California (USA), etc. France is considered a reference in broiler building ventilation technology and exports its building and ventilation system models. Other nearby countries with this climate (e.g., Spain, Italy, Portugal, Greece...) adopted these models and ventilation. However, cross-mechanical ventilation is only an acceptable system for the moderate variant of this climate (Bustamante *et al.*, 2012; 2013). Nowadays, new ventilation systems (mechanical single sided, tunnel variants, etc.) are tested in areas (e.g., Spain) where cross-mechanical ventilation entails thermal problems. A feature of these adapted buildings is that air inlets are located in the lateral walls near the opposite façade to the fans, because in the original cross-mechanical ventilation systems the tendency was to build an office or control room there, which would remain in place when tunnel ventilation was installed.

In this work, we study a typical tunnel broiler building in Spain, using CFD techniques and a multi-sensor system (Bustamante *et al.*, 2012) to determine the exact indoor environment of this imported ventilation system. To this end, CFD can be a powerful tool to analyse indoor environments of broiler houses and obtain the CFD results for the entire indoor space, whereas direct measurements only provide results for a limited number of points (the physical sensors). This analysis will serve to assess optimal management of the whole broiler building and, especially, the programming of the fans and inlets.

Earlier works have broadly used CFD techniques to study the internal microclimate of livestock buildings (Bartzanas *et al.*, 2007; Harral *et al.*, 1997; Mistriotis *et al.*, 1997; Norton *et al.*, 2007) and poultry buildings with other ventilation systems (Blanes-Vidal *et al.*, 2008; Bustamante *et al.*, 2013, Lee *et al.*, 2007; Pawar *et al.*, 2007) and with tunnel ventilation under negative pressure-systems in (Mostafa *et al.*, 2012; Osorio JA *et al.*, 2011; Osorio R *et al.*, 2013). Tunnel ventilation from broiler buildings is found in different countries, such as Brazil (Osorio JA *et al.*, 2011; Osorio R *et al.*, 2013), Korea (Mostafa *et* *al.*, 2012), USA (Lacey *et al.*, 2003) and countries with a tropical climate (Daghir, 2001). According to these references, tunnel ventilation achieves high air velocity values. On the other hand, in some of these designs, the fans are placed on the opposite façade to the inlets (Daghir, 2001). Nevertheless, in this article we study a variant of tunnel ventilation with the inlets at the lateral end (Daghir, 2001) because in the original building design (with cross-mechanical ventilation) the control room precluded any other disposition.

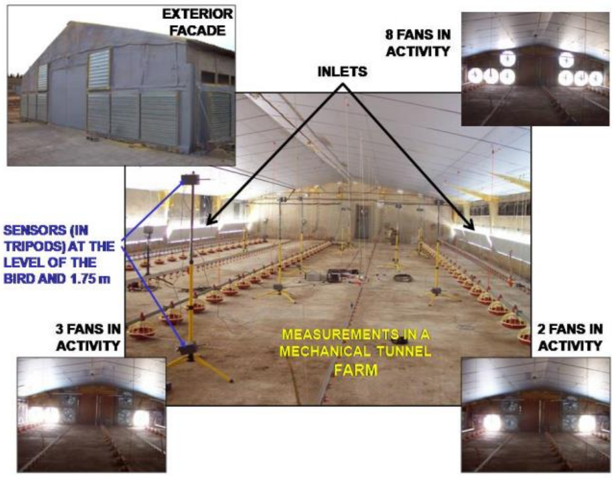
To summarise: (i) we studied a typical tunnel broiler building in Spain; (ii) tunnel ventilation can be easily installed in all broiler buildings with only a retrofit of one wall to install the fans there; (iii) the study is carried out using CFD techniques and a multi-sensor system; (iv) the numerical results of air velocity are validated; (v) tunnel ventilation achieves high air velocity values to improve the birds' welfare in hot seasons; (vi) future optimisation of design and assessments is required to improve this ventilation system; and (vi) CFD techniques can help by providing virtual designs and scenarios using information from the whole indoor space.

4.2. Materials and Methods

4.2.1. The Building

A broiler building equipped with tunnel ventilation located at Alcalá de Xivert (Castellón-Spain) was studied. The upper left corner of Figure 4.1 shows the exterior façade, with the eight frontal exhaust fans and one lateral fan. In other corners are the interior of the building in three operations; the fans in operation were in white, to allow the sunlight to enter; and in the central image of Figure 4.1 is the multi-sensor system with sensors at two heights (0.25 m and 1.75 m).

Figure 4.1. *Measurements in the tunnel broiler building.*



Building dimensions were: length, 120 m; width, 12.2 m; sidewall height 2.2 m; double pitched roof (slope 21.3%). The ventilation was equipped with ten exhaust fans (Model Euromunters EM 50n) with a diameter of 1.28 m, 1.1 kW of power consumption and nominal ventilation flow 42,125 $m^3 h^{-1}$ at $\Delta P=0$ Pa. Eight exhaust fans were located on the south façade (main façade) and the other two exhaust fans in the lateral façade, one fan in each lateral wall, near those located at the south façade as shown in Figure 4.1. The building was also equipped with twelve inlets measuring 4.7 × 0.45 m, placed at a height of 0.3 m, controlled by an automatic system of two groups of six inlets located in the lateral walls; all inlets were located near the north façade. The inlets are placed on the side walls because the control room is located behind the wall opposite the fans, preventing the fans being positioned there. According to Daghir, 2001, this is a variant of tunnel ventilation where the air entrance is equilibrated. The building was empty during the field experiments (as in other similar studies: (Blanes-Vidal *et al.*, 2008; 2010; Bustamante *et al.*, 2012; 2013; Harral *et al.*, 1997) to prevent the broilers undergoing sudden changes of pressure and air flow during the experiment.

This broiler building was built in 1983, and until a few years ago had natural ventilation, after which it was equipped with cross-mechanical ventilation; currently, it also has tunnel ventilation installed. The main orientations of walls and roofs were determined using a compass (we designated them North-Wall, South-Wall, East-Wall, West-Wall, East-Cover, West-Cover and floor, according to the main orientation reached).

4.2.2. Experimental Scenarios (Operations)

In this paper, the field experiments comprised nine experimental scenarios (operations) at different boundary conditions (BCs). By means of differential pressure sensors (Bustamante *et al.*, 2012), differential pressure was fixed at a constant30 Pa—which, according to the farmer, was a typical differential pressure in the management of this building—and the number of fans running was gradually increased. First, two fans were activated, and gradually we added one fan at a time until all eight fans on the south façade were on. Finally, the two lateral wall fans were also in action. (Operation I corresponds to two fans in action, Operation II with three fans in action, *etc.*, until Operation IX, with ten fans in action). Operation I began with two fans because no typical real operation in the building uses a single working fan. In the cooler winter months, high air velocity values are not required; then, a minimum number of fans working (2, 3 or 4 fans located near the floor) is enough. In hot seasons, the air velocity requirements are higher and it is necessary to activate more fans (the 5 or 6 fans located near floor level), triggering the rest of the fans (the two higher fans and the two laterals) if the weather is very hot. The two higher fans can improve the efficiency of the cooling system if it is activated (to improve indoor movement of the air on the whole).

To maintain the differential pressure at 30 Pa during these operations, the flaps of the inlets change by means of the automatic system.

4.2.3. CFD Background and Turbulence Models

CFD FLUENT (Fluent Inc., Lebanon, NH, USA) (Fluent, 2001) was used to carry out the CFD simulations in this article. CFD FLUENT (Fluent, 2001) had been used with great success in previous CFD simulations of poultry buildings, as mentioned previously (Blanes-Vidal *et al.*, 2008; Bustamante *et al.*, 2013; Lee et al., 2007; Mostafa *et al.*, 2012; Pawar et al., 2007).

CFD techniques solve a set of partial differential equations (PDEs) (Norton *et al.*, 2007; Patankar, 1980): equations of continuity (Equation (4.1)), conservation of momentum (Navier-Stokes law) (Equation (4.2)) and the energy equation (Equation (4.3)).

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = S_m \tag{4.1}$$

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla(\rho\vec{v}\vec{v}) = -\nabla p + \nabla(\bar{\tau}) + \rho\vec{g} + \vec{F} \tag{4.2}$$

$$\frac{\partial}{\partial t}(\rho E) + \nabla(\vec{v}(\rho E + p)) = \nabla\left(k_{eff}\nabla T - \sum_j h_j \vec{J}_j + (\bar{\tau}\vec{v})\right) + S_h \tag{4.3}$$

Where ρ: fluid density (kg·m^{-3}); t: time (s); u, v, w: velocity (m·s^{-1}); S_m: mass source (kg·m^{-3}); p: pressure (Pa); τ: stress tensor (Pa); g: gravitational acceleration (m·s^{-2}); F: external force vector (N·m^{-3}); E: total energy (J); k_{eff}: heat transmission coefficient; T: temperature (K); h: specific enthalpy (J·kg^{-1}); S_h: total entropy (J·K^{-1}).

Reynolds-averaged Navier-Stokes equation (RANS) turbulence models are commonly used in the study of indoor environments of livestock buildings. Moreover, from the RANS turbulence models, the RNG k-ε model was chosen to carry out the CFD simulations. The standard k-ε turbulence model has been used by some authors (Blanes-Vidal *et al.*, 2008; Bustamante *et al.*, 2013) because it offers reasonable precision and easy convergence (Launder & Spalding, 1974). However, in this article, the RNG k-ε model (a variant of the standard k-ε turbulence) was used because it performs well. The RNG k-ε turbulence model includes additional terms for the dissipation rates, describing more the physical phenomenon in greater detail and improving the accuracy of the results. It should be noted that none of the existing turbulence models are complete, *i.e.*, their prediction performance is highly reliant on turbulent flow and geometry (Norton *et al.*, 2007). The transport equations of this turbulence model were 4.4 and 4.5 (Fluent, 2001):

$$\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i}\left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_i}\right) + G_k + G_b - \rho\varepsilon - Y_M \tag{4.4}$$

$$\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i}\left(\alpha_\varepsilon \mu_{eff} \frac{\partial k}{\partial x_i}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{K} - R \tag{4.5}$$

where k: turbulent kinetic energy ($m^2 \cdot s^{-2}$); α_k: the generation of kinetic energy due to the mean velocity gradient ($kg \cdot m^{-1} \cdot s^{-2}$); μ_{eff}: effective viscosity ($m^2 \cdot s$); G_k: the generation of kinetic energy due to the variations of the components of the average velocity of the flow ($kg \cdot m^{-1} \cdot s^{-2}$); G_b: the generation of kinetic energy by boundary push ($kg \cdot m^{-1} \cdot s^{-2}$); ε: turbulent dissipation rate ($m^2 \cdot s^{-3}$); α_ε: the generation of kinetic energy due to buoyancy ($kg \cdot m^{-1} \cdot s^{-2}$); Y_M: contribution of the pulsatile expansion associated to the compressible turbulence ($kg \cdot m^{-1} \cdot s^{-2}$); R: the gas-law constant ($8.314 \cdot 10^3$ $J \cdot kg \cdot mol^{-1} \cdot K^{-1}$); $C_{1\varepsilon}$: constant; $C_{2\varepsilon}$: constant; $C_{3\varepsilon} = \tanh[u_1/u_2]$; u_1: velocity of flow parallel to g_i (gravitational vector); u_2: velocity of flow perpendicular to g_i. Moreover, the constant values were $C_{1\varepsilon} = 1.42$, $C_{2\varepsilon} = 1.68$ (Fluent, 2001; Launder & Spalding, 1974).

In this article, we carried out nine three-dimensional CFD simulations, corresponding to nine tested scenarios (nine typical conditions of operation of the building).

4.2.4. Geometry, Mesh and BC

The geometry and mesh of the broiler building were performed in the pre-processor GAMBIT (Gambit, 2001) (Geometry and Mesh Building Intelligent Toolkit) of FLUENT (Fluent, 2001). This building geometry was modelled in its real dimensions. The exhaust fans were modelled as circles 1.28 m in diameter and the twelve inlets were accurately modelled in the form adopted in each scenario as in similar studies (Blanes-Vidal *et al.*, 2008; Bjerg *et al.*, 2002; Bustamante *et al.*, 2013).

Each scenario was mainly characterised by the number of fans operating, maintaining the differential pressure at 30 Pa (Bustamante *et al.*, 2012). In these setups, the ventilation rate was measured using the procedures of Calvet *et al.*, 2010, although the fans are new and the values are very similar to those from the manufacturer. This measurement protocol (Calvet *et al.*, 2010) consisted of ducting the exhaust air 50 cm from the fan and then measuring by means of a hot wire anemometer at 24 different locations in the section, as indicated ASHRAE, 2001.

A mesh dependency test was performed, analysing four different meshes: Mesh 1 (516,055 cells & 105,427 nodes), Mesh 2 (908,025 cells & 174,979 nodes), Mesh 3 (1,937,181 cells & 363,604 nodes) and Mesh 4 (3,627,052 cells & 661,559 nodes). In this study, the numerical results are stabilised and minor differences are observed from Mesh 3 to Mesh 4. According to this mesh study, Mesh 4 was chosen. By this procedure, we ensure that the numerical results obtained are not affected by the grid.

The meshing comprised unstructured tetra and prism layers. Applying thin prism layers to the first rows near the surfaces provides a more accurate result near the boundary layers. In this way, the quality of the mesh is also studied using the equiangular skewness command in GAMBIT (Gambit, 2001).

The geometry and mesh domain built in GAMBIT (Gambit, 2001) was exported to the CFD-solver FLUENT (Fluent, 2001). Moreover, it was considered that the flow (air) is steady, three-dimensional, viscous, turbulent, incompressible and isothermal. The air properties are considered constants. Table 4.1 shows the properties of the air and associated values.

To link the pressure and the velocity, the SIMPLE algorithm was used (Fluent, 2001) as well as the second order upwind scheme (Patankar, 1980).

Table 4.1. *Main inputs and BCs at CFD simulations.*

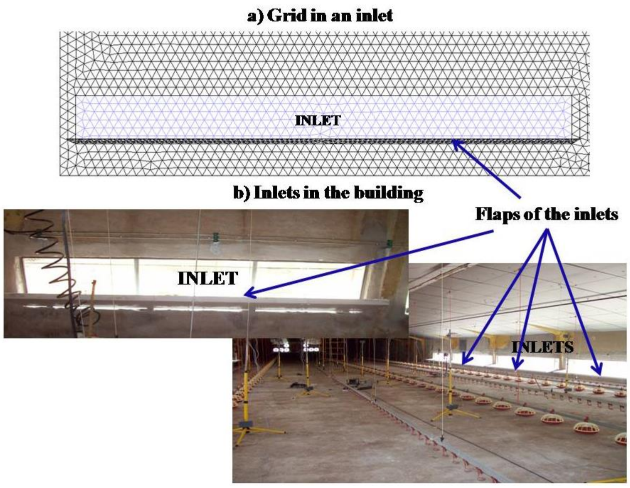
CFD Simulation	Fans in Action	Total Mass Flux Rate (1) ($kg{\cdot}s^{-1}$)	Average of Air Velocity at Inlets ($m{\cdot}s^{-1}$)
I	2	24.68	0.83
II	3	37.02	1.23
III	4	49.36	1.61
IV	5	37.02	2.04
V	6	61.70	2.45
VI	7	74.04	2.85
VII	8	86.38	3.25
VIII	9	98.72	3.67
IX	10	111.06	4.04

(1) Measured by the procedures of Calvet et al., 2010.

The air velocity at inlets (windows) and mass flux rate of each outlet (fans) were BC used to carry out the CFD simulations. For each operation and considering negligible fluctuations of values, we assumed that the air velocity at all inlets was the same and the mass flux rate was the same for the fans, as in earlier studies (Blanes-Vidal *et al.*, 2008; Bustamante *et al.*, 2013). The input of the air velocity at inlets was obtained from the measurements at each inlet using a Testo 425 hot-wire anemometer (Testo, 2014) (calibrated in a wind tunnel by Testo AG Lenzkirch (Spain) (Testo, 2014) according to UNE EN ISO 9001:2001), and the average from all inlets is the required input. The input of the ventilation rate of each fan was obtained using the protocol of Calvet *et al.*, 2010. Table 4.1 indicates the main computational settings and the cited BC.

Considering that the building was empty during the field experiments, the broiler presence was not modelled, nor other elements such as feeding and water equipment (Blanes-Vidal *et al.*, 2008; Bustamante *et al.*, 2013). Obviously, CFD points with special relevance are the physical location points of the sensors. Figure 4.2a shows the grid in an inlet and Figure 4.2b the inlets in the building. In this Figure 4.2, we can observe that the inlets and associated flaps form an angle. This angle changes (from 4° to 38°) in order to maintain the differential pressure constant throughout the nine operations (30 Pa, in our field experiment).

Figure 4.2.(a) *Grid in an inlet;* ***(b)*** *Inlets in the building.*



4.2.5. Validation of CFD Results

4.2.5.1. General Context: the Multi-Sensor System and Points of Measurement

The indoor turbulence intensity generated in mechanical ventilation of livestock buildings is very high (from 1% to 20%), with sudden changes in the air velocity values in the same coordinate throughout the experiment (Bustamante *et al.*, 2012; 2013; Heber *et al.*, 1996). For this reason, a high-capacity measurement system is needed, both in number of sensors and number and quality of signals. The validation of CFD simulations (Oberkampf *et al.*, 2002) was thus carried out by means of a specific measuring system (Bustamante *et al.*, 2012). This measuring system consisted of air velocity sensors and differential pressure sensors and was able to acquire up to a maximum of 128 signals simultaneously at 5 s intervals. The sensors of air velocity were platinum resistance temperature detectors (RTD), the thin film detector was the Pt100 from Omega Inc. (TFD, 2015) and the differential pressure sensors were HCXM010D6Vs from Sensortechnics Inc. (Sensortechnics, 2015). This measuring system is described in depth in (Bustamante *et al.*, 2012). In our case, only 32 sensors were read: 30 air velocity sensors and 2 differential pressure sensors (Bustamante *et al.*, 2012). The sensors were placed on 15 tripods at two heights: at adult broiler level 0.25 and at 1.75 m. These measurements were taken in three sections of the building: one section near the inlets, another section in a central zone (when the inlets were finished) and finally another section closer to the fans. The spatial distribution of the tripods was random, in an attempt to measure all areas of the test sections (central section, near the fans and the inlets). Moreover, Daghir, 2001 mentioned that the area of inlets and the area of fans are vital in the design of tunnel ventilation. At the centre of Figure 4.1, some tripods and the multi-sensor system in an operation are shown.

During this field experiment (10 min registering in each operation) we received the signals from the sensors. In each of the three sections for each operation we received 3600 measurements of air velocity (30 s × 10 min × 60/5 data/min); thus, a total of 97,200 air velocity measurements (3600 × 9 scenarios × 3 sections) were taken at the 9 scenarios and three sections. Figure 4.3 shows the test section and Table 4.2 the sensor coordinates.

Figure 4.3. *Test sections.*

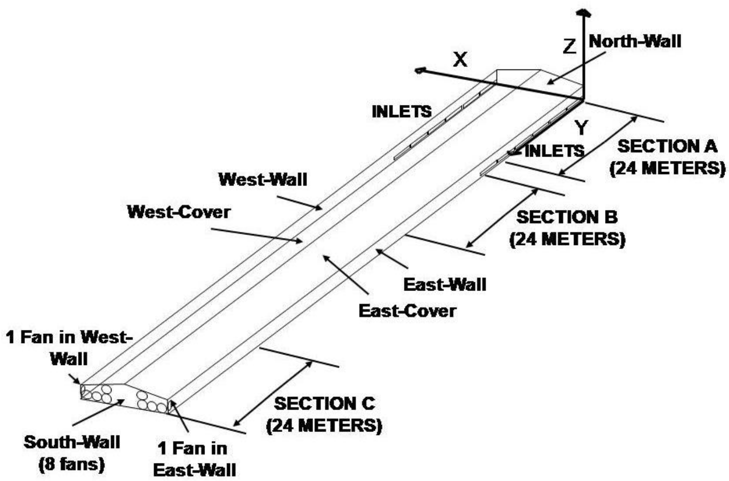


Table 4.2. *Sensor coordinates.*

Sensor number*	Section A		Section B		Section C	
	***X*-coord. (*m*)**	***Y*-coord. (*m*)**	***X*-coord. (*m*)**	***Y*-coord (*m*)**	***X*-coord. (*m*)**	***Y*-coord. (*m*)**
1–2	5.56	4.34	5.92	32.14	5.87	99.23
3–4	5.39	8.42	5.62	36.54	5.42	103.90
5–6	5.83	13.64	5.73	43.25	5.69	108.76
7–8	5.61	16.51	8.57	39.36	5.58	110.33
9–10	10.66	22.78	9.47	43.32	9.89	118.02
11–12	8.16	18.65	10.60	40.22	8.78	115.14
13–14	7.18	19.17	9.00	39.36	10.03	116.25
15–16	5.50	20.20	9.04	36.88	6.21	118.93
17–18	2.22	3.87	1.50	29.20	1.86	96.48
19–20	2.52	7.06	3.47	33.65	2.94	101.15
21–22	3.45	11.24	3.92	39.21	3.75	107.40
23–24	10.61	3.55	11.48	34.83	11.26	98.06
25–26	8.74	9.86	5.83	48.17	9.13	105.18
27–28	1.54	19.54	1.54	52.00	2.34	117.49
29–30	2.81	15.76	0.82	47.00	3.11	113.07

***** The first sensors at animal level, the second at 1.75 m.

During the operations in the same section there was no change in the tripods' location, in order to measure and compare the fluctuations of values acquired as the number of fans in action increased. The 30 air velocity sensors (in their tripods) were moved from one section to another at each ventilation regime case.

4.2.5.2. Statistical Model and Variables

In the present article, the validation model consisted of a statistical procedure by means of an analysis of variance (ANOVA).

The validation model for this article is:

$$\begin{aligned} Y_{ijkl} &= \mu + S_i + F_j + H_k + M_l + (S\times F)_{ij} + (S\times H)_{ik} + (S\times M)_{il} + \\ &+ (F\times H)_{jk} + (F\times M)_{jl} + (H\times M)_{kl} + (S\times F\times H)_{ijk} + \\ &+ (S\times F\times M)_{ijl} + (S\times H\times M)_{ikl} + (F\times H\times M)_{jkl} + \\ &+ (S\times F\times H\times M)_{ijkl} + \varepsilon_{ijkl} \end{aligned} \tag{4.6}$$

where the different variables and interactions are explained below:
Y_{ijkl}: Air velocity in the section *i* with *j* Fans in action at Height *k* and by the methodology *l*;
S_i : Measurement section (3);
F_j : Fans in action (9);
H_k : Height of the sensor (2);
M_l : Methodology: CFD *vs.* direct measurements by multi-sensor system (2);
$(S \times F)_{ij}$: Interaction between Section-Fan (27);
$(S \times H)_{ik}$: Interaction between Section-Height (6);
$(S \times M)_{il}$: Interaction between Section-Methodology (6);
$(F \times H)_{jk}$: Interaction between Fans-Height (18);
$(F \times M)_{jl}$: Interaction between Fans-Methodology (18);
$(H \times M)_{kl}$: Interaction between Height-Methodology (4);
$(S \times F \times H)_{ijk}$: Triple interaction between Section-Fan-Height (54);
$(S \times F \times M)_{ijl}$: Triple interaction between Section-Fan-Methodology (54);
$(S \times H \times M)_{ikl}$: Triple interaction between Section-Height-Methodology (12);
$(F \times H \times M)_{jkl}$: Triple interaction between Fan-Height-Methodology (36);
$(S \times F \times H \times M)_{ijkl}$: Fourfold interaction between Section-Fan-Height-Methodology (108);
ε_{ijkl} : Error of the model.
Numbers in parentheses indicated number of factors. To study these effects, all factors were considered random. The model was analysed using the GLM procedure from SAS systems (SAS, 1998). We shall perform an initial analysis to obtain first results. The non-significant interactions will then be eliminated from the model, and another analysis will be conducted to obtain the refined results. Using this procedure, the model will have improved results, making the significant effects more robust.

4.2.5.3. Regression Line (CFD vs. Measurements)

To compare the CFD results and the measurements, a linear regression is proposed. The model of this linear regression is:

$$V_{CFD} = \alpha + \beta \times V_{meas} \tag{4.7}$$

where,
V_{meas} is the average of the measured air velocity values
V_{CFD} is the air velocity obtained in the CFD simulations

4.2.5.4. Relative Error at Each Point

The indoor turbulence in broiler buildings equipped with mechanical ventilation is high (Bustamante *et al.*, 2012; 2013; Heber *et al.*, 1996). Thus, the fluctuations of the air velocity values at the same point over time may be relevant (Bustamante *et al.*, 2012). We used a robust measurement system in terms of number of sensors and in received signals; nevertheless, it is necessary to test a possible relative error in the *i* studied points. This relative error in the *i* point (E_i) can be defined as:

$$E_i = \frac{V_{meas} - V_{CFD}}{V_{meas}} \tag{4.8}$$

where:

V_{meas} is the average of the measured air velocity using the multi-sensor system at point *i* taken as the real air velocity, and

V_{CFD} is the air velocity obtained in the CFD simulations at point *i*.

4.3. Results

4.3.1. Results of the Validation Model

In Table 4.3, we can see the ANOVA results for the proposed validation model after the refinement. The main result is that the “Methodology” variable is not significant (*p*-value<0.1155), nor are the interactions; *i.e.*, there is no difference between using the CFD techniques or the direct measurements using the multi-sensor system. At this point and by means of these results from Table 4.3, we validated the CFD results for air velocity.

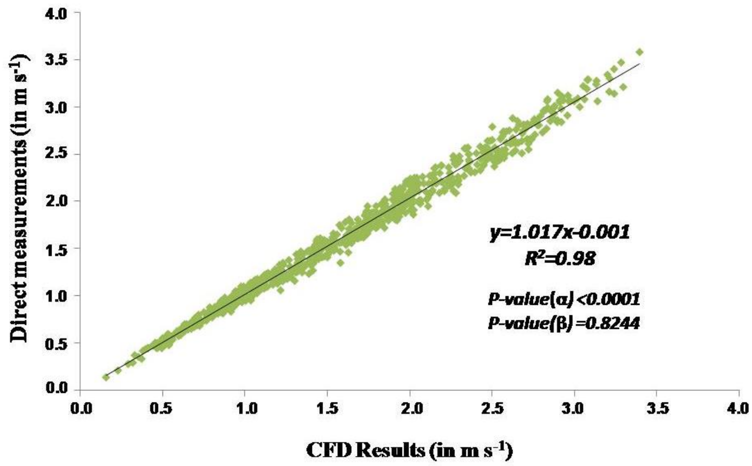
Table 4.3. *ANOVA of air velocity at different scenarios.*

Variables	DF	Sum of Squares	Mean Square	F-ratio	*p*-value
Section	2	33.10	16.55	149.07	<0.0001
Fans	8	555.09	69.39	625.08	<0.0001
Height	1	1.07	1.07	9.61	0.0020
Methodology	1	0.28	0.28	2.48	0.1155
Section × Fan	16	45.75	2.86	25.76	<0.0001
Section × Height	2	21.18	10.59	95.42	<0.0001
Fans × Height	8	5.88	0.73	6.62	<0.0001
Error	1581	175.50	0.111		

According to the proposed linear regression for the 90 points studied (physical location of the sensors), we obtained a dependent term near one (+1.7%) and an independent term near zero

(−0.1%). Moreover, we obtained a coefficient of determination of 0.98. In Figure 4.4, we can see this linear regression.

Figure 4.4. *Regression curve of CFD results vs. direct measurements in the 90 points studied.*



4.3.2. CFD Results and the Direct Measurements

CFD-air velocity results and the measurements using the multi-sensor system have similar values, as shown in Table 4.4.

Table 4.4. *Air velocity in m·s^{-1} (average ± standard deviation) in the field experiment based on direct measurements and CFD simulations. The number of averaged data is indicated in parenthesis.*

Op.	Height (m)	Method.	Section A	Section B	Section C	Average
I	0.25	Measur.	0.75±0.24 (15)	0.66 ± 0.18 (15)	0.47 ± 0.11(15)	0.63 ± 0.22(45)
		CFD	0.77 ± 0.20(15)	0.69 ± 0.18(15)	0.49 ± 0.12(15)	0.65 ± 0.21(45)
	1.75	Measur.	0.62 ± 0.22 (15)	0.56 ± 0.11(15)	0.58 ± 0.09(15)	0.59 ± 0.15(45)
		CFD	0.62 ± 0.22(15)	0.60 ± 0.12(15)	0.60 ± 0.10(15)	0.61 ± 0.15(45)
	Aver.	Measur.	0.69 ± 0.24 (30)	0.61 ± 0.16(30)	0.53 ± 0.12 (30)	0.61 ± 0.19 (90)
		CFD	0.70 ± 0.22 (30)	0.64 ± 0.16 (30)	0.55 ± 0.13 (30)	0.63 ± 0.18 (90)
II	0.25	Measur.	1.15 ± 0.35 (15)	1.01 ± 0.24 (15)	0.69 ± 0.14 (15)	0.95 ± 0.32 (45)
		CFD	1.16 ± 0.30 (15)	1.05 ± 0.25 (15)	0.71 ± 0.13 (15)	0.97 ± 0.30 (45)

	1.75	Measur.	0.85 ± 0.27 (15)	0.84 ± 0.16 (15)	0.84 ± 0.16 (15)	0.84 ± 0.20 (45)
		CFD	0.90 ± 0.31 (15)	0.88 ± 0.18 (15)	0.90 ± 0.18 (15)	0.89 ± 0.23 (45)
	Aver.	Measur.	1.00 ± 0.34 (30)	0.92 ± 0.22 (30)	0.76 ± 0.17 (30)	0.89 ± 0.27 (90)
		CFD	1.03 ± 0.33 (30)	0.97 ± 0.23 (30)	0.80 ± 0.18 (30)	0.93 ± 0.27 (90)
III	0.25	Measur.	1.42 ± 0.41 (15)	1.28 ± 0.31 (15)	0.91 ± 0.24 (15)	1.20 ± 0.38 (45)
		CFD	1.43 ± 0.38 (15)	1.29 ± 0.26 (15)	0.95 ± 0.25 (15)	1.22 ± 0.36 (45)
	1.75	Measur.	1.11 ± 0.36 (15)	1.13 ± 0.24 (15)	1.20 ± 0.22 (15)	1.15 ± 0.28 (45)
		CFD	1.13 ± 0.36 (15)	1.20 ± 0.28 (15)	1.22 ± 0.20 (15)	1.19 ± 0.29 (45)
	Aver.	Measur.	1.26 ± 0.41(30)	1.21 ± 0.28 (30)	1.05 ± 0.27 (30)	1.17 ± 0.33 (90)
		CFD	1.28 ± 0.40(30)	1.24 ± 0.27 (30)	1.09 ± 0.26 (30)	1.20 ± 0.32 (90)
IV	0.25	Measur.	1.50 ± 0.35 (15)	1.57 ± 0.34 (15)	1.15 ± 0.22 (15)	1.40 ± 0.36 (45)
		CFD	1.57 ± 0.36 (15)	1.64 ± 0.36 (15)	1.17 ± 0.22 (15)	1.46 ± 0.38 (45)
	1.75	Measur.	1.28 ± 0.35 (15)	1.43 ± 0.24 (15)	1.46 ± 0.23 (15)	1.39 ± 0.28 (45)
		CFD	1.32 ± 0.40 (15)	1.47 ± 0.28 (15)	1.51 ± 0.22 (15)	1.43 ± 0.31 (45)
	Aver.	Measur.	1.39 ± 0.36 (30)	1.50 ± 0.30 (30)	1.30 ± 0.27 (30)	1.40 ± 0.32 (90)
		CFD	1.44 ± 0.40 (30)	1.55 ± 0.33 (30)	1.34 ± 0.28 (30)	1.45 ± 0.34 (90)
V	0.25	Measur.	1.61 ± 0.29 (15)	1.81 ± 0.31 (15)	1.39 ± 0.30 (15)	1.60 ± 0.35 (45)
		CFD	1.67 ± 0.34 (15)	1.89 ± 0.33 (15)	1.40 ± 0.32 (15)	1.66 ± 0.38 (45)
	1.75	Measur.	1.38 ± 0.33 (15)	1.71 ± 0.27 (15)	1.76 ± 0.24 (15)	1.62 ± 0.33 (45)
		CFD	1.45 ± 0.38 (15)	1.75 ± 0.32 (15)	1.82 ± 0.23 (15)	1.67 ± 0.35 (45)
	Aver.	Measur.	1.49 ± 0.33 (30)	1.76 ± 0.29 (30)	1.57 ± 0.33 (30)	1.61 ± 0.33 (90)
		CFD	1.56 ± 0.37 (30)	1.82 ± 0.33 (30)	1.61 ± 0.34 (30)	1.66 ± 0.36 (90)
VI	0.25 m	Measured	1.63 ± 0.33 (15)	2.12 ± 0.36 (15)	1.60 ± 0.31 (15)	1.78 ± 0.40 (45)
		CFD	1.69 ± 0.37 (15)	2.20 ± 0.35 (15)	1.62 ± 0.31 (15)	1.84 ± 0.43 (45)
	1.75	Measur.	1.48 ± 0.34 (15)	2.03 ± 0.37 (15)	2.00 ± 0.29 (15)	1.84 ± 0.42 (45)
		CFD	1.56 ± 0.40 (15)	2.04 ± 0.35 (15)	2.09 ± 0.28 (15)	1.90 ± 0.42 (45)
	Aver.	Measur.	1.55 ± 0.34 (30)	2.08 ± 0.36 (30)	1.80 ± 0.36 (30)	1.81 ± 0.41 (90)
		CFD	1.63 ± 0.39 (30)	2.12 ± 0.35 (30)	1.85 ± 0.38 (30)	1.87 ± 0.42 (90)
VII	0.25	Measur.	1.77 ± 0.36 (15)	2.40 ± 0.34 (15)	1.83 ± 0.37 (15)	2.00 ± 0.45 (45)
		CFD	1.83 ± 0.36 (15)	2.52 ± 0.36 (15)	1.85 ± 0.40 (15)	2.06 ± 0.49 (45)
	1.75 m	Measur.	1.61 ± 0.43 (15)	2.27 ± 0.36 (15)	2.33 ± 0.32 (15)	2.07 ± 0.49 (45)
		CFD	1.69 ± 0.49 (15)	2.35 ± 0.40 (15)	2.41 ± 0.30 (15)	2.15 ± 0.51 (45)
	Aver.	Measur.	1.69 ± 0.40 (30)	2.33 ± 0.35 (30)	2.08 ± 0.42 (30)	2.03 ± 0.47 (90)
		CFD	1.76 ± 0.43 (30)	2.43 ± 0.39 (30)	2.13 ± 0.45 (30)	2.11 ± 0.50 (90)

Table 4.4.*Cont.*

Op.	Heig. (m)	Method.	Section A	Section B	Section C	Average
VIII	0.25	Measur.	1.74 ± 0.45 (15)	2.58 ± 0.29 (15)	2.03 ± 0.42 (15)	2.12 ± 0.52 (45)
		CFD	1.77 ± 0.48 (15)	2.72 ± 0.31 (15)	2.07 ± 0.42 (15)	2.19 ± 0.56 (45)
	1.75	Measur.	1.76 ± 0.55 (15)	2.63 ± 0.32 (15)	2.55 ± 0.35 (15)	2.32 ± 0.61 (45)
		CFD	1.85 ± 0.60 (15)	2.68 ± 0.34 (15)	2.69 ± 0.35 (15)	2.41 ± 0.59 (45)
	Aver.	Measur.	1.75 ± 0.49 (30)	2.61 ± 0.30 (30)	2.30 ± 0.46 (30)	2.22 ± 0.55 (90)
		CFD	1.81 ± 0.53 (30)	2.71 ± 0.32 (30)	2.38 ± 0.49 (30)	2.30 ± 0.58 (90)
IX	0.25	Measur.	1.79 ± 0.50 (15)	2.59 ± 0.44 (15)	2.35 ± 0.47 (15)	2.24 ± 0.57 (45)
		CFD	1.88 ± 0.54 (15)	2.68 ± 0.53 (15)	2.37 ± 0.49 (15)	2.31 ± 0.61 (45)
	1.75	Measur.	1.91 ± 0.61 (15)	2.83 ± 0.26 (15)	2.75 ± 0.33 (15)	2.50 ± 0.59 (45)
		CFD	2.00 ± 0.66 (15)	2.97 ± 0.27 (15)	2.92 ± 0.37 (15)	2.63 ± 0.64 (45)
	Aver.	Measur.	1.85 ± 0.55 (30)	2.71 ± 0.38 (30)	2.55 ± 0.45 (30)	2.37 ± 0.59 (90)
		CFD	1.94 ± 0.60 (30)	2.82 ± 0.44 (30)	2.65 ± 0.51 (30)	2.47 ± 0.64 (90)
X	0.25	Measur.	1.48 ± 0.48 (135)	1.78 ± 0.73 (135)	1.38 ± 0.67 (135)	1.55 ± 0.66 (405)
		CFD	1.53 ± 0.50 (135)	1.85 ± 0.77 (135)	1.40 ± 0.67 (135)	1.59 ± 0.68 (405)
	1.75	Measur.	1.33 ± 0.56 (135)	1.72 ± 0.79 (135)	1.72 ± 0.76 (135)	1.59 ± 0.73 (405)
		CFD	1.39 ± 0.60 (135)	1.77 ± 0.82 (135)	1.79 ± 0.80 (135)	1.65 ± 0.77 (405)
	Aver.	Measur.	1.41 ± 0.53 (270)	1.75 ± 0.76 (270)	1.55 ± 0.74 (270)	1.57 ± 0.70 (810)
		CFD	1.46 ± 0.56 (270)	1.81 ± 0.80 (270)	1.60 ± 0.76 (270)	1.62 ± 0.73 (810)

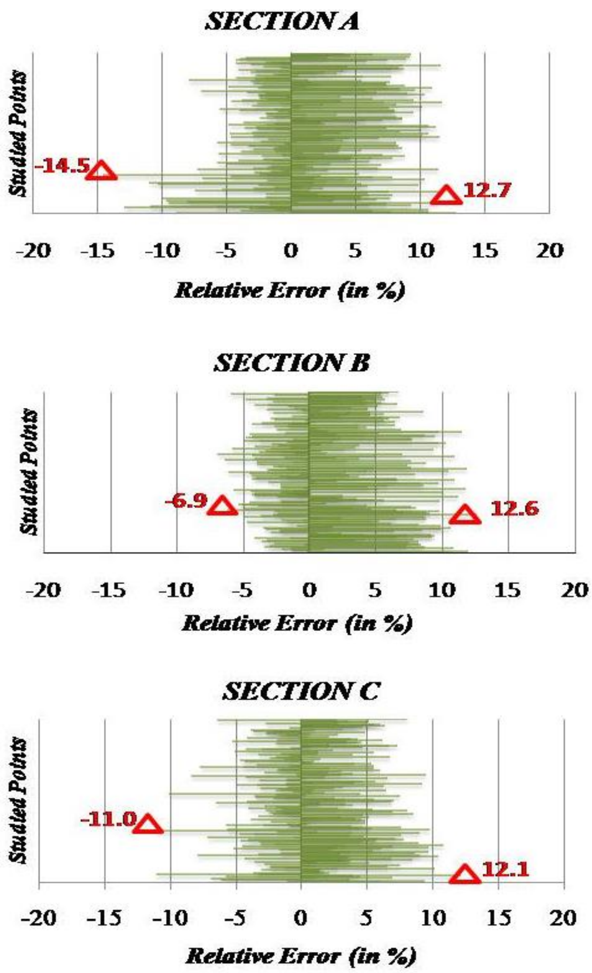
Despite the fact that the CFD simulations are performed in steady state (obtaining a single value for a point), the number of averaged data leads to results in this form similar to those of the direct measurements (average ± standard deviation). The studied 90 points (30 points in each section, 15 points at 0.25 m and 15 points at 1.75 m) by the 9 scenarios leads to 810 data (810 data for CFD and 810 data for direct measurements). At broiler level (0.25 m), the average (an average of 405 data for CFD and 405 data for direct measurements) of the air velocity values is very similar in CFD (1.59±0.68 $m \cdot s^{-1}$) and by means of the direct measurements (1.55±0.66 $m \cdot s^{-1}$).

4.3.3. Results of the Relative Error at Each Point

Despite the fact that the average air velocity value is very similar when comparing CFD and direct measurements, as seen in Table 4.4, the relative error defined in Equation (4.8) at some points is occasionally significant. Figure 4.5 shows this relative error.

Figure 4.5 shows the discrepancies of the relative error. The red triangle indicates the maximum and minimum error in each section. In Section A, the maximum error was 12.7% (Operation I) and the minimum was −14.5% (Operation III); in Section B, the maximum error was 12.6% (Operation III) and the minimum was −6.9% (Operation VI) and in Section C, the maximum error was 12.1% (Operation I) and the minimum was −11.0% (Operation III). The results for these relative errors are common and in the expected ranges, as they do not exceed 20% (Posner *et al.*, 2003). Moreover, the averaged relative error is small and very similar in all sections (+1.7% in Section A, +2.07% in Section B and +1.25% in Section C).

Figure 4.5. *Relative error in each operation.*



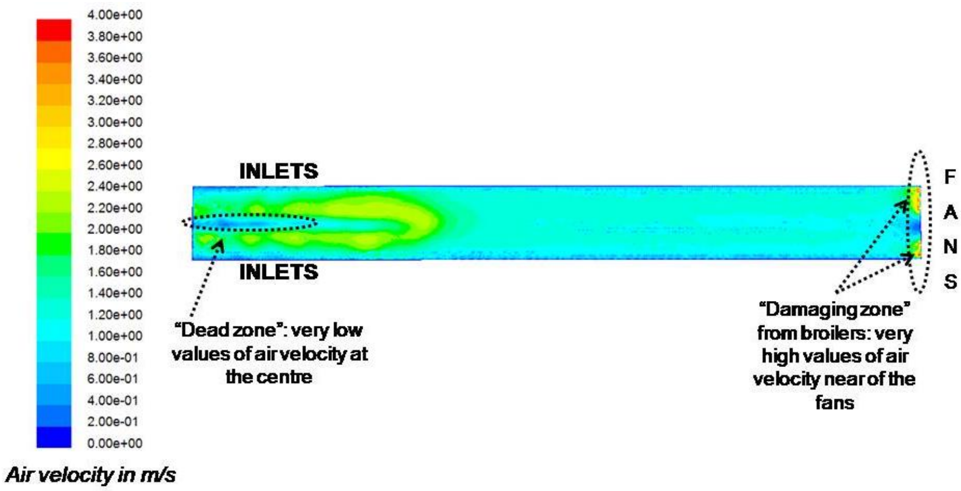
4.3.4. CFD-Air Velocity Results

CFD simulations provide very visual and interesting outputs that give an idea of the trends in air flow and an estimation of values by vectors or colours.

Figure 4.6 shows the air velocity values by colours at broiler level (0.25 m) in a typical operation (Operation IV, 5 fans in action) in summer seasons. Here, we can clearly observe three different indoor behaviours in terms of air velocity distribution. Near the inlets, we can see a zone with very heterogeneous values, where very high air velocity values are found close to an area with very low values ("dead zone"). In the central zone, we observe homogeneous air velocity values (very good area). Near the fans, we can again observe the heterogeneity of the air velocity values, notably the high air velocity values near the fans, which can seriously disturb the birds ("damaging zone"), causing feeding or health problems (colds, respiratory diseases) (Lott *et al.*, 1998).

It is necessary to distinguish the use of this ventilation system for winter (cold seasons) or summer (hot seasons). As shown in Figure 4.6, all the air enters via Section A (inlets section); in summer, only air velocity is required, but in winter it is also necessary to heat the cold air. In cross-ventilation systems, the air inlets are located along the whole length of the building and less energy is needed to heat the incoming air than in a shorter entry section to the tunnel ventilation.

Figure 4.6. *Air velocity values at broiler level (0.25 m) in the Operation IV (5 fans in action).*



4.4. Discussion

In this paper, we have analysed air velocity values in tunnel ventilation in a broiler building in Spain (Mediterranean climate). Whereas this ventilation system is quite commonplace in some countries (Daghir, 2001; Lacey *et al.*, 2003), it has only recently been incorporated in countries with a medium-extreme Mediterranean climate. The aim of adopting this ventilation system is to resolve repetitive mortality and stress for the animals in summer, accentuated by the effects of climate change and global warming.

As this ventilation system has only recently been installed in these areas due to the widespread use of cross-mechanical ventilation, no published article addressing management and the air velocity distribution *vs.* fans in action could be found. This issue is crucial to optimise the management of these buildings. In this article, we respond to this question using powerful methodologies such as CFD and a multi-sensor system that also validated the numerical simulations. After the validation, CFD techniques can play an important role in developing virtual buildings and BCs in order to choose the best designs and managements. Moreover, they can provide information on the whole indoor environment, whereas the number of physical sensors is limited.

The field experiment took place in a broiler building in the Valencian Community (Spain), but it must be emphasised that there are diverse subclimatic areas within large countries such as Spain, and adopting a uniform ventilation system for the whole country is not an ideal solution.

In this article, we address the indoor air velocity distribution; obviously, other environmental parameters such as temperature or relative humidity are also relevant, especially if the broiler building is occupied. Along these lines, some interesting articles on occupied broiler buildings in other climatic areas were found, related to temperature (Osorio JA *et al.*, 2011) and the temperature and ammonia distribution (Mostafa *et al.*, 2012). Since we found that the air temperature had already been analysed by (Mostafa *et al.*, 2012; Osorio JA *et al.*, 2011) and due to limitations on the length of this article, we focused only on the air velocity distribution as the crucial parameter for our needs and for automation of the broiler building.

Hence, an excessive number of fans working will waste unnecessary energy, cause colds in broilers or decrease the consumption of feed or water, whereas an insufficient number of fans running will lead to thermal stress and associated mortality.

The field experiments took place at a constant differential pressure measured as per Bustamante *et al.*, 2012, and the number of fans in action was gradually increased from two fans to ten fans in order to compare air velocity development, as indicated in Table 4.4. According to the specific literature on tunnel ventilation (Daghir, 2001), the inlets area and fans area are key in tunnel ventilation design; thus, almost three main areas need to be analysed (near fans, near inlets and the intermediate area). Moreover, due to the large dimensions of the building and as indicated in the literature, the measurements only covered these areas of the building (Section A, Section B and C). As the building has no background of mortality in specific points and this ventilation system had recently been installed, the location of the tripods was randomly trying to cover the entire area of the study.

CFD simulations and direct measurements will confirm these three sections have different air velocity behaviour. In this sense, Figure 4.6 shows this different behaviour in terms of air velocity distribution:

(1). Section A showed great changes in air velocity and trajectories; we find a "dead zone" (very low air velocities) very close to zones with high values and turbulence.

(2). Section B was very homogeneous in air velocity distribution and presented high values if several fans were working; the trajectories did not show multi-directionality, as they are almost perpendicularly oriented to the fans.

(3). Section C showed very high air velocity values with a discrete number of fans working; air velocity trajectories are oriented to the fans the same as in Section B, but the air velocity values were higher than in Section B mainly when the number of fans was increased.

One simple assumption in tunnel ventilation is to calculate the air exchange and to divide it by the section (Daghir, 2001); the result is estimative, because it is assumed equal for the whole horizontal plane and this is not true, as shown in Figure 4.6. Turbulence, roughness or the assumptions of dimensions give rise to estimative results in comparison with accurate methods such as CFD or direct measurements. CFD also provides the trends of airflow in planes as we can see in Figure 4.6. For example, in the case of the Operation IV, the air exchange of the five fans is 190,000 $m^3 \cdot h^{-1}$(38,000 $m^3 \cdot h^{-1} \times$ 5 fans), the section is 34.77 m^2; thus, 190,000/34.77= 5464.48 $m \cdot h^{-1}$(=1.52 $m \cdot s^{-1}$) while the CFD results are 1.45± 0.34 $m \cdot s^{-1}$ (Table 4.4) and for direct measurements the outcomes are 1.40± 0.30 $m \cdot s^{-1}$. The results are similar in finding discrepancies in this method for the above mentioned reasons (turbulence, roughness...).

In Table 4.4, we can see very high air velocity values if the number of fans working is increased; these values can be dangerous for the broilers, as they may suffer from colds, respiratory diseases or feeding problems.

According to Table 4.4 and Figure 4.6, tunnel ventilation is a good system to lower heat in broilers and the associated mortality, as it achieves high air velocity values. At broiler level, the maximum air velocity was 2.72±0.31 m·s^{-1} (CFD) and 2.58±0.29 m·s^{-1} (measured) in Operation VIII, Section B and the minimum was 0.49±0.12 m·s^{-1} (CFD) and 0.47±0.11 m·s^{-1} (measured) in Operation I, Section C.

The Validation model for CFD simulations concluded that the variable "Methodology" (results by CFD simulations or direct measurements) and its interactions were not significant, as shown in Table 4.3. So, there is no difference between the use of these direct measurements or the corresponding CFD simulations to explore indoor air velocity in a tunnel ventilated broiler building, as in other similar studies of other ventilation systems (Bustamante *et al.*, 2013). Therefore, CFD procedures are confirmed as suitable to explore this ventilation system using virtual geometries. Although we can obtain the exact values of air velocities using CFD simulations, as shown in Table 4.4, with CFD simulations we can also obtain excellent visual displays that provide a lot of information on the air flow characteristics and magnitude, as in Figure 4.6. After the good compromise between measurements and CFD, the main reason to have a dead zone is the location of the inlets in the lateral walls. If the tunnel building had the inlets in the opposite wall to the fans, this "dead zone" would disappear, according to some virtual CFD simulations to be developed in future works. Of course, tunnel ventilation has a predominant dimension in air velocity (the longitudinal axis) and we observed minor deviations between measurements and CFD results. These small deviations are found in all sections, with the least punctual (maximum and minimum) relative error in the central section (Figure 4.5), as it is the most one-dimensional. However, the averaged relative error is very similar and small in all the sections. The amount of the data minimises the deviations in the averaged relative error. The sources of these errors can come from both sides (the CFD or the direct measurements).

A broiler building which installs both mechanical ventilation systems (cross and tunnel) can be an interesting design. Combined periods using each ventilation system can be developed (cross in cold periods and tunnel in warm periods). In any case and in terms of air velocity values (obtained in Table 4.4), tunnel ventilation can be used for cold and warm periods.

In subsequent studies, it will be interesting to compare empty and occupied broiler buildings by the specific nature of the broiler metabolism. In any case, an empty building is a permanent state to be analysed in depth. In fact, in this building, the level of occupation can be 22,000 broilers. A one-day-old broiler weighs around 44 grams and a broiler on the last day of rearing has a weight of 4202 grams (Zuidhof *et al.*, 2014). The broiler metabolism at different levels and the same type of birds (also the feather, *etc.*) will lead to great changes in the measurements and numerical results. In this sense, it will be necessary to adapt the measurement system for the tough conditions in occupied broiler buildings.

4.5. Conclusions

In this study, a CFD model of tunnel ventilated broiler building has been validated with direct measurements. No statistical difference has been found between measured and modelled data and therefore this model allows exploring practical management options of a tunnel ventilated building.

Under warm conditions, tunnel ventilation is adequate in general terms to achieve a proper air velocity for broilers with a relatively low number of fans in action. CFD simulations allow prediction of the behaviour of airflow under different circumstances. This is essential information to optimise the management of tunnel ventilation.

A tunnel ventilation system with lateral air entrances at one end of the building and exhaust fans at the other end, and three areas were identified according to ventilation patterns. Most of the building area achieves an adequate air velocity distribution for broiler growth under warm conditions. However, ventilation patterns are not optimal near building ends due to dead areas or excessive air velocity. Therefore, design of tunnel ventilation systems could be improved to avoid or minimise this effect and contribute to a sustainable broiler production.

4.6. References

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). ASHRAE Fundamentals Handbook; American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.: Atlanta, GA, USA, 2001.

Bartzanas, T.; Kittas, C.; Sapounas, A.A.; Nikita-Martzopoulou, C. Analysis of airflow through experimental rural buildings: Sensitivity to turbulence models. *Biosyst. Eng.* 2007, 97, 229–239.

Bjerg, B.; Svidt, K.; Zhang, G.; Morsing, S.; Johnsen, J.O. Modeling of air inlets in CFD prediction of airflow in ventilated animal houses. *Comput. Electron. Agr.* 2002, 34, 223–235.

Blanes-Vidal, V.; Guijarro, E.; Balasch, S.; Torres, A.G. Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. *Biosyst. Eng.* 2008, 100, 105–116.

Blanes-Vidal, V.; Guijarro, E.; Nadimi, E.S.; Torres, A.G. Development and field test of an on-line computerized instrumentation system for air velocity, temperature and differential pressure measurements in poultry houses. *Span. J. Agric. Res.* 2010, 8, 570–579.

Bustamante, E.; García-Diego, F.J.; Calvet, S.; Estellés, F.; Beltrán, P.; Hospitaler, A.; Torres, A.G. Exploring Ventilation Efficiency in Poultry Buildings: The Validation of Computational Fluid Dynamics (CFD) in a Cross-Mechanically Ventilated Broiler Farm. *Energies* 2013, 6, 2605-2623.

Bustamante, E.; Guijarro, E.; García-Diego, F.J.; Balasch, S.; Torres, A.G. Multisensor system for isotemporal measurements to assess indoor climatic conditions in poultry farms. *Sensors* 2012, 12, 5752–5774.

Calvet, S.; Cambra-López, M.; Blanes-Vidal, V.; Estellés, F.; Torres, A.G. Ventilation rates in mechanically ventilated commercial poultry buildings in Southern Europe: Measurement system development and uncertainty analysis. *Biosyst. Eng.* 2010, 106, 423–432.

Charles, D.; Walker, A. Poultry Environment Problems: A Guide to Solutions, 1st ed.; Charles, D., Walker, A., Eds.; Nottingham University Press: Nottingham, UK, 2002.

Clements-Croome, T.D.J. What do we mean by intelligent buildings? *Automat. Constr.* 1997, 6, 395–400.

Dawkins, M.S.; Donnelly, C.A.; Jones, T.A. Chicken welfare is influenced more by housing conditions than stocking density. *Nature* 2004, 427, 342–344.

Daghir, N.C. Poultry Production in Hot Climates; CAB International: Wallingford, UK, 2001.

DEFRA (Department for Environment, Food and Rural Affairs). Heat Stress in Poultry. Solving the Problem; DEFRA: London, UK, 2008.

El País, Anonymous. Medio millón de pollos mueren fuerte calor últimos días. Available online: http://www.elpais.com/articulo/Comunidad/Valenciana/Medio/millon/pollos/mueren/fuerte/calor/ultimos/dias/elpepiespval/20030617elpval_4/Tes (accessed on 12 May 2014).

Fluent User's Guide, version 6.0; Fluent Inc.: Lebanon, NH, USA, 2001.

Gambit User's Guide, version 2.0; Fluent Inc.: Lebanon, NH, USA, 2001.

Harral, B.B.; Boon, C.R. Comparison of predicted and measured air flow patterns in a mechanically ventilated livestock buildings without animals. *J. Agric. Eng. Res.* 1997, 66, 221–228.

Heber, A.J.; Boon, C.R.; Peugh, M.W. Air patterns and turbulence in an experimental livestock building. *J. Agric. Eng. Res.* 1996, 64, 209–226.

Holmes, M.J.; Hacker, J.N. Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century. *Energ. Build.* 2007, 39, 802–814.

Lacey, R.E.; Redwine, J.S.; Parnell, C.B. Particulate matter and ammonia emission factors for tunnel-ventilated broiler production houses in the Southern U.S. *Trans. ASAE* 2003, 46, 1203–1214.

Launder, B.E.; Spalding, D.B. The numerical computation of turbulent flows. *Comput. Method. Appl. M.* 1974, 3, 269–289.

Lee, I.B.; Sase, S.; Sung, S.H. Evaluation of CFD accuracy for the ventilation study of a naturally ventilated broiler house. *Jpn. Agric. Res. Q.* 2007, 41, 53–64.

Lott, B.D.; Simmons, J.D.; May, J.D. Air velocity and high temperature effects on broiler performance. *Poultry Sci.* 1998, 77, 391–393**.**

Mistriotis, A.; de Jong, T.; Wagemans, M.J.M.; Bot, G.P.A. Computational fluid dynamics as a tool for the analysis of ventilation and indoor microclimate in agriculture buildings. *Neth. J. Agr. Sci.* 1997, 45, 81–96.

Mitchell, M.A.; Kettlewell, P.J. Physiological stress and welfare of broiler chickens in transit: Solutions not problems! *Poult. Sci.* 1998, 91, 1803–1814.

Mostafa, E.; Lee, I.B.; Song, S.H.; Kwon, K.S.; Seo, I.H.; Hong, S.W.; Hwang, H.S.; Bitog, J.P.; Han, H.T. Computational fluid dynamics simulation of air temperature distribution inside broiler building fitted with duct ventilation system. *Biosyst. Eng.* 2012, 112, 293–303.

MWPS. Mechanical Ventilating Systems for Livestock Housing, 1st ed.; Midwest Plan Service, Iowa State University: Ames, IA, USA, 1990.

Nardone, A.; Ronchi, B.; Lacetera, N.; Ranieri, M.S.; Bernabucci. U. Effects of climate changes on animal production and sustainability of livestock systems. *Livest. Sci.* 2010, 130, 57–69.

Norton, T.; Sun, D.; Grant, J.; Fallon, R.; Dodd, V. Applications of computational fluid dynamics (CFD) in the modeling and design of ventilation systems in the agricultural industry: A review. *Bioresour. Technol.* 2007, 98, 2386–2414.

Oberkampf, W.L.; Trucano, T.G. Verification and validation in computational fluid dynamics. *Progr. Aerosp. Sci.* 2002, 38, 209–272.

Osorio, J.A.; Ferreira, I.F.; Oliveira, K.S.; Arêdes, M.; Oliveira, M. Modelling and experimental validation to estimate the energy balance for a poultry house with misting cooling. *Dyna* 2011, 78, 167–174.

Osorio, R.; Ferreira, I.F.; Osorio, J.A.; Oliveira, K.S.; Guerra, L.M. Modeling of the thermal environments in shed negative pressure tunnel cycle of chicks. *Rev. Fac.Nac. Agric.* 2013, 66, 7085–7093.

Patankar, S.V. Numerical Heat Transfer and Fluid Flow; Hemisphere Publishing Corporation: Washington, WA, USA, 1980.

Pawar, S.R.; Cimbala, J.M.; Wheeler, E.F.; Lindberg, D.V. Analysis of poultry house ventilation using computational fluid dynamics. *Trans. ASABE* 2007, 50, 1373–1382.

Posner, J.D.; Buchanan, C.R.; Dunn-Rankin, D. Measurement and prediction of air flow in a model room. *Energ. Build.* 2003, 35, 515–526.

SAS. SAS User's Guide: Statistics, version 6.12; SAS Institute Inc.: Cary, NC, USA, 1998.

Sensortechnics Inc. Available on line: http://www.sensortechnics.com (accessed on 12 May 2014).

Sohail, M.U.; Hume, M.E.; Byrd, J.A.; Nisbet, D.J.; Ijaz, A.; Sohail, A.; Shabbir, M.Z.; Rehman, H. Effect of supplementation of prebiotic manan-oligosaccharides and probiotic mixture on growth performance of broilers subjected to chronic heat stress. *Poult. Sci.* 2012, 91, 2235–2240.

Testo Inc. Homepage. Available online: http://www.testo.com (accessed on 12 May 2014).

TFD. Omega Engineering, Inc. Available online: http://www.omega.com/Temperature/pdf/TFD_RTD.pdf (accessed on 15 May 2014).

WorldPoultry, Anonymous. Korea heat wave kills off 830,000 chickens (in August 2012). Available online: http://www.worldpoultry.net/Broilers/Health/2012/8/S-Korean-heat-wave-kills-off-830000-chickens-WP010736W/ (accessed on 12 May 2014).

Zuidhof, M.J.; Schneider, B.L.; Carney, V.L.; Korver, D.R.; Robinson, F.E. Growth, efficiency, and yield of commercial broilers from 1957, 1978, and 2005. *Poult. Sci.* 2014, 93, 2970–2982.

Chapter 5

Single-sided mechanical ventilation in broiler houses

An adapted version is submitted to an international journal indexed in Journal Citations Report.

Abstract: In recent years, some broiler production farmers have incorporated mechanical single-sided ventilation (air inlets and fans located in the same lateral wall), especially in Mediterranean areas. Nevertheless, very little scientific information on the performance of mechanical single-sided ventilation systems is available to date. This ventilation system is fitted because it seems appropriate for these climatic areas and to diminish the stress and mortality of broilers in hot seasons. Obviously, it is essential to carry out studies using the scientific method. To this end, two powerful methodologies were found to study the indoor environments of broiler houses: CFD (Computational Fluid Dynamics) simulations and sensors (direct measurements). Thus, by means of a specific multi-sensor system, the CFD air velocity simulations were validated under very different typical scenarios in this type of livestock building. The ANOVA for the proposed validation leads to a p-value of 0.3908. In regard to this result, the methodology employed (CFD or sensors) is not significant. These CFD simulations were focused on this environmental parameter because its control and values were the most widespread method used to regulate the convective heat of broilers, which causes stress and mortality in hot seasons. The results show a wide range of air velocity values: the minimum CFD-value of air velocity at broiler level was 0.52±0.40 m s^{-1} and the maximum was 1.29±0.41 m s^{-1}. In this study, two major conclusions are drawn in terms of the indoor air velocity values: (i) excessively heterogeneity in their distribution on the plane of presence of the animals; and (ii) insufficient values to contribute to the thermoregulation of the birds and lower their internal heat and associated thermal stress in occasional periods of hot weather. In this article, mechanical single-sided ventilation was evaluated in a Mediterranean broiler house using CFD and sensors. This study can serve as guidance to explore other broiler house architectures and their management.

Keywords: mechanical ventilation; single-sided; broiler house; Computational Fluid Dynamics (CFD); sensors.

5.1. Introduction

Mechanical ventilation systems are needed in warm climates for broiler production. The configuration and management of these systems has been under investigation for decades (Charles *et al.*, 2002; MWPS, 1990). Nowadays, cross ventilation systems are the most frequent in the Mediterranean area (Blanes-Vidal *et al.*, 2008; Bustamante *et al.*, 2013). However, in recent years, poultry houses from Mediterranean broiler production areas have been built installing mechanical single-sided ventilation as an emergent system. As its name suggests, mechanical single-sided ventilation consists of the inlets and outlets (fans) being located in the same wall. Scientific information on the performance of mechanical single-sided ventilation systems is not available today. All these experimental ventilation systems attempt to diminish the global energetic cost of the farms, while at least maintaining the needs of the animals, minimising pollutant emissions and using energy and water consumption efficiently, together with an improvement in the work of the farmers and their economic income.

Due to the great importance of intensive broiler production farms worldwide, it is essential to explore all these ventilation systems to compare them. In fact, these studies were essential because the housing conditions influenced the animal welfare more than the flock density did (Dawkins *et al.*, 2004). Basically, the mechanical single-sided ventilation system consists of exhaust fans located at the same wall as the inlets (Figure 5.1), and its effectiveness must be analysed using scientific methodologies.

Earlier works have used CFD techniques to study the internal microclimate of poultry houses with other mechanical ventilation systems (Blanes-Vidal *et al.*, 2008; Bustamante *et al.*, 2013; 2014; Osorio *et al.*, 2011; Mostafa *et al.*, 2012; Pawar *et al.*, 2007). A suitable control of some environmental parameters such as air velocity, temperature and differential pressure might lead to a reduction of energy and water consumption (May *et al.*, 2000; Yavah *et al.*, 2004) as well as improving broiler performance (Lott *et al.*, 1998; Yanagi *et al.*, 2002). On the other hand, we can find very interesting articles referring to the application of CFD techniques in naturally single-sided ventilation (Allocca *et al.*, 2003; Dascalaki *et al.*, 1996; Mokhtarzadeh-Dehghan *et al.*, 1990; Papakonstantinou *et al.*, 2000), but neither applied to livestock buildings nor to mechanical single-sided ventilation. Evidently, the validation of CFD simulations by specific measurement systems in broiler buildings and livestock buildings was necessary. In this sense, Bustamante *et al.*, 2012 developed a multi-sensor system for isotemporal measurements of air velocities that will validate the CFD results. Moreover, in this article, we study the exact effect of the installation of diffusers in fans in this ventilation system, as their influence has not been analysed to date. These diffusers are used to prevent direct air flow to the birds located in front of the fans, avoiding colds or respiratory diseases of the birds, especially when they are featherless (early stages of the bird's life). Nevertheless, farmers think that this installation worsens the indoor environment in the fatal episodes of hot seasons.

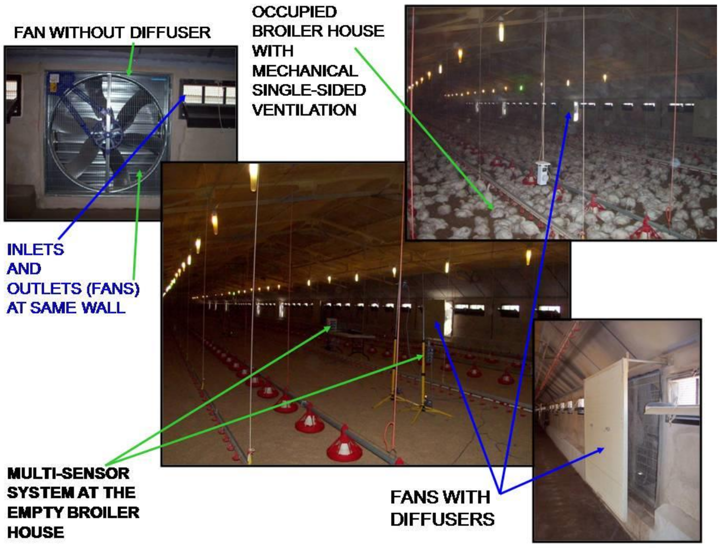
Summarising, the objectives of this article are to study the indoor air velocity distribution achieved in mechanical single-sided ventilation on broiler houses. In this research, by means of two methodologies (CFD procedures and the direct measurements using a multi-sensor system), we shall obtain several results to characterise this ventilation model. In this sense, direct measurements can only provide values at the discrete coordinates of location of sensors, whereas the CFD results can offer knowledge of the whole indoor environment. For this reason, a validation of the CFD results is performed. Therefore, considering this validation, the CFD results are accepted as a valid methodology to study the whole indoor environment and also to analyse the effect of the diffusers. The field experiments are performed in different typical scenarios on a broiler house in Western Europe (Spain) and focused on the distribution of the air velocity values, because the control of this environmental parameter is the most widespread method to regulate the convective heat of broilers, which causes stress and mortality in hot seasons.

5.2. Materials and methods

5.2.1. Assay building

A broiler building equipped with mechanical single-sided ventilation located in Western Europe (Spain) was evaluated. Figure 5.1 shows the broiler building and how the inlets and outlets (exhaust fans) were located in the same wall. The building dimensions were: length, 110 m; width, 12.60 m; sidewall height 2.6 m; doubled pitched roof (slope 21.53 %). As shown in Figure 5.1, several exhaust fans (nine) were installed. The building was also equipped with 66 inlets placed at 1.51 metres height, with automatic management. The building was empty during the field experiments. Due to the dimensions and the complexity of measurements, the test zone was set to be a 24 m section of the building in which there were 2 exhaust fans and 14 inlets. This section approximation can be considered representative, as previously suggested by Blanes-Vidal *et al.*, 2008 and Bustamante *et al.*, 2013.

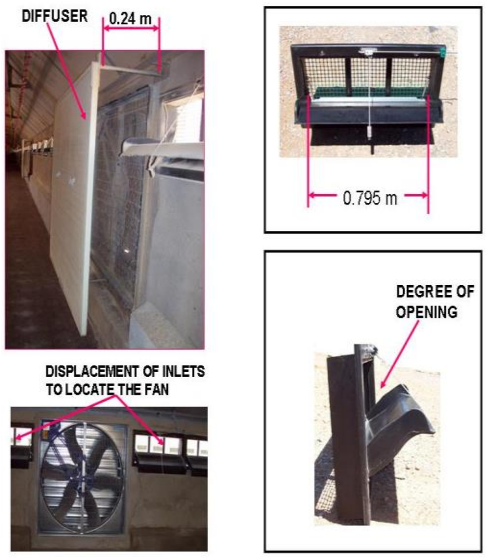
Figure 5.1. *Mechanical single-sided ventilated broiler house.*



5.2.2. Fans, inlets and diffusers

The degree of opening of inlets is the same when selecting the operation settings. The 14 inlets were located at the same height from the floor (1.51 m), distributed equally, and only three inlets were longitudinally displaced (a few centimetres) to locate the exhaust fans (see Figure 5.2).

Figure 5.2. *Inlets, outlets (fans) and diffusers.*



The exhaust fans were located at 1.14 m height on the same wall. The diffusers were also used to hermetically close the fans when they were not in action; the diffusers can easily be dismantled and the fans can operate without them. In the experimental broiler building, the diffusers opened a length of 0.24 metres when the fans were in action and this distance was also calibrated from all diffusers (see Figure 5.2).

5.2.3. Scenarios

The field tests comprised 6 experimental scenarios at different Boundary Conditions (BCs). These scenarios were used in the habitual management of this broiler building. Three scenarios were performed using the fans without diffusers, while the other three scenarios were performed repeating the same BCs (degree of opening of inlets and fans in action) but including the diffusers at fans opening to the maximum length of 24 cm. The first three scenarios without diffusers were performed at a differential pressure of 30 Pa, 38 Pa and 50 Pa and the degrees of opening of inlets for each scenario were 90º, 50.56º and 28.95º respectively. This degree of opening of the inlet refers to the angle formed by the inlet and the associated flap, as shown Figure 5.2.

5.2.4. Multi-sensor system and points of measurement

By means of a multi-sensor system previously designed (Bustamante *et al.*, 2012) with sensors of air velocity, temperature and differential pressure, the air velocity was measured at 30 different points. The 30 air velocity sensors were placed in 15 different locations at two heights: at the level of one adult broiler (0.25 metres) and at 1.75 metres. The spatial distribution of the tripods was set randomly, trying to measure at all areas of the test section. Figure 5.3 shows the test section and Table 5.1 the coordinates of sensors.

Figure 5.3. *Test section in the broiler house.*

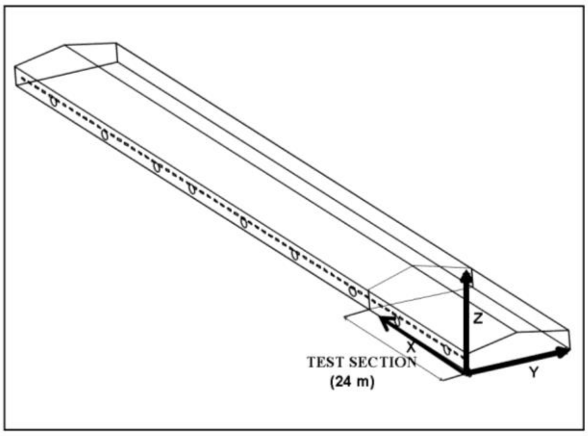


Table 5.1. *Sensor coordinates (the origin of the coordinates is indicated in Figure 5.3).*

Sensor number	***Test Section***	
	X-coordinate (m)	***Y-coordinate (m)***
1–2	2.74	6.44
3–4	5.50	4.70
5–6	8.98	7.13
7–8	19.28	6.34
9–10	14.61	6.31
11–12	18.37	1.52
13–14	15.57	2.74
15–16	14.55	4.96
17–18	1.75	11.33
19–20	5.00	8.89
21–22	6.91	7.77
23–24	3.81	1.65
25-26	5.63	3.67
27-28	21.33	11.31
29-30	15.33	9.98

5.2.5. CFD techniques

In the present study, CFD FLUENT (Fluent, 2001) was used to perform the CFD simulations. The geometry model and mesh were developed using the pre-processor GAMBIT (Gambit, 2001) by FLUENT. These CFD techniques resolve a set of partial differential equations (PDEs) (Norton *et al.*, 2007; Patankar, 1980) that corresponded to equations of continuity (Equation 5.1), conservation of momentum (Navier-Stokes's law) (Equation 5.2) and the energy equation (Equation 5.3).

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = S_m \tag{5.1}$$

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla(\rho \vec{v} \vec{v}) = -\nabla p + \nabla(\bar{\tau}) + \rho \vec{g} + \vec{F} \tag{5.2}$$

$$\frac{\partial}{\partial t}(\rho E) + \nabla(\vec{v}(\rho E + p)) = \nabla\left(k_{eff} \nabla T - \sum_j h_j \vec{J}_j + (\bar{\tau} \vec{v}) \right) + S_h \tag{5.3}$$

where $\boldsymbol{\rho}$: fluid density (kg m^{-3}); $\boldsymbol{t}$: time (s); ***u, v, w***: velocity (m s^{-1}); $\boldsymbol{S_m}$: mass source (kg m^{-3}); $\boldsymbol{p}$: pressure (Pa); $\boldsymbol{\tau}$: stress tensor (Pa); $\boldsymbol{g}$: gravitational acceleration (m s^{-2}); $\boldsymbol{F}$: external force vector (N m^{-3}); $\boldsymbol{E}$: total energy (J); $\boldsymbol{k_{eff}}$: heat transmission coefficient; $\boldsymbol{T}$: temperature (K); $\boldsymbol{h}$: specific enthalpy (J kg^{-1}); $\boldsymbol{J}$: component of diffusion flux (kg m^{-2} s^{-1}); $\boldsymbol{S_h}$: total entropy (J K^{-1}).

Moreover, CFD simulations were conducted using the standard k-ε turbulence model. Reynolds Averaged Navier-Stokes (RANS) turbulence models are generally used to perform CFD simulations in livestock buildings (Bartzanas *et al.*, 2007; Norton *et al.*, 2007). This standard k-ε turbulence model is robust with good results and easy convergence (Launder and Spalding, 1974); besides, it was already used to study transversal mechanical ventilation (cross) in broiler houses (Blanes-Vidal *et al.*, 2008; Bustamante *et al.*, 2015).

5.2.6. Geometry, meshed and BC

The geometry of the farm was modelled in its real dimensions. The exhaust fans are considered circles of diameter 1.28 m and the inlets were accurately modelled, including the flap in the degree of opening at each scenario (Bjerg *et al.*, 2002).
Following the same experimental set up as in direct measurements, CFD simulations were developed which corresponded with the six scenarios tested (three with diffusers and three without them). The mesh domain built in GAMBIT (Gambit, 2001) was exported to the CFD-solver FLUENT (Fluent, 2001), which solved the above mentioned governing PDEs (Equations 5.1, 5.2 and 5.3) in each mesh of the computational domain. In the present article, three-dimensional CFD simulations discretised in finite volumes using SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm (Patankar, 1980), second order discretisation schemes (Patankar, 1980), standard k-ε turbulence model and wall functions (Fluent, 2001) were used in the numerical simulations. Concluding CFD simulations were selected as the numerical results were stabilised when refinement of the mesh was increased. To this end, a mesh convergence test was performed. In this test, four different meshes were analysed: Mesh A (~0.6 millions of cells), Mesh B (~1.8 millions of cells), Mesh C (~2.3 millions of cells) and Mesh D (~3.5 millions of cells). Increasing the number of cells, the numerical results are stabilised and for this reason, we chose Mesh D to perform the CFD simulations. By this procedure, we ensure that the numerical results are not affected by the mesh (grid independence). Moreover, to also study the quality of the mesh (composed mainly of tetrahedral cells), the equiangular skewness command of GAMBIT (Gambit, 2001) was used.
It was assumed that the flow is steady, three-dimensional, viscous, turbulent and incompressible. The air properties are considered constants and their values are shown in Table 5.2. Gravitational acceleration was also considered. Table 5.2 summarises the constants and computational settings applied to all CFD simulations.

Table 5.2. *Constants and computational settings in all CFD simulations.*

Computational settings and constants in all CFD simulations	
Precision	*3D double precision*
Turbulence Mode	*Standard k-ε*

Wall Treatment	*Standard Wall Functions*
Pressure-velocity coupling	*SIMPLE algorithm*
Discretization Scheme for: ***Pressure*** ***Momentum*** ***Turbulent kinetic Energy*** ***Turbulent Dissipation Rate*** ***Energy***	 *Second Order Upwind* *Second Order Upwind* *Second Order Upwind* *Second Order Upwind* *Second Order Upwind*
Air properties: ***Density*** ***Cp*** ***Thermal Conductivity*** ***Viscosity***	 $1.225\ Kg\ m^{-3}$ $1006.43\ J\ kg^{-1}K^{-1}$ $0.0242\ W\ m^{-1}\ K^{-1}$ $1.789{\cdot}10^{-5}\ kg\ m^{-1}s^{-1}$
Atmospheric Pressure	*101,325 Pa*
Gravitational acceleration	$9.81\ m\ s^{-2}$

In addition, some specific Boundary Conditions (BCs) for each CFD simulation were required as particular inputs. In this study, the air velocity at inlets and the airflow and pressure at outlets were measured. The average of air velocity at inlets from each scenario was entered into the CFD software, as indicated in Table 5.3. The air velocity at inlets ($m\ s^{-1}$) was obtained from the measurements at each inlet using a calibrated Testo 425 hot-wire anemometer (Testo, 2015); then, the average of all inlets was calculated and entered into the CFD software. The % of airflow from each outlet was determined considering a same equal value for each single fan (outlet) at each scenario, and the same equal value of pressure was considered from each fan (outlet) at each scenario. The air flow was measured using the procedures of Calvet *et al.*, 2010; these procedures consist of ducting the exhaust air 50 cm from the fan and then measuring at 24 different locations in the section using a hot wire anemometer (ASHRAE, 2001). The pressure at outlets was measured using HCXM010D6V differential pressure sensors from Sensortechnics Inc (Sensortechnics, 2015). These differential pressure sensors are already used and calibrated again from this study by the procedures described in depth in Bustamante *et al.*, 2012. Blanes-Vidal *et al.*, 2008 concluded that both BC options (% of airflow or pressure) led to good numerical results but the best fit and results were obtained when the BCs are the air velocity at inlets and % of airflow at outlets. In this study and in accordance with this comment, we performed the CFD simulations using these two BC options, but only developing the validation and characterisation of this ventilation system from the option with best fit and accuracy.

On the other hand, the air temperatures at inlets and at outlets was also measured, as the temperature fluctuations at inlets and at outlets were negligible in each scenario; one average from air temperature at inlets and another average from air temperature at outlets was introduced, as indicated in Table 5.3. The surface temperature of internal solid elements was measured using a portable non-contact thermometer. Table 5.3 summarises the specific BCs and particular characteristics set to perform the CFD simulations.

Table 5.3. *Specific BCs and particular characteristics to perform the CFD simulations.*

CFD Simul (Scen.)	***Diffusers***	***Degree of opening of inlets***	***Total airflow of the broiler house (m^3 h^{-1})***	***% Airflow of each single fan (m^3 h^{-1}) [kg s^{-1}]***	***Press. at outlets (Pa)***	***Air temper. at outlets (K)***	***Air veloc. at inlets (m s^{-1})***	***Air temperature at inlets (K)***
I	No	90º	333,000	37,000 [12.34]	30	304.6	7.70	305.3
II	Yes	90º	329,850	36,650 [12.22]	32	304.6	7.63	305.3
III	No	50.56º	320,400	35,600 [11.87]	38	304.3	7.41	305.1
IV	Yes	50.56º	314,100	34,900 [11.63]	42	304.3	7.26	305.1
V	No	28.95º	301,500	33,500 [11.16]	50	304.6	6.97	305.5
VI	Yes	28.95º	293,400	32,600 [10.87]	55	304.6	6.78	305.5

5.2.7. Validation of CFD results

5.2.7.1. General context

The validation was carried out in two ways: a regression line and an ANOVA analysis. As explained above, the validation of CFD simulations was performed by comparing the simulation results with direct measurements at 30 locations. During the field experiment (10 minutes registering in each scenario), a total of 21,600 air velocity measurements were taken at the 6 scenarios.

5.2.7.2. Regression model comparing CFD vs. measurements, errors

To compare both types of data (CFD vs. direct measurements), a lineal regression was done. This lineal regression model is in the form:

$$V_{CFD} = \alpha + \beta \times V_{meas} \tag{5.4}$$

where,

V_{meas} is the average of the measured air velocity using the multi-sensor system

V_{CFD} is the air velocity obtained in the CFD simulations

The slope of Equation 5.4 (β) is an indicator of systematic errors if significantly differs from 1.

Moreover, the relative error in the *i* point (E_i) can be calculated by Equation (5.5):

$$E_i = \frac{V_{meas} - V_{CFD}}{V_{meas}} \tag{5.5}$$

where,

V_{meas} is the average of the measured air velocity the multi-sensor system at point *i*

V_{CFD} is the air velocity obtained in the CFD simulations at point *i*

5.2.7.3. ANOVA for validation

The validation consists of a statistical comparison between CFD-air velocity results and the direct measurements. By means of an analysis of variance (ANOVA), we can study the significance of the different variables ("Pressure": *P*, "Height": *H*, "Methodology": *M* and "Diffuser": *D*) with the most important being the "Methodology" (*M*) variable and the "Diffuser" (*D*) variable.

The proposed models for the validation are Equation (5.6) (eliminating the "Diffuser" variable) and the Equation (5.7) (including the "Diffuser" variable):

$$Y_{ijk} = \mu + P_i + H_j + M_k + (P \times H)_{ij} + (P \times M)_{ik} + (H \times M)_{jk} + \\ + (P \times H \times M)_{ijk} + + \varepsilon_{ijk} \tag{5.6}$$

$$U_{ijkl} = \lambda + P_{eqi} + H_j + M_k + D_l + (P_{eq} \times H)_{ij} + (P_{eq} \times M)_{ik} + (P_{eq} \times D)_{il} + \\ + (H \times M)_{jk} + (H \times D)_{jl} + (M \times D)_{kl} + (P_{eq} \times H \times M)_{ijk} + (P_{eq} \times H \times D)_{ijl} + \\ (P_{eq} \times M \times D)_{ikl} + (H \times M \times D)_{jkl} + (P_{eq} \times H \times M \times D)_{ijkl} + \varepsilon_{ijkl} \tag{5.7}$$

In both models, we also included all the possible interactions between the deployed variables: *P*, *H*, *M* and *D* as shown in Equation (5.6) and Equation (5.7).

5.2.8. Characterisation of the ventilation model

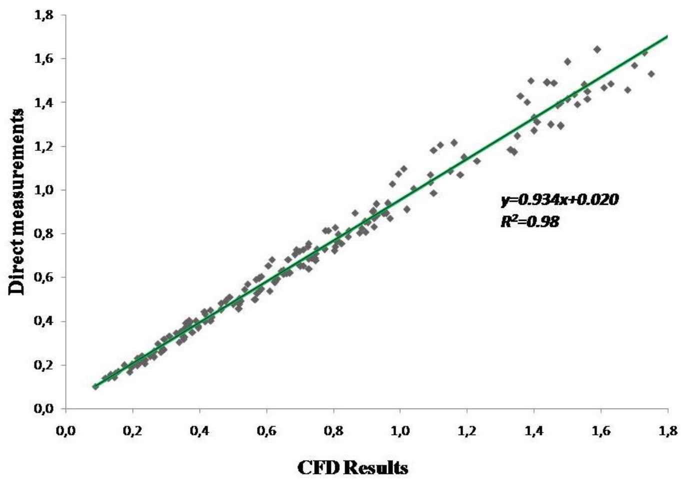
CFD techniques offer an important variety of resources and commands able to characterise this ventilation system. In this way, we highlight the strategy of creating points of interest and isosurfaces. Thus, we can create points of interest in the three-dimensional space of the broiler building that correspond to real or "virtual" sensors and obtain the numerical results there. On the other side, we can create isosurfaces; by definition, an isosurface is a surface that connects points of equal nature. For the needs of this study, we created isosurfaces that connect points of equal height. In this sense, we created isosurfaces at 0.25 m from the floor because they can correspond to the height of an adult broiler. By this procedure, we obtained an easy visualisation mode to understand the behaviour of this ventilation system in crucial surfaces such as the plane of presence of animals or the diffuser areas. These isosurfaces can incorporate a variety of scales of colours very illustrative of the desired parameter, in our study, for the air velocity distribution.

5.3. Results

5.3.1. Regression line

The lineal regression in the 180 studied points of the measured air velocity and that obtained by CFD simulations were performed (Equation 4). As we expected and according to the comments of Blanes-Vidal *et al.*, 2008, the best fit is achieved when the BCs are the air velocity at inlets and the % of airflow at outlets, although both numerical results are very similar (differences of less than 4 %). For the best option and fit (air velocity at inlets and % airflow at outlets), the coefficient of determination of the linear regression was 0.98 (Figure 5.4).

Figure 5.4. *Regression line of CFD results vs. direct measurements in the 180 points studied.*



The independent term is 0.934; thus, CFD results overestimate the direct measurements by 6.6 % (systematic error). The dependent term is 0.020, nearly 0.

The relative error (Equation (5.5)) shows maximums and minimums. The maximum relative error for the whole experiment was 14.70 % (Scenario II) and the minimum was -14.62 % (Scenario V).

5.3.2. ANOVA results of the validation Models

Using the analysis of variance (ANOVA) in SAS system (SAS, 1998) from the proposed models of validation (Equations 5.6 and 5.7), we determined that the “Methodology” variable (CFD results or direct measurements) is not significant (P-value<0.3908), i.e., the methodology used is indifferent. Similarly, the “Diffuser” variable (inclusion or elimination of the diffuser) is not significant either (P-value<0.6106), i.e., the incorporation of the diffusers is indifferent because it did not significantly affect the indoor environment. In contrast, we determined that the “Height” variable and the “Pressure” variable are both significant (P-value<0.0001); therefore, both variables have a significant effect on the resulting indoor air velocities. Table 5.4 and Table 5.5 show all of the ANOVA results from the proposed validation models (Equations 5.6 and 5.7 respectively).

Table 5.4. *ANOVA for air velocity at different scenarios excluding the “diffuser” variable (from Equation 5.6).*

Variables	**DF**	**Sum of squares**	**Mean Square**	**F-ratio**	**p-value**
Pressure	5	12.82	2.56	24.47	<0.0001
Height	1	11.33	11.33	108.12	<0.0001
Methodology	1	0.08	0.08	0.74	0.3908
Pressure × Height	5	4.93	0.99	9.41	<0.0001
Pressure × Methodology	5	0.01	0.002	0.02	0.9999
Height × Methodology	1	0.02	0.02	0.18	0.6739
Pressure × Height × Methodology	5	0.02	0.003	0.03	0.9996
Error	336	35.22	0.10		

Table 5.5. *ANOVA for air velocity at different scenarios including the “diffuser” variable (from Equation 5.7).*

Variables	**DF**	**Sum of squares**	**Mean Square**	**F-ratio**	**p-value**
Pressure	2	12.58	6.29	60.00	<0.0001
Height	1	11.33	11.33	108.12	<0.0001

Methodology	1	0.08	0.08	0.74	0.3908
Diffuser	1	0.03	0.03	0.26	0.6106
Pressure × Height	2	4.89	2.44	23.31	<0.0001
Pressure × Methodology	2	0.007	0.004	0.04	0.9655
Pressure × Diffuser	2	0.22	0.11	1.04	0.3549
Height × Methodology	1	0.02	0.02	0.18	0.6739
Height × Diffuser	1	0.0003	0.0003	0.00	0.9553
Methodology × Diffuser	1	0.00002	0.00002	0.00	0.9880
Pressure × Height × Methodology	2	0.01	0.006	0.06	0.9422
Pressure × Height × Diffuser	2	0.05	0.02	0.22	0.8033
Pressure × Methodology × Diffuser	2	0.001	0.0007	0.01	0.9934
Height × Methodology × Diffuser	1	0.003	0.003	0.002	0.8754
Pressure × Height × Methodology × Diffuser	2	0.00008	0.00004	0.00	0.9996
Error	336	35.22	0.10		

5.3.3. CFD numerical results in the sensor coordinates

Using the strategy of the creation of points of interest in CFD at the same coordinates (30 coordinates, 6 scenarios) that correspond to the location of the physical sensors, we obtained the average of the numerical results of air velocity in these coordinates. These values (in m s^{-1}) are expressed in Table 5.6.

Table 5.6. *Air velocity in m s^{-1} (average ± standard deviation) obtained in CFD simulations.*

Scenario	***Diffusers***	***Height***	***Air velocity (m s^{-1})***	***Scenario***	***Diffusers***	***Height***	***Air velocity (m s^{-1})***
I	*No*	*0.25 m*	*0.52±0.40*	***II***	*Yes*	*0.25 m*	*0.54±0.37*
		1.75 m	*0.44±0.30*			*1.75 m*	*0.53±0.36*
III	*No*	*0.25 m*	*1.29±0.41*	***IV***	*Yes*	*0.25 m*	*1.26±0.39*
		1.75 m	*0.69±0.23*			*1.75 m*	*0.62±0.22*
V	*No*	*0.25 m*	*1.08±0.39*	***VI***	*Yes*	*0.25 m*	*1.01±0.36*
		1.75 m	*0.63±0.25*			*1.75 m*	*0.58±0.23*

In Table 5.6, we can observe the minimum influence of the inclusion of the diffusers in the indoor air velocity values, comparing the results of Scenario I vs. II (differences of 0.02 m s^{-1} at 0.25 m), Scenario III vs. IV (differences of 0.03 m s^{-1} at 0.25 m) and Scenario V vs.

VI (differences of 0.07 m s^{-1} at 0.25 m). Moreover, in all the scenarios, we can observe the great variability (large standard deviation) in the air velocity results. According to Table 5.6, the highest ventilation rates of the broiler building (much exhausted air) do not necessary imply much air velocity at one space or surface of the broiler building (in this study, at the crucial level of the broilers' life). Whereas the maximum exhausted air (the airflow is specified in Table 5.3) is in Scenario I and II, the air velocity values are less than half compared to Scenario III and IV with less exhausted air (Table 5.3). Thus, the adopted physical geometry of the broiler building (inlets and outlets) is essential to determine the air velocity distribution and values at each resulting scenario.

5.3.4. CFD-air velocity isosurfaces

Using the isosurface creation strategy, we obtained very illustrative planes that give an idea of the airflow trends and an estimation of values by colours or vectors in different critical spaces that are considered in the figures below.

Comparing Figure 5.5 vs. Figure 5.6, we can observe the obstructive effect of the diffusers in the air in the plane of the diffusers (Y=0.24 m). In both figures, we can see the high values of the air entrance at the inlets. Despite the clear obstructive effect shown in the plane of Figure 5.6, the ranges of the air entrance at inlets are similar in both cases.

Figure 5.5. *Air velocity (values in m s^{-1}) in a plane perpendicular to floor at 0.24 m of fans without diffusers (using colour scale). Scenario I.*

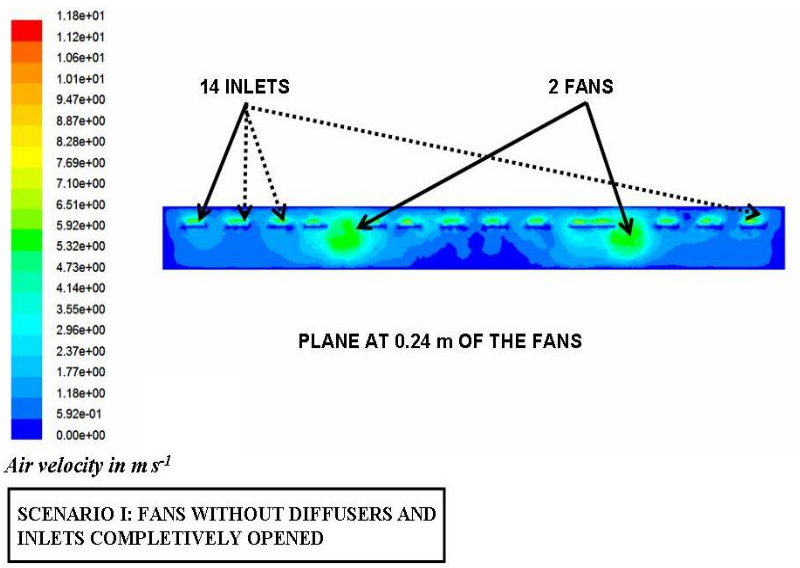


Figure 5.6. *Air velocity (values in m s^{-1}) in a plane perpendicular to floor at 0.24 m of fans with diffusers (using colour scale). Scenario II.*

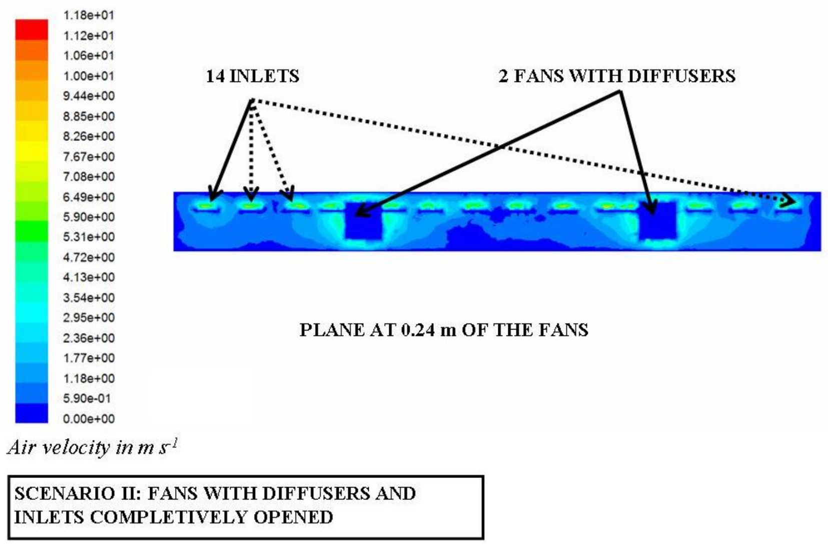


Figure 5.7 and Figure 5.8 show the air velocity circuit, indicating poor development of the air circuit in the opposite wall to the fans.

Figure 5.7. *Air velocity (values in m s^{-1}) in a plane (X=18 m) without diffusers (using colour scale). Scenario III.*

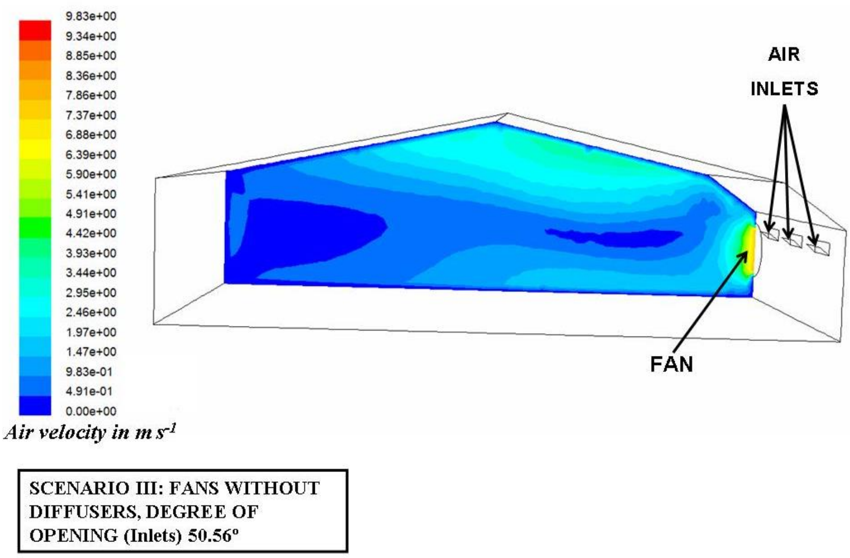
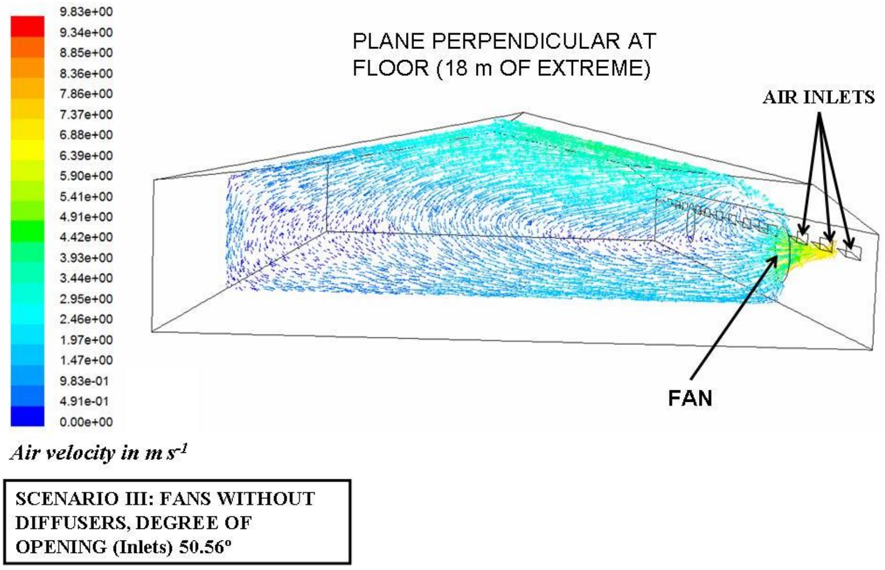


Figure 5.8. *Air velocity (values in m s^{-1}) in a plane (X=18 m) without diffusers (using vectors). Scenario III.*



In these Figures 5.7 and 5.8, we can appreciate the shape and intensity of the air circuit; the air passes through the inlets at high velocity, adopting a direction parallel to the roof and towards the opposite wall. Nevertheless, the intensity of the air velocity decreases rapidly and does not reach the opposite wall forcefully. The great influence of the geometry of the broiler building in the air velocity circuit is perceptible, especially the width and the slope of the roof. Moreover, the characteristics of the inlets (geometry and adopted form) and the fans (exhaust air) are also crucial in the development and intensity of these air velocity circuits.

In Figure 5.9 and Figure 5.10, the undesired effect of poor ventilation in the opposite wall of fans can also be clearly appreciated. This air velocity distribution shows very low velocities in the wall opposite the fans. On the other side, we can see good ventilation near the roof and some stratification of the air velocity in parallel planes from the roof near the wall of inlets. This effect indicates the influence of the inlets and adopted geometry (flap orientation) in this air velocity distribution.

Figure 5.9. *Air velocity (values in m s^{-1}) in a plane (X=18 m) with diffusers (using colour scale). Scenario IV.*

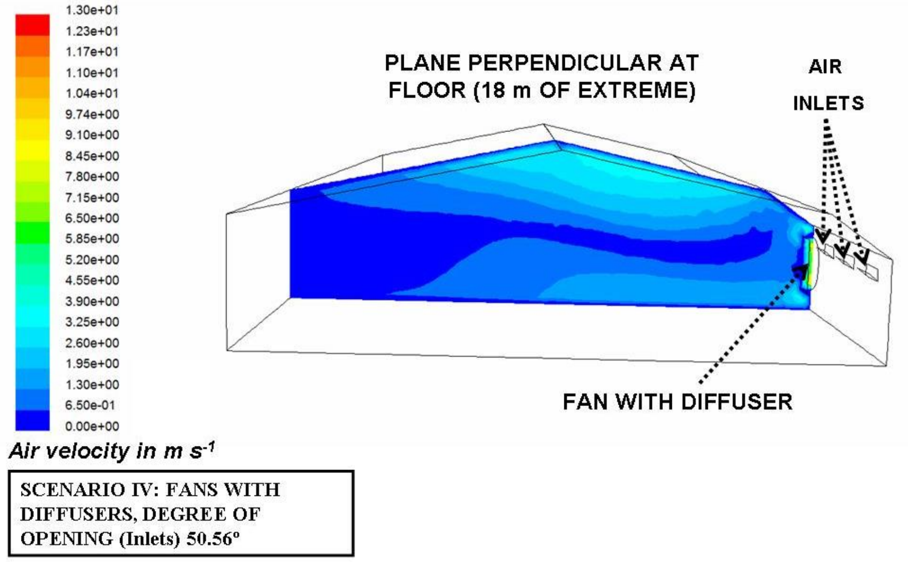
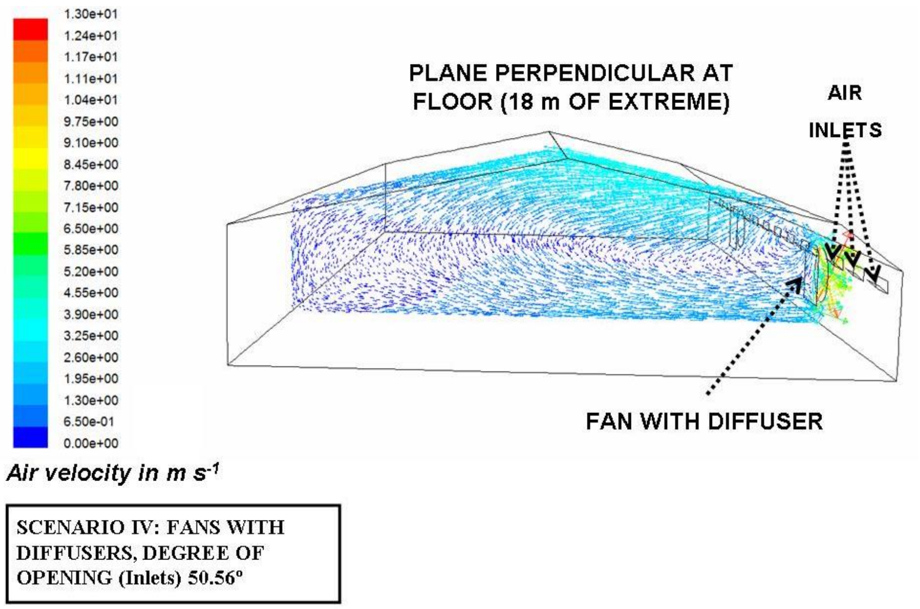


Figure 5.10. *Air velocity (values in m s^{-1}) in a plane (X=18 m) with diffusers in another scenario (using vectors). Scenario IV.*



Finally, the planes at broiler level (0.25 m) in Figure 5.11 and Figure 5.12 are also crucial, because they show the air velocity distribution in the huge living space of the bird.

Figure 5.11. *Air velocity (values in m s^{-1}) in the broiler level plane without diffusers (using colour scale). Scenario V.*

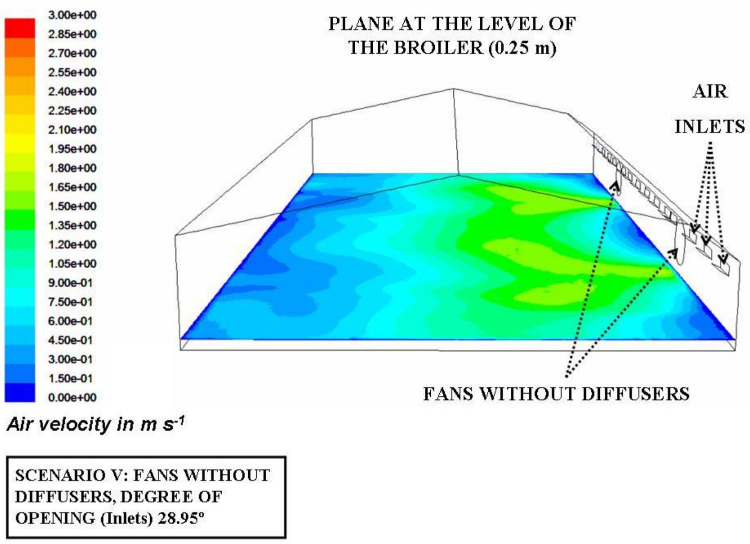
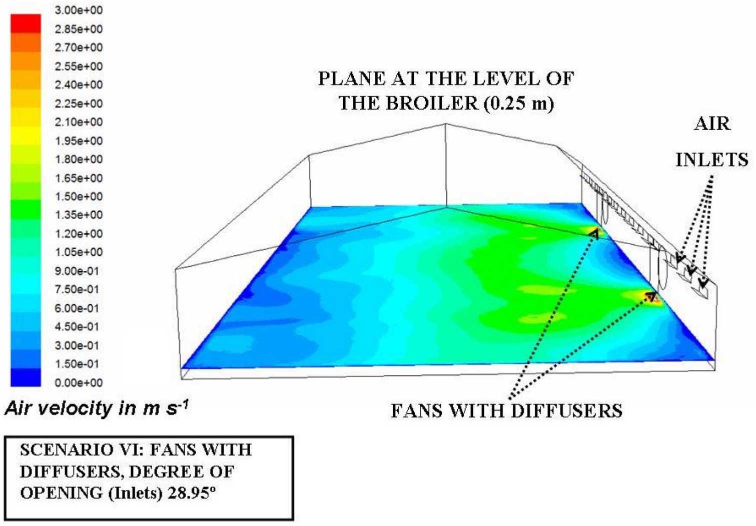


Figure 5.12. *Air velocity (values in m s^{-1}) in the same plane as Figure 11 with diffusers (using colour scale). Scenario VI.*



As we expected, poor ventilation in the opposite wall of the fans (especially between fans) and enormous heterogeneity are visibly appreciated. Thus, the heterogeneity in the air velocity distribution is one of the main characteristics and a big problem in mechanical single-sided ventilation. Furthermore, we can use the visualisation of these planes to choose the suitable scenario for each season (summer or winter, for example) or climatic situation. As we can observe in Table 5.6, the highest rates of ventilation on the broiler building do not necessary imply much air velocity at broiler level and this illustrative CFD-isosurfaces strategy may be an easy way to choose the best scenario for each climatic situation in terms of air velocity distribution.

According to the visualisation of all the figures, the heterogeneity is mainly caused by a poor development of the air velocity circuit, which does not reach the opposite wall to the fan and between fans with intensity. In this sense, the mortality of broilers in hot seasons on this experimental broiler building is observed in these areas of poor ventilation.

5.4. Discussion

In the present article, mechanical single-sided ventilation in livestock buildings was studied in a poultry house under a negative pressure system applied for broiler production. This emergent ventilation system has recently been incorporated, especially in Mediterranean areas and designed for some businesses in the sector (Serupa, 2015; Warkup, 2015). Surprisingly, no published scientific literature was found referring to mechanical single-sided ventilation in livestock buildings or broiler houses; only some papers referring to naturally single-sided ventilation (Allocca *et al.*, 2003; Dascalaki *et al.*, 1996; Mokhtarzadeh-Dehghan *et al.*, 1990; Papakonstantinou *et al.*, 2000), but neither applied to livestock buildings nor to mechanical single-sided ventilation. This ventilation system was analysed using two methodologies: direct measurements by means of a multi-sensor system and CFD simulations. To this end, we validated the CFD simulations and also analysed mechanical single-sided ventilation in a typical broiler house of Spain (Europe).

The results of field experiments (direct measurements) and CFD simulations showed that the ranges of air velocities at broiler' level were between ~0.40 m s^{-1} to ~1.30 m s^{-1}. Both methodologies (CFD and direct measurements) showed similar air velocities, with values at the average. In this sense, the validation models for CFD simulations by means of a Generalised Linear Model (GLM) using SAS systems (SAS, 1998) concluded that the "Methodology" variable (results by CFD simulations or direct measurements) is non significant (P-value<0.3908), along with its interactions. Thus, we can use direct measurements or CFD simulations to explore indoor air velocity in this ventilation system in broiler buildings. Moreover, it was also confirmed by ANOVA that the "Diffuser" variable is not significant (P-value<0.6106), as well its interactions. Thus, the inclusion of the diffuser altered the air velocity distribution, but no significant variations or tendencies were observed. On the contrary, the "Pressure" variable and "Height" variable had a significant effect (P-value<0.0001) on the indoor air velocities.

The results of Table 5.6 are very interesting, as they show that highest ventilation rates on the broiler building (much exhausted air) do not necessary imply much air velocity at level of the broilers. If the maximum exhausted air (the airflow is specified in Table 5.3) took place in Scenario I, the air velocities reached at broilers' level are the minimum of all the scenarios (less than half, compared with Scenario III with less exhausted air). Thus, the adopted geometry of the broiler building (physical configuration of inlets and outlets, associated BCs…) is crucial to obtain a determinate air velocity distribution and values, more than the rates of ventilation of the whole broiler building. In this sense, we can use CFD techniques to explore "virtual" geometries of broiler buildings and to find the optimal building designs, best scenarios and associated best managements. Obviously, according to the season (summer, winter…) or climatic situation, the management of a broiler building will be different in order to obtain some ranges of values of air velocity or others. Moreover, we can use CFD techniques and their strategies to compare with other mechanical ventilation systems (cross, tunnel…). Validation was essential in order to use CFD procedures securely to explore and characterise this ventilation system and in future comparisons with other ventilation systems. In this sense, we also obtained a good fit (R^2=0.98) in the regression line and a minimum acceptable systematic error (overestimation of CFD simulations by 6.6 %). Having validated the CFD simulations, we have obtained a powerful tool to understand the whole indoor air velocity behaviour, as they can offer more possibilities (full knowledge of the indoor environment, easy building of "virtual" farms and geometries, illustrative graphics…) than complex direct measurements.

In this broiler building, the air velocity values are acceptable in normal weather of Mediterranean climate and discretely superior to those obtained in cross mechanical ventilation (Blanes-Vidal *et al.*, 2008; Blanes-Vidal *et al.*, 2010; Bustamante *et al.*, 2013) although a future precise comparison is necessary. The minimum CFD-value of air velocity at broiler level was in Scenario I (0.52±0.40 m s^{-1}) and the maximum was in Scenario III (1.29±0.41 m s^{-1}), as shown in Table 5.6. Unfortunately, this forced ventilation is a good ventilation system for broiler production only in normal weather conditions, as it does not provide much air velocity at broiler level (Table 5.6) to prevent occasional episodes of high mortality or thermal stress in hot seasons or hot climate.

However, the exact values of air velocities can be obtained by CFD techniques (Table 5.6) at points that may represent real or "virtual" sensors. CFD outputs using isosurfaces (Figure 5.5, 5.6, 5.7, 5.8, 5.9, 5.10, 5.11 and 5.12) are a very illustrative strategy, as commented above. These figures are essential in showing the characteristics of the ventilation system. According to the ANOVA and these figures, we can observe that the diffusers "break" the airflow and diminish the air velocity only in their immediate vicinity, but do not affect the overall indoor air velocity significantly in other areas of the broiler building. Figure 5.6 showed very clearly that they "obstructed" and "strangulated" airflow near them. On the other hand, Figure 5.9 (colours) and Figure 5.10 (vectors) showed their "obstructive effect", as though forming a wall. Moreover, these two figures showed that the air velocity vector was altered only near the diffusers, without affecting the indoor air velocity; the air velocity module was "broken up", gaining in multidirectionality. This effect was homogenised and decreased the high air velocities values near the diffusers, with a gain in multidirectionality of air velocity and a decrease in ventilation rates of fans. In this sense, the height location of fans (at 1.14 metres height) minimises their effect, as shown in Figure 5.11 and Figure 5.12. Figure 5.7 and Figure 5.8 are crucial in understanding the main drawback of this ventilation system: the air velocity circuit has poor development and the intensity of the air velocity drops rapidly and does not reach the opposite wall and between fans forcefully. In this sense, the characteristics of the inlets (geometry and adopted form) and the fans (exhausted air) are also crucial in these air velocity circuits. Logically, the fatal episodes of high mortality of broilers are precisely observed by the farmer in these areas of poor ventilation.

According to this article, the use of the diffusers is recommended because they do not significantly alter the values of indoor air velocities at broiler level, as the farmers erroneously used to believe, and they prevent high air velocities near the broilers. Furthermore, considering their non significant global consequences in indoor air velocity behaviour, their installation is positive because they could prevent colds or respiratory diseases, especially in the early stages of broiler life.

In line with the results, mechanical single-sided ventilation does not solve occasional problems of thermal stress and mortality of broilers in hot seasons or hot climate. In addition, two important problems are currently found: the great hetereogeneity of the air velocity distribution and the poor ventilation in some areas of the broiler building. In this sense, the ventilation efficiency can be improved by optimising the geometry of the broiler building (especially width and slope of the roof), building "virtual" geometries by means of CFD techniques, because in this experimental standard model of geometry of a Mediterranean broiler building the air circuits do not reach the opposite wall of fans and between them with intensity. According to Dawkins *et al.*, 2004, which affirmed « housing conditions had a greater influence than flock density on animal welfare», it is essential to find an optimal ventilation system and the best broiler building design for suitable management.

5.5. Conclusions

In this article, a mechanical single-sided ventilated poultry house from broiler production was studied using powerful methodologies: direct measurements by means of a multi-sensor system and CFD techniques. Before this article, no scientific published literature of mechanical single-sided ventilation for livestock buildings can be found; only some interesting articles referring to naturally single-sided ventilation, but neither applied to livestock buildings nor to mechanical single-sided ventilation.

CFD simulations are an important tool to explore the ventilation systems, offering more possibilities (exploration of "virtual" broiler houses and geometries, knowledge of the whole indoor environment, illustrative planes or surfaces…) than complex direct measurements. In this sense, we validated the CFD simulations using a regression line and an ANOVA analysis.

In the present article, we have obtained the first results of indoor air velocity in a broiler building in Spain (Europe) that has installed this ventilation system. At the present time and on this broiler building, we can affirm that mechanical single-sided ventilation is a good system, but does not achieve a great increase in air velocity at broiler level. The air velocity values are similar (discretely superior) to those obtained in cross mechanical ventilation, but more precise comparisons of both transversal mechanical ventilation systems must be done in the future.

In this way, this ventilation is appropriate under normal weather conditions in Mediterranean climate but does not prevent occasional episodes of high mortality or thermal stress in hot seasons, because very high air velocities cannot be reached. In future studies, we can use both methodologies (direct measurements or CFD simulations) to explore indoor environments of this type of broiler houses, although CFD offers more possibilities and strategies.

In this article, we can conclude that the highest rates of ventilation on the broiler building do not necessary imply much air velocity at broiler level, because the adopted geometry of the building (inlets, outlets…) is crucial and CFD techniques can help in this sense.

The influence of the diffusers was also tested and their use is recommended as they do not significantly alter indoor air velocity behaviour at broiler level, as the farmers previously and erroneously believed, and their use also prevents direct air flow to the broilers.
The heterogeneity of the air velocity distribution and poor ventilation in some areas of the broiler building are a great problem in this ventilation system. To this end, the efficiency of the ventilation system can be improved by an optimisation of the geometry of the building (especially width and slope of the roof) using "virtual" geometries by means of CFD simulations, as in this standard model of geometry of Mediterranean broiler house the air circuits do not reach the wall opposite the fans and between them with intensity. In this research line, it is essential to find the best ventilation system and the best broiler house design, developing the suitable management for each season or climatic situation.
Future works must be carried out comparing empty and occupied broiler houses and also comparing all the current ventilation systems (cross, tunnel, single-sided...).

5.6. References

Allocca, C.; Chen, Q.; Glicksmann, L.R. Design analysis of single-sided natural ventilation. *Energ. Buildings* 2003, 35, 785-795.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). ASHRAE Fundamentals Handbook; American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.: Atlanta, GA, USA, 2001.

Bartzanas, T.; Kittas, C.; Sapounas, A.A.; Nikita-Martzopoulou, C. Analysis of airflow through experimental rural buildings: Sensitivity to turbulence models. *Biosyst. Eng.* 2007, 97, 229–239.

Bjerg, B.; Svidt, K.; Zhang, G.; Morsing, S.; Johnsen, J.O. Modeling of air inlets in CFD prediction of airflow in ventilated animal houses. *Comput. Electron. Agr.* 2002, 34, 223–235.

Blanes-Vidal, V.; Guijarro, E.; Balasch, S.; Torres, A.G. Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. *Biosyst. Eng.* 2008, 100, 105–116.

Blanes-Vidal, V.; Guijarro, E.; Nadimi, E.S.; Torres, A.G. Development and field test of an on-line computerized instrumentation system for air velocity, temperature and differential pressure measurements in poultry houses. *Span. J. Agric. Res.* 2010, 8, 570–579.

Bustamante, E.; García-Diego, F.J.; Calvet, S.; Estellés, F.; Beltrán, P.; Hospitaler, A.; Torres, A.G. Exploring Ventilation Efficiency in Poultry Buildings: The Validation of Computational Fluid Dynamics (CFD) in a Cross-Mechanically Ventilated Broiler Farm. *Energies* 2013, 6, 2605-2623.

Bustamante E., García-Diego F.J., Calvet S., Torres A.G., Hospitaler A. Measurement and numerical simulation of air velocity in a tunnel-ventilated broiler house. *Sustainability* 2015, 7, 2066-2085.

Bustamante, E.; Guijarro, E.; García-Diego, F.J.; Balasch, S.; Torres, A.G. Multisensor system for isotemporal measurements to assess indoor climatic conditions in poultry farms. *Sensors* 2012, 12, 5752–5774.

Calvet, S.; Cambra-López, M.; Blanes-Vidal, V.; Estellés, F.; Torres, A.G. Ventilation rates in mechanically ventilated commercial poultry buildings in Southern Europe: Measurement system development and uncertainty analysis. *Biosyst. Eng.* 2010, 106, 423–432.

Charles, D.; Walker, A. Poultry Environment Problems: A Guide to Solutions, 1st ed.; Charles, D., Walker, A., Eds.; Nottingham University Press: Nottingham, UK, 2002.

Dascalaki, E.; Santamouris, S.; Argirou, A.; Helmis, C.; Asimakopoulos, D.N. On the combination of air velocity and flow measurements in single-sided natural configurations. *Energ. Buildings* 1996, 24, 155-165.

Dawkins, M.S.; Donnelly, C.A.; Jones, T.A. Chicken welfare is influenced more by housing conditions than stocking density. *Nature* 2004, 427, 342–344.

Fluent User's Guide, version 6.0; Fluent Inc.: Lebanon, NH, USA, 2001.

Gambit User's Guide, version 2.0; Fluent Inc.: Lebanon, NH, USA, 2001.

Launder, B.E.; Spalding, D.B. The numerical computation of turbulent flows. *Comput. Method. Appl. M.* 1974, 3, 269–289.

Lott, B.D.; Simmons, J.D.; May, J.D. Air velocity and high temperature effects on broiler performance. *Poultry Sci.* 1998, 77, 391–393**.**

May, J.D.; Lott, B.D.; Simmons, J.D. The effect of air velocity on broiler performance and feed and water consumption. *Poult. Sci.* 2000, 79, 1396–1400.

Mokhtarzadeh-Dehghan, M.R.; Telebany, M.M.M.E.L.; Reymonds, A.J. Transfer rates in single-sided ventilation. *Energ. Buildings* 1990, 37, 155-161.

Mostafa, E.; Lee, I.B.; Song, S.H.; Kwon, K.S.; Seo, I.H.; Hong, S.W.; Hwang, H.S.; Bitog, J.P.; Han, H.T. Computational fluid dynamics simulation of air temperature distribution inside broiler building fitted with duct ventilation system. *Biosyst. Eng.* 2012, 112, 293–303.

MWPS. Mechanical Ventilating Systems for Livestock Housing, 1st ed.; Midwest Plan Service, Iowa State University: Ames, IA, USA, 1990.

Norton, T.; Sun, D.; Grant, J.; Fallon, R.; Dodd, V. Applications of computational fluid dynamics (CFD) in the modeling and design of ventilation systems in the agricultural industry: A review. *Bioresour. Technol.* 2007, 98, 2386–2414.

Osorio, J.A.; Ferreira, I.F.; Oliveira, K.S.; Arêdes, M.; Oliveira, M. Modelling and experimental validation to estimate the energy balance for a poultry house with misting cooling. *Dyna* 2011, 78, 167–174.

Papakonstantinou, K.A.; Kiranoudis, C.T.; Markatos, N.C. Numerical simulation of air flow field in single-sided ventilated buildings. *Energ. Buildings* 2000, 33, 41-48.

Patankar, S.V. Numerical Heat Transfer and Fluid Flow; Hemisphere Publishing Corporation: Washington, WA, USA, 1980.

Pawar, S.R.; Cimbala, J.M.; Wheeler, E.F.; Lindberg, D.V. Analysis of poultry house ventilation using computational fluid dynamics. *Trans. ASABE* 2007, 50, 1373–1382.

SAS. SAS User’s Guide: Statistics, version 6.12; SAS Institute Inc.: Cary, NC, USA, 1998.

Sensortechnics Inc. Available on line: http://www.sensortechnics.com (accessed on 12 June 2015).

Serupa. Serupa France Webpage. Available online: http://www.serupa.fr (accessed on 12 June 2015).

Testo Inc. Homepage. Available online: http://www.testo.com (accessed on 12 June 2015).

Yanagi, T.; Xin, H.; Gates, R.S. A research facility for studying poultry responses to heat stress and its relief. *Appl. Eng. Agric.* 2002, 18, 255–260.

Yavah, S.; Straschnow, A.; Luger, D.; Shinder, D.; Tanny, J.; Cohen, S. Ventilation, sensible heat loss, broiler energy and water balance under harsh environmental conditions. *Poult. Sci.* 2004, 83, 253–258.

Warkup. Warkup Webpage. Available online: http://www.amwarkup.co.uk/single_sided_buildings.html (accessed on 12 June 2015).

Chapter 6

CFD applications in the heating and cooling systems of broiler houses: Designing a fogging system using CFD and sensors

An adapted version is submitted to an international journal indexed in Journal Citations Report.

Abstract: Modern broiler houses have different variants of geometrical designs and ventilation systems installed. A properly designed cooling system is crucial to optimise their indoor environments, especially in hot weather. Fogging systems are usually installed in these broilers houses and require comprehensive knowledge of the indoor air velocity profiles. This complete knowledge and behaviour is essential to optimise the location of the pipes and the orientation of the fog spray nozzles. CFD simulations can provide this in-depth information and contribute to the design. Although each broiler house model needs a different fogging system design, the protocol and steps described in this study can be extrapolated to other broiler house models. Finally, an estimation of the cooling system water consumption is proposed and performed.

Keywords: cooling, fogging systems, water-in-use, livestock buildings, broiler house, CFD.

6.1. Introduction

The use of water in livestock buildings is vital to meet the biological needs of the animals. On the other hand, water is also indispensable to develop associated key functions of the livestock buildings and installed devices. In terms of installed devices and essential functions of these buildings, the heating and cooling systems are indispensable to ensure suitable indoor microclimate and psychometric conditions. Moreover, intensive animal production nowadays generally involves confining the animals in specific and technologically complex livestock buildings. Moreover, modern broiler houses usually install mechanical ventilation under negative pressure systems (Charles *et al.*, 2002; MWPS, 1990).

Livestock building cooling systems need an important amount of water to operate and their design and consumption must be optimised using current scientific procedures. In this sense, Computational Fluid Dynamics (CFD) can help in the general design and geometry of agricultural buildings (greenhouses or livestock facilities) (Bustamante *et al.*, 2013; Mistriotis *et al.*, 1997; Norton *et al.*, 2007). These CFD techniques can also help in specific parts of the building design, such as the heating and cooling systems. In the case of heating systems, CFD techniques can incorporate the radiators or heat surfaces (Sevilgen *et al.*, 2011; Zajicek *et al.*, 2014) in their simulations. For cooling systems, they can include analysis of the pad cooling (Franco *et al.*, 2011) or fogging systems (Kim *et al.*, 2008).

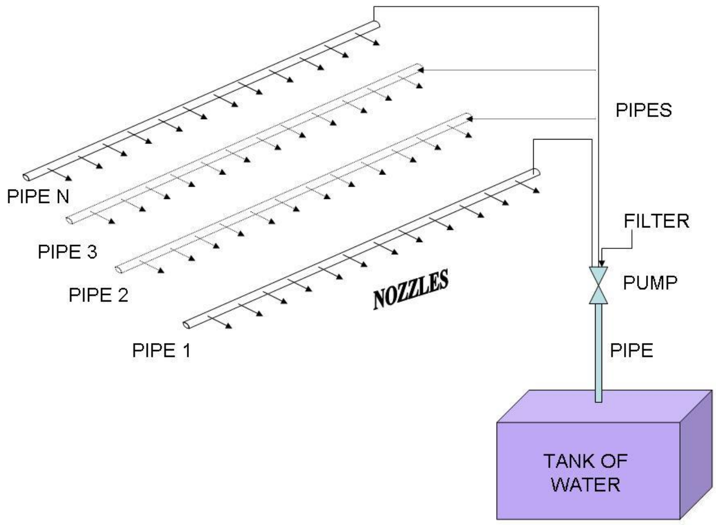
Among livestock buildings, broiler houses are of great interest in terms of production and economic significance. Poultry production for meat (broilers) is a crucial food sector, with a total world production of 92,811,674 tonnes in 2012 alone (FAO, 2015). In this sense, a well-designed heating (for winter or cold weather) or cooling system (for summer or hot weather) is crucial to optimise animal production in modern broiler houses. Heating systems are required in cold weather, being especially necessary when the animals are younger and in the case of featherless birds. On the other hand, cooling systems are required in hot weather, developing two main variants: (i) use of pad cooling; (ii) use of fogging systems or nebulisation. However, in some discrete cases, both variants (pad cooling and fogging systems) may coexist in the same livestock building.

The main purpose of cooling is to diminish the internal heat of the building (and therefore, the heat of the animals) to decrease the thermal stress on the animals. In some cases of medium-low temperature, an increase in air velocity is all that is required to increase the convective flux rate of the broilers and thereby reduce their thermal stress. However, if the temperatures are high, the assistance of the cooling systems is necessary because the increase in air velocity alone is not enough to adjust the thermoregulation of the broilers.

Moreover, bad indoor conditions such as high temperatures cause physiological responses including animal depression, exhaustion, a decrease in feed consumption and an increase in mortality (Donkoh, 1989; European Union Report, 2000). In these adverse conditions, the final weight of the broiler will decrease and it will be necessary to extend the rearing time in the broiler house to achieve the desired final weight of the broilers, involving an increase in costs and resources such as feed, water, electricity, human resources...

As there is no single model for broiler building geometry and the ventilation possibilities can vary greatly, the design of the location of the pipes and the orientation of the fogging system nozzles will change. However, we can find minimum elements of any fogging system common to all broiler buildings: a water tank, a pump, filters, pipes and nozzles. Figure 6.1 shows the schematic of a fogging system in a broiler building.

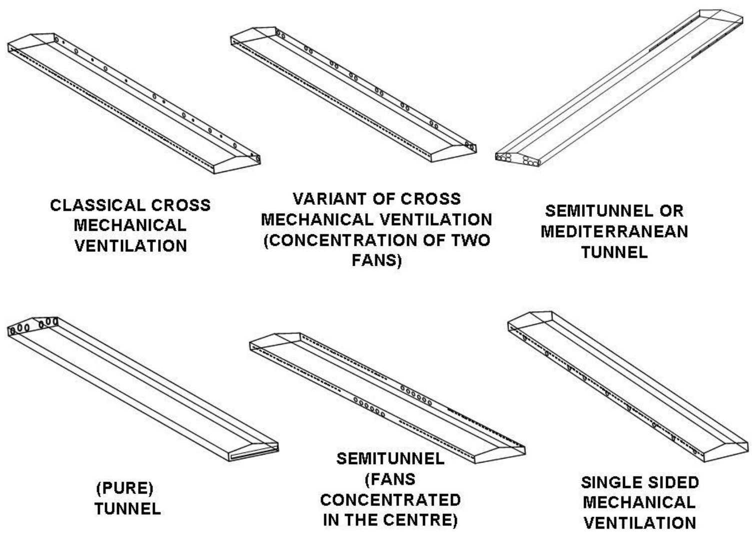
Figure 6.1. *Minimum elements of a fogging system in a broiler building.*



The pump drives the water from the tank to the pipes (generally stainless steel) and the fog spray nozzles are located in these pipes. The fog spray nozzles expel the water in droplets of different size (diameter) according to the nature of the nozzles and the water pressure. This process is also called “nebulisation” and the greater the pressure, the smaller the droplets will be, in order of microns (generally between 10-20 microns) (Li *et al.*, 2008). It is essential to control the diameter of the water droplets, because if they are large they will drip down and soak the litter in the broiler building. This excess humidity in the litter could provoke sanitary problems and corns may also appear on the feet of the broilers, decreasing the quality of their meat (Almeida *et al.*, 2010; Ross Breeders, 1996). Comprehensive knowledge of the indoor air velocities (magnitude and direction) is crucial for the best design of the localisation of the pipes and the orientation of the fog spray nozzles when expelling water. To this end, CFD techniques provide this complete information. Obviously, direct measurements provide only some points of knowledge (the physical sensors), but it is necessary to validate the CFD outcomes to be able to use the numerical results reliably. Of course, Verification and Validation (V&V) of CFD results is crucial in these studies (Oberkampf *et al.*, 2002). To this end and for broiler houses, we validated the CFD results for air velocity in a previous article (Bustamante *et al.*, 2015 -chapter 4-) using a multi-sensor isotemporal system (Bustamante *et al.*, 2012). For these reasons and in this article, we use the same CFD procedures as in Bustamante *et al.*, 2015 (chapter 4), but focused on these particular needs.

The different variants of broiler building geometries and the different mechanical ventilation systems installed are a great drawback. Thus, there is no single optimum design for a fogging system, as the broiler buildings are different. Each broiler building model needs to be analysed separately, because the nature of the indoor air velocity can be different. Figure 6.2 shows some variant broiler building designs and the mechanical ventilation system installed: transversal ventilation (cross and single-sided), semi-tunnel or Mediterranean tunnel, (pure) tunnel....

Figure 6.2. *Some broiler building design variants. Mechanical ventilation systems installed.*



Although each broiler building model needs to be analysed separately, the protocol for their study will be the same; i.e., implementing the use of CFD techniques to understand the full behaviour of the indoor air velocity and then, to determine the best location of the pipes and orientation of the nozzles. Of course, some models may be more or less complicated depending on the nature of the indoor air velocity profiles.

To sum up, in this study we focused on the design of the fogging systems, especially on the best geometrical disposition of the pipes and orientation of the fog spray nozzles. Finally, we calculated the water in use during a fogging period in order to estimate future consumption and maintenance procedures. In the present study, we experimented in a broiler building with mechanical tunnel ventilation under a negative pressure system described in depth in chapter 4 with very different indoor air velocity behaviour. Nevertheless, the protocol and procedures described in this study can be applied to any broiler house model.

6.2. Materials and Methods

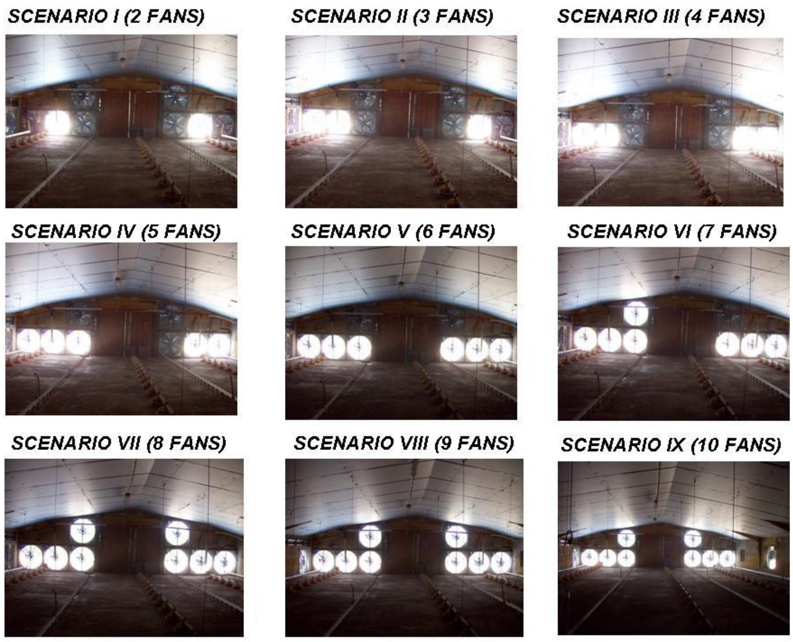
6.2.1. The building

In this study, we designed the location of the fogging system pipes and orientation of the nozzles of an important broiler house model: the Mediterranean tunnel or semi-tunnel. The geometry of this broiler house model appears in the upper right corner of Figure 6.2. The experimental broiler building is located in the Valencian Community (Spain) and is described in depth in chapter 4. Main dimensions were: length, 120 metres; width, 12.2 metres; sidewall height 2.2 metres; double pitched roof (slope 21.3 %). Ten exhaust fans 1.28 metres in diameter were installed. Eight exhaust fans were located on one façade (main façade) and the other two exhaust fans on the lateral façade, one fan on each lateral, near those located on the main facade of fans, as shown in the upper right corner of Figure 6.2. The broiler building was also equipped with twelve inlets of dimensions 4.7x0.45 metres placed at 0.3 metres height, controlled by an automatic system of two groups of six inlets located in the lateral walls; all inlets were located near the opposite façade of fans.

6.2.2. Scenarios and field experimentation

The combination of scenarios (fans in action) can be huge. However, we analysed an important number of scenarios that provide enough significant knowledge of the behaviour of the indoor air velocity characteristics (magnitude and direction) to successfully pursue our objective. In this study, we analysed nine typical settings, the same scenarios described in chapter 4. Initially, we started up the fans nearest the floor, followed by the fans farthest from the floor and, finally, the fans located on the lateral walls. In scenario I, two fans were run at first, gradually adding one fan at a time until all eight fans on the main façade were on (scenario VII). Finally, the two lateral wall fans were also in action (scenario IX). Figure 6.3 shows an illustrative summary of the nine scenarios analysed.

Figure 6.3. *Fans in action. Summary of scenarios.*



6.2.3. Instrumentation and measurements

For the needs of this study, we used different types of instrumentation depending on the specific requirements:

a) A multi-sensor system to measure the indoor air velocity values at different locations (this system has 30 physical sensors of air velocity measuring in isotemporal regime). These measurements were used to perform the validation of CFD results carried out and described in depth in chapter 4.

b) Three 425 Testo hot-wire anemometers (Testo, 2015) for discrete measurements such as the air velocity at the inlets (windows) and the air velocity at the fog spray nozzles after design and construction of the fogging system.

c) Two 2000 mL graduated test-tubes to measure the water expelled by some fog spray nozzles (the same nozzles at which we measure the air velocity by means of anemometers).

6.2.4. CFD techniques and General Validation

CFD techniques can be used to explore "virtual geometries" to construct new broiler buildings or to retrofit those already built to achieve greater efficiency (by retrofitting new walls, changing the slope of the roof, installing of new equipment…). CFD is already used to study indoor environments of poultry farms (Blanes-Vidal *et al.*, 2008; Bustamante *et al.*, 2013; 2015; Mostafa *et al.*, 2012, Norton *et al.*, 2007; Osorio *et al.*, 2011). Obviously, validation of CFD is mandatory for this exploration, to ensure that the numerical results are valid and accurate. Likewise, it is also necessary to validate the procedures applied (Boundary Conditions adopted, protocol to obtain grid independence…). In chapter 4, we validated the CFD simulations of air velocity corresponding to the scenarios in the present study. For the needs of this study, we performed the CFD simulations of these scenarios and chose the best location for pipes based on these numerical simulations, which provide ample information on the indoor air velocity (magnitude and orientation). Then, we distributed the fog spray nozzles evenly along the pipes, orienting the direction of the water expelled from these nozzles, taking the magnitude and orientation of this air velocity into account. In CFD, we introduced the pipe coordinates (lines in CFD) and the coordinates of the fog spray nozzles to obtain these magnitudes and components (x, y and z) of the air velocity vectors.

Although CFD procedures are described in depth in chapter 4, we summarise these CFD procedures here:

a) We used the CFD commercial software Fluent (Fluent, 2001) and Gambit (Gambit, 2001). In the pre-processor of Fluent (Gambit) (Gambit, 2001), we created the broiler building geometry and the mesh.

b) We studied the mesh sensitivity (grid independence) in a convergence test study. In this way, increasing the refinement of the mesh, we achieved stability of the numerical results in meshed of roughly 3,6 millions of cells.

c) We used the same Boundary Conditions (BCs) and the same protocols to obtain these BCs for the inlets and outlets (fans). Hot-wire anemometry by means of Testo anemometers (Testo, 2015), the procedures of Calvet *et al.*, 2010 to measure the airflow at fans and the differential pressure sensors described in Bustamante *et al.*, 2012 to measure this parameter at fans.

d) We used the same turbulence model (RNG k-ε turbulence model) and wall functions (Patankar, 1980).
e) Pressure and velocity were linked using the SIMPLE algorithm (Fluent, 2001) as well as the second order upwind scheme (Patankar, 1980).
f) The air was considered steady, three-dimensional, viscous, turbulent and incompressible. Thus, the air properties are considered constants.
In chapter 4, we validated the CFD simulations, concluding that there was no difference between the use of CFD or direct measurements by means of a multi-sensor system designed for online measurements in broiler houses.

6.2.4.1. CFD-isosurfaces

In CFD, we can use interesting strategies with illustrative outputs that quickly show the general trends of the indoor air velocity. In this way, we can create isosurfaces. An isosurface is a surface that connects points of equal nature. In our case, we can create planes of interest in some strategic locations in the broiler building. Thus, we can create transversal isosurfaces (planes) at the different transversal sections of the broiler building. On the other side, we can create other planes at different level of height from the floor (among others, the main interesting sections are the plane at broiler level and at the level of the sidewall - fog spray nozzle height -). In those isosurfaces which show the air velocity parameter, we can incorporate the colour scale and use of vectors.

6.2.4.2. CFD-air velocity at fog spray nozzles and pipes

In CFD, we can also create points and lines that represent the fog spray nozzles and pipes, respectively. By this strategy, we can obtain the CFD numerical results at the fog spray nozzles and at the pipes. As mentioned previously, it is crucial to know the air velocity characteristics; in our case, the magnitude and the direction or vector components (the main component of air velocity: in the three axes -X, Y or Z-) in order to best orient the fog spray nozzles when expelling water inside the broiler building. CFD Fluent (Fluent, 2001) provides the values of the air velocity in the different axes (v_x, v_y and v_z). Of course, it is also important to know the air velocity value in the fog spray nozzle in order to determine whether this air velocity can assist the trajectory of the expelled water.
In addition, using the "Area Weighted Average" command of Fluent (Fluent, 2001), we can determine the average air velocity in the whole pipe (line). To do so in Fluent (Fluent, 2001), we simply enter the coordinates of the line (pipe) corresponding to the physical pipe.

6.2.5. Testing the final fogging system design. Additional CFD Validation

6.2.5.1. Testing the nozzles and determining the water in use in the fogging system

After designing the fogging system and before its current use, we perform a final check. This final check consists of:

(i) A visual inspection of the fogging system in operation. Before the current use in the broiler building with the birds, we start up the fogging system. This way, we can check that the nozzles expel water, as in some cases they may be blocked or not working properly. In this step, we check that they expel water and the orientation of the expelled water.

(ii) By means of the graduated test-tubes (of 2000 mL), we estimate the exact amount of water expelled by each fog spray nozzle. In a broiler building, the number of nozzles is usually high and after an initial positive visual inspection (if they are not obstructed), we measure the exact quantity of expelled water. To do so, we place the graduated test-tube inside the fog spray nozzle and without losing any expelled droplets, we estimate the quantity of water in the graduated test-tube. In this experiment, we calculate the amount of water expelled over a 12 minute period.

By this procedure, testing a set number of fog spray nozzles; e.g. analysing 3 nozzles per pipe (at the beginning, middle and end of the pipe), we obtain the minimum sample size with information and standard error and a % of confidence interval. The overall quantity of water in the cooling period in the broiler house will be the quantity of water from each fog spray nozzle by the total number of nozzles. As the fog spray nozzles share the same characteristics, in normal conditions (if the cooling system works well) each fog spray nozzle must expel the same quantity of water. In the present study, the expelled water will be measured in the same nozzles in which the air velocity is measured by means of the hot-wire anemometers.

6.2.5.2. Additional CFD Validation. Comparing CFD air velocity results with direct measurements at nozzles

Although we performed a general validation of the CFD results described in depth (chapter 4) and the entire CFD air velocity results are justified for the whole indoor space of the broiler building, we also deployed an additional and specific final validation at some key points, such as the location of the nozzles. As commented above, a typical broiler building usually contains a huge number of nozzles. For this reason, only in some discrete nozzles (in this case, in the same nozzles used to measure the expelled water), we shall measure the air velocity using three calibrated 425 Testo hot-wire anemometers (Testo, 2015). The protocol to measure air velocity at fog spray nozzles is very easy and rudimentary, using the shape of the fog spray nozzles and the pipe. Using wire, adhesive tape and brackets, we hang the three hot-wire anemometers up to measure for 20 minutes in each scenario. To save time, we keep the three anemometers in these fog spray nozzles and so can easily change the scenario from the PC in the control room. We repeat this procedure (hang and fasten the three anemometers in the fog spray nozzles) each time, changing the scenarios until a set number of nozzles (the sample size) has been studied. We follow this protocol when the nozzles are not expelling water.

Using the CFD results and these measurements with the anemometers, a lineal regression will be performed. This lineal regression model is in the form (Equation 6.1):

$$V_{CFD} = \alpha + \beta \times V_{meas} \tag{6.1}$$

where,

α is the dependent term

β is the independent term

V_{meas} is the measured air velocity using the hot-wire anemometers

V_{CFD} is the air velocity obtained in the CFD simulations

Additionally, we shall calculate the relative error of air velocity (E_{Vel_i}) in each fog spray nozzle (Equation (6.2)),

$$E_{Vel\_i} = \frac{V_{meas} - V_{CFD}}{V_{meas}} \tag{6.2}$$

6.2.5.3. Number of fog spray nozzles tested. Sample size in finite populations

The total number of fog spray nozzles in a broiler building is high. To test them in their entirety is impractical. Of course, a visual inspection of the fogging system can determine if the whole array expels more or less water. If one fog spray nozzle is blocked by the limes or impurities, it is easily noticeable. However, the exact quantity of expelled water due to partial obstructions or minor technical deficiencies in the nozzle is difficult to discover, due to the large number of nozzles. For this reason, from the total of fog spray nozzles, we studied a determinate number of nozzles.

In this study, we test key locations of the nozzles in the pipes: near the beginning of the pipe, in the middle and near of the end of the pipe. In a scientific approach, we can translate this into statistical terms: the number of nozzles studied can represent the minimum sample size of a finite population with information with a standard error in a confidence interval. For this aim, Equations 6.3 and 6.4 can be used to find this minimum sample size with a standard error in a confidence interval.

$$n = \frac{n'}{1 + \frac{n'}{N}} \tag{6.3}$$

$$n' = \frac{s^2}{\sigma^2} \tag{6.4}$$

Where,
n is the number of studied fog spray nozzles that represents the minimum sample size
N is the total of the fog spray nozzles
n' is the initial minimum sample size
s is the sample standard deviation
σ is the population standard deviation
Moreover, the relation between σ^2 and the standard error is (Equation 6.5):

$$\sigma^2 = (\text{standard error})^2 \tag{6.5}$$

Additionally, the relation between s^2 and the confidence interval is (Equation 6.6):

$$s^2 = p(1-p) \tag{6.6}$$

Where,
p is the confidence interval
In this study, we choose a confidence interval of 95 % (0.95).

6.3. Results

6.3.1. CFD isosurfaces

In this type of Mediterranean tunnel broiler houses, we found three different indoor behaviours of air velocity: near inlets, near fans and a central zone (chapter 4). Near inlets, the air enters and rises to the roof of the broiler house. The air velocity vectors are mainly oriented to the roof and sense to the centre of the broiler house, describing circuits. In Figure 6.4, we can see these air velocity circuits and the mentioned effect. However, at the end of the inlets area, the trajectories of the air velocity change, now being oriented in the longitudinal sense in direction to the fans. If the high fans are not in action, homogeneity in air velocity values is achieved in the central area and fans area at the plane of the sidewall height (Z=2.20 m), as we can see in Figure 6.5, which depicts a typical scenario with 5 fans in action (scenario IV). However, in scenarios with more fans in action, and especially when the high fans are in action, high air velocities are found near the fans area, as we concluded in chapter 4.

Figure 6.4. *Air velocity vectors (in m s^{-1}) in a transversal section (plane X=15 m) at the inlets area. Circuits of air velocity.*

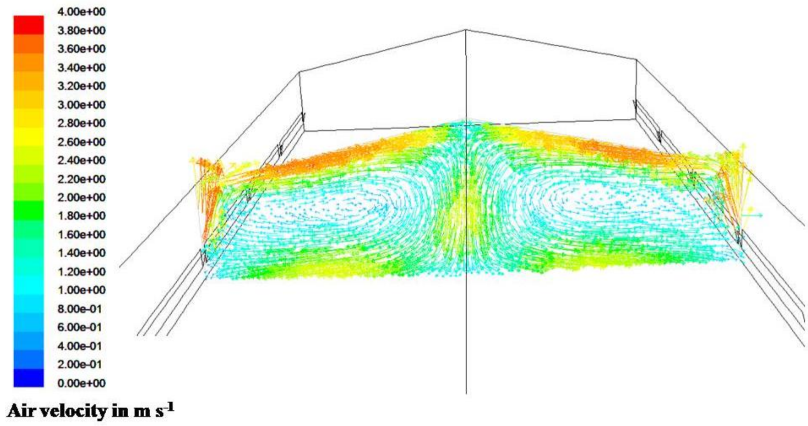
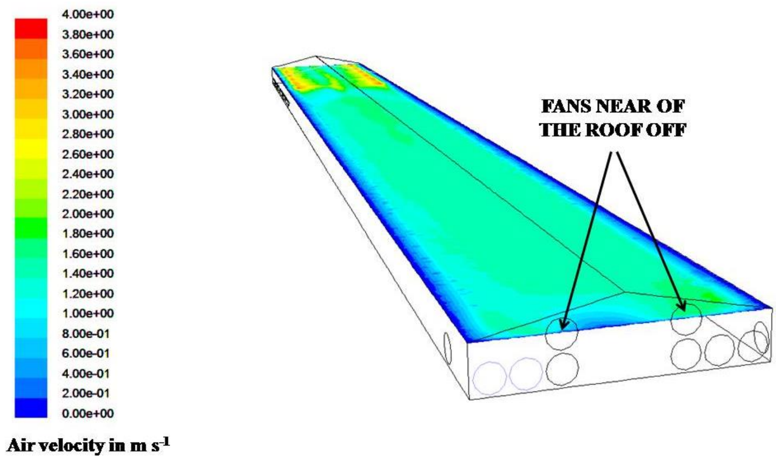
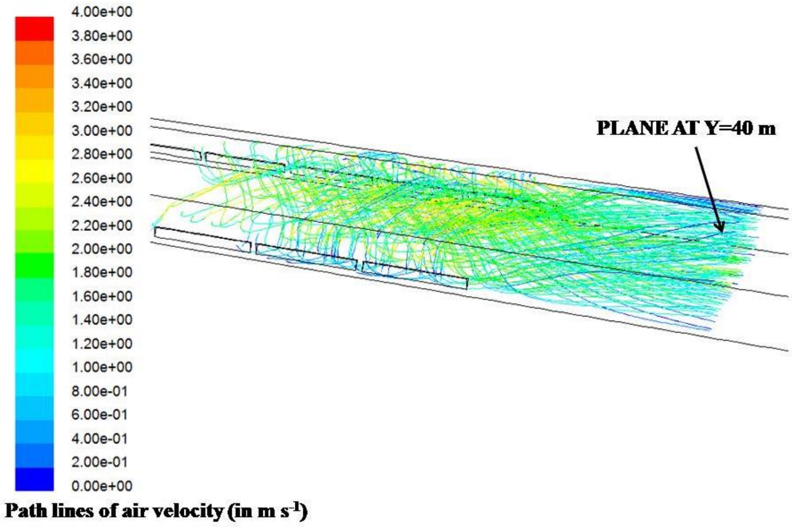


Figure 6.5. *Air velocity (in m s^{-1}) at the plane at the height of the sidewall (Plane Z=2.20m).*



When the inlets area finishes, the air velocity vectors gradually change orientation, becoming more oriented towards the fans. In Figure 6.6, we can see this effect in the path lines of air velocity and the curvature that it describes, showing this changing from transversal components (to the centre of the building) to longitudinal components oriented towards the fans. Approximately, in the transversal plane Y = 40 m, the main component of air velocity in all scenarios is v_y (longitudinal sense with sense to the fans).

Figure 6.6. *Air velocity path lines (in m s^{-1}) changing the air velocity orientation. Scenario IV (5 fans in action).*



6.3.2. Location of pipes and nozzle orientation

According to the nature of the indoor air velocity and the CFD outputs, we proposed this pipe layout:

We placed a first pipe (Pipe 1) at the height of the sidewall (Z=2.20 m) parallel to the longitudinal axis of the broiler house (parallel to the lateral wall of inlets), with the fog spray nozzles oriented in horizontal sense to the centre of the broiler house.

We installed a second pipe (Pipe 2) at the height of the sidewall (Z=2.20 m) parallel to the longitudinal axis of the broiler house (parallel to the lateral wall of inlets), with the nozzles oriented in horizontal sense to the centre of the broiler house.

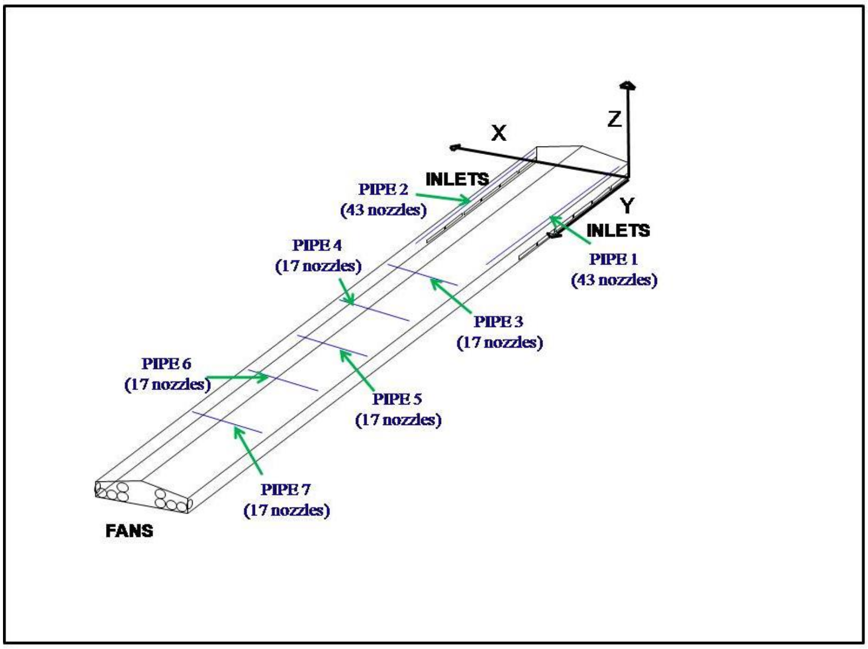
We put five pipes at the height of the sidewall (Z=2.20 metres) perpendicular to the longitudinal axis of the broiler house, with the nozzles oriented in horizontal sense to the fans. These five pipes are equidistant from each other. According to the possible high air velocity values near fans, the pipe (Pipe 7) closest to the fans is slightly more separate from the fans to prevent water seeping through from outside or damp affecting the fans (causing breakdown in electric circuits, rusting…).

Approximately 50% of the fog spray nozzles, i.e., half of the cooling system output, will be located in the two pipes of the inlets section. The other 50% of the fog spray nozzles are located in the other 5 transversal pipes. All nozzles are equally distributed on all the pipes at a distance of 0.70 metres.

In Pipe 1, we find 43 nozzles, In Pipe 2, another 43 nozzles, and Pipes 3, 4, 5, 6 have 17 nozzles each. Pipe 1 and Pipe 2 have 86 nozzles and Pipe 3. 4, 5, 6 and 7 have 85 nozzles. This cooling system design comprises a total of 7 pipes and 171 nozzles, as shown in Figure 6.7.

Although one only stopcock could be used for the all the pipes, it is better to use seven stopcocks, as the economic cost and human effort involved in installing one stopcock in each pipe is minimal. This way, each pipe has its own stopcock, so can be more easily controlled, avoiding the use of one or several pipes during the cooling period; for example, in the event of unexpected occasional escapes in one pipe. This way, the rest of the pipes can work to keep the cooling system going. Figure 6.7 shows the broiler building and the pipes proposed.

Figure 6.7. *Broiler building, pipes and nozzles.*



Moreover, in Table 6.1, we indicated the coordinates of the lines and the number of fog spray nozzles in each pipe (line).

Table 6.1. *Coordinates of pipes (lines in CFD) and number of nozzles.*

Pipe number	***(0)_Coordinates(0)***			***(1)_Coordinates***			***Number of nozzles in each pipe***
	X_0	Y_0	Z_0	X_1	Y_1	Z_1	
1	0.30	0.70	2.20	0.30	30.10	2.20	43
2	11.90	0.70	2.20	11.90	30.10	2.20	43
3	0.50	40.00	2.20	11.90	40.00	2.20	17
4	0.50	55.00	2.20	11.70	55.00	2.20	17
5	0.50	70.00	2.20	11.70	70.00	2.20	17
6	0.50	85.00	2.20	11.70	85.00	2.20	17
7	0.50	100.00	2.20	11.70	100.00	2.20	17

6.3.3. CFD-air velocity at the fog spray nozzles (points) and at pipes (lines)

As the whole validation for the entire broiler house is performed in chapter 4, another test or set of measurements would be not compulsory. However, as we want to study the expelled water in some fog spray nozzles, we can also easily measure the air velocity at these nozzles when they are not expelling water. Table 6.2 shows the coordinates of these fog spray nozzles studied and the pipe where they are located (3 by pipe).

Table 6.2. *Studied 21 fog spray nozzles in the pipes. Orientation in design.*

Nozzle Number	***Pipe***	***X-Coord (in m)***	***Y-Coord (in m)***	***Z-Coord (in m)***	***Main component of air velocity (v_x,v_y,v_z)***	***Orientation of the nozzle***
1	1	0.30	2.80	2.20	+v_x	+X

2	1	0.30	15.40	2.20	$+v_x$	+X
3	1	0.30	28.00	2.20	$+v_x$	+X
4	2	11.90	2.80	2.20	$-v_x$	-X
5	2	11.90	15.40	2.20	$-v_x$	-X
6	2	11.90	28.00	2.20	$-v_x$	-X
7	3	1.90	40.00	2.20	$+v_y$	+Y
8	3	6.10	40.00	2.20	$+v_y$	+Y
9	3	11.00	40.00	2.20	$+v_y$	+Y
10	4	1.90	55.00	2.20	$+v_y$	+Y
11	4	6.10	55.00	2.20	$+v_y$	+Y
12	4	11.00	55.00	2.20	$+v_y$	+Y
13	5	1.90	70.00	2.20	$+v_y$	+Y
14	5	6.10	70.00	2.20	$+v_y$	+Y
15	5	11.00	70.00	2.20	$+v_y$	+Y
16	6	1.90	85.00	2.20	$+v_y$	+Y
17	6	6.10	85.00	2.20	$+v_y$	+Y
18	6	11.00	85.00	2.20	$+v_y$	+Y
19	7	1.90	100.00	2.20	$+v_y$	+Y
20	7	6.10	100.00	2.20	$+v_y$	+Y
21	7	11.00	100.00	2.20	$+v_y$	+Y

The study of 21 fog spray nozzles of the total 171 nozzles represents the minimum sample size with information with a standard error less than 0.045 in 95% of the confidence interval.

As the standard error is 0.045, from the Equation 6.5:

$$\sigma^2 = 0.045^2 = 2.025\cdot 10^{-3} \qquad (6.7)$$

As we choose a 95% of the confidence interval, from the Equation 6.6:

$$s^2 = 0.95(1-0.95) = 0.0475 \quad (6.8)$$

Substituting in Equation (6.4):

$$n' = \frac{s^2}{\sigma^2} = \frac{0.0475}{2.025 \cdot 10^{-3}} = 23.456 \quad (6.9)$$

As, N = 171 (the total of the fog spray nozzles),
Substituting in Equation (6.3):

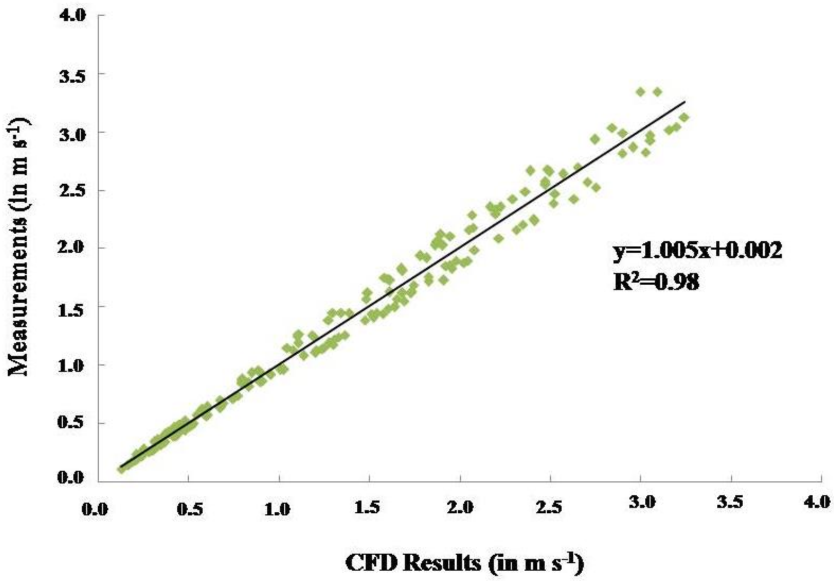
$$n = \frac{n'}{1+\frac{n'}{N}} = \frac{23.456}{1+\frac{23.456}{171}} = 20.63 \approx 21 \text{ fog spray nozzles} \quad (6.10)$$

Thus, studying 21 fog spray nozzles, we have the minimum sample size with information with a standard error less than 0.045 in a 95% of confidence interval.

6.3.4. Regression line of CFD-air velocity results and measurements in the studied fog spray nozzles

The lineal regression (Equation 6.1) in the 184 studied points (21 points x 9 scenarios) shows a good fit. The coefficient of determination of the linear regression was 0.98 (Figure 6.8).

Figure 6.8. *Regression line of CFD results vs. measurements in the 184 points studied.*



The whole results show a good fit, as observed in Figure 6.8. However, we found some important relative errors. Table 6.3 shows the minimum and maximum relative error in each scenario.

Table 6.3. *Minimum and maximum relative error (in %) in each scenario.*

Scenario	***I***	***II***	***III***	***IV***	***V***	***VI***	***VII***	***VIII***	***IX***
Max. error (%)	7.61	6.52	7.77	8.95	6.98	7.13	8.45	11.29	10.43
Min. error (%)	-12.02	-11.20	-14.72	-13.88	-11.51	-11.52	-8.96	-11.95	-12.11

Moreover, using the "Area Weighted Average" command of Fluent (Fluent, 2001), we obtained the average air velocity at each pipe and in each scenario (Table 6.4).

Table 6.4. *Air velocity (in m s^{-1}) in each pipe and at each scenario using the "Area Weighted Average" command of Fluent.*

Pipe number	**Scenario**								
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**
1	0.802	1.239	1.646	1.807	1.977	2.096	2.251	2.322	2.485
2	0.774	1.140	1.545	1.706	1.879	1.996	2.143	2.132	2.328
3	0.546	0.788	1.281	1.349	1.626	1.915	2.207	2.661	2.995
4	0.586	0.873	1.123	1.455	1.749	2.047	2.335	2.517	2.778
5	0.588	0.880	1.157	1.468	1.739	2.050	2.330	2.636	2.926
6	0.581	0.869	1.153	1.455	1.730	2.022	2.309	2.615	2.927

7	0.582	0.870	1.157	1.455	1.746	2.044	2.335	2.609	2.934
Average of all pipes	0.746	1.123	1.511	1.693	1.885	2.040	2.217	2.304	2.502

6.3.5. Water used in fogging system

Using graduated test tubes, we collected and measured the amount of water expelled in 12 min in a cooling system at 80 bar operating pressure, obtaining a value of 1601.90 ±20 mL. As 12 minutes is a fifth of one hour, the expelled water in one hour is 1601.90 x 5= 8009.52 mL ~ 8010 mL (8.01 l). As the number of fog spray nozzles is 171, the total water in use in one hour is (8.01 l x 171 fog spray nozzles =) 1369.71 l.
Thus, the whole cooling system consumption is 1369.71 l h^{-1}.

6.4. Discussion

The indoor air velocity profiles are crucial in the best location of the pipes and orientation of the fog spray nozzles in a fogging system. However, we can find different geometrical models of broilers buildings and installed ventilation systems. Thus, the cooling design will change, although the protocol to determine the optimum will be the same: the use of CFD simulations that provide full information on the indoor air velocity profiles (especially magnitude and components). In the experimental Mediterranean tunnel broiler house, we found three important different indoor behaviours: near inlets, near fans and central area (chapter 4). According to the present study, the pipes in the inlets area must be located at the height of the sidewall (Z=2.20 m) parallel to the lateral walls of inlets, with the fog spray nozzles oriented in horizontal sense to the centre of the broiler house. In Figure 6.4, we can see the air velocity circuits to support this decision on the location of pipes and orientation of the fog spray nozzles. We installed two pipes, one pipe on each lateral wall, and 50 % of the fog spray nozzles (i.e. the half of the cooling system) in this crucial area, where all the air enters the broiler building. The air velocity circuits assist the trajectory of the expelled water to the centre of the broiler building with a slight tendency to rise towards the roof (due to the elliptic shape of the air velocity circuits shown in Figure 6.4) without soaking.
According to Figure 6.6, the main air velocity component changes from transversal to longitudinal with sense to the fans when the area of inlets ends. In this Figure 6.6 and at the

plane Y = 40 m, the main component of the air velocity is already $+v_y$. Thus, when the inlets area ends, we change the layout of the pipes and place the first of the transversal pipes at the plane Y = 40 m. In addition, Table 6.2 shows the main component of the air velocity obtained in the CFD simulations (v_x, v_y or v_z) to support this disposition of pipes and orientation of the fog spray nozzles. The air velocity of the central area and fans' area helps in the trajectory of the expelled water with sense to the fans. Figure 6.5 shows a typical scenario with 5 fans in action (scenario IV). However, in scenarios with more fans in action and especially when the high fans are in action, high air velocities are found near the fans area, as we concluded in chapter 4. High fans can be activated in hot weather and to assist the whole indoor air movement during the cooling time, increasing this described phenomenon. For this reason, the last pipe (the Pipe 7, the closest to the fans) is kept slightly more separate from the fans, to avoid water coming through from outside or damp reaching the fans (causing breakdown in electric circuit, rusting of the metallic pieces of the fans…).

All the fog spray nozzles are separated the same distance (0.70 metres in this study) from the pipe, because the "spray" phenomenon is the same in all cases, and only depends on the cooling system operating pressure (80 bar in this study) and the type of fog spray nozzle (these fog spray nozzles are commercial and designed by a company that builds them specifically for broiler houses and recommends this distance and this operating pressure).

The cooling system is equilibrated, as 50 % of the fog spray nozzles are in the inlets area through which all the air enters and the other 50 % of the fog spray nozzles are in the rest of the broiler building. The designed system consists of a total of 7 pipes and 171 fog spray nozzles. Figure 6.7 summarises this proposed fogging system, Table 6.1 shows the pipe coordinates (lines in CFD) and Table 6.2 the 21 studied fog spray nozzles. In CFD, we can create points that represent the nozzles or lines that represent the pipes simply by entering their coordinates in CFD (Table 6.1 and 6.2). This is a powerful tool to determine the magnitude and components of the air velocity, knowledge indispensable for optimal design of the fogging system. A whole validation is performed in chapter 4; nevertheless, we perform a final validation in a determinate number of nozzles. Of course, to study the total fog spray nozzles in a broiler house would be impractical and it is necessary to determine a size. In this study, we study three nozzles per pipe (one nozzle near the beginning of the pipe, near the end and in the middle of the pipe). As we have 7 pipes, we study 21 fog spray nozzles, i.e. 12.28 % of the total 171 fog spray nozzles. According to the formulation of the sample size in a finite population (Equation 6.3 and 6.4), this number of fog spray nozzles represents the minimum sample size with information with a standard error less than 0.045 in a 95% of the confidence interval.

The use of the "Area Weighted Average" command of Fluent (Fluent, 2001) is very interesting. By this validated command, because we have validated the whole CFD space in chapter 4, we can determine the average air velocity in the whole pipe in each scenario, as shown in Table 6.4. This command of Fluent (Fluent, 2001) is very interesting to ascertain the whole air velocity profiles by means of virtual CFD broiler buildings that also incorporate virtual designs of fogging systems. In this study, the ranges of values are wide (from 0.746 m s^{-1} to 2.502 m s^{-1} on average from all lines at each scenario). The minimum air velocity (0.546 m s^{-1}) is obtained in scenario I in pipe 3, and the maximum air velocity (2.995 m s^{-1}) is obtained in scenario IX in pipe 3.

Using three Testo hot-wire anemometers (Testo, 2015), we measured the air velocity values for 20 minutes in each fog spray nozzle. This procedure may be unnecessary, as the whole space was validated in chapter 4. However, we wanted to perform this final validation. The regression line shows a good fit similar to that obtained with the multi-sensor system. Of course, we use calibrated anemometers and the same hot anemometry principles as Blanes-Vidal *et al.*, 2008 and Bustamante *et al.*, 2012. Whereas it took four people four entire days to install and measure just at the 21 points (nozzles), measuring using the multi-sensor system at the level of broilers is very easy in terms of time and minimum human resources (using the multi sensor system we can measure more points and scenarios in only one morning or a single day, with minimal human resources-one or two people maximum-). It is true that taking measurements in the fog spray nozzle is complicated due to their location, calling for rudimentary and intuitive procedures (using wire, adhesive tape and brackets, we hang the three hot-wire anemometers following the shape of the nozzle and pipe…). We also spent 20 minutes on each three measurements per scenario when with the multi-sensor system we took only half the time (10 minutes) for thirty indoor measurements. We use three measurements per time because Blanes-Vidal *et al.*, 2008 use isotemporal three measurements per time with a good CFD validation; besides, we have a limited number of hot-wire anemometers and human resources (operators). The regression shows a good fit with similar results as in chapter 4 with relevant relative errors as shown in Table 6.3. Of course, the multi-sensor system (Bustamante *et al.*, 2012) is also based on hot-wire anemometry principles, but measuring isotemporally with more sensors (30 sensors, i.e., multiplying by ten the field measurements of the present study). For this reason, we want to increase the quality of the measurements, extending the measuring time 100% (20 minutes). We recall that Blanes-Vidal *et al.*, 2008 measured isotemporally in three points using a sensor system that uses hot-wire anemometry principles with good results in a difficult place (at the level of the broilers). Although we used three people to measure and control the hot-wire anemometers (and the fourth person to monitor the control room PC and fans in action), the average height of these people is about 1.70 metres, whereas the fog spray nozzles are located at 2.20 metres from the floor (0.50 metres distance over their heads). It is true that operators inside the broiler building can disturb the measurements, but the people remain still in their place and the disturbance is minimal, because the measurements are not at the level of the broilers and in the surroundings of their legs; the measurements are over their heads at sufficient distance (0.50 metres approx.). Moreover, the location of the fog spray nozzles leads to better numerical results there than the numerical results in locations very near the floor, such as from the sensors at the broiler level. Thus, in chapter 4, an equal roughness (0.5) was assumed for the whole floor of the broiler building and this is an approximation that can affect the numerical results near the floor (the numerical results at the level of the broiler), because it is an assumption. Besides, to obtain good numerical results near the floor we need to be able to solve the boundary layer problem by means of good and precise meshed, such as thin prisms near the floor. Of course, direct measurements with the multi-sensor system can also have inaccuracies due to the small influence of the tripods. In this study, we find good results in fit due to the nature of the locations of the nozzles (net and high locations), the use of experienced operators and the important amount of time preparing the field experiment and doubling the time of direct measurements and complexity. However, in other field measurements for other purposes, the use of people (operators) to measure at the space of the presence of birds near the floor is impractical in terms of time and human resources and the distortion of measurements there can be relevant. Also, for precise measurements it is necessary to measure during the whole rearing cycle (about 7 weeks) and with the animal presence, totally avoiding the use of human operators or hot wire anemometers.

Water technology studies need to implement a protocol to estimate the consumption and a protocol for maintenance of the fog spray nozzles. No protocol was found in the published literature to perform this water consumption when broiler production needs a colossal amount of water for cooling; in this study alone, we have estimated 1369.71 l h^{-1}. The use of graduated test tubes to measure the expelled water in a sample size of nozzles may be an interesting protocol, because the vast number of them in a typical broiler building precludes testing all the nozzles. As mentioned above, using the formulation of the determination of the sample size in finite populations we have measured in 21 fog spray nozzles. To be consistent, we studied the same nozzles in which we measured the air velocity by the hot wire anemometers and there are keys in the pipes (near the beginning of the pipe, in the middle and near of the end of the pipe). In this study, working the cooling system one day (24 h), the consumption of water is 8873.04 l (24 h x 1369.71 l h^{-1}). Future periodic maintenance works using this protocol for measuring expelled water must be carried out, because whereas total obstructions are easily detected, partial obstructions or minor technical deficiencies are more difficult to find, deteriorating the litter. Incorrect functioning of fog spray nozzles can create dry areas or pools on the litter, with several potential sanitary problems for the broilers (infections, corns on their feet decreasing the quality of their meat (Almeida *et al.*, 2010; Ross Breeders, 1996)). Although one only stopcock could be used for all the pipes, it is better to use seven stopcocks, because the economic costs and human effort to install one stopcock in each pipe is minimal. This way, each pipe has its own stopcock and can be more easily controlled, avoiding the use of one or several pipes during the cooling cycle; for example, in case of unexpected occasional escapes in one pipe; this way, the rest of the pipes can keep working, keeping the cooling system running. Figure 6.7 shows the broiler building and the proposed pipes.

The protocol and steps described in this model of broiler building may be extrapolated to any broiler building model. A future second phase of this chapter would analyse the different commercial fog spray nozzles in order to compare them and to optimise their design. Thus, CFD techniques could analyse the different droplet sizes or the spraying phenomenon. It is clear that some designs for the location of the pipes and orientation of the fog spray nozzles may be easier depending on the nature of the indoor air velocity profiles of the broiler building model. Moreover, depending on the geographical area, the lime, impurities and the quality of the water provided can cause more obstructions and technical problems in the nozzles, so in these areas the revision time must be shortened.

6.5. Conclusions

In this study, we have designed the optimum location for the pipes and the best orientation for the fog spray nozzles of a cooling system in a Mediterranean tunnel broiler house. A well-designed cooling system is indispensable to maintain the proper indoor environment of broiler houses. The optimal fogging system design requires comprehensive knowledge of the indoor air velocity profiles (magnitude and main components of the air velocity vectors). CFD simulations can provide this complete knowledge much better than the physical sensors (which only offer information from a limited number of points: the physical sensors), which also require complex measurements. Although each broiler house model needs a different layout of pipes and nozzles according to the specific building geometry and the ventilation system installed, the protocol and the requirement to build it will be the same: full knowledge of the indoor air velocity patterns. After the design of the fogging system, an estimation of the consumption of water in use is performed and can be considered a valid protocol for futures maintenance of the fogging system. Water technologies in livestock buildings need studies using powerful scientific approaches to optimise water consumption and proper indoor animal house conditions.

6.6. References

Almeida, I.C.L.; García, R.G.; Bernardi, R.; Nääs, I.A.; Caldara, F.R.; Freitas, L.W.; Seno, L.O.; Ferreira, V.M.O.S.; Pereira, D.F.; Cavichiolo, F. Selecting appropriate bedding to reduce locomotion problems in broilers. *Braz J Poult Sci* 2010, 12, 189-195.

Blanes-Vidal, V.; Guijarro, E.; Balasch, S.; Torres, A.G. Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. *Biosyst. Eng.* 2008, 100, 105–116.

Bustamante, E.; García-Diego, F.J.; Calvet, S.; Estellés, F.; Beltrán, P.; Hospitaler, A.; Torres, A.G. Exploring Ventilation Efficiency in Poultry Buildings: The Validation of Computational Fluid Dynamics (CFD) in a Cross-Mechanically Ventilated Broiler Farm. *Energies* 2013, 6, 2605-2623.

Bustamante E.; García-Diego F.J.; Calvet S.; Torres A.G.; Hospitaler A. Measurement and numerical simulation of air velocity in a tunnel-ventilated broiler house. *Sustainability* 2015, 7, 2066-2085.

Bustamante, E.; Guijarro, E.; García-Diego, F.J.; Balasch, S.; Torres, A.G. Multisensor system for isotemporal measurements to assess indoor climatic conditions in poultry farms. *Sensors* 2012, 12, 5752–5774.

Calvet, S.; Cambra-López, M.; Blanes-Vidal, V.; Estellés, F.; Torres, A.G. Ventilation rates in mechanically ventilated commercial poultry buildings in Southern Europe: Measurement system development and uncertainty analysis. *Biosyst. Eng.* 2010, 106, 423–432.

Charles, D.; Walker, A. Poultry Environment Problems: A Guide to Solutions, 1st ed.; Charles, D., Walker, A., Eds.; Nottingham University Press: Nottingham, UK, 2002.ç

Donkoh, A. Ambient temperature a factor affecting performance and physiological response of broiler chickens. *Int J Biometeorol* 1989, 33, 259-265.

European Union (EU). The welfare of chickens kept for meat production (broilers) ; Report of the Scientific Committee on Animal Health and Animal Welfare Adopted 21 March 2000; European Union: Brussels, Belgium, 2000.

FAO. Faostat-Agriculture. Available online: http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor (accessed on 15 January 2015).

Franco, A.; Valera, D.L.; Peña, A.; Pérez, A.M. Aerodynamic analysis and CFD simulation of several evaporative cooling pads used in Mediterranean greenhouses. *Comput. Electron. Agr.* 2011, 76, 218–230.

Fluent User's Guide, version 6.0; Fluent Inc.: Lebanon, NH, USA, 2001.

Gambit User's Guide, version 2.0; Fluent Inc.: Lebanon, NH, USA, 2001.

Kim, K.; Yoon, J.Y.; Kwon, H.J.; Han, J.H.; Son, J.E.; Nam, S.W.; Giacomelli, G.A.; Lee, I.B. 3-D CFD analysis of relative humidity distribution in a greenhouse with a fog cooling system and refrigerative dehumidifiers. *Biosyst. Eng.* 2008, 100, 245-255.

MWPS. Mechanical Ventilating Systems for Livestock Housing, 1st ed.; Midwest Plan Service, Iowa State University: Ames, IA, USA, 1990.

Li, S.; Willits, D.H. Comparing low-pressure and high pressure fogging systems in naturally ventilated greenhouses. *Biosyst. Eng.* 2008, 101, 69-77.

Mistriotis, A.; de Jong, T.; Wagemans, M.J.M.; Bot, G.P.A. Computational fluid dynamics as a tool for the analysis of ventilation and indoor microclimate in agriculture buildings. *Neth. J. Agr. Sci.* 1997, 45, 81–96.

Mostafa, E.; Lee, I.B.; Song, S.H.; Kwon, K.S.; Seo, I.H.; Hong, S.W.; Hwang, H.S.; Bitog, J.P.; Han, H.T. Computational fluid dynamics simulation of air temperature distribution inside broiler building fitted with duct ventilation system. *Biosyst. Eng.* 2012, 112, 293–303.

Norton, T.; Sun, D.; Grant, J.; Fallon, R.; Dodd, V. Applications of computational fluid dynamics (CFD) in the modeling and design of ventilation systems in the agricultural industry: A review. *Bioresour. Technol.* 2007, 98, 2386–2414.

Oberkampf, W.L.; Trucano, T.G. Verification and validation in computational fluid dynamics. *Progr. Aerosp. Sci.* 2002, 38, 209–272.

Osorio, J.A.; Ferreira, I.F.; Oliveira, K.S.; Arêdes, M.; Oliveira, M. Modelling and experimental validation to estimate the energy balance for a poultry house with misting cooling. *Dyna* 2011, 78, 167–174.

Patankar, S.V. Numerical Heat Transfer and Fluid Flow; Hemisphere Publishing Corporation: Washington, WA, USA, 1980.

Ross Breeders, 1996. Producing quality broiler meat. Ross broiler management manual. Ross Breeders Limited, Midlothian, UK.

Sevilgen, G.; Kilic, M. Numerical analysis of air flow, heat transfer, moisture transport and thermal comfort in a room heated by two-panel radiators. *Biosyst. Eng.* 2011, 43, 137-146.

Testo Inc. Homepage. Available online: http://www.testo.com (accessed on 15 January 2015).

Zajicek, M.; Kic, P. Heating of large agricultural and industrial buildings. *Agronomy Research* 2014, 12, 237-244.

Chapter 7

General Results and Discussion

This chapter presents:
- An introductory overview.
- General discussion and results.
- Achievement of the PhD dissertation's general aim and specific objectives.
- Acquisition of skills in the PhD dissertation.

7.1. Introduction

As indicated in Chapter 1, this PhD thesis aimed to characterise the ventilation and indoor air velocities (ranges and distribution) of the main mechanical ventilation systems in different types of broiler buildings in order to outline an optimum general model. Despite the technology deployed in these animal houses, they are not optimised, which leads to repeated episodes of animal mortality with the associated economic costs and greater animal suffering. In this vein, in the Mediterranean climate (an important geographical area in broiler rearing worldwide), the heat stress on the broilers in hot seasons is a significant, cyclic problem. By means of CFD techniques and suitable electronic instrumentation, the different mechanical ventilation systems can be characterised.

This PhD thesis is broken down into different chapters towards this aim:

Chapter 1 to introduce the doctoral thesis, objectives, and structure of the thesis.

Chapter 2 to develop the instrumentation to measure indoor environmental parameters in broiler houses.

Chapter 3 to analyse one mechanical ventilation system (cross) in a typical Mediterranean broiler house.

Chapter 4 to analyse the mechanical tunnel ventilation system in one retrofit, with a view to installing this ventilation system in other Mediterranean broiler houses.

Chapter 5 to analyse another emergent mechanical ventilation system (single-sided).

Chapter 6 to analyse one crucial variable of broiler design of buildings, such as the cooling system using fogging systems.

Chapter 7 to present the general results and discussion.

Chapter 8 to conclude and discuss further studies.

7.2. General Discussion and Results

Empiricism in Broiler Building Design And in the Ventilation Systems Installed

The status of broiler building design and the ventilation systems installed before this PhD dissertation may be summarised in a single paragraph: "Empiricism or intuition is not the way to build animal houses in the third millennium. The uncertainty and customisation in broiler building design and the ventilation systems installed is currently the essence of the nature of broiler buildings." This was the main reason in deciding to carry out this PhD dissertation.

Modern intensive broiler production (not exempt from controversy, as seen in other intensive farming systems) arose from the recent introduction of “livestock industrialisation”.

The world’s human population is large, land is limited, and it is imperative to produce food for this population at a reasonable price and good quality. Poultry meat is accepted by nearly all cultural and religious groups, whereas other types of meat have problems in being accepted. Amongst the different intensive livestock production systems, poultry production is the most efficient in terms of feed conversion (Steinfeld *et al.*, 2006). Poultry production for meat (broilers) is one of the most important food industries, with a 633.34 % increase in world production from 1972 to 2012 (FAO, 2015). Perhaps most importantly, broiler meat is also cheap and of high quality (Slingenbergh *et al.*, 2007). In terms of intensive production, broilers are confined in buildings of two fundamental types: production in broiler buildings with natural ventilation, and production in broiler buildings with mechanical ventilation. Modern broiler buildings generally use mechanical ventilation by negative pressure through exhaust fans (ASAE, 1986; MWPS, 1990; Pedersen, 1999). Ventilation is crucial in ensuring the appropriate indoor conditions to achieve high broiler productivity (growth and food conversion) and low mortality (Charles *et al.*, 2002; Lott *et al.*, 1998). Surprisingly, there are no precise guidelines or an optimum model for a broiler building with mechanical ventilation from the point of view of dimensions and/or design or from the point of view of the ventilation system *per se*. However, there are three important types of mechanical ventilation installed: cross, tunnel and single-sided.

Thermal Stress and Mortality of the Broilers

Broilers can suffer from great episodes of thermal stress and mortality in different types of broiler buildings during some meteorological events. These fatal episodes are especially relevant in the hot seasons of the Mediterranean climate, where a significant number of broiler buildings are found. Proper air velocity values around the birds are crucial to assist in their biological thermoregulation and to diminish or eliminate the negative effect of the adverse meteorological events on the birds (DEFRA, 2008, Simmons *et al.*, 2003). Unfortunately, climate change and global warming are increasing the geographical areas of meteorological uncertainty and occasional unexpected extreme weather (heat or cold waves).

Current Methods to Characterise Ventilation in Broiler Buildings. Verification and Validation (V&V)

Current trends to characterise the ventilation of agricultural buildings (greenhouses and livestock buildings, including broiler buildings, of course) use two major methods: direct measurements with the appropriate electronic instrumentation (sensors) (Berckmans *et al.*, 1991; Blanes-Vidal *et al.*, 2010; van Wagenberg *et al.*, 2003; Wilhelm *et al.*, 2001; Zhang *et al.*, 1996) and indirect methods such as Computational Fluid Dynamics (CFD) techniques (Bartzanas *et al.*, 2007; Bjerg *et al.*, 2002; Blanes-Vidal *et al.*, 2008; Lee *et al.*, 2007; Norton *et al.*, 2007; Pawar *et al.*, 2007; Xia *et al.*, 2002). However, this indirect method (CFD) also needs verification and validation (V&V) (Oberkampf *et al.*, 2002).

Electronic Instrumentation (Sensors)

It was essential to develop and build instrumentation to measure the indoor environment of mechanically ventilated broiler buildings, bearing in mind the specific nature and requirements. The main issue was to build the instrumentation to assess the design and function of the ventilation systems and to verify and validate (V&V) the CFD simulations. As these indoor environments are turbulent by nature (Heber *et al.*, 1996), we need to receive sufficient signals from a large number of physical sensors. Thus, discrete measurements or a small number of sensors are not suitable for these studies. Isotemporality in measuring is important due to changing air velocity values at the same point and in the same scenario. Therefore, the standard deviation of air velocity is nearly the average, and so a multi-sensor isotemporal system is the most suitable instrumentation to perform the research. It was also necessary to automate measurement taking, to avoid the physical presence of a technician which might distort the records (Wheeler *et al.*, 2003).

The choice of the type of sensors was also an important factor. Air velocity and temperature sensors (hot-wire type sensors) and RTDs were chosen based on several advantages such as their observed robustness in other documented cases (Ibrahim, 2002).

Wired systems were used instead of wireless systems, as wireless sensors consume large amounts of energy necessitating battery changes. Wired systems are currently applied in other fields of engineering to measure environmental parameters with great success (Zarzo *et al.*, 2011), and are sufficient to conduct the field experiment throughout a whole rearing season (6-7 weeks).

Calibration was also essential and original, because we used dummy variables (Kutman *et al.*, 2005) for sensor calibrations as an innovative method. Obtaining a single calibration curve is ideal, but slight differences among the calibration of sensors were found as a consequence of differences in the fabrication process or components. A single calibration curve was obtained for all velocity sensors, whereas we found five calibration curves for the air temperature sensors, although these differences were irrelevant in practical terms. The calibration of differential pressure sensors demonstrated similar calibration curves, as was expected.

In summary, the measurement system consisted of a laptop, a data acquisition card, a multiplexor module and a set of 24 air temperature sensors, 24 air velocity sensors and two differential pressure sensors. The system was able to acquire up to a maximum of 128 signals simultaneously at 5 second intervals.

The measurement system is robust enough to resist the aggressive environmental conditions (e.g. dust, high relative humidity, gas concentration) that prevail in buildings during animal rearing. Additional sensors (i.e. humidity sensors) can be implemented using other channels in the collecting module for wider studies in occupied broiler buildings.

This measurement system was used in all field experiments included in this PhD dissertation to compare the different types of mechanical ventilation systems at broiler buildings.

The first field experiment was conducted in a cross mechanically ventilated broiler building demonstrating interesting statistical results - the variation between air velocity sensor measurements was not significant (P-value <0.4428). This lack of statistical significance of the "Sensor" variable indicates homogeneous behaviour of all sensors on average for the different sections and boundaries studied. In this field experiment, the overall average of the measurements of the air velocity was 0.63 ± 0.54 m s^{-1}. The averages by section were 0.59 ± 0.50 m s^{-1} (Section A) and 0.68 ± 0.58 m s^{-1} (Section B) and 0.51 ± 0.70 m s^{-1} (Boundary *I*), 0.64 ± 0.37 m s^{-1} (Boundary *II*), 0.75 ± 0.39 m s^{-1} (Boundary *III*) and 0.64 ± 0.62 m s^{-1} (Boundary *IV*). The maximum (0.80 ± 0.31 m s^{-1} Section B, Boundary *III*) was not obtained at the bird height level (0.25 metres). This variability is due to air turbulence in broiler buildings and the location of the sensors.

Cross-Mechanical Ventilation

CFD simulations were performed for the cross-mechanical ventilation system in experiments on the broiler building where the first evaluation of the multi-sensor system designed was carried out. As expected, similar air velocity values were obtained in the numerical simulations compared with those obtained by direct measurement. The average of these values using CFD techniques was 0.60 ± 0.56 m s^{-1} and using the direct measurements the average was 0.64 ± 0.54 m s^{-1}.

Validation was conducted using an ANOVA model and linear regression. The results of the ANOVA found that the "Methodology" variable was non-significant (P-value <0.5271), and the same was found for its interactions. Therefore, CFD techniques and direct measurements using the multi-sensor system designed will give similar results. The regression line slope value was close to 1 and the independent term was near zero, while the determination coefficient of the linear regression analysis shows a good fit (R^2= 0.888).

CFD outputs provide illustrative graphics that show the trends of air velocity distribution and good visualisations. These graphic representations also provide additional information on airflow characteristics and patterns which may contribute to a more effective ventilation design. The scale of colours and the use of vectors that incorporate these outputs are explicatory in themselves. Compared to direct measurements, CFD techniques can present more information and a more general view of indoor climatic conditions of broiler buildings through these graphics.

Our results show that mechanical cross ventilation systems are suitable under most common weather conditions in the Mediterranean region, but they do not prevent episodes of mortality caused by heat stress, as they provide lower air velocity values than those required by animals in these conditions. At broiler level (0.25 metres), the maximum air velocity was 0.89 ± 0.43 m s^{-1} for CFD and 0.80 ± 0.31 m s^{-1} for direct measurement. The minimum velocity was 0.34 ± 0.29 m s^{-1} for CFD and 0.37 ± 0.31 m s^{-1} for direct measurements. The distribution at the broiler level is heterogeneous and so the homogenisation of air velocity should be compulsory in future broiler buildings designs.

Having validated the CFD techniques, we can now explore and find the best geometry for broiler buildings that wish to install cross-mechanical ventilation. In this endeavour, the building characterisation and relative elements must be evaluated and suitable management operations will be assessed. We note that forced ventilation systems require electric energy to activate the fans and automation, which are not required in naturally ventilated broiler buildings, and so electric energy consumption efficiency is also an important factor to study.

Mechanical Tunnel Ventilation

While mechanical tunnel ventilation is commonplace in some countries, it has only recently been installed in southern Europe, in countries with a medium-extreme Mediterranean climate. The purpose of adopting this ventilation system is to solve the repetitive mortality and stress on animals which occurs in warmer seasons (El País, 2003). In these latitudes, cross-mechanical ventilation is the most widespread ventilation system (Blanes-Vidal *et al.*, 2008), but this system is not effective during hot seasons/weather as it does not provide sufficiently high air velocity. Mechanical tunnel ventilation may be the solution, but detailed analysis of this system is required. In this study we took direct measurements using the multi-sensor system and by means of CFD simulations.

The studied broiler building was a retrofit of the traditional cross broiler building with inlets concentrated at the end of the laterals of the opposite wall of fans, as it was impossible to place them exactly opposite the wall of fans (pure tunnel). Currently, the control room in Mediterranean broiler buildings using cross ventilation is precisely located at one end of the building to avoid placing new inlets on the opposite wall of fans. We ran different numbers of fans (moving from two fans to ten fans in increments of one) to obtain "air velocity distribution" *vs.* "fans in use" in order to address fan management in summer seasons. The results of both methodologies (CFD and direct measurements) demonstrated similar results for air velocity at the height of the broiler (0.25 metres). The maximum air velocity was 2.72±0.31 $m{\cdot}s^{-1}$ (CFD) and 2.58±0.29 $m{\cdot}s^{-1}$ (direct measurement), and the minimum air velocity was 0.49±0.12 $m{\cdot}s^{-1}$ (CFD) and 0.47±0.11 $m{\cdot}s^{-1}$ (direct measurement). Therefore, this type of ventilation system can provide high air velocity values to increase the convective flux heat of broiler farms and thereby decrease the thermal stress and associated mortality. This system can be used for normal weather or winter in Mediterranean regions, as we also obtained low air velocity values. Unfortunately, this system is still not optimised, as there is high air velocity heterogeneity at the broiler level (0.25 metres), finding full valid behaviour only in the central zone of the studied broiler building. From the CFD outputs, we observed three different zones: the inlet zone, central zone and near the fans. Near the fans, we found very high air velocity values, preventing the normal presence of broilers; in contrast, in the area of the inlets, a "dead zone" (low air velocities) and high variability were found. Thus, optimisation of this ventilation system is required through the application of "virtual" geometries by means of CFD techniques, as these are more complete and easier to use than complex direct measurements.

To optimise this ventilation system by means of CFD simulations, it is crucial to assure their validity. In a similar manner as for cross-mechanical ventilation, we performed the validation of CFD simulations of air velocity using an ANOVA model and a linear regression analysis. The ANOVA analysis showed that the "Methodology" variable (results by CFD simulations or direct measurements) is non-significant (P-value<0.1155), along with its interactions. The regression line slope had a value near 1 and the independent term near zero, while the determination coefficient was R^2= 0.98. Therefore, we can use CFD simulations or direct measurements to explore indoor air velocity in this ventilation system in broiler buildings.

The CFD outputs indicated that mechanical tunnel ventilation was not the ideal design for broiler buildings of short length because the best and most homogeneous indoor environment was only located in the central zone. It remains the best solution for hot seasons in the Mediterranean region, as high air velocity values can be obtained. Farmers can save the energy as a smaller number of fans can achieve the same air velocity values as when using a large number of fans and a traditional ventilation system. However, while high air velocity values are easily reached, inappropriate management can easily lead to animal health problems due to excessive ventilation. Although mechanical tunnel ventilation can be used for normal weather in the Mediterranean region, the traditional ventilation system (cross) is more suitable as broiler density is higher, as in tunnel-type ventilation there are areas of the broiler buildings that cannot be occupied by animals due to air velocity distribution problems. During winter/cold seasons, higher electricity consumption is required to heat the incoming air flow compared to traditional ventilation systems (cross). Tunnel ventilation management is also more complicated and the programming of fans requires more time and experience than cross (traditional) ventilation.

Despite mechanical tunnel ventilation solving the problems of thermal stress and associated mortality, it is only fully valid for hot seasons. Future studies must optimise this ventilation system using "virtual" geometries by means of CFD techniques.

Single-sided Mechanical Ventilation

Mechanical single-sided ventilation under a negative pressure system was studied in a Mediterranean broiler building. Apart from the associated publication of this chapter, little published scientific literature was found which referred to mechanical single-sided ventilation in broiler buildings. The need to explore new ventilation types arises from the need to reduce mortality and thermal stress of broilers in hot seasons in the Mediterranean climate. To this end, this emergent ventilation system has recently been incorporated and designed for some businesses in the sector (Serupa, 2015; Warkup, 2015), albeit without scientific justification or publication. We have analysed mechanical single-sided ventilation by means of designed instrumentation and CFD techniques. We performed the validation of the CFD simulations of air velocity in the same manner as for cross mechanical ventilation: an ANOVA model and a linear regression analysis. The ANOVA analysis demonstrated that the "Methodology" variable (results by CFD simulations or direct measurements) is non significant (P-value<0.3908), along with its interactions. The regression line slope had a value close to 1 and the independent term near zero, while the coefficient of determination was R^2= 0.98. A minimum acceptable systematic error (overestimation of CFD simulations by 6.6 %) was found. Therefore, we can use direct measurements or CFD simulations to explore indoor air velocity for this ventilation system in broiler buildings.

The expectations for this ventilation type were not fulfilled, as it is very similar to cross-mechanical ventilation and does not serve to solve the problems of mortality and thermal stress. The average air velocity (using CFD or direct measurements) ranged from ~0.40 m s^{-1} to ~1.30 m s^{-1} at the animal level (0.25 metres). Several heterogeneity issues were found at this level, especially for the walls opposite the fans and the areas between the fans. So, we believe that investment in this ventilation system is a bad decision, as it does not provide sufficient air velocity at broiler level, although it does represent an excellent ventilation system for broiler production in normal weather conditions in the Mediterranean region.

We also studied the use of fan diffusers, as these are included in building designs. Farmers currently believe that that their use worsens the indoor environment during hot seasons, and prevents direct airflow to the animals located near the fans avoiding respiratory diseases or colds. Therefore, we included the “Diffuser” variable in the ANOVA model. The results of the ANOVA showed that their installation was non-significant (P-value<0.6106) in the indoor environment. However, the “Pressure” variable and “Height” variable did have a significant effect (P-value<0.0001) on the indoor air velocities. The CFD outputs do show that diffuser inclusion altered the air velocity distribution near the fans, but not at broiler height (0.25 metres). So, we recommended the use of diffusers, as they do not significantly alter the indoor air velocities values at broiler level, as the farmers erroneously used to believe, and they prevent high air velocities near the broilers that can cause respiratory diseases.

It is important to note that the high ventilation rates on the broiler building do not necessary entail high air velocity at broiler level. Thus, the geometry of the building is crucial in obtaining proper air velocity distribution and values, with respect to the ventilation rates of the whole farm. Whereas the maximum exhaust air output was in Scenario I and II, the air velocity values are less than half compared to Scenario III and IV with less air output. Therefore, having validated the CFD simulations, we can use CFD techniques to explore “virtual” geometries of broiler buildings and to find the optimal building designs, best scenarios and associated management of this ventilation system. CFD techniques provide resources and commands to characterise ventilation systems, highlighting the strategy of creating points of interest and isosurfaces. By definition, an isosurface is a surface that connects points of equal nature, and we created isosurfaces that connect points of equal height, such as the plane of the broiler presence.

In summary: (i) CFD simulations provide more possibilities than complex direct measurements; (ii) Mechanical single-sided ventilation involves two important problems: high heterogeneity of the air velocity distribution at the height of the broilers presents low-medium values and so does not provide sufficient air velocity at broiler level to prevent high mortality or thermal stress in hot conditions, and the poor ventilation in some areas of the broiler building (opposite wall from the fans and between the fans). We propose that CFD simulations will be the best way to optimise these ventilation systems.

Design of Cooling Systems (Fogging Systems) in Broiler Buildings

The equipment installed in broiler buildings can also be studied using CFD techniques and sensor approaches. Heating systems can be studied by simulating radiators or hot surfaces (Sevilgen *et al.*, 2011; Zajicek *et al.*, 2014). Cooling systems can analyse pad cooling (Franco *et al.*, 2011) or the profiles of indoor air velocities to optimise the proper location of the pipes and the best orientation for the fog spray nozzles.

As the main aim of this PhD dissertation is to characterise the ventilation systems and this issue is the key to an optimum design for a fogging system, the mechanical tunnel ventilation for the broiler building from chapter 4 was designed for this. Of course, this protocol and these steps can be applied to any broiler building design and ventilation system installed. In addition, a protocol is proposed for maintenance and estimation of water consumed in a period of cooling.

The Optimum broiler building and ventilation system installed

(An adaptation of this part forms the body of a publication submitted about the state of the art and future perspectives of poultry housing for meat (broilers)).

Throughout the different chapters of this PhD dissertation, the different mechanical ventilation systems in different types of broiler buildings were analysed and characterised. By means of these characterisations, it is possible in this chapter to discuss and outline the optimum broiler building and the optimal ventilation system installed. A differentiation has been made between the general optimums and the specific optimums because the specific optimums are conditioned by particular needs (the specific requirements of the clients, specific dimensions and size of the broiler buildings, planned investment, number of animals, etc.), on the basis of the general optimum model outlined here.

General Optimum for Broiler Building and Ventilation System Installed

Broiler buildings must be designed to remain stable and useful for the whole period of their useful life, while the weather is also an important factor in the design of the building, as it affects the animals during the rearing process. Unfortunately, meteorological predictions have a high degree of uncertainty due, among other variables, to the effects of climate change and global warming. Indeed, climates may change over the short term in some areas. Heat or cold waves or unexpectedly extreme seasons are therefore highly probable. Although it is certain that advances are expected in terms of the materials for the buildings' design (i.e. insulating materials) or livestock turbo-machinery, meteorological events will affect animal mortality and their stress if broiler buildings are not equipped sufficiently well. In this vein, poultry housing ventilation for meat (broiler) in the 3rd millennium needs to integrate all the advantages of all the types of current mechanically ventilated systems (cross, single-sided and tunnel) analysed in this PhD dissertation. Cross and single-sided are transversal ventilation systems, whereas the tunnel is a longitudinal system. Cross-mechanical ventilation is the current and fully valid ventilation system for mild climates (e.g. Mediterranean climate), except for one-off days of very hot weather (in summer) when this system has several thermal problems. In this PhD dissertation, it is demonstrated that the higher air velocity values needed to diminish the heat stress and the mortality of the broilers cannot be reached. Single-sided mechanical ventilation is a ventilation system still in its early stages. In this PhD dissertation, it was also demonstrated that it cannot solve these thermal problems despite the air velocity values obtained being slightly higher than in cross-mechanical ventilation. Therefore, neither of the two transversal mechanical ventilation systems (cross or single-sided) is able to achieve high enough values of air velocity to solve the heat stress on the birds. On the other hand, mechanical tunnel ventilation is commonplace in some climatic locations and this was tested in a broiler building in a Mediterranean climate (Valencia, Spain), an area in which it has been recently incorporated. The results of the characterisation carried out in this PhD dissertation showed that tunnel mechanical ventilation is less suitable than the transversal mechanical ventilation systems (cross or single-sided mechanical ventilation) in mild climatic locations, except for days of unusually hot weather (in summer). In these hot events, it becomes necessary and fully valid because it can reach higher air velocity values to diminish the heat stress on the broilers and their mortality rates.

Therefore, the general optimum broiler building for the future and for current complicated climatic areas with both extreme conditions (hot and cold weather) must install a hybrid mechanical ventilation system (transversal and longitudinal). These general optimums of broiler buildings need to install a transversal mechanical ventilation system such as a cross or single-sided one for cold or fair weather (with low to medium values of air velocity). In addition, it is also indispensable to install a longitudinal ventilation system (tunnel mechanical ventilation) for hot seasons (summer) or heat waves. By means of tunnel mechanical ventilation, it is possible to obtain higher air velocity values in order to minimise the heat stress and the associated mortality in unusually hot events. Indoor environments of future broiler buildings will need full control over the air velocity, as this is the key variable to assist in the biological thermoregulation of the broilers in order to minimise their thermal stress. However, in climatic regions where the hot weather is always constant throughout the year (e.g. tropical climate) and without meteorological uncertainty, the broiler building model would include only the optimised tunnel ventilation system. On the other hand, in climate regions where the temperature is always cold and without meteorological uncertainty, the optimum broiler building model will include only the optimised transverse ventilation system (cross or single-sided). This hybrid mechanical model is correct for the current mild climate (e.g. Mediterranean climate) and for geographical areas with meteorological uncertainty (accentuated by the effects of climate change and global warming). It is necessary to remark that in some cases and geographic locations, it may be uneconomical to install the hybrid mechanical system, but it does promote animal welfare. In my opinion, there are two key issues in the current absence of this hybrid mechanical ventilation system in modern broiler buildings:

(i) A lack of the knowledge about the different characterisations of ventilation before this PhD dissertation was written.

(ii) Economic criteria: in some cases, the losses in mortality and broiler weight due to thermal stress are lower than the investment required when installing a hybrid mechanical ventilation system only to solve unexpected meteorological events or for a small part of the broilers reared.

In this regard and in the Mediterranean climate of the Valencia Community region (Spain), in broiler buildings with hybrid mechanical ventilation the tunnel type ventilation system should only be used occasionally in the hot season (summer) during heat waves. From an economic point of view, the losses in the final weight and mortality of the broilers will be less than the investment in a mechanical tunnel ventilation system, which is only used for a small part of the hot season. From an ethical and an animal welfare point of view, it is immoral to maintain only the traditional cross-mechanical ventilation system in the Mediterranean climate because, in this PhD dissertation, we have demonstrated that the animals' mortality and heat stress can be resolved by installing a tunnel mechanical ventilation system for the hot season or days, even though it may not be economical.

The days of use of each of the two installed mechanical ventilation systems will depend on the location or the possible meteorological events. Of course, using both ventilation systems involves twice the investment and training for farmers. We should also remember that in cold seasons the transversal mechanical ventilation system is more economical in terms of the energy used to heat the air (chapter 4). Therefore, the climatic location of the broiler building and the predictions for the useful life of the building are crucial. In my opinion, planning laws should exist to regulate broiler buildings depending on their geographical location, making it compulsory to install both mechanical ventilation systems (the hybrid system) in certain areas. In addition, in my opinion financial assistance is necessary in some areas, such as in the Mediterranean climate, since given the lack of financial help, many farmers may refuse to install both mechanical ventilation systems.

In this general optimum broiler building, it is also a good trend to eliminate the slope of the roof because this will diminish the indoor volume of air that needs to be heated (in hot weather), cooled (in cold weather) or moved (always). Furthermore, as we commented in chapter 2, changes in the direction of the air velocity affects the broilers' behaviour and for this reason it is also a good idea to gradually change the ventilation systems by means of transitional fans near corners (see Figure 7.1).

As we concluded in chapter 4, broiler buildings of short length are not optimum when they have tunnel mechanical ventilation.

Therefore, the general optimum broiler building involves a hybrid mechanical ventilation system (transversal plus tunnel), elimination of the roof's slope, transitional fans and a long length to avoid instability in the distribution of the air velocity when tunnel mechanical ventilation is being used.

A transversal mechanical ventilation system can be considered to mean cross, single-sided or the use of heat exchangers (if the ventilation needs are lower; i.e., when the broilers are featherless or during the first days of rearing). In this sense, a cross mechanical ventilation setup can be used as the preferable transversal system, because it is already installed and the farmers are familiar with managing it (at least in the Mediterranean climate).

In this general optimum broiler building, it is necessary to make the air velocity values uniform at the level where the animals are present so as to avoid indoor migration and dense concentrations of the broilers in some areas inside the building, which can also cause stress and mortality (Blanes-Vidal *et al.*, 2008).

Specific Optimums

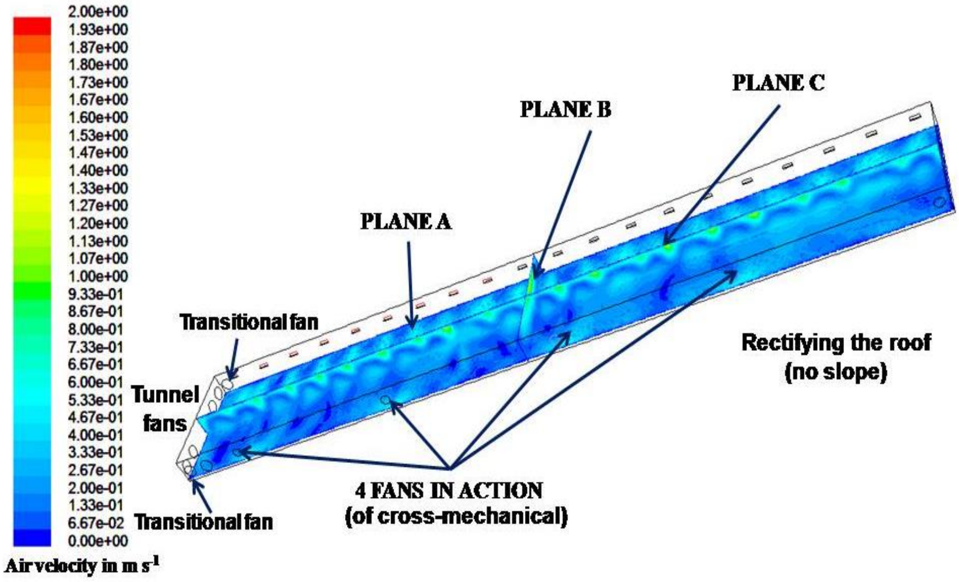
The clients' specific requirements (dimensions and size of the broiler building, planned investment, number of animals, etc.) will determine the specific optimums for each particular need and case. Based on these precise requirements and on the general optimum's outlined trends, the specific optimum for each particular need and location will be found.

As commented above, in clear climatic areas of constant hot weather, the optimum will be an optimised mechanically ventilated tunnel broiler building. In areas of constant cold weather, the optimum will be an optimised mechanically ventilated transversal broiler building.

In most climatic areas (e.g. Mediterranean climate and areas with meteorological uncertainty), the optimum broiler building should install the aforementioned hybrid mechanical ventilation system (longitudinal plus transversal). The elimination of the roof's slope and transitional fans are some compulsory general trends that need to be present in the search for specific optimums. Using "virtual" broiler buildings, "virtual" ventilation systems" and "virtual" management in CFD software under the guidance of heuristics algorithms (Gen *et al.*, 2000; Goldberg, 1989; Tam, 1992) will be the way to find this specific optimum for each particular need and possible client. In this search for specific optimums, the influence of the inlets and outlets (fans) is essential (Bustamante *et al.*, 2011). The variables (building dimensions, investment, number of animals, stocking, demands of oxygen, demands from ventilation renewal rates, characteristics of inlets and their location, characteristics of outlets (fans) and their location, days of use of each mechanical ventilation system if there is a hybrid model, capacity of the lorry to transport the broilers to the slaughterhouse, etc.) must be well weighted, included in the restrictions and optimised in the objective function of the heuristic algorithm (Gen *et al.*, 2000; Goldberg, 1989; Tam, 1992). It is necessary to point out that altitude changes the levels of oxygen. At high altitude, the atmospheric pressure, and hence oxygen, is lower than at sea level, influencing the broiler rearing and performance (Tekeli, 2014). Thus, the renewals and specific demands of oxygen need to take into account the specific altitude of the specific projected broiler building. Furthermore, in mechanical tunnel ventilation (chapter 4), it was demonstrated that with a discrete number of fans (2 or 3) in action, it is possible to obtain the same air velocity values as working with 8 or 9 fans in the transversal mechanical ventilation systems (chapter 3 and 5). In this sense, it is necessary to remark that equivalent indoor air velocity values are not equivalent to the broilers' adequate required oxygen. Moreover, the age of the air (the time the air spends inside the broiler building) is greater in tunnel ventilation than in transversal mechanical ventilation systems (chapter 4). Under these circumstances and in tunnel ventilation, the concentration of pollutants in some scenarios will be higher, especially near the fans (at the end of the air velocity trajectories) (Carvalho *et al.*, 2012). Therefore, the animals' oxygen requirements and low concentrations of pollutants must be especially taken into account when researching optimum broiler buildings.

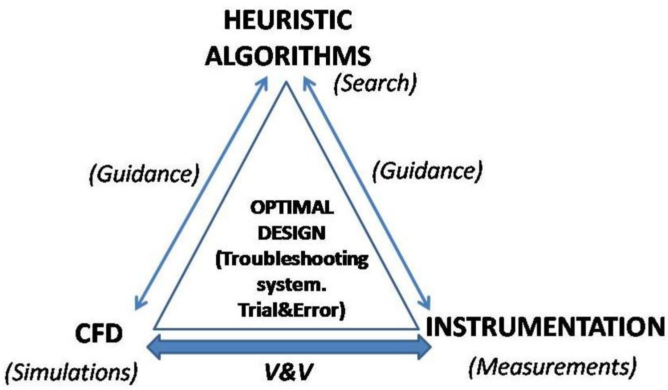
To sum up, it is necessary to spend time working with CFD under the premises of the specific requirements of the projected broiler building and under the guidance of a heuristic algorithm that optimises the search, gives weight to the variables and accelerates the process of conception and design. As an example of this work, Figure 7.1 shows a "virtual" broiler building that has a hybrid mechanical ventilation system (cross and tunnel) installed for a specific client that demands a broiler building with a specific investment. In this simulation, four mechanical cross ventilation fans are running; the other fans are off. In this Figure 7.1, we have created three interesting planes: Plane A, at the level of the broilers (0.25 metres); Plane B, halfway along the broiler building; and Plane C, halfway across the broiler building, in order to describe the indoor air velocity trends.

Figure 7.1. *CFD simulation of a "virtual" broiler building (with four transversal fans in action).*



In this broiler building (Figure 7.1) some of the trends described for the general optimum can be seen: elimination of the slope in the roof and transitional fan in the corner to gradually change the ventilation system. In hybrid mechanical ventilation systems (transversal plus longitudinal), the search must optimise both ventilation systems at the same time. Figure 7.2 shows a diagram of a protocol to search for specific optimums for broiler buildings.

Figure 7.2. *Searching for specific optimums of broiler buildings (involving CFD, instrumentation and heuristic algorithms).*



Other Mechanically Ventilated Livestock Buildings

These analyses and characterisations of the different mechanical ventilation systems in different types of broiler buildings studied in this PhD dissertation can be extrapolated to other animal houses. Of course, the nature of broiler production (without internal walls or other elements) enables easier simplifications of building space so as to attain more precise results. Pig, cattle or rabbit farms can use CFD techniques and direct measurements (specific sensors) to analyse their indoor environments. In our country and in Mediterranean countries, the analysis of the indoor environments of rabbit houses will be an interesting field of study. In this sense and for rabbit houses, some motivating articles have appeared in local journals (Estellés *et al.*, 2011) and at certain congresses (Estellés *et al.*, 2012).

7.3. Achievement of the PhD dissertation's general aim and specific objectives. Acquisition of skills in the PhD dissertation

The general aim and specific objectives proposed at the beginning of this PhD dissertation have been achieved in depth and to a more suitable extent in the corresponding chapters as planned.

The planned research for the PhD dissertation has been accomplished, as well as the general aim and the specific objectives. This PhD dissertation has led to some articles published in an international journal indexed in *Journal Citations Report* (3) and some other submitted articles (3). Moreover, several contributions to conferences that have been made obtained an award in an international conference.

The formal presentation of this PhD dissertation has been guided and accepted in this format by the supervisors. The whole process of this PhD dissertation was assessed and guided by the supervisors and by specific assessments by the co-authors (professors/lecturers at the university) regarding the published/submitted articles and conferences. Therefore, in this PhD dissertation, the skills needed for a well-guided and well-planned PhD dissertation have been achieved. Some of these acquired skills are described below:

S1: Systematic understanding of this field of study.

S2: Mastery of skills and research methods in this field of study.

S3: Skill and ability to conceive of a substantial research process with academic meticulousness.

S4: Skill and ability to design a substantial research process with academic scrupulousness.

S5: Skill and ability to carry out a substantial research process with academic rigour.

S6: Skill and ability to implement a substantial research process with academic thoroughness.

S7: Skill and ability to make several contributions via this original research work that push back the frontier of knowledge by creating a substantial corpus, part of which has already been published (in international journals indexed in *Journal Citations Report*) and has been recognised on appearing in publications of national and international renown.

S8: Skill and ability to make several contributions thorough this original research that broaden the frontier of knowledge by creating a substantial corpus, part of which may be recognised in future publications of national and international renown.

S9: Skill and ability to make a critical analysis, evaluation and summary of new and complex ideas.

S10: Skill and ability to communicate with colleagues, lecturers, supervisors, the academic community as a whole and with society in general about the areas of expertise developed during the doctoral period and previous training.

S11. Skill and ability to foster and develop technological, social and cultural progress in an academic context, in a society based on knowledge via the training achieved during the doctoral period.

S12. Skill and ability to foster and develop technological, social and cultural progress in a professional context, in a society based on knowledge via the training achieved during the doctoral period.

S13: Skill, capability and perspectives for applying the results of this PhD dissertation.
S14: Skill, capability and perspectives for transferring the results of this PhD dissertation.

7.4. References

ASAE EP270.5. Design of Ventilation Systems for Poultry and Livestock Shelters. In ASABE Standards 2009; American Society of Agricultural and Biological Engineers (ASABE): St. Joseph, MI, USA, 1986; pp. 1–19.

Bartzanas, T.; Kittas, C.; Sapounas, A.A.; Nikita-Martzopoulou, C. Analysis of airflow through experimental rural buildings: Sensitivity to turbulence models. *Biosyst. Eng.* 2007, 97, 229–239.

Berckmans, D.; Vandenbroeck, P.; Goedseels, V. Sensor for continuous measurement of the ventilation rate in livestock building. *Indoor Air* 1991, 1, 323–336.

Bjerg, B.; Svidt, K.; Zhang, G.; Morsing, S.; Johnsen, J.O. Modeling of air inlets in CFD prediction of airflow in ventilated animal houses. *Comput. Electron. Agr.* 2002, 34, 223–235.

Blanes-Vidal, V.; Guijarro, E.; Balasch, S.; Torres, A.G. Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. *Biosyst. Eng.* 2008, 100, 105–116.

Blanes-Vidal, V.; Guijarro, E.; Nadimi, E.S.; Torres, A.G. Development and field test of an on-line computerized instrumentation system for air velocity, temperature and differential pressure measurements in poultry houses. *Span. J. Agric. Res.* 2010, 8, 570–579.

Bustamante, E., García-Diego F.J.; Estellés, F.; Calvet, S.; Hospitaler, A.; Torres, A.G. Influencía de las condiciones de entrada y salida del aire sobre los parámetros ambientales en granjas avícolas de pollos (Premio a la mejor comunicación en el área temática de Tecnología de la Producción Animal). Proceedings of the VI Congreso Ibérico AGROINGENIERÍA 2011, September 5-7, Évora, Portugal.

Carvalho, T.M.R.; Moura, D.J.; Souza, Z.M.; Souza, G.S.; Freitas, L.G.; Lima, K.A.O. Use of geostatistics on broiler production for evaluation of different minimum ventilation systems during brooding phase. *R. Bras. Zootec.* 2012, 41, 194-202.

Charles, D.; Walker, A. Poultry Environment Problems: A Guide to Solutions, 1st ed.; Charles, D., Walker, A., Eds.; Nottingham University Press: Nottingham, UK, 2002.

DEFRA (Department for Environment, Food and Rural Affairs). Heat Stress in Poultry. Solving the Problem; DEFRA: London, UK, 2008.

El País, Anonymous. Medio millón de pollos mueren fuerte calor últimos días. Available online: http://www.elpais.com/articulo/Comunidad/Valenciana/Medio/millon/pollos/mueren/fuerte/calor/ultimos/dias/elpepiespval/20030617elpval_4/Tes (accessed on 14 June 2015).

Estellés, F.; Bustamante, E.; Torres, A.G.; Calvet, S. Control ambiental en explotaciones cunícolas. Boletín de Cunicultura, 166, 6-18.

Estellés, F.; Bustamante, E.; Torres, A.G.; Calvet, S. Evaluation of climate control strategies in rabbit houses. Proceedings of 10th World Rabbit Congress, September 3-6, Sharm El Sheikh, Egypt, 2012.

Franco, A.; Valera, D.L.; Peña, A.; Pérez, A.M. Aerodynamic analysis and CFD simulation of several evaporative cooling pads used in Mediterranean greenhouses. *Comput. Electron. Agr.* 2011, 76, 218–230.

Gen, M.; Cheng, R. Genetic algorithms and engineering optimization; Wiley Ed.; 1st Edition: New York, USA, 2000.

Goldberg, D.E. Genetic algorithms in search, optimization and machine learning; Addison-Wesley Longman Publishing Co., 1st Ed.: Boston, MA, USA, 1989.

Heber, A.J.; Boon, C.R.; Peugh, M.W. Air patterns and turbulence in an experimental livestock building. *J. Agric. Eng. Res.* 1996, 64, 209–226.

Ibrahim, D. RTD Temperature Sensors. Microcontroller Based Temperature and Control; Newnes: Oxford, UK, 2002.

Kutman, M.H.; Nachtsheim, J.; Nefer, J.; Li, W. Applied Linear Statistical Models; McGraw Hill: New York, NY, USA, 2005.

Lee, I.B.; Sase, S.; Sung, S.H. Evaluation of CFD accuracy for the ventilation study of a naturally ventilated broiler house. *Jpn. Agric. Res. Q.* 2007, 41, 53–64.

Lott, B.D.; Simmons, J.D.; May, J.D. Air velocity and high temperature effects on broiler performance. *Poultry Sci.* 1998, 77, 391–393.

MWPS. Mechanical Ventilating Systems for Livestock Housing, 1st ed.; Midwest Plan Service, Iowa State University: Ames, IA, USA, 1990.

Norton, T.; Sun, D.; Grant, J.; Fallon, R.; Dodd, V. Applications of computational fluid dynamics (CFD) in the modeling and design of ventilation systems in the agricultural industry: A review. *Bioresour. Technol.* 2007, 98, 2386–2414.

Oberkampf, W.L.; Trucano, T.G. Verification and validation in computational fluid dynamics. *Prog. Aerosp. Sci.* 2002, 38, 209–272.

Pawar, S.R.; Cimbala, J.M.; Wheeler, E.F.; Lindberg, D.V. Analysis of poultry house ventilation using computational fluid dynamics. *Trans. ASABE* 2007, 50, 1373–1382.

Pedersen, S. Forced Ventilation. In CIGR Handbook of Agricultural Engineering: Animal Production & Aquacultural Engineering; American Society of Agricultural Engineers (ASAE):St. Joseph, MI, USA, 1999; pp. 68–87.

Serupa. Serupa France Webpage. Available online: http://www.serupa.fr (accessed on 14 June 2015).

Sevilgen, G.; Kilic, M. Numerical analysis of air flow, heat transfer, moisture transport and thermal comfort in a room heated by two-panel radiators. *Biosyst. Eng.* 2011, 43, 137-146.

Simmons, J.D.; Lott, B.D.; Miles, D.M. The effects of high-air velocity on broiler performance. *Poult. Sci.* 2003, 82, 232–234.

Slingenbergh, J.; Gilbert, M. Do Old and New Forms of Poultry Go Together? In Proceedings of the International Poultry Conference, Bangkok, Tailand, 5–7 November 2007. Available online: http://www.fao.org/ag/againfo/home/events/bangkok2007/docs/part2/2_3.pdf (accessed on 14 June 2015).

Steinfeld, H., Gerber, P.; Wassenaar, T.; Castel, V.; Rosales, M.; de Haan, C. Livestock's long shadow environmental issues and options. FAO, 2006.

Tam, K.Y. Genetic algorithms, function optimization, and facility layout design. *Eur. J. Oper. Res.* 1992, 63, 322-346.

Tekeli, A. Effects of ascites (pulmonary hypertension syndrome) on blood gas, oxymetry parameters and heart sections of broilers grown at high altitude. *J. Anim. Plant. Sci.* 2014, 24, 998-1002.

Van Wagenberg, A.V.; de Leeuw, M.T.J. Measurement of air velocity in animal occupied zones using an ultrasonic anemometer. *Appl. Eng. Agric.* 2003, 19, 499–508.

Warkup. Warkup Webpage. Available online: http://www.amwarkup.co.uk/single_sided_buildings.html (accessed on 14 June 2015).

Wheeler, E.F.; Zajaczkowski, J.L; Saheb, N.C. Field evaluation of temperature and velocity uniformity in tunnel and conventional ventilation broiler houses. *Appl. Eng. Agric.* 2003, 19, 367–377.

Wilhelm, L.R.; Milner, J.M.; Snyder, S.D.; McKinney, D.B. An instrumentation system for environmental measurements in broiler and swine housing. *Appl. Eng. Agric.* 2001, 17, 677–681.

Xia, B.; Sun, D.-W. Applications of computational fluid dynamics (CFD) in the food industry:A review. *Comput. Electron. Agric.* 2002, 34, 5–24.

Zajicek, M.; Kic, P. Heating of large agricultural and industrial buildings. *Agronomy Research* 2014, 12, 237-244.

Zarzo, M.; Fernández-Navajas, A.; García-Diego, F.J. Long-term monitoring of fresco paintings in the cathedral of Valencia (Spain) through humidity and temperature sensors in various locations for preventive conservation. *Sensors* 2011, 11, 8685–8710.

Zhang, G.; Strøm, J.S.; Morsing, M. A Computerized Multi-point Temperature and Velocity Measurement System. In Proceedings of the Fifth International Conference on Air Distribution in Rooms (RoomVent'96), Yokohama, Japan, 17–19 July 1996; pp. 531–538.

Chapter 8

Conclusions

This chapter presents:
- Summary of brief statements and specific conclusions for each chapter.
- General conclusions.
- Future work.

8.1. Summary of brief statements and specific conclusions for each chapter

A summary of the main statements and the specific conclusions of each chapter is listed below:

Chapter 1

- There are currently two major groups of poultry farms: for laying hens and for meat production (broilers).
- Broiler production is increasing more than other livestock sectors with a 633.34 % increase in world production in the period from 1972 to 2012 (FAO, 2015), producing high-quality meat at a reasonable price (Slingenbergh *et al.*, 2007).
- Among the different types of intensive livestock production, poultry is the most efficient in terms of feed conversion (Steinfeld *et al.*, 2006).
- Poultry meat (broiler) is accepted by almost all cultural and religious groups, whereas pig, cattle or rabbit meet with acceptance issues in some cultures or religions.
- Intensive agricultural systems (not exempt from controversy) are one way to provide food at reasonable price-quality to all social strata.
- In this vein, the trend in the livestock sector is towards this intensive production in a process called “livestock industrialisation”.
- Broiler production has developed genetic improvements, better and concentrated feed, an improvement in preventive disease controls and biosecurity measures, and the use of technology to exhaustively control in-house environmental conditions (Havenstein *et al.*, 2003).
- Intensive broiler production consists of confining the birds in animal houses and has two fundamental variants: production in broiler buildings with natural ventilation and production in broiler buildings with mechanical ventilation.
- The dominant intensive production system for broilers takes place in broiler buildings with mechanical ventilation, mainly with negative pressure by means of exhaust fans (ASAE, 1986; MWPS, 1990; Pedersen, 1999).
- Ventilation plays a critical role in ensuring appropriate indoor conditions to achieve high animal productivity (growth and food conversion) and low mortality (Charles *et al.*, 2002; Lott *et al.*, 1998).

- The ventilation issues represent the main spend in total electricity consumption (45 %) (Corkery *et al.*, 2013; Teagasc, 2011).
- Housing conditions are acknowledged as having a greater impact than animal density on broilers' welfare (Dawkins *et al.*, 2004).
- There are currently no optimum models for broiler buildings, either in terms of the types or the ventilation systems installed.
- According to the climatic conditions, broiler building conceptions are different and the problems are different.
- Cold stress significantly affects broiler health, welfare and performance (Blahova *et al.*, 2007; Yang *et al.*, 1999).
- Cold stress significantly affects broilers' health, welfare and performance (Blahova *et al.*, 2007; Yang *et al.*, 1999).
- Heat stress significantly affects broilers' health, welfare and performance (Daghir, 2001; Deaton *et al.*, 1997; DEFRA, 2008; Sohail *et al.*, 2012; Yanagi *et al.*, 2002; Yavah *et al.*, 2004).
- An important part of world broiler production is located in mild climate (e.g. Mediterranean climate).
- Spain is the thirteenth broiler meat producing country worldwide (FAO, 2015) and an important amount of this broiler production is concentrated in the Valencian Community (Martínez *et al.*, 2008).
- Nowadays, repetitive and massive episodes of broiler mortality and animal stress occur in hot seasons (El País, 2003) or climates with high temperatures and high relative humidity, especially in this strategic Mediterranean climate.
- Poultry production for meat in the third millennium needs to be revised to prevent these inadmissible thermal problems in terms of animal welfare and economic criteria, among others.
- Empiricism or intuition is not the way in the third millennium to build animal houses.
- As in any building, each broiler building needs to be designed according to the requirements for the entire period of its useful life. However, climate change and global warming cause meteorological uncertainty in the designs of any building (Holmes *et al.*, 2007) and evidently in livestock systems (Nardone *et al.*, 2010).
- Current broiler buildings are very heterogeneous in terms of dimensions, location of windows, doors, ventilation systems...

- Despite this heterogeneity, we can group the broiler buildings into categories or groups according to the mechanical ventilation system installed: cross, single-sided and tunnel.
- Current trends in studying the indoor environments and the characterisation of the ventilation in poultry buildings have two important methodologies: direct measurements with the appropriate instrumentation (Berckmans *et al.*, 1991; Blanes-Vidal *et al.*, 2010; van Wagenberg *et al.*, 2003; Wilhelm *et al.*, 2001; Zhang *et al.*, 1996) and indirect methods such as Computational Fluid Dynamics (CFD) techniques (Bartzanas *et al.*, 2007; Blanes-Vidal *et al.*, 2008; Lee *et al.*, 2007; Norton *et al.*, 2007).
- Using these methodologies, we can analyse and characterise the ventilation in different mechanical ventilation systems in different broiler buildings typologies.
- Each type of broiler building will be analysed by CFD techniques and direct measurements using suitable electronic instrumentation (sensors).
- The CFD simulations will be validated, as this point is crucial to ensure the results of the numerical simulations (Oberkampf *et al.*, 2002).
- We shall discuss the characteristics (advantages and disadvantages) of each type of the mechanical ventilation system.
- Through these analyses and characterisations, we shall establish futures design trends and protocols for new broiler buildings and retrofits of the broiler buildings already constructed, assessing the best operations in management terms.
- This PhD dissertation will be a big step towards finding optimum models for broiler buildings and the associated best ventilation systems.
- To meet these objectives, other related variables of the broiler building design such as the cooling system will also analysed and designed.

Chapter 2

- A multi-sensor system is necessary to receive enough signals from a large number of points due to the turbulent nature of mechanical ventilation (Heber *et al.*, 1996).
- Due to the turbulent nature of the airflow in mechanical ventilation, the changes in values of air velocity at the same point and in the same scenario are large.
- Field measurements show great fluctuation in the values when measuring air velocity and in some cases the standard deviation is nearly the average.
- Isolated measurements only, or small numbers of sensors, are not valid to perform studies of broiler building indoor environments.

- The isotemporality in receiving signals from the sensors is crucial.
- Absence of operators and minimum maintenance are required to prevent possible distortions of the measurements during the field experiments (Wheeler *et al.*, 2003).
- For their advantages, hot-wire type sensors and RTDs, respectively, were chosen for air velocity and temperature (Ibrahim, 2002).
- The sensors are calibrated with great success.
- The use of dummy variables (Kutman *et al.*, 2005) for sensor calibration has been an innovative method for this purpose.
- The different calibration curves (very similar) indicate that slight differences among sensors could arise from differences in the fabrication process or components.
- This isotemporal multi-sensor system was able to integrate the calibrated sensors of temperature, air velocity and differential pressure.
- The measurement system included a laptop, a data acquisition card, a multiplexor module and a set of 24 air temperature, 24 air velocity and 2 differential pressure sensors. The system was able to acquire up to a maximum of 128 signals simultaneously at 5 second intervals.
- A wyred system is preferable to wireless, because more energy consumption is involved and it is necessary to change the batteries, distorting the operator recordings. Moreover, a wireless system is not suitable for our needs when measuring throughout rearing.
- According to the evaluation of effects on air velocity measurements, results obtained show that the variation between sensors was not significant (P-value< 0.4428).
- The lack of statistical significance of the "Sensor" variable in this simple effect indicates homogeneous behaviour of all sensors on average for the different sections and boundaries studied.
- A measurement system for these aims must be robust to withstand the aggressive environmental conditions (e.g., dust, high relative humidity and gas concentration), occurring in broiler buildings during poultry rearing.
- Although the field experiments were conducted in an empty broiler building, the measurement system is robust to work with poultry.

- In occupied broiler houses, indoor environmental boundary conditions are more complex than in an empty broiler building, making it necessary to measure not only air velocity, but also indoor temperature, differential pressure and relative humidity.
- Additional sensors (i.e., humidity sensors) can be implemented at the other channels of the collecting module for wider studies in occupied broiler houses.
- In occupied broiler houses, sensors placed at poultry level must be protected (e.g., using a mesh) to avoid access by the poultry. It is also recommendable to include more sensors at a different level above the birds' heads in order to reduce the effect of the animals on measurements.
- This multi-sensor system was tested in a cross mechanically ventilated broiler building of the Valencia Community (Spain).
- From these measurements, we concluded that cross-mechanical ventilation is a good system for mild weather, but it is neccessary to explore other conditions of the ventilation system to prevent episodes of high mortality during summer months, as this mechanical ventilation system does not provide high air velocities at broiler level.
- The overall average of these measurements is 0.63 ± 0.54 m s^{-1}.
- The multi-sensor system developed can be used to obtain quasi-instantaneous fields of the air velocity and temperature, as well as differential pressure maps to assess the design and functioning of ventilation system and as a V&V system of CFD simulations.

Chapter 3

- CFD simulations were performed in the same broiler building and scenarios of the chapter 2.
- As we expected in the previous chapter, the CFD results of this cross mechanically ventilated broiler building show low air velocity values.
- Minor differences were found between CFD results and direct measurements using the multi-sensor system. Thus, the average air velocities values using CFD techniques were 0.60 ± 0.56 m s^{-1}, whereas in direct measurements using the multi-sensor system they were 0.64 ± 0.54 m s^{-1}.
- An ANOVA model and a regression line were proposed to perform the validation of CFD results.
- In this ANOVA model, we concluded that the "Methodology" variable was not significant (P-value <0.5271), and the same was found for its interactions.

Accordingly, there is no difference in using the CFD techniques or the direct measurements with the multi-sensor system employed here.

- In the regression line the slope was near one and the independent term near zero. The coefficient of determination of the linear regression shows a good fit, R^2= 0.888.
- An important advantage of CFD simulations is that they provide a visual representation which gives a comprehensive idea of the airflow trends, in which parameters are represented by colours or vectors at different trial scenarios.
- These graphic representations also provide additional information on airflow characteristics and patterns, which may contribute to a more effective ventilation design.
- CFD techniques provide more points of knowledge and a more general view of indoor climatic conditions of broiler buildings through the graphics than direct measurements.
- As we concluded in chapter 2, we can affirm that mechanical cross ventilation systems are adequate under the most common weather conditions, but they do not prevent episodes of mortality caused by heat stress, as they provide lower velocity values than those required by animals in these conditions.
- A main issue of study should be how to achieve a homogeneous distribution of increased air velocity at poultry level to reduce broiler stress and the associated mortality in summer seasons, and at the same time to keep an acceptable level of energy consumption.

Chapter 4

- Tunnel-type mechanical ventilation was studied in a broiler building in Mediterranean climate.
- It was analysed using two methodologies: direct measurements by means of the multi-sensor system and CFD simulations.
- Both methodologies (CFD and direct measurements) showed similar air velocity results.
- At broiler level (0.25 metres), the maximum air velocity was 2.72±0.31 $m \cdot s^{-1}$ (CFD) and 2.58±0.29 $m \cdot s^{-1}$ (measurements).
- An ANOVA model and a regression line were proposed to perform the validation of CFD results.

- The validation for CFD simulations performed in the ANOVA analysis concluded that the "Methodology" variable (results by CFD simulations or direct measurements) is non significant (P-value<0.1155), along with its interactions. Thus, we can use direct measurements or CFD simulations to explore indoor air velocity in this ventilation system in broiler buildings.
- In the regression line the slope was near one and the independent term near zero. The coefficient of determination of the linear regression shows a good fit R^2= 0.98.
- As the experimental broiler building is a retrofit of a traditional cross mechanically ventilated broiler building of these areas, the inlets are concentrated in the lateral end of the opposite wall of fans.
- This ventilation system is very commonplace in some countries (USA, Brazil, countries of tropical climate...); it has only recently been incorporated in southern Europe.
- The aim of adopting this ventilation system is to solve the repetitive mortality and animal stress in summer seasons in southern Europe (Mediterranean climate).
- Mechanical tunnel ventilation provides high air velocity values to increase the convective flux heat of broilers and thereby decrease the thermal stress and associated mortality.
- Thermoregulation of the broilers by high air velocities around the poultry is crucial to decrease their thermal stress and mortality (DEFRA, 2008).
- The current traditional ventilation system (cross mechanical) in Mediterranean climate is not valid for hot seasons or weather, as it does not provide high enough air velocity.
- Except for the publication of this chapter, no published article addressing management and air velocity distribution *vs.* fans in action is found.
- In this experimental broiler building, we observed three differentiated zones: inlets zone, central zone and near the fans. Relevant problems of very high air velocity values near the fans are found; in contrast, near the inlets a "dead zone" (low air velocities) and great changes are also found.
- Mechanical tunnel ventilation is still not optimised, due to the issue of air velocity heterogeneity at broiler level (0.25 metres), finding full valid behaviour in the central zone of the experimental broiler building.

- Mechanical tunnel ventilation was not the ideal design for broiler buildings of short length because the best and most homogeneous indoor environment is only located in the central zone.
- Higher electricity consumption is needed than in the traditional ventilation system (cross) in winter or cold seasons to heat the incoming air.
- In summer seasons, the farmers in these areas can save the energy used to run the fans, as with a small number of fans working they can achieve the same air velocity values as when using a large number of fans in the traditional ventilation system.
- Due to the ease with which high air velocity values are reached, inappropriate management can easily lead to health problems in broilers due to possible excessive ventilation.
- Although tunnel mechanical ventilation can be used for normal weather in Mediterranean climate, the traditional ventilation system (cross) is more suitable because the broiler density is higher, as in tunnel-type ventilation there are areas of the broiler building that cannot be occupied by broilers due to problems of air velocity distribution.
- Management of tunnel ventilation is more complicated and the programming of fans in action requires more time and experience than in cross (traditional) ventilation.
- Mechanical tunnel ventilation solves the problems of thermal stress and associated mortality in some latitudes of the Mediterranean climate, but is only fully valid for the hot season.
- In future works, we can optimise this ventilation system using “virtual” geometries and BC by means of CFD techniques validated in this chapter.

Chapter 5

- Mechanical single-sided ventilation in livestock buildings was studied in a broiler building under a negative pressure system.
- Except for publication of this chapter, no published scientific literature was found referring to mechanical single-sided ventilation in livestock buildings or broiler buildings.
- This emergent ventilation system has recently been incorporated, especially in Mediterranean areas and designed for some businesses in the sector (Serupa, 2015; Warkup, 2015) without scientific justification or publication.

- Mechanical single-sided ventilation was analysed using two methodologies: direct measurements by means of the multi-sensor system and CFD simulations.
- Both methodologies (CFD and direct measurements) showed similar air velocities, (at broiler level, between ~0.40 m s^{-1} and ~1.30 m s^{-1}).
- An ANOVA model and a regression line were proposed to perform the validation of CFD results.
- The validation for CFD simulations performed in the ANOVA analysis concluded that the “Methodology” variable (results by CFD simulations or direct measurements) is non significant (P-value<0.3908), along with its interactions. Thus, we can use direct measurements or CFD simulations to explore indoor air velocity in this ventilation system in broiler buildings.
- In the regression line the slope was near one and the independent term near zero. The coefficient of determination of the linear regression shows a good fit R^2= 0.98.
- A minimum acceptable systematic error (overestimation of CFD simulations by 6.6 %) was found.
- The “Diffuser” influence (an element to avoid direct airflow to the poultry, which may suffer from colds or respiratory diseases) has been also tested concluded that its use is not significant (P-value<0.6106), as well its interactions. Thus, the inclusion of the diffuser altered the air velocity distribution, but no significant variations or tendencies were observed.
- Highest ventilation rates in the broiler building (much exhausted air) do not necessary imply much air velocity at broiler level. Thus, the adopted geometry of the broiler building (physical configuration of inlets and outlets, associated BC…) is crucial to obtain a determinate air velocity distribution and values, more than the rates of ventilation of the whole broiler building.
- Having validated the CFD simulations, we can use CFD techniques to explore “virtual” geometries of broiler buildings and to find the optimum building designs, best scenarios and associated best management practices of this ventilation system.
- CFD simulations offer more possibilities (full knowledge of the indoor environment, easy building of “virtual” broiler houses and geometries, illustrative graphics…) than complex direct measurements.

- The air velocity values are acceptable for normal weather in Mediterranean climate and slightly higher than those obtained in cross-mechanical ventilation, although a future precise comparison is necessary.
- The minimum CFD-value of air velocity at broiler level (0.25 metres) was 0.52±0.40 m s^{-1} and the maximum was 1.29±0.41 m s^{-1}.
- Mechanical single-sided ventilation is a good ventilation system for broiler production only in normal weather conditions, as it does not provide much air velocity at broiler level to prevent occasional episodes of high mortality or thermal stress in hot seasons or hot climate.
- Use of the diffusers is recommended because they do not significantly alter the values of indoor air velocities at broiler level, as the farmers erroneously used to believe, and they prevent high air velocities near the broilers that can cause respiratory diseases.
- Mechanical single-sided ventilation entails two important issues: the great heterogeneity of the air velocity distribution at broiler level and the poor ventilation in some areas of the broiler building (opposite wall of the fans and between them).

Chapter 6

- It is possible to use CFD procedures to design heating or cooling systems in broiler buildings.
- In the case of heating systems, the radiators or heat sources can be modelled in CFD (Sevilgen *et al.*, 2011; Zajicek *et al.*, 2014).
- In the case of cooling systems, it is possible to analyse the pad cooling (Franco *et al.*, 2011) or the fogging system using CFD.
- An optimum fogging system design needs a full knowledge of the indoor air velocity.
- By means of CFD it is possible to know the full behaviour of the indoor air velocity profiles (magnitude and directionality).
- In a tunnel mechanical broiler building, the location of the pipes and orientation of the fog spray nozzles was designed based on the information obtained from CFD air velocity results (magnitude and directionality).
- Each broiler building model will have a specific optimum design of the location of the pipes and orientation of the fog spray nozzles according to the specific indoor nature of the air velocity.

- CFD techniques can determine the optimum design of the location of the pipes and orientation of the fog spray nozzles for each type of broiler building and ventilation system installed.
- A protocol for maintenance and estimation of water consumption within a cooling time is proposed.

Chapter 7

- Broiler production in the third millennium needs to incorporate all the advantages of all type of the current mechanical ventilation systems (transversal and longitudinal).
- An important premise when designing a broiler building is to know the exact climatology at the moment and for the future.
- A building needs to be entirely designed for the whole period of its useful life.
- It is necessary take into account future breakthroughs in building design and devices.
- Weather predictions entail great uncertainty due to the effects of climate change or global warming. In this sense, some climate areas can be converted into other areas within short and/or unexpected periods of time.
- The general optimums and the specific optimums were differentiated because the specific optimums are conditioned by particular needs (the specific requirements of the clients, specific dimensions and size of the broiler building, planned investment, number of animals, etc.) based on the general optimum model outlined here.
- In areas with some climatic uncertainty or average climate such as the Mediterranean, the ideal is a hybrid mechanical ventilation system: one ventilation system for winter or cold seasons (medium-low air velocities) and another ventilation system for hot seasons (medium-high air velocities).
- In some cases, the installation of a double (hybrid) mechanical ventilation system can be uneconomical in some areas because the losses in mortality and efficiency in the final weigh of broiler are outweighed by the investment in a mechanical ventilation tunnel system for only a small part of the hot seasons.
- From an ethical and animal welfare standpoint, it is immoral to maintain only one mechanical ventilation system if there are possibilities of mortality or animal suffering due to thermal stress.

- There must be planned laws to regulate, depending on the geographical location where it is compulsory to install both ventilation systems.
- Farmers of Mediterranean areas would choose as the transversal system the cross-mechanical ventilation, because it is already installed and/or known, more than single-sided.
- Using CFD techniques, validated in this PhD dissertation, we can build "virtual" geometries of broiler buildings to determine the specific optimum broiler design, the best ventilation system and assess the most appropriate management operations.
- In this search of optimum broiler building design, it is necessary to homogenise the required air velocity to avoid indoor migration and larger concentrations in some areas of the building, which also cause stress and mortality.
- Adequate indoor air velocity is not equivalent to the adequate required oxygen of the broilers. In mechanical tunnel ventilation, it is possible to obtain the required air velocity with a discrete number of fans in action but the oxygen needs must be controlled.
- Due to the specific nature of mechanical tunnel ventilation, the age of the air (the time inside the broiler building) is greater that in mechanical transversal ventilation systems (cross, single-sided…). Thus, the concentrations of pollutants of the air in tunnel systems may be higher, especially at the end of air trajectories (near fans) (Carvalho *et al.*, 2012). Pollutant concentrations affect the indoor environment as well as the broilers.
- These different design variables must be evaluated and quantified. The use of heuristic algorithms making restrictions on the variables (investment, days of use of one mechanical ventilation system, number of broilers…) determining an objective function (Gen *et al.*, 2000; Goldberg, 1989; Tam, 1992) will be the means to search for specific optimum broiler building designs.
- In future studies, it will be necessary to choose the appropriate heuristic algorithm (Gen *et al.*, 2000; Goldberg, 1989; Tam, 1992) to achieve easy convergence of results.
- It is possible to extend the protocols of this PhD dissertation to other livestock buildings such as cattle, pigs, rabbits…
- In our region (Valencian Community) and in Mediterranean countries, the indoor environments of rabbit houses have not yet been analysed in depth. This animal house model can be analysed using CFD and sensors in a similar methodology as that for broiler buildings described in this PhD dissertation.

8.2. General conclusions

All the chapters have followed a logical, chronological order according to the general aim, specific objectives and particular needs with the aim of analysing and characterising the different mechanical ventilation systems installed in different types of broiler buildings. In this PhD dissertation, three-dimensional CFD simulations were developed in order to analyse and characterise the three main mechanical ventilation systems (cross, single-sided and tunnel) installed in broiler buildings. In this vein, an original multi-sensor system conceived and built for this PhD dissertation carried out the corresponding measurements in large field experiments. The precise validation of CFD simulations by means of regression lines and validation models shows the good accuracy of these numerical results. Finally, and according to these characterisations, the general optimum for a broiler building was outlined. Thus, the general conclusion is that the general aim and the associated specific objectives have been sufficiently covered in this PhD dissertation.

By means of this PhD dissertation, several contributions to the scientific and academic community have been made, obtaining the fourteen skills in the general discussion described above. In this way, important perspectives for application and transference in academic and professional contexts can be found in this PhD dissertation. Of course, the research methods (CFD, sensors and validation of CFD) make up the bulk of the contribution (the numerical setups such as the turbulence models' analyses, boundary conditions and simulations, etc. were improved). However, in my opinion the main contribution is the ability to integrate and improve all of the very different spheres of knowledge involved in this PhD dissertation at the same time. In this sense, I think that the resulting monographic work (the PhD dissertation) has exponentially improved the isolated chapters or spheres of specific knowledge (CFD, sensors, validation, field experiments, biological issues, aviculture, etc.). The entire systematisation, organisation, integration, evaluation, coherence, synthesis of ideas, skills, methods, results and their critical analyses within the monographic work has all enriched the chapters already published and submitted much more.

Although the different statements and particular conclusions for each chapter have been outlined above, they can be summarised as follows:

1. Broiler production is very important and intensive production takes place in broiler buildings with mechanical ventilation, mainly by negative pressure by means of exhaust fans.

2. These broiler buildings are not optimised and there is currently no optimum model of a broiler building with mechanical ventilation, either in term of dimensions and/or design or from the point of view of the ventilation system.
3. Ventilation plays a critical role in ensuring appropriate indoor conditions to achieve high animal productivity (growth and food conversion) and low mortality.
4. Empiricism or intuition is not the way to build animal houses in the third millennium.
5. Current trends in studying indoor environments and the characterisation of the ventilation of broiler buildings apply two important methodologies: direct measurements with the appropriate instrumentation and indirect methods such as CFD techniques.
6. The instrumentation (measurement system) must be integrated for a large number of sensors receiving signals in an isotemporal regime, due to the turbulent nature of mechanical ventilation. In broiler buildings, the main environmental parameter to be studied is the air velocity, since this can serve to control the biological thermoregulation of the broilers to minimise their thermal stress. On hot days or hot seasons in a mild climate, high air velocity values reduce the heat stress and associated mortality.
7. Validation of CFD simulations is crucial, as using CFD techniques we can achieve fuller knowledge of the ventilation (not only the discrete physical sensors), to build “virtual” geometries of broiler buildings and “virtual” ventilation systems to search the optimum models.
8. There are many variants of mechanical ventilation in broiler buildings, the main ones being transversal (cross or single-sided) and longitudinal (tunnel).
9. Cross mechanical ventilation is the traditional ventilation system in Mediterranean climate, but cannot solve the problems of mortality and thermal stress of the broilers because it does not achieve high air velocity values. Thus, the biological thermoregulation of the birds by means of high air velocity values is the key point. On the other hand, tunnel mechanical ventilation provides high air velocity values and is the solution for the hot seasons (summer).
10. We can optimise each ventilation system and associated architecture separately using CFD simulations or the hybrid mechanical ventilation system (transversal plus longitudinal) if the broiler building is located in an area with climatic uncertainty. This optimisation involves an integration of different design variables and requires the proper air velocities needed by the animals at each period of rearing. Homogeneity of air velocity at the level of presence of the animals is required because indoor migrations and bigger concentrations in some areas of the building also cause stress and mortality. The oxygen requirements and low levels of pollutants must be controlled.

These large general statements and conclusions can be summarised to the minimum length in five spheres:

1. **Instrumentation:** We built and tested the instrumentation to measure indoor environmental parameters (especially the air velocity parameter, as it is the key to reducing thermal stress and mortality by controlling their thermoregulation) in modern broiler buildings.
2. **CFD:** We used the CFD tool to analyse and characterise the different mechanical ventilation systems in different broiler building typologies.
3. **Validation:** We have validated the CFD simulations.
4. The **analysis and characterisation of each main type mechanical ventilation** in different broiler buildings: We analysed the different ventilation systems (**cross, single-sided and tunnel**), concluding that transversal ventilation systems (cross and single-sided) are appropriate for broiler rearing all year round in a mild climate, except in hot seasons or heat waves, as the air velocity cannot achieve sufficiently high values. On the other hand, in mechanical tunnel it is possible to achieve high air velocity values and it is valid for hot seasons or heat waves. In all cases, the heterogeneity at the plane of presence of the animals is found and this fact is an important problem, as indoor migration and larger concentrations of animals appear, which also cause stress.
5. **The optimum broiler building design**: In mild climate (e.g. Mediterranean climate) and some areas with climatic uncertainty, the broiler building will need to incorporate a hybrid mechanical ventilation system (tunnel and another transversal) to solve all the possible climatic events. Tunnel ventilation system for some occasional days of hot seasons or heat waves and a mechanical transversal system (cross or single-sided) for the whole year, except for hot periods. Climate change and global warming must be taken into account, as a broiler building needs to be designed for the entire period of its useful life and these effects strongly condition the concept of the broiler building. In some cases and in some geographical locations, the hybrid mechanical system will be uneconomical, but can solve the problems of improving thermal comfort in animal welfare.

In some areas of constant hot weather, the optimum broiler building design will incorporate a single optimised tunnel ventilation system. On the contrary, in some areas of constant medium/cold weather, the broiler building optimum design will incorporate a single optimised transversal ventilation system.

8.3. Future work

The first paragraph of the motivation to this PhD dissertation was: «Earth's planet is overpopulated and a great percentage of its people suffers famine or is not properly fed. For the future, biological, agricultural and industrial engineers face a great challenge: to provide the necessary food knowing that the land is limited, offer it at a reasonable price-quality to reach all social strata and supplying food considering the rapid increase in population. At this point, intensive production (not exempt from controversy) in agriculture, livestock and fisheries is crucial to provide food to the earth's population». I hope that this modest PhD dissertation has contributed in some way to help find methods to increase the production of broilers through procedures respectful with nature, animals and humans. In this sense, this sustainable increase in production must lower the cost of this meat to reach all social strata, while at the same time increasing the economic benefits for the farmers.

In future works, we can continue to seek specific optimum models for broiler buildings using CFD simulations under the guidance of heuristic algorithms.

Future CFD simulations should include the presence of the broilers. These broilers could be modelled in CFD as heat sources or radiators, taking different heat emission values depending on the week of rearing.

In the study of occupied broiler buildings, additional sensors (i.e., humidity sensors...) can be developed and integrated into the multi-sensor system.

New prototypes of multi-sensor systems (e.g. air velocity sensors that determine the components...) can be developed by first experimenting with the ventilation in laboratories and later in the broiler buildings.

In occupied broiler buildings, new CFD results can be validated and analysed (i.e. temperature, humidity...).

Each ventilation system and associated architecture of the broiler building can be optimised separately. In some clear areas (milder climate or tropical climate without climatic uncertainty) a mechanical hybrid system will not be the optimum choice. Nevertheless, in areas with climatic uncertainty, the hybrid ventilation systems composed of a longitudinal mechanical ventilation system and a mechanical ventilation transversal system must be optimised together using these CFD simulations under the guidance of the heuristic algorithms.

Other variables of broiler building design such as the heating systems (hothouses) or different cooling systems (pad cooling...) can be also studied using the synergy of direct measurements and the CFD simulations.

Livestock fans or other turbo-machinery can be studied using CFD techniques and direct measurements to obtain easy boundary conditions such as the ventilation rate without the current complex procedures.

Other livestock buildings such as animal houses for pigs, cattle, rabbits or turkeys… can be studied using CFD techniques and their buildings optimised by the procedures described in this PhD dissertation, because some parts of these studies can be extrapolated to other animal houses. A good line of research in our culture and country is the analysis of indoor environments of rabbit houses.

8.4. References

ASAE EP270.5. Design of Ventilation Systems for Poultry and Livestock Shelters. In ASABE Standards 2009; American Society of Agricultural and Biological Engineers (ASABE): St. Joseph, MI, USA, 1986; pp. 1–19.

Bartzanas, T.; Kittas, C.; Sapounas, A.A.; Nikita-Martzopoulou, C. Analysis of airflow through experimental rural buildings: Sensitivity to turbulence models. *Biosyst. Eng.* 2007, 97, 229–239.

Berckmans, D.; Vandenbroeck, P.; Goedseels, V. Sensor for continuous measurement of the ventilation rate in livestock building. *Indoor Air* 1991, 1, 323–336.

Blahova, J.; Dobsikova, R.; Strakova, E.; Suchy, P. Effect of low environmental temperature on performance and blood system in broiler chickens (Gallus domesticus). *Acta Vet. (Brno)* 2007, 76, 17-23.

Blanes-Vidal, V.; Guijarro, E.; Balasch, S.; Torres, A.G. Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. *Biosyst. Eng.* 2008, 100, 105–116.

Blanes-Vidal, V.; Guijarro, E.; Nadimi, E.S.; Torres, A.G. Development and field test of an on-line computerized instrumentation system for air velocity, temperature and differential pressure measurements in poultry houses. *Span. J. Agric. Res.* 2010, 8, 570–579.

Carvalho, T.M.R.; Moura, D.J.; Souza, Z.M.; Souza, G.S.; Freitas, L.G.; Lima, K.A.O. Use of geostatistics on broiler production for evaluation of different minimum ventilation systems during brooding phase. *R. Bras. Zootec.* 2012, 41, 194-202.

Corkery, G.; Ward, S.; Kenny, C.; Hemmingway, P. Monitoring environmental parameters in poultry production facilities. Institute for Process and Particle Engineering. Graz University of Technology, Graz, Austria, 2013.

Charles, D.; Walker, A. Poultry Environment Problems: A Guide to Solutions, 1st ed.; Charles, D., Walker, A., Eds.; Nottingham University Press: Nottingham, UK, 2002.

Daghir, N.C. Poultry Production in Hot Climates; CAB International: Wallingford, UK, 2001.

Dawkins, M.S.; Donnelly, C.A.; Jones, T.A. Chicken welfare is influenced more by housing conditions than stocking density. *Nature* 2004, 427, 342–344.

Deaton, J.W.; Reece, F.N.; Mcnaughton, N. The effect of temperature during the growing period on broiler performance. *Poult. Sci.* 1997, 57, 1070-1074.

DEFRA (Department for Environment, Food and Rural Affairs). Heat Stress in Poultry. Solving the Problem; DEFRA: London, UK, 2008.

El País, Anonymous. Medio millón de pollos mueren fuerte calor últimos días. Available online: http://www.elpais.com/articulo/Comunidad/Valenciana/Medio/millon/pollos/mueren/fuerte/calor/ultimos/dias/elpepiespval/20030617elpval_4/Tes (accessed on 14 June 2015).

FAO. Faostat-Agriculture. Available online: http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor (accesed on 14 June 2015).

Franco, A.; Valera, D.L.; Peña, A.; Pérez, A.M. Aerodynamic analysis and CFD simulation of several evaporative cooling pads used in Mediterranean greenhouses. *Comput. Electron. Agr.* 2011, 76, 218–230.

Gen, M.; Cheng, R. Genetic algorithms and engineering optimization; Wiley Ed.; 1st Edition: New York, USA, 2000.

Goldberg, D.E. Genetic algorithms in search, optimization and machine learning; Addison-Wesley Longman Publishing Co., 1st Ed.: Boston, MA, USA, 1989.

Havenstein, G.B.; Ferket, P.R.; Qureshi, M.A. Growth, livability and feed conversion of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. *Poultry Sci.* 2003, 82, 1500–1508.

Heber, A.J.; Boon, C.R.; Peugh, M.W. Air patterns and turbulence in an experimental livestock building. *J. Agric. Eng. Res.* 1996, 64, 209–226.

Holmes, M.J.; Hacker, J.N. Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century. *Energ. Build.* 2007, 39, 802–814.

Ibrahim, D. RTD Temperature Sensors. Microcontroller Based Temperature and Control; Newnes: Oxford, UK, 2002.

Kutman, M.H.; Nachtsheim, J.; Nefer, J.; Li, W. Applied Linear Statistical Models; McGraw Hill: New York, NY, USA, 2005.

Lee, I.B.; Sase, S.; Sung, S.H. Evaluation of CFD accuracy for the ventilation study of a naturally ventilated broiler house. *Jpn. Agric. Res. Q.* 2007, 41, 53–64.

Lott, B.D.; Simmons, J.D.; May, J.D. Air velocity and high temperature effects on broiler performance. *Poultry Sci.* 1998, 77, 391–393.

Martínez, M.; Marín, C.; Torres, A.; Laínez, M. Characterization of chicken farm of the Valencian Community (In Spanish); Fundación Agroalimed, Conselleria d´Agricultura, Pesca i Alimentació. Generalitat Valenciana: Valencia, Spain, 2008; pp. 93–97.

MWPS. Mechanical Ventilating Systems for Livestock Housing, 1st ed.; Midwest Plan Service, Iowa State University: Ames, IA, USA, 1990.

Nardone, A.; Ronchi, B.; Lacetera, N.; Ranieri, M.S.; Bernabucci. U. Effects of climate changes on animal production and sustainability of livestock systems. *Livest. Sci.* 2010, 130, 57–69.

Norton, T.; Sun, D.; Grant, J.; Fallon, R.; Dodd, V. Applications of computational fluid dynamics (CFD) in the modeling and design of ventilation systems in the agricultural industry: A review. *Bioresour. Technol.* 2007, 98, 2386–2414.

Oberkampf, W.L.; Trucano, T.G. Verification and validation in computational fluid dynamics. *Prog. Aerosp. Sci.* 2002, 38, 209–272.

Pedersen, S. Forced Ventilation. In CIGR Handbook of Agricultural Engineering: Animal Production & Aquacultural Engineering; American Society of Agricultural Engineers (ASAE):St. Joseph, MI, USA, 1999; pp. 68–87.

Serupa. Serupa France Webpage. Available online: http://www.serupa.fr (accessed on 14 June 2015).

Sevilgen, G.; Kilic, M. Numerical analysis of air flow, heat transfer, moisture transport and thermal comfort in a room heated by two-panel radiators. *Biosyst. Eng.* 2011, 43, 137-146.

Slingenbergh, J.; Gilbert, M. Do Old and New Forms of Poultry Go Together? In Proceedings of the International Poultry Conference, Bangkok, Tailand, 5–7 November 2007. Available online: http://www.fao.org/ag/againfo/home/events/bangkok2007/docs/part2/2_3.pdf (accessed on 14 June 2015).

Sohail, M.U.; Hume, M.E.; Byrd, J.A.; Nisbet, D.J.; Ijaz, A.; Sohail, A.; Shabbir, M.Z.; Rehman, H. Effect of supplementation of prebiotic manan-oligosaccharides and probiotic mixture on growth performance of broilers subjected to chronic heat stress. *Poult. Sci.* 2012, 91, 2235–2240.

Steinfeld, H., Gerber, P.; Wassenaar, T.; Castel, V.; Rosales, M.; de Haan, C. Livestock's long shadow environmental issues and options. FAO, 2006.

Tam, K.Y. Genetic algorithms, function optimization, and facility layout design. *Eur. J. Oper. Res.* 1992, 63, 322-346.

Teagasc. Energy use in agriculture. Oak Park, Carlow, Ireland, 2011.

Van Wagenberg, A.V.; de Leeuw, M.T.J. Measurement of air velocity in animal occupied zones using an ultrasonic anemometer. *Appl. Eng. Agric.* 2003, 19, 499–508.

Warkup. Warkup Webpage. Available online: http://www.amwarkup.co.uk/single_sided_buildings.html (accessed on 14 June 2015).

Wheeler, E.F.; Zajaczkowski, J.L; Saheb, N.C. Field evaluation of temperature and velocity uniformity in tunnel and conventional ventilation broiler houses. *Appl. Eng. Agric.* 2003, 19, 367–377.

Wilhelm, L.R.; Milner, J.M.; Snyder, S.D.; McKinney, D.B. An instrumentation system for environmental measurements in broiler and swine housing. *Appl. Eng. Agric.* 2001, 17, 677–681.

Yanagi, T.; Xin, H.; Gates, R.S. A research facility for studying poultry responses to heat stress and its relief. *Appl. Eng. Agric.* 2002, 18, 255–260.

Yang, H.M.; Lee, S.Z. Research progress of cold stress in animals. *Heilomgjiang Anim. Sci. Vet. Med.* 1999, 3, 42-44.

Yavah, S.; Straschnow, A.; Luger, D.; Shinder, D.; Tanny, J.; Cohen, S. Ventilation, sensible heat loss, broiler energy and water balance under harsh environmental conditions. *Poult. Sci.* 2004, 83, 253–258.

Zajicek, M.; Kic, P. Heating of large agricultural and industrial buildings. *Agronomy Research* 2014, 12, 237-244.

Zhang, G.; Strøm, J.S.; Morsing, M. A Computerized Multi-point Temperature and Velocity Measurement System. In Proceedings of the Fifth International Conference on Air Distribution in Rooms (RoomVent'96), Yokohama, Japan, 17–19 July 1996; pp. 531–538.