Airborne pollutant emissions from naturally ventilated buildings: proposed research directions

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Abstract

The present article describes the current research focus and the future research trends associated with investigating emissions from naturally ventilated buildings as identified at the technical session entitled "Emission from naturally ventilated buildings (Measurement, modelling, reduction and assessment)", that was held during the International Commission of Agricultural and Biosystems Engineering (Commission Internationale du Genie Rural, CIGR) World Congress in Quebec, Canada, between the 13th and 18th of June 2010.

Current knowledge and measurement techniques can only provide reasonable estimates of emissions from naturally ventilated livestock buildings. Thus, further research and development are required. Its final goal is a point where the measurements are precise enough to validate simulation models and to obtain more consistent and accurate emission estimates. To achieve this, better synergy between mathematical modelling, physical modelling and field measurements of ventilation rates in naturally ventilated livestock buildings is required.

The review of the research presented at the Quebec meeting identified the following intermediate goals:
1. Investigate and determine error sources and measurement inaccuracies. Error analysis might be necessary to interpret results and establish research priorities.

2. Develop intelligent ventilation control systems that can handle highly fluctuating ventilation condition in naturally ventilated livestock buildings.
3. Develop practical field methods that can be used as reference standards.
4. Establish a dedicated facility that could be used to obtain precise reference measurements of ventilation rates in naturally ventilated building. To enable this, a parallel development of new technologies (instrumentation and methodology) is required.

1. Introduction

Environmental impact of ammonia (NH_3) and greenhouse gases (GHG) as well as odour and aerosol emissions from livestock buildings has been identified as important issues in the last decades. Considerable efforts, (mainly on NH_3 emission) have been extended to (1) understand the mechanisms of emission, (2) to solve problems associated with measurement accuracy and (3) to reduce emissions. Despite all these efforts; there are still challenges and problems associated with measuring emissions from naturally ventilated (NV) buildings that agricultural engineers and scientists have to solve. NV livestock buildings need to have large openings to obtain required ventilation rates. Consequently, the difference between inside and outside air pressure is extremely small, i.e. often 1 Pa or lower, and outdoor wind direction and speed plays the main role for the air exchange in the building. This results in rapidly fluctuating airflow, changing air inlet and outlet locations and non-homogeneous pollutant distribution. Our knowledge about these dynamic conditions for airflow and pollutant emission is not at the level, where we can measure ventilation rates and pollutant/gas concentrations precise enough to validate simulation models and obtain consistent and accurate emission estimates.

With this background in mind, a technical session entitled “Emission from naturally ventilated buildings (Measurement, modelling, reduction and assessment)” was included in the World Congress of International Commission of Agricultural and Biosystems Engineering (CIGR) in Quebec on 13 -18 June 2010. Agricultural engineers and scientists from all over the world gathered and discussed the latest achievements in order to identify future research opportunities. Participating scientists agreed to work together to publish this present Special Issue “Emissions from naturally ventilated livestock buildings” to clarify the important aspect of emission measurement from NV livestock buildings.

This article aims at describing the current research focus and the future research challenges associated with investigations of emissions from NV livestock buildings as identified at the Quebec meeting. For facilitating the interpretation, some of the research topics are cross referenced to the papers included in the conference proceedings and in this preset Special Issue, where more detailed analyses and in-depth discussions can be obtained.

2. Overview of the Quebec meeting

Table 1 shows the results from categorization of the 24 presentations at the Quebec meeting. The majority of the presentations at the meeting focused on assessment methods. The main objectives of 11 presentations were to evaluate/improve known assessment methods and 7 presentations aimed at development/demonstration of new assessment methods. Assessment methods and their measurement accuracy were the main focus of 14 and 13 presentations, respectively. Researchers were interested in improving assessment methods, and then especially the accuracy of ventilation rate measurements. Ventilation and /or airflow measurement in the livestock buildings was identified, as the main study object of 14 presentations. Ammonia emission was the main study objective of 13 presentations. This indicates that NH_3 emission is an important environmental issue in many countries. Carbon dioxide (CO_2) measurement was the main study objective of 7 presentations. In most of the studies CO_2 concentrations were recorded in connection with the CO_2 mass balance method for determining ventilation rates. There were only a few studies dealing with GHGs, i.e. CO_2, methane (CH_4) and nitrous oxide (N_2O). Yet, it is no doubt that GHG emission from NV livestock buildings will have a more central role in research activities in coming years. It is expected that measurement of GHGs that are present in NV livestock buildings in very low concentrations (e.g. N_2O) , will require improved knowledge and measuring methods due to uncontrolled air movements and fluctuating pollutant concentrations. It was interesting to note that at the Quebec meeting there was no study presented on odour emission from NV livestock buildings. Possibly, there are fewer incidences of odour nuisance reported in conjunction with NV livestock buildings when compared to mechanically ventilated (MV) buildings. This may mainly related with the type of animals normally raised in NV respectively MV buildings in the countries with intensive livestock farming. Many of the presentations at the meeting dealt with cattle buildings, as most cattle buildings are naturally ventilated. However, in the temperate and hot climate regions, pigs are also raised in NV livestock buildings. Therefore, emissions and odour nuisance from NV pig buildings are as important as emissions from cattle buildings in these parts of the world.

3. Measurement accuracy

Placement of measurement points in relation to measurement accuracy was one of the main subjects at the Quebec meeting. By using a scaled open type dairy building model in a wind tunnel, Ikeguchi and Moriyama (2010) studied the tracer gas method for determination of the air exchange rates. The study demonstrated that (1) the locations of gas sampling in relation to the gas injection points and (2) airflows in the building have crucial effects on the measurement accuracy when the constant emission method was applied. The reported magnitude of the error was large. In fact, tracer gas methods have a crucial weakness because these methods assume that the air and the tracer gases mix perfectly in the ventilated airspace albeit a perfect mixing can only be obtained under an ideal condition. In addition, it is also assumed that the measurement points represent the average ventilation efficiency or gas emission within the ventilated airspace. With this in mind, Özcan and Berkmans (2010) studied measurement errors due to sampling positions by comparing the tracer gas method with a more precise measurement of the ventilation rate in a laboratory test installation. The experiments demonstrated that the measurement errors can be as high as 86% of the actual ventilation rate. By reviewing CO_2 production models and analyzing the results from field measurements, Zhang, Pedersen and Kai (2010) found that the potential error due to incorrect sensor placement increases progressively with the size of wall and roof openings and it can be the major error source in open buildings with high ventilation rates. The effect of the sensor placement on measurement accuracy is also influenced by the timing and the duration of the measurement due to the varying activity level over time and at different life stages of the animals.

Another error source for CO_2 mass balance method is the imprecise knowledge of CO_2 production in the buildings. The total CO_2 production includes CO_2 produced by the animals and CO_2 emitted from the manure. It is influenced by many factors such as feeding level, nutrient composition, animal activity and manure handling methods. It also varies diurnally, seasonally and over different growing stages.

The lack of a reliable reference method is the main reason for these error sources and their effects on the reliability of emission measurements in NV livestock buildings are not fully understood. Although establishment of a facility that provides reference measurements of ventilation rates in NV livestock building appears to be an elusive goal today; it is still highly desired. It would improve the ability of researchers to investigate and determine error sources and underlying mechanisms for measurement inaccuracies. Also more in-depth studies of the nature and contributions of individual errors sources to the overall measurement inaccuracy are necessary. The knowledge that might be generated by such research efforts would be an essential tool for development and selection of proper measurement techniques with higher accuracy at reasonable costs. The cost aspect is important as the measurement technique selected will only be used universally, if it can be obtained cost effectively. More detailed analyses and in-depth discussions on the origin and magnitude of errors are given by Calvet et al. (2012). Ogink et al. (2012) suggested to develop a practical field method that can be used as a ‘reliable standard’ reference. They found that improvements in tracer gas ratio methods might lead to a widely applicable reference method.

4. Methods to determine ventilation rates

4.1 CO_2 mass balance method

Reliability of the data on CO_2 production in the buildings and CO_2 concentration differences (ΔCO_2) between inside and outside of the building was an issue discussed at the Quebec meeting. Zhang, Pedersen and Kai (2010) reviewed the CO_2 production models and analyzed the results from field measurements of five dairy cattle buildings in order to estimate the feasibility of applying CO_2 production models for determination of the ventilation rates in NV livestock buildings. In animal buildings where the manure is not stored in the building for a long period, the CO_2 production from the manure handling system is small compared to the CO_2 production from animals. However, in animal buildings with deep litter (i.e. animal buildings where the depth of the litter is more than 0.5m), the CO_2 production from the litter can be significant. Because of this, it is difficult to estimate the ventilation rate in buildings with deep litter. They also noticed that the animal CO_2 production varies diurnally about ±20% due to animal activity. However, they also found that the diurnal variation in CO_2 production is of minor importance in open animal buildings with high ventilation rates. This is because the dominating error is caused by the difficulty of acquiring reliable CO_2 concentration measurements due to fluctuating airflow in such buildings. Calvet et.al. (2010) reported that a correction of ventilation rates for animal activity for CO_2 production was necessary to determine effects of dark and light photo period on the ventilation rates in MV buildings for broilers.

4.2 Tracer gas method

The tracer gas method enables measurement of ventilation rates in occupied buildings under real conditions. Use of the tracer gas method may facilitate an accurate estimation of ventilation rates since it takes into account the effect of occupancy and other conditions under actual field conditions, (such as the effects of structural components of the buildings, e.g. open doors and windows). SF_6 is a widely used tracer gas; but it is also a very potent GHG. Also Krypton85 is used as tracer gas although it has a human health hazard potential. This is due to the sensitivity of the detection method that allows the determinations of very high ventilation rates. Kiwan et al. (2010 and 2012) applied the method for determination of the air exchange rates in two NV buildings for dairy cattle. They compared it with the CO_2 mass balance method and with calculations based on a natural ventilation theory called discharge coefficient method. They found that the Krypton85 method is an appropriate technique to be used on farms; but further development is required. It deals with optimization of sensor location/distribution and mixing of tracer gas and air. The method is relatively unexploited compared with the CO_2 mass balance method. Nevertheless, it may gain more attentions as isotope measurement enables a high number of measuring points and delivers accurate concentration data with high spatial and time resolution.

4.3 Direct measurement

Kiwan et al. (2010) installed 24 impeller anemometers in two NV diary buildings along the side wall facing the dominant wind direction (upwind side) to measure the horizontal air velocity through the openings. They emphasized that the selection of measuring locations is a crucial factor for accurate measurements as it must ensure a sufficient accuracy in all expected openings of the curtain-wall.

Simultaneous monitoring of airflow and gas concentration at carefully selected multiple locations may provide better emission estimates than what is achieved today. However, non-homogeneous and fluctuating gas distribution and airflow put demands on the number of measurement locations, measurement frequencies and measurement periods. Practical measurement methods that can achieve all this cost effectively need to be developed. Wireless sensor networks with spatially distributed autonomous devices to sample gas concentrations and airflow data, maybe a candidate technology.

Ultrasonic anemometers that provide high frequency measurements of 3D air velocities are robust and easy-to-use instruments to monitor fluctuating airflow in relatively challenging and aggressive environments like animal buildings. They provide turbulent characteristic data indicating the airflow pattern around the measurement points. Multi point 3D ultrasonic anemometers are readily available.. By using such instruments, Fiedler et al. (2012) determined air velocities and turbulence characteristics in two NV buildings for dairy cattle to reveal effects of outside boundary conditions (approaching wind direction and velocity as well as obstructions due to other buildings) on inside airflow.

4.4 Imitation of naturally ventilated livestock building (NVB) with mechanically ventilated building (MVB)

In a turkey grow-out building, Jacobson, Hetchler and Noll (2010) demonstrated a method to determine ventilation rates (on a per animal basis) in a NVB. The method is based on the assumption that NVB and MVB were similar to each other in all aspects except regarding ventilation principles will produce similar relationships between CO_2 concentrations and ventilation rates per animal basis. The procedure of the determination of the ventilation rate in NVB was as follows: CO_2 concentration differences between outside and inside of the MVB and the NVB ($\Delta CO2_M$ and $\Delta CO2_N$) were measured continuously along with the ventilation rate (VR_M) in MVB. Then, ventilation rates (VR_N) in the NVB were determined by multiplying the ratio $\Delta CO2_M/\Delta CO2_N$ with the ventilation rate VR_M measured in the MVB. This is essentially a modified CO_2 mass balance approach. It relies on the same assumption regarding homogeneity of CO_2 in the room and placement of the measurement points as the CO_2 mass balance method. It has, therefore, the same weakness. However, the utilization of $\Delta CO2_M/\Delta CO2_N$ and VR_M that were determined in real animal buildings permits estimations based on near real conditions. This is probably the strength of the method compared with the ordinary CO_2 mass balance method, which uses prediction equations (for CO_2 and heat production) derived basically from laboratory experiments, which could differ significantly from actual farm conditions.

5. Methods to determine gas emission rate

Hassouna et al. (2010) proposed a new method of determining gas emission rates from cattle buildings. The study used gas-concentration gradients and mass-balance deficits of carbon which were estimated on the basis of livestock-related data (e.g., feeds, production, effluents) as well as intermittent measurements of outdoor and indoor gas concentrations (water, H_2O, CO_2, NH_3, CH_4, and N_2O), temperature and relative humidity. The method was validated with water-budget observations and simulation model predictions of CH_4 and CO_2 emissions exclusively from animals. For the studied buildings with slurry evacuated twice a day, a good agreement was found between CO_2 and CH_4 emissions estimated with the new method and those predicted by the simulation model. Whereas for the deep litter cattle buildings, it was observed that the emissions of CH_4 and CO_2 were higher than the emissions predicted by the simulation models.

The tracer gas ratio method, which is widely used to measure emissions from NV livestock buildings, relies on the assumption that the ratio between the emission rates of the pollutant and the tracer gas is equal to the ratio between the pollutant and tracer gas concentrations (Ogink et al., 2012). Schrade et al. (2010a; 2010b) applied the method with two different tracer gasses, (SF_6 and SF_5CF_3) in order to determine ammonia emissions from two different sources, i.e. a NV dairy building and the neighbouring outdoor exercise area. A photo acoustic sensor for NH_3 quantification and a recently developed GC-ECD method, which simultaneously quantifies the tracer gasses, were used. The diluted tracer gases were continuously injected directly above the emitting areas via tube systems with 46 critical capillaries, thereby mimicking the source of the NH_3 emissions. An air-collection system at a height of 3 m consisting of a Teflon hose and 39 glass critical capillaries 3 m apart was used for sampling of the tracer gases and NH_3. A set of relevant descriptive data such as weather conditions, climate in the building and at the outdoor exercise area, animals' area usage, aisle/exercise-area, soiling and nitrogen balance, were used to characterise measurement conditions. The method demonstrated its ability to quantify seasonal effects and variations between individual farms.

Reliable and robust sensors, which can provide high frequency concentration measurement of relevant gasses (e.g. NH_3, GHGs, odorous compounds, SF_6,) have to be developed and used in the livestock buildings for multi-location measurement of gas concentrations.

6. Modelling of gas emission

Modelling of gas emission involves studies on (1) pollutant production in the substrate (manure etc), (2) transfer from the liquid to the gas phase (3) transfer through the boundary layer (4) mixing inside the building envelope and (5) transport to the wider environment. Hassouna et al. (2010) and Schrade et al. (2010) presented studies on modelling of pollutant production. Wu, Kai and Zhang (2010) determined NH_3 concentrations and air velocities around simulated manure surfaces in a wind tunnel in order to get fundamental understanding on the nature of the NH_3 evaporation from manure, i.e. gas emission and transportation within and near the boundary layer. A review study of Bjerg et al. (2012a) presented in this Special Issue deals with ammonia release modelling. For the modelling of gas mixing inside the building envelope, researchers are working with two model categories: 1) CFD (Computational Fluid Dynamic) models (Bjerg and Andersen, 2010 and Choi et. al. 2010; Bjerg et al. 2012c), which require detailed geometrical modelling and 2) lumped models, which are faster to use and have greater potential to simulate the influences of weather conditions (Liberati and Zappavigna, 2010; Bjerg et al. 2012b). Lumped model simplifies the description of the airflow and approximate its behaviour under certain assumptions. It requires less geometrical details and computational time. These models might be applied to aid design of low emission buildings and to design intelligent online ventilation and emission control systems in NV livestock buildings. However, there are still substantial challenges related to generating experimental data for the development and validation of the models (Bjerg et al. 2012a, b, c). Ultimately, a set of models or a comprehensive simulation model, which can handle all processes, (i.e. from pollutant production in the substrate to the wider environment) is needed.

Youssef et al. (2010) demonstrated the usefulness of model-based procedures for the determination of NH_3 emission from manure storage. The model was developed based on the knowledge that NH_3 emission is strongly related to some easily measurable variables such as near manure surface air temperature and manure surface temperature. This method allows a continuous modelling of the NH_3 emission rates. They found that a steady-state regression model was good enough for calculation of the cumulative NH_3 emission over the whole measuring period.

Determining proper measurement locations requires good knowledge about airflows in the buildings. To obtain such knowledge, CFD modelling may be useful. Validation of the model can probably be done by using the data obtained by multi-position instrumentation of 3D ultrasonic anemometers.

Modelling is a cost effective method of obtaining knowledge about the performance of new technical solutions developed for emission reduction. Thus, many researchers invested efforts in model development. An important aspect of this work is the validation of the models, which is normally done by comparing the results obtained from the model with the experimental measurements. This means that no model, in principle, can be more accurate than the validation measurements. Unfortunately, as mentioned before, the current techniques used in the experimental studies can only provide reasonable estimates of emissions.

7. Flux chamber

Use of flux chambers for determination of pollutant emission from surfaces, e.g. floors and manure pits, appears to be a useful method for evaluation of abatement technologies. Mosquera et al. (2010) investigated characteristics of flux chamber measurements and studied spatial and temporal variation of floor surface emissions. For a good estimation of the NH_3 emissions from floors, they recommend to measure NH_3 emission at different floor sections thoughout a number of days and under different weather conditions. Studies of Wheeler et al. (2010) aimed at comparing NH_3 emissions from dairy manure as a whole-room mass balance calculation versus emission measurements performed within the room using portable flux chambers. Steady-state flux and non-steady-state recirculation flux chambers were used. The later was shown to be provide more accurate estimates by measuring 90 to 119% of ammonia emissions of the whole room's mass balance calculations. The steady-state flux chamber method, although universally recognized in USA for emission evaluations, demonstrated strong tendencies for underestimations. The flux chambers can potentially be used to also determine emissions of pollutants other than NH_3. Yet, at the Quebec meeting, there was no study involving measurements of other pollutants, e.g. CH_4, CO_2, N_2O and particulate. A more detailed review of flux chamber methods is given in this Special Issue by Ogink et al. (2012).

8. Abatement methods

By a laboratory experiment Wu, Kai and Zhang (2010) demonstrated the possibility of using pit exhaust in pollutant abatement: The most polluted air is drawn through pit exhaust and purified before it is released to the outside. According to their estimation; 70-80% of the NH_3 emission can be reduced by a pit exhaust rate of about 10% of the total ventilation rate. Van Dooren and Mosquera (2010) investigated the potential effects of two emission reduction principles: (1) Reducing floor emission by using a fast removal of urine and a separate removal of faeces by scrapers and (2) Reducing pit emissions by covering the slurry in the pit. They used the flux chamber method to estimate the effects and found more promising prospects with the first principle, i.e. reducing floor emission. Rets et al. (2010) cut concrete slatted floor elements out of the existing floor and brought them into closed chambers to measure NH_3 emission from the floor elements. The study was aimed at investigating the impact of the manure removal from the slatted floor. A special cleaning device, designed to combine the advantages of a wet, mechanical cleaning-method was used. It featured high-pressure water nozzles, mechanical star-discharge-rotors and a rubber-scraper. However, no significant effect on the NH_3 emission was detected by cleaning of the slats. In CFD modelling Bjerg and Andersen (2010) demonstrated a potential reduction of ammonia emissions from NV livestock building by adjusting the size of ventilation opening according to outdoor wind conditions in order to avoid over ventilation and consequently increase ammonia emission in windy periods. In addition the work demonstrated that a significant further reduction can be obtained by cleaning a minor airstream expelled mechanically from the pit beneath the slatted floor.

9. Conclusions/ Future research directions

Current knowledge and measurement techniques can only provide reasonable estimates of emissions from NV livestock buildings. Further research and development are required to develop measurements that are precise enough to validate simulation models and to obtain more consistent and accurate emission estimates. To achieve this better synergy between mathematical modelling, physical modelling and field measurements of ventilation rates in NV livestock buildings is required.

The review of the research presented at the Quebec meeting identified the following intermediate research and development goals:

1. Investigate and determine error sources and measurement inaccuracies. Error analysis might be necessary to interpret results and establish research priorities.
2. Develop intelligent ventilation control systems that can handle highly fluctuating ventilation condition in NV livestock buildings.
3. Develop practical field methods that can be used as reference standards.
4. Establish a dedicated facility that could provide precise reference measurements of ventilation rates in naturally ventilated buildings. To enable this, a parallel development of new technologies (instrumentation and methodology) is required.

Reference

List of the proceedings and the abstracts presented at the technical session titled "Emission from naturally ventilated buildings (Measurement, modelling, reduction and assessment)", Section II: Farm Buildings, Equipment, Structures and Livestock Environment Conference, XVIIthWorld Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)
Available online: https://www.bioeng.ca/publications/meetings-papers?catid=19 (Use CSBE No. to find the proceedings or abstracts)
(The numbers in square brackets refer to the reference number shown in Table 1.)

Berg, W., Fiedler, M., Kiwan, A., & Brunsch R. (2010): Measurements of air ventilation rates in naturally ventilated dairy cattle buildings, (CSBE100762), [1]

Bjerg, B. & Andersen, M. (2010): Numerical simulation of a pit exhausts system for reduction of ammonia emission from a naturally cattle building (CSBE), [2]

Bjerg, B., Zhang G. Q., Madsen, J., & Rom, H. B. (2010): Use of gas concentration data for estimation of methane and ammonia emission from naturally ventilated livestock buildings (CSBE), [3]

Calvet, S., Cambra-López, M., Estellés, F., Torres, A. G., & Van Den Weghe, H. F. A. (2010): The influence of animal activity and the litter on carbon dioxide balances to determine ventilation flow in broiler production (CSBE100401), [4]

Choi, J. S, Lee, I. B., Hong, S. W, Hwang, H. S., Seo, I. H., Bitog, J. P., Kwon, K. S., & Song, S. Y. (2010): Aerodynamic analysis of air pollutants in pig farms using CFD technology, (CSBE100888), [5]

Estellés, F., Blumetto, O., Calvet, S., & Torres, A.G. (2010): Use of carbon dioxide balances to determine ventilation rates from fattening rabbits farms (CSBE100932), [6]

Hassouna, M, Robin, P. Brachet, A, Paillat J. M., Dollé, J. B., & Faverdin, P. (2010): Development and validation of a simplified method to quantify gaseous emissions from cattle buildings, (CSBE100758), [7]

Ikeguchi, A. & Moriyama, H. (2010): Measurement method of ventilation rate with tracer gas method in open type livestock houses (CSBE101061), [8]

Ikeguchi, A. (2010): Gas emission rate from different Japanese open type pig houses with natural ventilation (CSBE101059), [9]

Jacobson, L. D., Hetchler, B. P., & Noll, S. L. (2010): Measuring emissions from a naturally ventilated turkey grow-out building (CSBE101211), [10]

Kiwan, A. K., Brunsch, R., Özcan, S. E., Berg, W., & Berckmans, D. (2010): Tracer gas technique in comparison with other techniques for ventilation rate measurements through naturally ventilated barns (CSBE100975), [11]

Liberati, P., & Zappavigna, P. (2010): A simulation model to predict the internal climatic conditions in livestock houses as a tool for improving the building design and management (CSBE100548), [12] Mosquera, J., Van Dooren, H. J., Aarnink, A., & Ogink, N. W. M. (2010): Development of a fast measurement method for the determination of ammonia emission reduction from floor related measures, (CSBE100682), [13]

Özcan, S. E., & Berckmans, D. (2010): Acritical evaluation of the accuracy of tracer gas measurements in ventilated spaces, (CSBE100467), [14]

Özcan, S. E., Vranken, E., & Berckmans, D. (2010): A summary of ventilation rate measuring techniques through ventilated buildings, (CSBE100472), [15]

Retz, S. K., Georg, H., Godbout, S., Van den Weghe, & H. F. A. (2010): Impact of the manure removal from slatted floor in a dairy barn on the ammonia emission (CSBE100616), [16]

Schrade, S., Keck, M., Zeyer K., Emmenegger. L., & Hartung, E. (2010a): Measuring concept for determining ammonia emissions from naturally ventilated dairy housing with an outdoor exercise area (CSBE101131), [17]

Schrade, S., Keck, M., Zeyer, K., Emmenegger, L., & Hartung E. (2010b): Comparison of ammonia emissions from a naturally ventilated dairy loose housing with solid floor surfaces over two seasons (CSBE101117), [18]

Van Dooren, H. J. C., & Mosquera, J. (2010): Measurement of ammonia emissions from three ammonia emission reduction systems for dairy cattle using a dynamic flux chamber, (CSBE101322), [19]

Wang, K., Ye, Z., & Li, H., (2010): Preliminary study of ammonia emissions from naturally ventilated fattening pig houses in the South-East Cina, (CSBE101254), [20]

Wheeler, E. F., Topper, P. A., Adviento-Borbe, M. A. A., Brandt, R. C., Topper, D. A., & Elliot, H. A. (2010): Flux chamber validation for ammonia measurement versus whole room emission (CSBE100656), [21]

Wu, W., Kai, P., & Zhang G. Q. (2010): Reduce emission by applying pit exhaust in naturally ventilated livestock production buildings – Feasibility studies based on a wind tunnel investigations:(CSBE10543), [22]

Youssef, A., Özcan. S. E., Guiziou, F., Burton, C., Robin, P., & Berckmans, D. (2010): Intermittent Measurements Technique to Estimate Ammonia Emission from Manure Storage (CSBE100773), [23]

Zhang, G. Q., Pedersen, S, & Kai, P.: Uncertainty analysis of using CO2 production models by cows to determine ventilation rate in naturally ventilated buildings (CSBE100542), [24]

List of the cross referenced papers in the Special Issue on 'Emissions from naturally ventilated livestock buildings', Biosystems Engineering:

Bjerg B., G. Cascone, I.-B. Lee, T. Bartzanas, T. Norton, S.-W. Hong, I-H Seo, T. Banhazi, P. Liberati, A. Marucci, G. Zhang:.Modelling of ammonia emissions from naturally ventilated livestock buildings – Part three: CFD modelling:

Bjerg B., P. Liberati, A. Marucci, G. Zhang, T. Banhazi, T. Bartzanas, G. Cascone, I.-B. Lee, T. Norton:.Modelling of ammonia emissions from naturally ventilated livestock buildings – Part two: Air change modelling:

Bjerg B., T. Banhazi, G. Zhang, T. Bartzanas, P. Liberati, G. Cascone, I.-B. Lee, A. Marucci, T. Norton, S.-W. Hong and I-H Seo: Modelling of ammonia emissions from naturally ventilated livestock buildings – Part one: Ammonia release modelling:

Calvet S., R.S. Gates, G. Zhang, F. Estellés, Ogink, N.W.M., Pedersen, S., Berckmans, D.: Measuring gas emissions from livestock buildings: a review on uncertainty analysis and error sources:

Fiedler, M.; W. Berg, C. Ammon, C. Loebsin, P. Sanftleben, M. Samer, K. von Bobrutzki, A. Kiwan, C. K Saha (2012): Air velocity measurements using Ultrasonic Anemometers in the animal zone of a naturally ventilated dairy barn

Kiwan A., A. K. Kiwan; W. Berg, M. Fiedler, C. Ammon, M. Gläser, H. J. Müller, R. Brunsch (2012): Air exchange rate measurements in naturally ventilated dairy barns using the tracer gas decay method with Krypton85, compared to the carbon dioxide mass balance method and the natural ventilation method

Ogink N.; N.W.M. Ogink, J. Mosquera, S.Calvet, G. Zhang (2012): Methods for measuring gas emissions from naturally ventilated livestock buildings: developments over the last decade and perspectives for improvement

Table

Table 1: Results from categorization of the 24 presentations at CIGR 2010 technical session on emission from naturally ventilated buildings.

Category group	Category	Number of presentations	Reference number [a]
Aims of the study	To evaluate / improve known assessment methods	11	1,2,4,6,9,11,14,15,21,22,24
	To develop / demonstrate new assessment methods	7	5,7,10,13,17,20,23
	To develop design / management tool	1	12
	To develop / evaluate abatement technology	3	2,16,19
	To determine emission rate inventory	2	9,18
Major topics	Assessment method	14	3,4,5,6,7,9,10,11,13,17,18,20, 22,23
	Measurement accuracy	13	1,3,4,6,8,9,11,13,14,15,21,22,23
	Factors influencing emissions	3	9,17,18
	Building design	2	5,12
	Abatement technology	4	2,16,19,24
Major study objects	Ventilation / Airflow	14	1,2,4,6,7,8,9,10,11,14,15,20,22, 24
	Internal climate	2	12,20
	NH_3	13	2,3,7,8,10,13,16,17,18,19,20,21, 23
	Dust	1	5
	CO_2	7	1,4,6,7,8,10,22
	Other gasses (CH_4, N_2O)	3	3,7,8
	Microorganism	1	5
Animal species	Cattle	13	1,2,3,7,11,12,13,16,17,18,19,21, 22
	Pig	6	5,8,9,12,20,23
	Poultry	2	4,10
	Rabbit	1	6
Principal methods of assessment	CO_2 mass balance	6	1,3,4,6,10,22
	Tracer gas method	7	1,8,9,11,14,17,18
	Direct measurements	2	11,24
	Imitate NVB with MVB[b]	1	10
	Modelling	5	2,5,7,12,23
	Flux chamber / element isolation	4	13,16,19,21

[a] Refer to the numbers in square brackets shown in the reference list.
[b] NVB = Naturally ventilated building; MVB = Mechanically ventilated building