Universitat Politécinica de Valencia
Escuela Técnica Superior de Ingeniería de Edificación
Camino de Vera Valencia

## Master of Science in Engineering Technology: Construction

# Measuring the effect of the heat flow through a chimney with different altitudes of a rescaled model and validating the results with TRNSYS, a computer-simulated model.

Promotor: Dr. Carolina Aparicio Fernández
Dr. José Luis Vivancos Bono

Thesis submitted to obtain the degree of
Master of Science in Engineering Technology Construction

Jasper Degraeuwe

Bertie Vandendorpe

Academic year: 2012 - 2013

# ACKNOWLEDGEMENTS

We would like to thank Erasmus for the opportunity to study at Universitat Politecnica De Valencia, Spain. Special thanks to Javier Calvo Diaz for the welcoming stay in Valencia. This has been an extraordinary learning experience that we will remember for life.

We would also like to thank our promoters Carolina Sabina Aparicio Fernandez and José Luis Vivancos Bono for being so helpful during our learning experience. They have been considerate and generous in providing us with advice and guidance during our Masterthesis. We have accumulated invaluable knowledge, even more patience and fortitude. Our gratitude also goes to Rafael Royo Pastor of the Instituto de Ingenieria Energetica for his help and hospitality to approach the theoretical part of this Masterthesis. Special thanks go to Javi Biscer for his assistance with all the problems we encountered during the calibration of the TRNSYS-file and Pepe José Segovia for all the help and kindness during the time in the laboratory. We are indebted to them for their helpfulness, judgment and guidance.

## PERMISSION FOR USAGE

# ABSTRACT

Our thesis subject is: “Building Physics”, specifically measuring the natural heat flow in an apartment building.

The objective of all the measurements is to verify that, the longer a chimney gets in a building, the higher the flow through that specific chimney gets, this by adjusting different parameters from inside and outside the building, such as: wind velocity, temperature inside, surface of the window opening, etc.

The flow was measured in two different ways.

In the first an existing model with wooden walls of 1 cm thickness was used to do the measurements on. The model had the following dimensions: 100 x 79 x 150 centimetres.

There were 4 halogen lamps placed in the construction, and the only object that could cause the heat flow was the chimney, made of PVC. Next, the heat flow was measured when 1, 2, 3 or 4 lamps were turned on. This was measured by taking the temperature inside and outside the model and using an air velocity-meter that was placed on top of the chimney.

Since there was no wind available, because the measurements were taken in a laboratory, another computer-simulated model was used to verify what happens when the wind velocity outside changes.

To gauge the flow in the second method was more difficult because a new program was used, named TRNFLOW. This program is a function of TRNSYS17 and in this program we created a model that was similar with our re-scaled model.

The results of the TRNSYS-program and the results of the measurements were similar. As expected, when the chimney increased in height, the heat flow also increased through the chimney. The opening of the windows didn’t have a big effect on the results, but when the opening was very small the TRNSYS-program couldn’t make a good simulation.

What was very noticeable is that when the wind velocity outside increased above 3 m/s, the velocity through the longest chimney changed directly to the lowest flow, so the flow through the chimney is very sensitive for the wind velocity outside.

Finally, for verifying the results, different methods were used: a mass balance was set up and the theory of Thermal Buoyancy was applied.

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# INTRODUCTION

What the title already reveals is that we want to define what the effect is of the heat flow through a chimney with different altitudes of a rescaled model, but we didn't only look at the different altitudes of that rescaled model, we also looked at: the temperature inside and outside, window opening, wind velocity outside, etc.

When you go on Erasmus you can't choose your Masterthesis by yourself, but what we already knew was that the project would handle Building Physics, which was good because we're both interested in this particular part of Building Engineering. That was also the main reason that we choose for Valencia to go on Erasmus.

This project is also important for society because in times of crisis everyone wants to spend less money, one way for achieving this goal is to save energy. A way to save some money is to spend less energy on ventilation. So natural ventilation looks the perfect solution for this problem. But in an apartment this is a delicate situation because of the different altitudes of the rooms in an apartment. This phenomenon is present in each apartment and it looked interesting to investigate this.

Before we began with the tests, we did some research about this phenomenon, this by reading scientific articles that we received from Prof. Carolina Sabina Aparicio Fernandez. Furthermore we read the manuals for using TRNSYS, the manual of TRNFLOW and Multi-Zone Building in particular.

To accomplish our goals we could use a model that already was used for another Masterthesis about the blower door. On this model (79 x 100 x 150 cm) tests were taken to see the effect of the heat flow when several parameters were changed (temperature, window opening, length of the chimney). For verifying the measured results, we compared these results with a computer-simulated model that was designed in Sketch-Up™ and afterwards implemented in TRNSYS, the simulation program.

The model was placed in a laboratory, so there was no wind velocity outside the box. Other tests were taken with another computer-simulated model to verify what happens when the wind velocity and direction changes outside the building. This model was an adaptation of a real apartment in Valencia.

Other options that we used to verify our measured results, was calculating the flow with the theory of Thermal Buoyancy and set up a thermal balance, therefore infrared pictures had to be taken to determine the wall temperatures.

So these are the several topics we talked about in our final project. Also the research about the project will be discussed and finally the results will give us the knowledge to show what the most sensitive parameter is, videlicet, the wind velocity outside, when we talk about natural ventilation in an apartment building by using a chimney.

# 1 CONCEPTS

## 1.1 TRNSYS

First of all what does TRNSYS mean: "**TR**a**N**sient **SY**stem **S**imulation Program. The program TRNSYS is a complete and extensible simulation based software environment for the transient simulation of systems and it also includes Multi-Zone Buildings" (KLEIN, 2009, p.8). It is used by engineers and researchers around the world to validate new energy concepts, from a simple model from a box to the design and simulation of buildings and their equipment, including control strategies, occupant behavior, alternative energy systems (wind, solar, photovoltaic, hydrogen systems), etc.

TRNSYS consists of two parts. The first part is an engine that reads and processes the input files, iteratively solves the system, determines convergence, and plots system variables. The engine also provides utilities that (among other things) determine thermo physical properties, invert matrices, perform linear regressions, and interpolate external data files.

The second part of TRNSYS is an extensive library of components. The standard library includes approximately 150 models ranging from pumps to Multi-Zone Buildings, weather data to economics routines, etc. Al those different models have a specific number, for example a Multi-Zone Building is Type 56. Models are constructed in such a way that users can modify existing components or write their own component.

TRNSYS has been in existence for 35 years and one of the key factors is its open, modular structure. The source code of the engine as well as the component models is delivered to the end users. This simplifies extending existing models to make them fit the user's specific needs.

The DLL-based architecture allows users and third-party developers to easily add custom component models, using all common programming languages (C, C++, PASCAL, FORTRAN, etc.). In addition, TRNSYS can be easily connected to many other applications, for pre processing or post processing or through interactive calls during the simulation (e.g. Microsoft Excel, Matlab, COMIS, etc.). TRNSYS applications include:

- Solar systems (solar thermal and PV)
- Low energy buildings and HVAC systems with advanced design features (natural ventilation, slab heating/cooling, double façade, etc.
- Renewable energy systems
- Cogeneration, fuel cells
- Anything that requires dynamic simulation

## 1.2 VALIDATE THE RESULTS OF A TRNSYS BUILDING PROJECT

The TRNSYS Simulation Studio can be divided into 3 subsequent parts:

- The inputs.
- The simulation and calculation. When using a Multi-Zone Building, the calculation generally is simulated by TRNBUILD a different program that interacts with TRNSYS;
- The outputs.

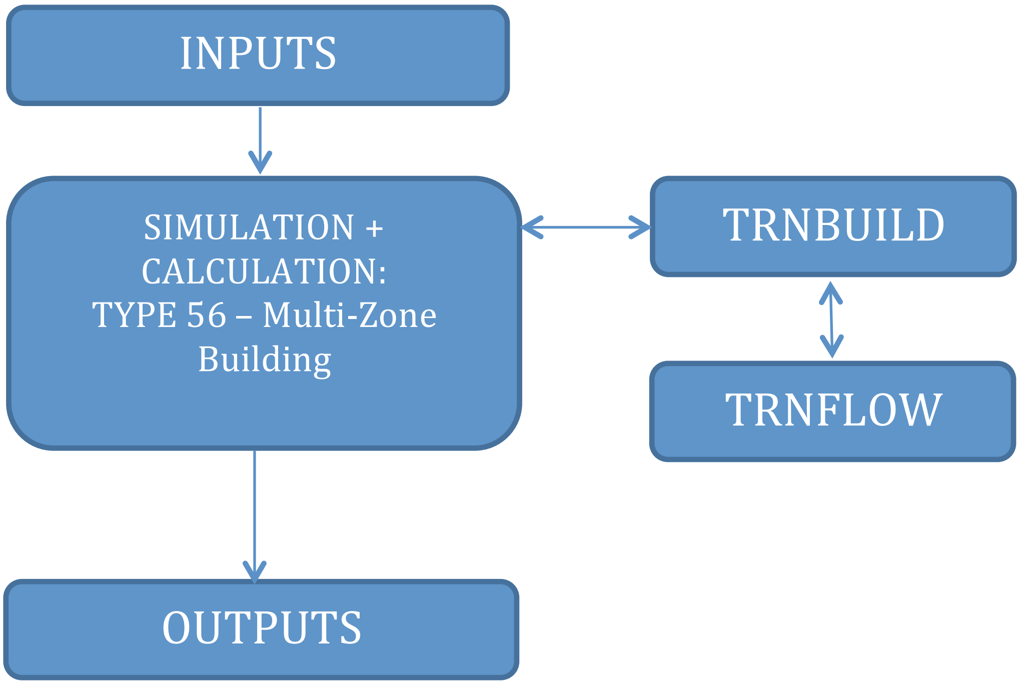


**FIGURE 1-1: SCHEME OF TRNSYS**

### 1.2.1 INPUTS

In generally, the inputs are divided into 2 different types for this rescaled model:

- The weather data reading and processing (Type 15).
- Data readers for generic data files (Type 9).

<u>Weather data Reading and Processing, Type 15:</u>

"This component serves the purpose of reading data at regular time intervals from an external weather data file, interpolating the data (including solar radiation for tilted surfaces) at time steps of less than one hour, and making it available to other TRNSYS components" (KLEIN, 2009, p.98) The model also calculates several useful terms including the mains water temperature, the effective sky temperature, and the heating and cooling season forcing functions.

Data readers, Type 9:

“This component serves the purpose of reading data at regular time intervals from a data file, converting it to a desired system of units, and making it available to other TRNSYS components as time-varying forcing functions.” (KLEIN, 2009, p.86) This component is very general in nature and can read many different types of files. The data from line to line must be at constant time intervals.

### 1.2.2 SIMULATION AND CALCULATION

This is the most important part of the Simulation Studio, because here is what the program is made for, videlicet: creating a simulation to compare (with results in real time), predict and confirm the obtained results.

Between the inputs and outputs a lot of calculations and simulations can take place, by using different types found in the TRNSYS library or functions found in the main toolbar, that are connected to each other by using the Link tool.

#### 1.2.2.1 TYPE 56 – MULTI-ZONE BUILDING

“This component models the thermal behavior of a building divided into different thermal zones. In order to use this component, a separate pre-processing program must first be executed.” (KLEIN, 2009, p.52) The TRNBUILD program reads in and processes a file containing the building description and generates two files that will be used by the TYPE 56 component during a TRNSYS simulation. The file containing the building description processed by TRNBUILD can be generated by the user with any text editor or with the interactive program TRNBUILD.

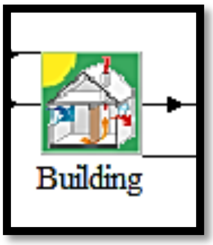


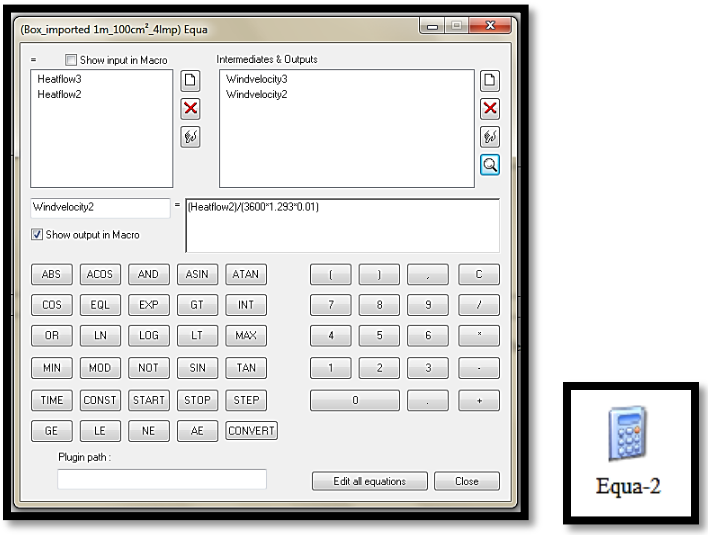
**FIGURE 1-2: ICON TRNFLOW- MULTI-ZONE BUILDING**

### 1.2.2.2 EQUATIONS

A common used feature in TRNSYS is the ability to define equations within the input file, which are not in a component. These equations can be functions of outputs of other components, numerical values, or previously defined equations. These equations can then be used as inputs to other components, or as parameters, initial values of inputs. The use of equations is most easily accomplished by using a special equations component.

This equations component can be placed in an assembly or saved like any other component.

Different blocks of equations can be placed anywhere within the input file and are arranged just like other components.



(Box_imported 1m_100cm²_4Imp) Equa

= ☐ Show input in Macro

Heatflow3
Heatflow2

Intermediates & Outputs

Windvelocity3
Windvelocity2

Windvelocity2 = (Heatflow2)/(3600*1.293*0.01)

☑ Show output in Macro

Plugin path :

**FIGURE 1-3: CALCULATOR TRNSYS**

### 1.2.2.3 LINK TOOL

Components are connected using the Link tool, which is activated by pressing the link button. When you move the mouse over a component icon, the 8 available connection points become visible. A newly created link is empty, what means it does not connect any (output or input) couple yet. This is shown by a different link color (blue by default, while links with connections are black).

By clicking on the link (using the selection tool) a new window will appear that shows all possible inputs and outputs of the link. These inputs can easily be connected with the outputs by using the Connection Mode.

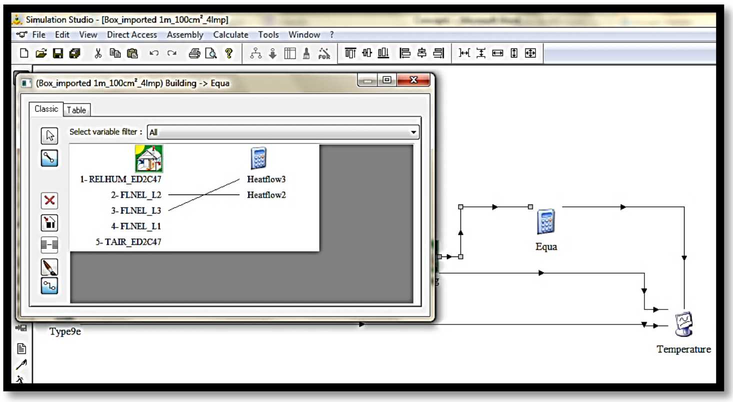


FIGURE 1-4: LINK TOOL

### 1.2.3 OUTPUTS

The TRNSYS Simulation studio has several outputs, videlicet:

- printegrator;
- printer;
- online plotter;
- scope;
- economics;
- simulation summary.

When simulating an assemblage of a Multi-Zone Building this output is common used, to compare them with a re-scaled model:

#### 1.2.3.1 TYPE 65-ONLINE PLOTTER

The online graphics component is used to display selected system variables while the simulation is progressing. "This component is widely used since it provides valuable variable information and allows users to immediately see if the system is not performing as desired." (KLEIN, 2009, p.62) The selected variables are displayed in a separate plot window on the screen.

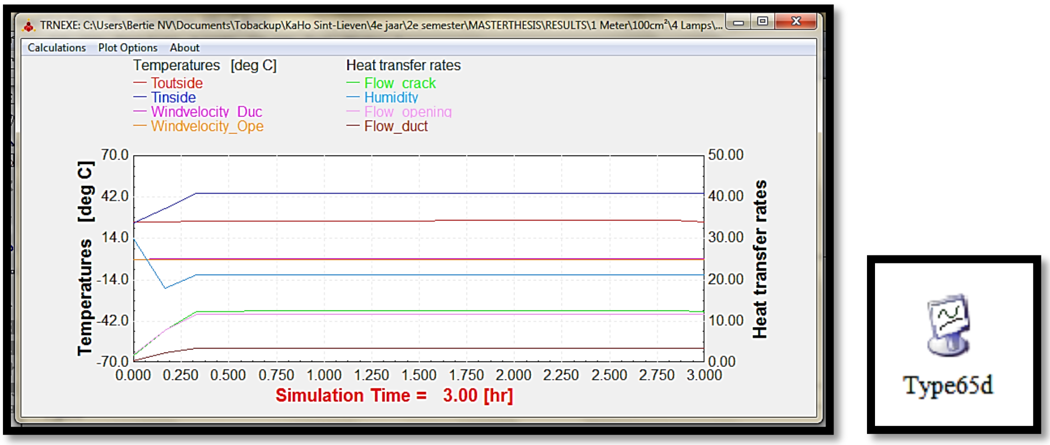


FIGURE 1-5: ONLINE PLOTTER

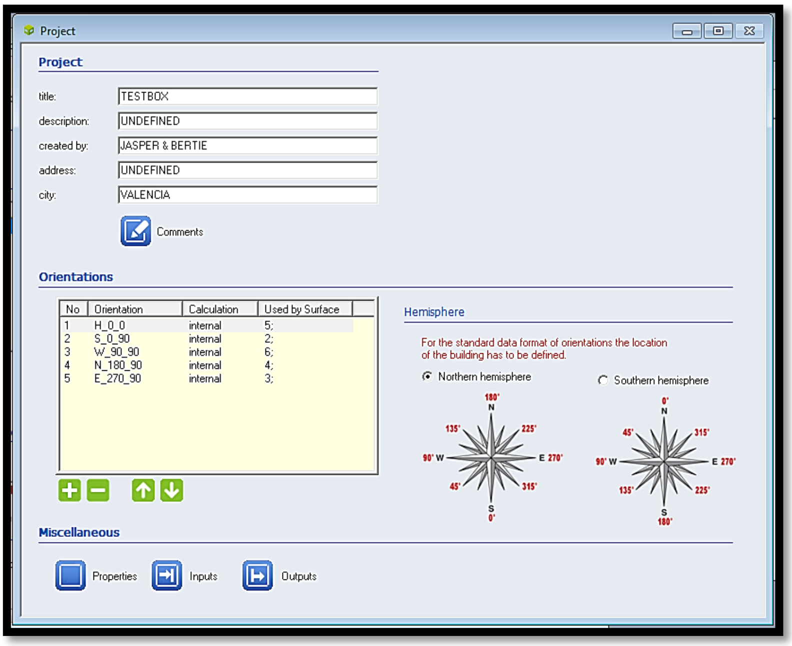
## 1.3 VALIDATE THE RESULTS IN TRNBUILD AND CIRCULARIZE THEM TO TRNSYS

TRNBUILD is a perfect program to identify the thermal behavior of a building divided into different thermal zones. In order to use this component, a separate pre-processing program must first be executed (TRNSYS). Because of the complexity of a Multi-Zone Building the parameters of TYPE 56 are not defined directly in the TRNSYS input file, that's why the TRNBUILD program that interacts with TRNSYS is used.

The TRNBUILD program reads in and processes a file containing the building description, a so-called BUI file. The file containing the building description processed by TRNBUILD can be generated by the user with any text editor or with the interactive program TRNBUILD.

The program is divided into 3 different windows, these windows will be explained in the 3 consecutive topics.

## 1.3.1 THE PROJECT INITIALIZATION WINDOW



title: TESTBOX
description: UNDEFINED
created by: JASPER & BERTIE
address: UNDEFINED
city: VALENCIA

| No | Orientation | Calculation | Used by Surface |
|---|---|---|---|
| 1 | H_0_0 | internal | 5; |
| 2 | S_0_90 | internal | 2; |
| 3 | W_90_90 | internal | 6; |
| 4 | N_180_90 | internal | 4; |
| 5 | E_270_90 | internal | 3; |

For the standard data format of orientations the location of the building has to be defined.

● Northern hemisphere ○ Southern hemisphere

FIGURE 1-6: INITIALIZATION WINDOW

In this window it's possible to change the general information of the project (title,), the wall orientations, the properties (parameters) or the inputs and outputs of the building file.

### 1.3.1.1 THE INPUTS

This is used to link components/types of the TRNSYS simulation studio with the TRNBUILD program, so it can create the desired BUI file.

### 1.3.1.2 THE OUTPUTS

The user may adjust the time base of the transfer function if necessary. The default value is 1, but for light walls 0.5 can be used.

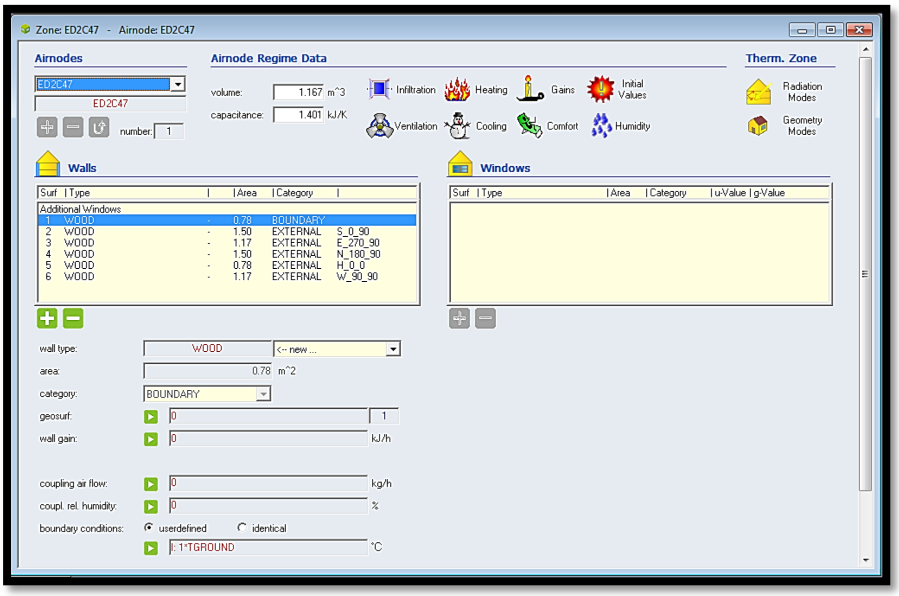
The outputs give the simulated results back to the Simulation Studio, it's possible to edit, add or delete outputs of type 56, the so-called NTYPES. The type of NTYPES is extensive, it goes from airnode- to zone-outputs, from surface- to comfort outputs and from balance- to groups-of-airnodes-outputs.

## 1.3.2 THE ZONE-AIRNODE WINDOW

The zone-airnode window can be opened, by clicking on the desired zone in the TRNBUILD Navigator. In the new version of TRNSYS (TRNSYS 17), a thermal zone can consist of one or more airnodes. Airnodes can be moved from one zone to another for creating multi-airnode zones.

The zone-airnode window can be divided into four main parts:

- The required regime data;
- The walls of the airnode;
- The windows of the airnode;
- Optional equipment (infiltration, ventilation, heating, gains, cooling and comfort).



ED2C47
ED2C47
number: 1

volume: 1.167 m^3
capacitance: 1.401 kJ/K

| Surf | Type | | Area | Category | |
|---|---|---|---|---|---|
| Additional Windows | | | | | |
| 1 | WOOD | - | 0.78 | BOUNDARY | |
| 2 | WOOD | - | 1.50 | EXTERNAL | S_0_90 |
| 3 | WOOD | - | 1.17 | EXTERNAL | E_270_90 |
| 4 | WOOD | - | 1.50 | EXTERNAL | N_180_90 |
| 5 | WOOD | - | 0.78 | EXTERNAL | H_0_0 |
| 6 | WOOD | - | 1.17 | EXTERNAL | W_90_90 |

wall type: WOOD <-- new ...
area: 0.78 m^2
category: BOUNDARY
geosurf: 0 1
wall gain: 0 kJ/h
coupling air flow: 0 kg/h
coupl. rel. humidity: 0 %
boundary conditions: ● userdefined ○ identical
I: 1*TGROUND °C

FIGURE 1-7: TRNBUILD NAVIGATOR

### 1.3.2.1 REGIME DATA

| Data | Function | Unit |
|---|---|---|
| Volume | Volume of the air within the airnode | $m^3$ |
| Capacitance | Total thermal capacitance of airnode air and that of any mass not considered as walls | kJ/K |
| Initial temperature | Initial temperature of the airnode air | °C |
| Initial relative humidity | Initial relative humidity of the airnode air | % |
| Humidity model | A simple (capacitance) or detailed (buffer storage) model | |

TABLE 1: REGIME DATA

### 1.3.2.2 WALLS OF THE AIRNODE

Here, the user can add, delete or edit the walls of an air node by indicating the area, surface number,… When the program created a new wall, it's possible to define a new wall type, by using the Wall Type Manager. In this function, the program asks for the thickness and U-value of the wall, so the calculations can run correctly.

#### 1.3.2.3 WINDOWS OF THE AIRNODE

This feature is mostly the same as the last option about the walls of an airnode. The only difference in comparison with the previous one is, that you must enter more parameters, like the g-value or shaded area.

#### 1.3.2.4 OPTIONAL EQUIPMENT

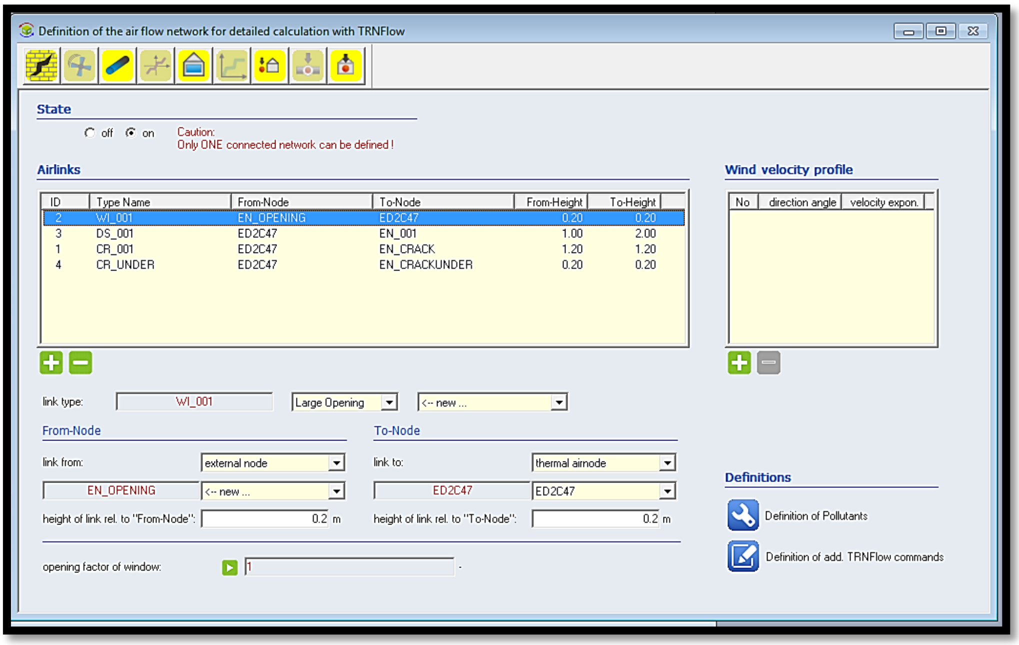
In the 4th main part of the TRNBUILD program, it’s possible to add 6 types of optional equipment. These are:

- Gains, by setting a certain gain, for example a person or computer;
- Ventilation, by giving an air change rate for the desired ventilation of the model;
- Heating, this option is to specify the max. heating temperature that takes place in the particular airnode, it’s called the room set temperature;
- Cooling, this you can compare with the heating except it’s now the opposite, so not the max. temperature but the min. temperature is defined;
- Comfort, this is to specify the internal comfort that interacts with the clothing factor of the people inside;
- Infiltration, an air flow that goes from the inside to the outside of a zone can be specified by the infiltration option, so it’s the leakage of the specific airnode.

### 1.3.3 THE TRNFLOW WINDOW

In the TRNSYS Simulation Studio, it’s possible to change the load or structure of the Multi-Zone Building into a Multi-Zone Building with a particular airflow. Then a new window appears in the TRNBUILD program called: “The definition of the air flow network for detailed calculation with TRNFLOW”. More information about this in the following topic.

## 1.4 VALIDATE THE RESULTS IN TRNFLOW, A SOFTWARE IN TRNBUILD THAT INTERACTS WITH TRNBUILD



○ off ● on

Caution:
Only ONE connected network can be defined !

| ID | Type Name | From-Node | To-Node | From-Height | To-Height |
|---|---|---|---|---|---|
| 2 | WI_001 | EN_OPENING | ED2C47 | 0.20 | 0.20 |
| 3 | DS_001 | ED2C47 | EN_001 | 1.00 | 2.00 |
| 1 | CR_001 | ED2C47 | EN_CRACK | 1.20 | 1.20 |
| 4 | CR_UNDER | ED2C47 | EN_CRACKUNDER | 0.20 | 0.20 |

link type: WI_001 Large Opening <-- new ...

link from: external node
EN_OPENING <-- new ...
height of link rel. to "From-Node": 0.2 m

link to: thermal airnode
ED2C47 ED2C47
height of link rel. to "To-Node": 0.2 m

opening factor of window: 1 -

FIGURE 1-8: TRNFLOW MANAGER

### 1.4.1 INTRODUCTION

By editing the loads and structures, of the Multi-Zone Building, to a Multi-Zone Building with TRNFLOW the air flows between the airnodes (coupling), from outside to the inside of the building (infiltration) and the airflow from the ventilation system (ventilation) can be calculated.

There are 2 kinds of models that are linked with each other as black boxes, into the TRNFLOW program. These models are the thermal- and airflow model. A simplification of the theorem is shown on the picture on the next page.

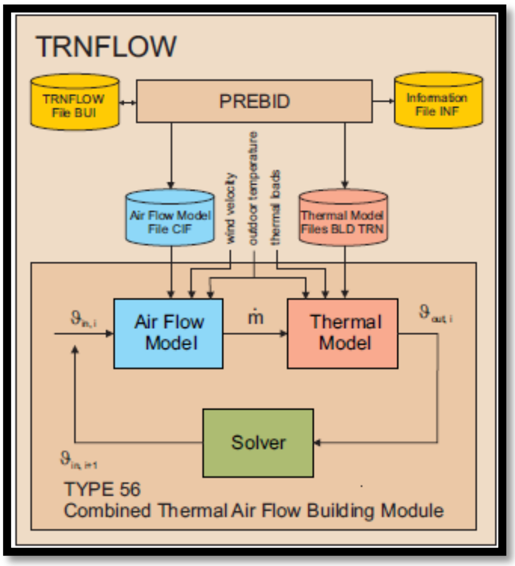


**FIGURE 1-9: SCHEME OF TRNFLOW**

In the calculation process, the air flow model starts with the input node temperatures $\vartheta_{in,1}$ and calculates the corresponding airflow $\dot{m}$ of each node. Thereafter these flows are used in the thermal model, which calculates the output room temperatures $\vartheta_{out,1}$ and with an iterative solver algorithm the input temperatures set is found which matches the output temperatures set.

### 1.4.2 THE AIRFLOW NETWORK

The network exists of nodes and these nodes are then connected to each other with air links.

#### 1.4.2.1 AIR FLOW NODES

The nodes are divided into four classes:

- Constant pressure nodes, is a fixed pressure outside of the building;
- Thermal airnodes, is assumed to be the airnodes in the thermal model that can be represented by a node with single values for temperature, humidity and pressure;
- Auxiliary nodes, defines the duct work of a possible ventilation;
- External nodes, represents the wind pressure outside of the building. $C_p$-values are used to identify the direction(s) of the wind outside.

For nodes, it's required to identify their reference height. For the outside airnodes (constant and external nodes) the height represents the building reference level, the height of the inside airnodes are defined in relation with the building reference level (see Figure 1-10).

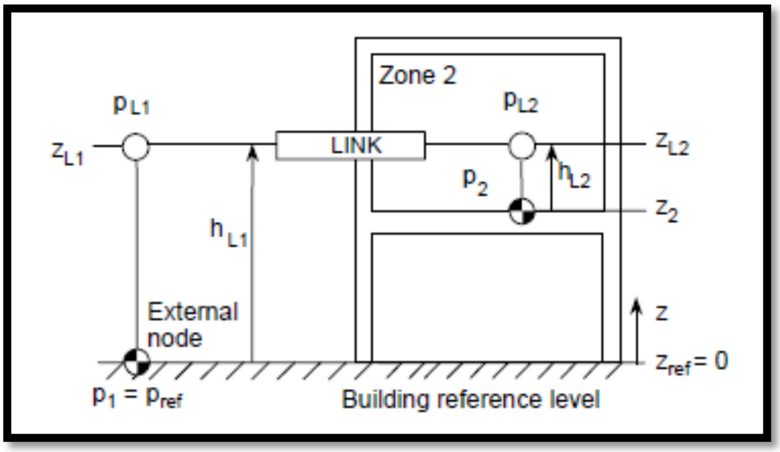


FIGURE 1-10: HEIGHT OF AIRNODE

### 1.4.2.2 AIR LINK TYPES

The airnodes are connected to each other by using a specific air link. It's possible to choose between four different air links:

- Crack, defines a small opening or several openings to express the leakage characteristic of the crack(s);
- Duct, defines the flow of a straight duct, this by using the friction loss and the dynamic losses due to fittings;
- Fan, defines a fan by calculating the flow characteristic of a fan at a certain fan speed;
- Large opening, this is a large opening that has a vertical velocity profile.

There is also a flow controller link or a test data link, but these are not commonly used to identify the airflow in buildings using a thermal chimney.

# 2 THE PROJECT

## 2.1 THE MODEL

### 2.1.1 POSITIONING

The site where the model was created is at the Universitat Politecnica de Valencia Campus de Vera. More specifically, the laboratory is located in building 1B: School of Building Management (Figure 2-1) in the construction area of "física de la construcción". The laboratory is a place where all the necessary tools are located and where a lot of tests already took place. The conditions in the lab are always different because there is no mechanical ventilation. The windows of the lab are open all the time because the room gets easily overheated.

**FIGURE 2-1: BUILDING 1B AT UPV**

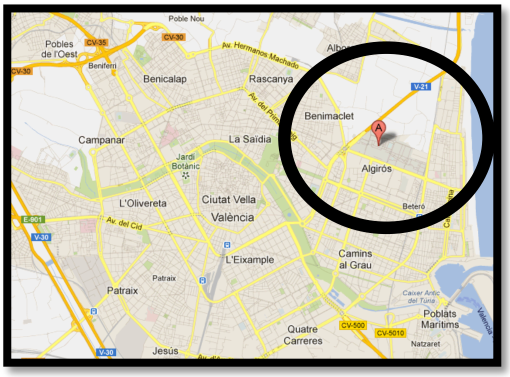


**FIGURE 2-2: LOCATION OF UPV IN VALENCIA**

A couple of tests will take place in this laboratory: the experiment, a blower door test and a thermo graphic test.

### 2.1.2 HOW IT'S MADE

The model that will be used for the tests is composed out of 16 panels (Figure 2-3) of MDF (Medium-Density Fibreboard) with a thickness of 1 cm. The panels are clamped between 2 wooden beams (Figure 2-4).

FIGURE 2-3: PANELS OF MDF

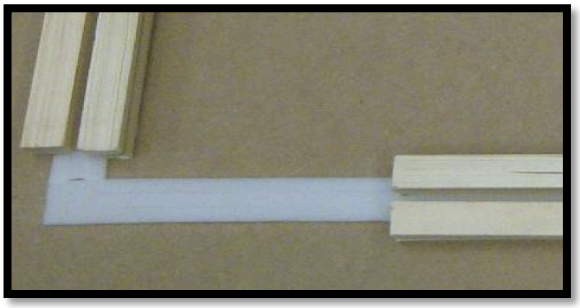


FIGURE 2-4: 2 WOODEN BEAMS (PANEL ON THE GROUND)

When everything was cut correctly out of the standard MDF, 16 panels were made. The panel edges (the roof and the base) were surrounded with adhesive foam strips (Figure 2-4) with a width of 1 cm. The strips were used for improving the grip of the vertical panel and the roof or base. For closing the panels properly, a rubber tap on every edge of all 16 panels was placed. This addition was the last thing that happened before connecting all the panels together with the metal connecting elements. A plan of the panels is shown in Figure 2-5. The inside of the box has a volume of 1,2 m$^3$ and was originally constructed for doing blower door tests.

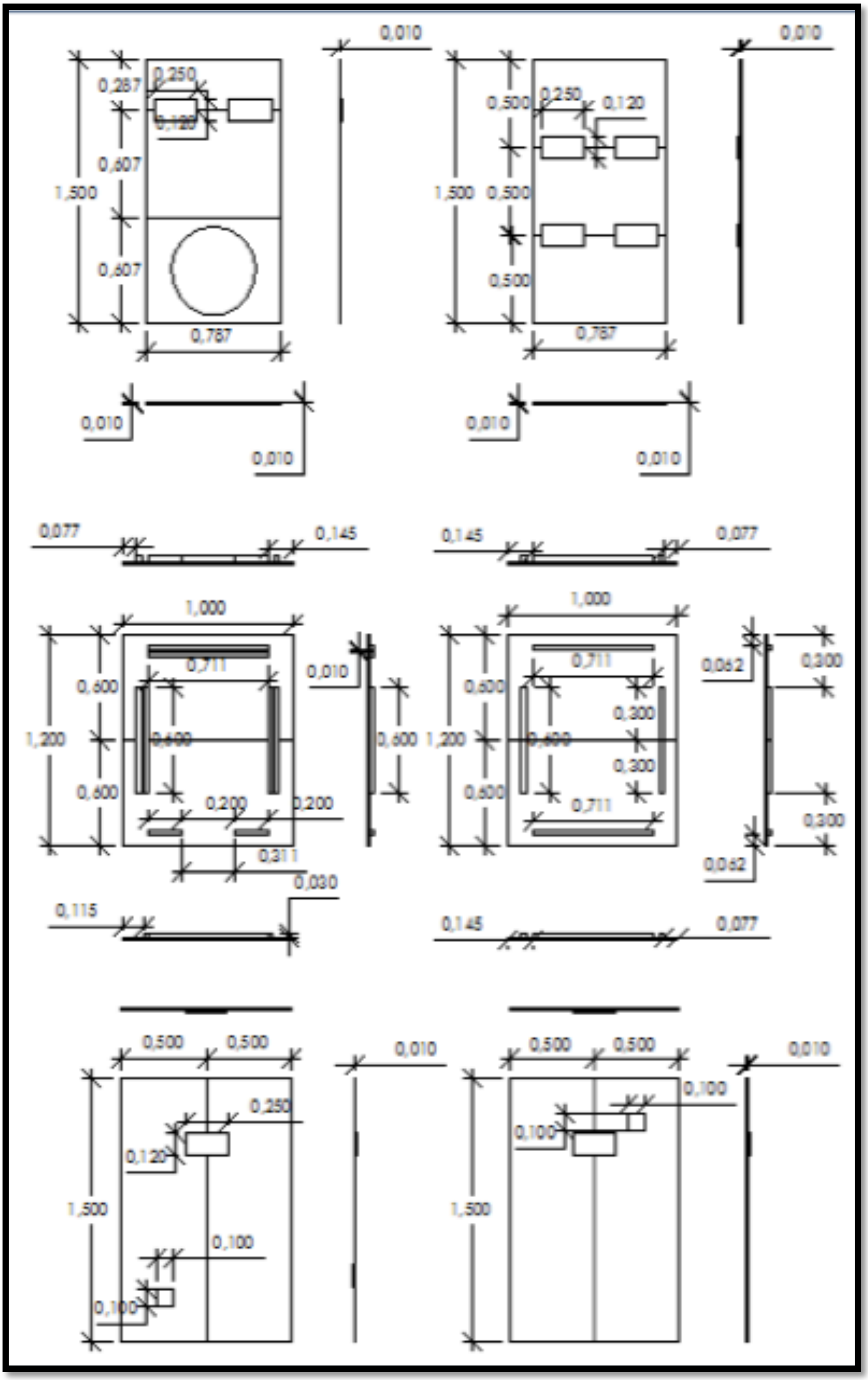


**FIGURE 2-5: CONSTRUCTIONPLAN OF THE MODEL**

Because the model was constructed for blower door test sand not for measuring the heat flow through a PVC-tube, adjustments had to take place. The counter measurements that needed to be done were: closing the big hole where the blower door was placed (Left top of Figure 2-5) and the box had to be connected with the PVC-tube (Figure 2-6). Before the connecting the PVC-tube to the box, the tube had to be covered in an isolation material called Rockwool. This was necessary because otherwise the heat-transfer through the PVC material would be too big.

RESULT

**FIGURE 2-6: PVC-TUBE COVERED WITH ROCKWOOL**

### 2.1.3 MATERIALS OF THE MODEL

MDF:

| | |
|---|---|
| ρ (kg/m³) | 760 |
| λ (J) | 720 |
| $C_p$ (J/kg*K) | 1700 |

**TABLE 2: SPECIFICATIONS MDF**

PVC-tube

| | |
|---|---|
| ρ (kg/m³) | 1400 |
| Vicat Softening Temperature (°C) | 82 |
| ε, Absolute Roughness Coefficient (mm) | 0,03 |

**TABLE 3: SPECIFICATIONS PVC-TUBE**

Connecting elements

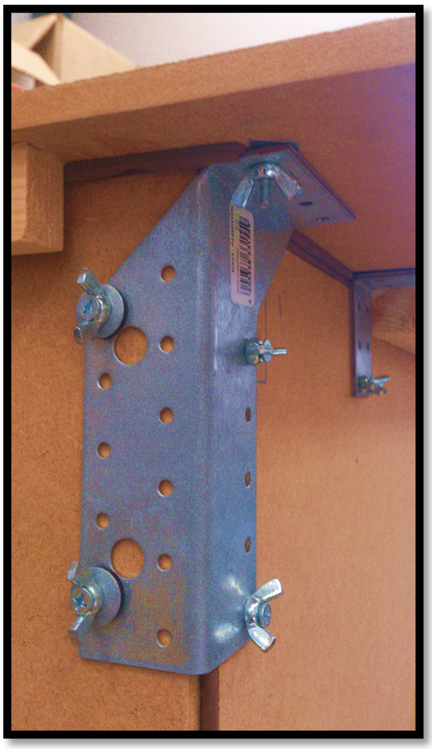


**FIGURE 2-7: A METAL CONNECTINGELEMENT**

Rockwool

Rockwool is an isolation material that is made out of stone wool. The Rockwool that was used in the model was Rockwool 201 VARIO, this type of stone wool is easily to transform in all kind of shapes.

| | |
|---|---|
| Thickness (cm) | 6 |
| $R_D$ ($m^2K/W$) | 1,60 |
| $\lambda$ (W/mK) | 0,037 |

**TABLE 4: SPECIFICATIONS ROCKWOOL**

## 2.2 THE APARTMENT BUILDING

### 2.2.1 GENERAL INFORMATION

The apartment building is situated in Valencia, more specifically:

Carrer de Cavanilles 20
46000 Valencia
Spain

**FIGURE 2-8: THE APARTMENT**

This block has 14 floors and a ground floor. On each floor there are 3 apartments with a different orientation.

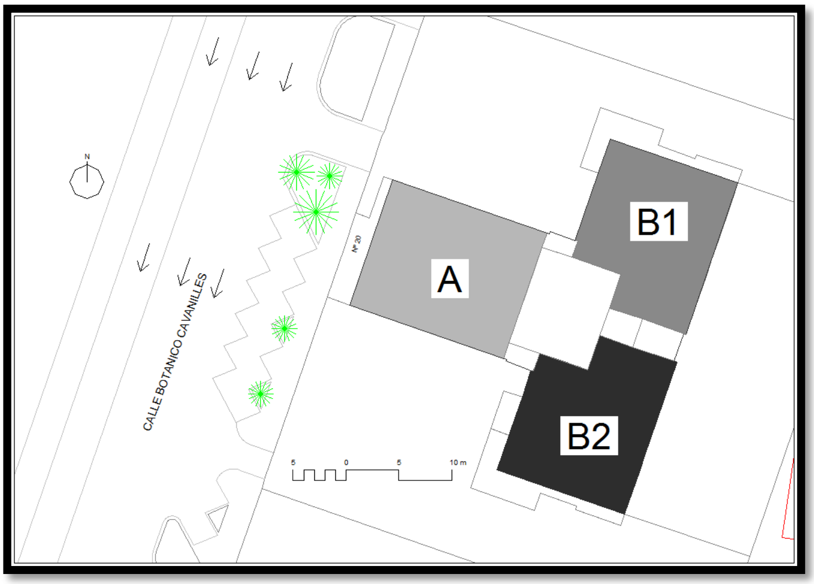


FIGURE 2-9: FLOORPLAN OF THE APARTMENT

As seen in Figure 2-9 the housing B1 and B2 are symmetrical.

The building is situated in the city so it's surrounded with similar buildings that will affect the wind and the sunlight on the apartment.

The three types of apartments have been modeled with TRNSYS-3D. There are 4 thermal zones in the apartment. The zones shown in Figure 2-10 are:

- Zone 1: Sleeping area (bedroom and bathroom outside);
- Zone 2: Day area (lounge);
- Zone 3: Service area and kitchen;
- Zone 4: Hall no external windows (access and bathroom).

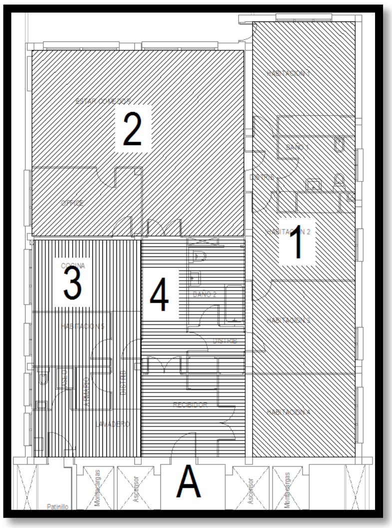


FIGURE 2-10: THERMAL ZONES

Meteorological data

The meteorological data that's used are those of the city of Valencia as the building is situated in the center of this city.

Parameters

The construction elements have the following parameters:

| | Thickness [m] | Heat transfer U [W/m²K] |
|---|---|---|
| Exterior wall | 0.20 | 0.842 |
| Interior wall | 0.10 | 3.08 |
| Roof | 0.41 | 1.40 |
| Floor | 0.41 | 1.40 |

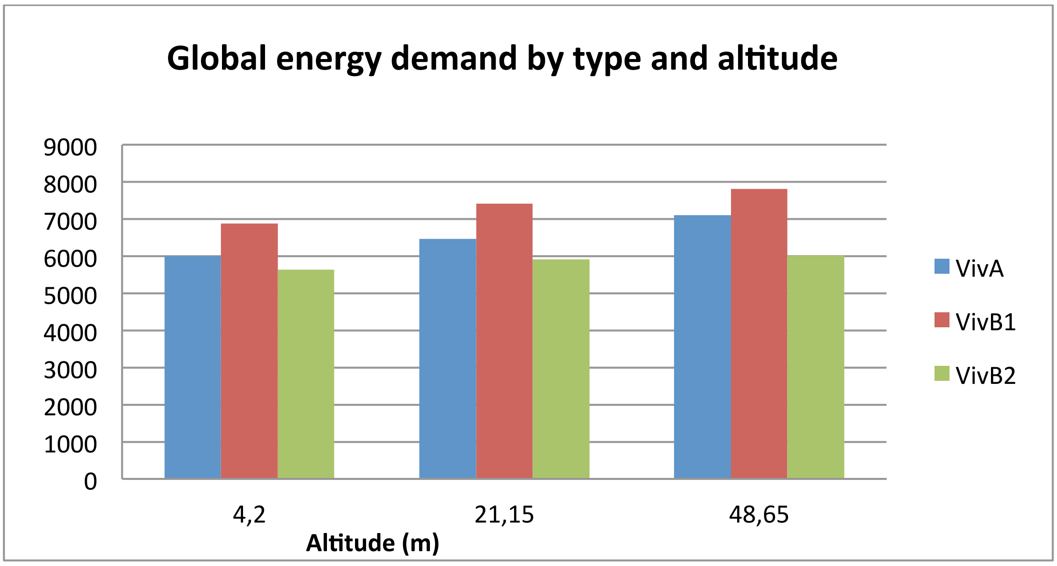
TABLE 5: PARAMETERS OF THE APARTMENT

### 2.2.2 PREVIOUS WORK

#### 2.2.2.1 ENERGY RATE

Demand requirements vary with each apartment and the orientation is different for each of the three types (levels).

These are the resulting energy demands of the 3 different apartments at 3 different heights:



GRAPHIC 1: GLOBAL ENERGY DEMAND BY TYPE AND ALTITUDE

It's clear that apartment B1 has the largest energy demand, mainly because the apartment is faced to the North, so it can't heat up as quickly as the other 2 apartments.

### 2.2.2.2 MODEL IN TRNSYS

The discussed apartment building was already constructed, first in TRNSYS and thereafter the apartment was designed in Sketch-Up™ and implemented into TRNFLOW by using the TRNSYS-3D-function.

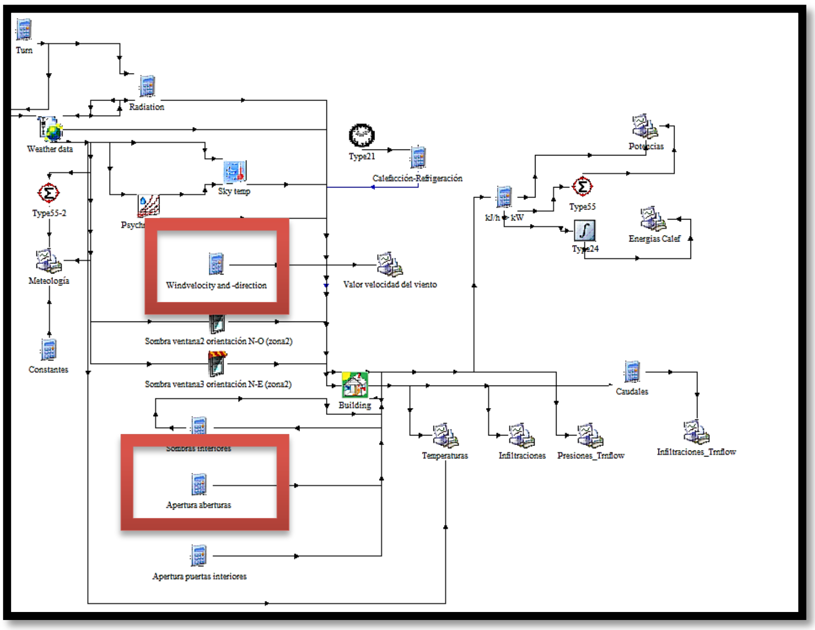


FIGURE 2-11: MODEL IN TRNSYS SIMULATION STUDIO

This project aims to analyze the air changes from a standard apartment by using TRNFLOW so the model developed in TRNSYS was again changed to a Multi-Zone-Building with airflow:

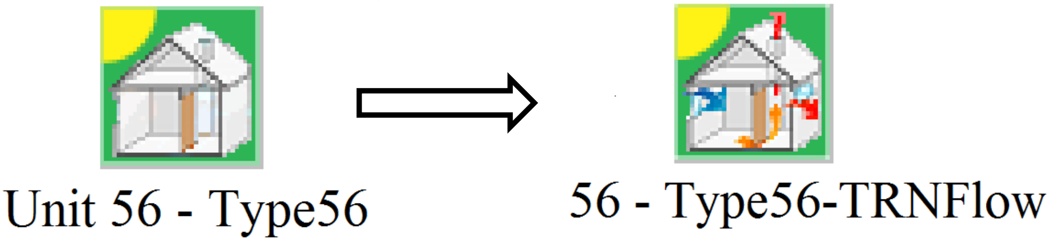


FIGURE 2-12: CONVERTING TYPE 56 TO TYPE 56 - TRNFLOW

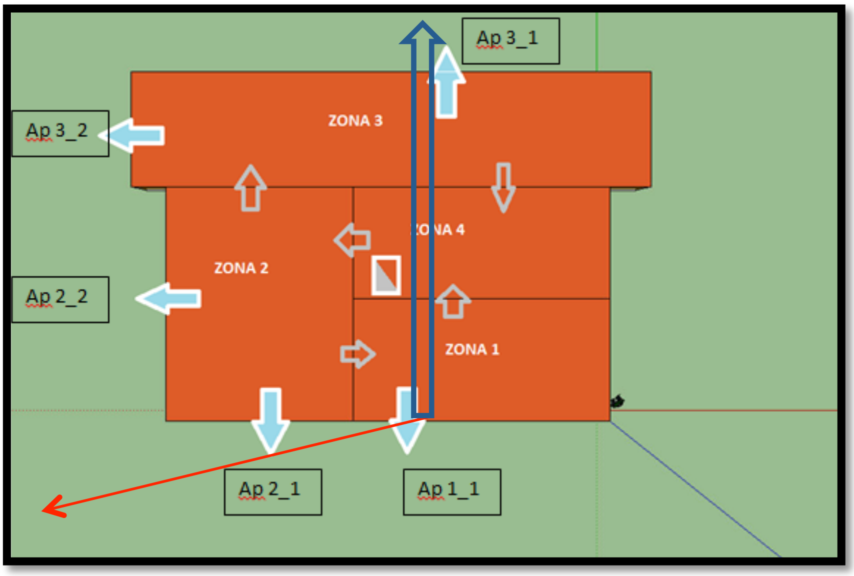


**FIGURE 2-13: DIFFERENT HOLES IN THE APARTMENT**

Figure 2-13 shows 5 different situated holes in the façade of apartment B1. These holes are useful to control the flow when doing tests with the blower door. The chimney is situated in zone 4.

What are also shown on this figure are 2 colored lines that define:

- **The meteorological North;**
- **North defined in Sketch-Up.**

The building is 110° counterclockwise rotated so that it's easier to design the building in Sketch-Up$^{TM}$. It is very important not to forget this adaptation.

### 2.2.2.3 MODEL IN TRNFLOW

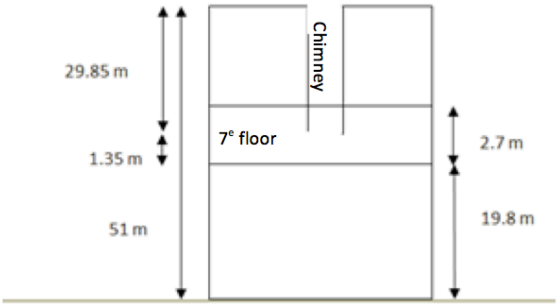
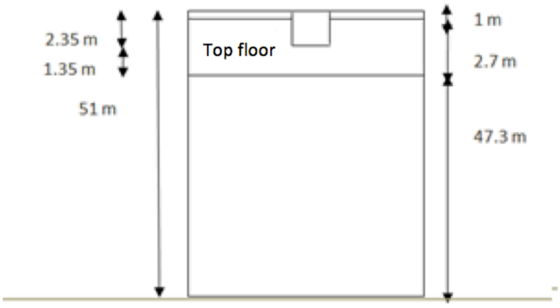
After the Sketch-Up building was implemented in TRNFLOW, by using the TRNSYS3D-file, the adaptions could take place.

In TRNFLOW we enter the following elements:

a) "Straight Duct Type" Manager. The duct has a dimension of 15x15cm and doesn't have any outlet obstruction. This duct connects zone 4 to the outside. Depending on the height of the apartment analyzed, it's required to change the output length.

| **Duct height [m]** | | |
|---|---|---|
| Ground | 7th floor | 14th floor |
| 49.62 | 29.85 | 2.35 |

**TABLE 6: DUCT HEIGHT**

| | |
|---|---|
|  | First floor apartment.<br>The duct length is 49.65 m. |
|  | Seventh floor apartment.<br>The duct length is 29,85 m. |
|  | Top floor apartment.<br>The duct length is 2.35 m. |

Furthermore we modified the height from the thermal- to the external node ("From node" to "To node"). For each floor the heights for the nodes are as follow:

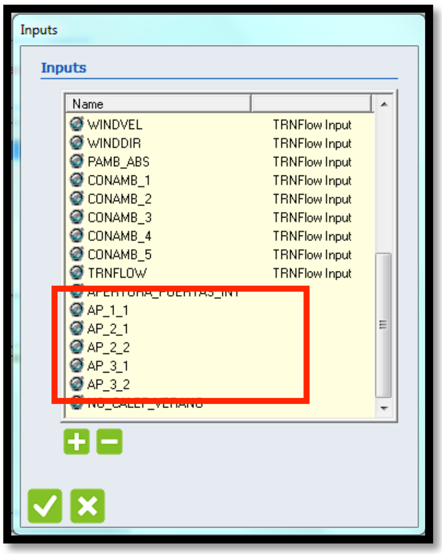
- Height thermal node ("From node") = 1.35 m
- External node ("To node") = 51 m

What also has to be modified, are the $C_p$-values for each height and orientation. The $C_p$-values are calculated with the $G_p$-generator (TNO web applications). With the "External Node Type"-function it's easy to define the $C_p$-values for each external node.

b) <u>"Large Opening Type" Manager</u>.

Openings in the joinery between an inner and outer zone, or between inner zones.

The openings to the outside are defined with the name WI_X_X where X is the size of the opening in centimeters. It has an "EXTERNAL FACTOR OF WINDOW" between 1 and 0. In TRNSYS, 5 inputs are defined with AP_X_X, this is to change the opening factor of the holes, so it's not necessary to change the opening factor in TRNBUILD, what makes it much more efficient. (AP_n° of façade_ n° of hole).



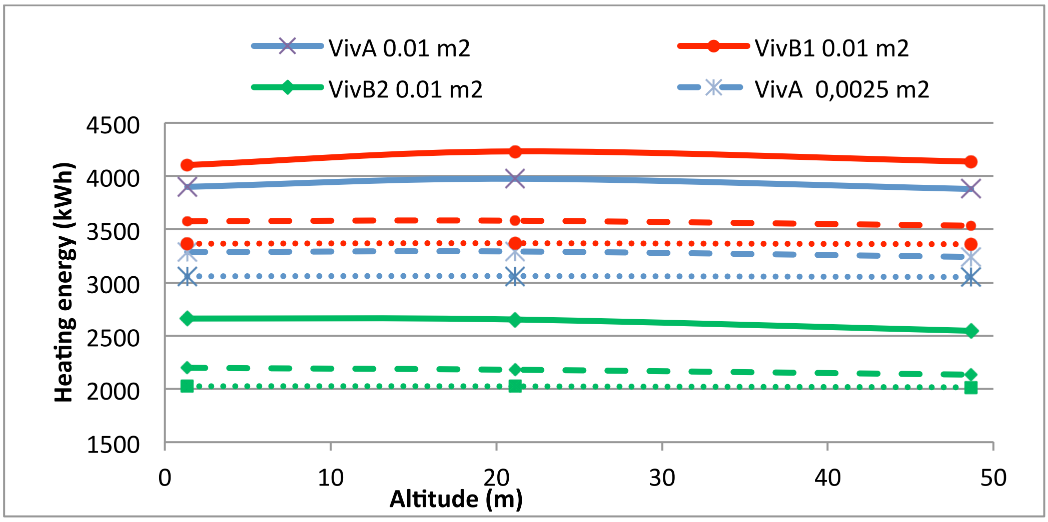
| Name | |
|---|---|
| WINDVEL | TRNFlow Input |
| WINDDIR | TRNFlow Input |
| PAMB_ABS | TRNFlow Input |
| CONAMB_1 | TRNFlow Input |
| CONAMB_2 | TRNFlow Input |
| CONAMB_3 | TRNFlow Input |
| CONAMB_4 | TRNFlow Input |
| CONAMB_5 | TRNFlow Input |
| TRNFLOW | TRNFlow Input |
| APERTURA_PUERTAS_INT | |
| AP_1_1 | |
| AP_2_1 | |
| AP_2_2 | |
| AP_3_1 | |
| AP_3_2 | |
| NO_CALEF_VERANO | |

**FIGURE 2-14: THE OPENINGS IN TRNBUILD**

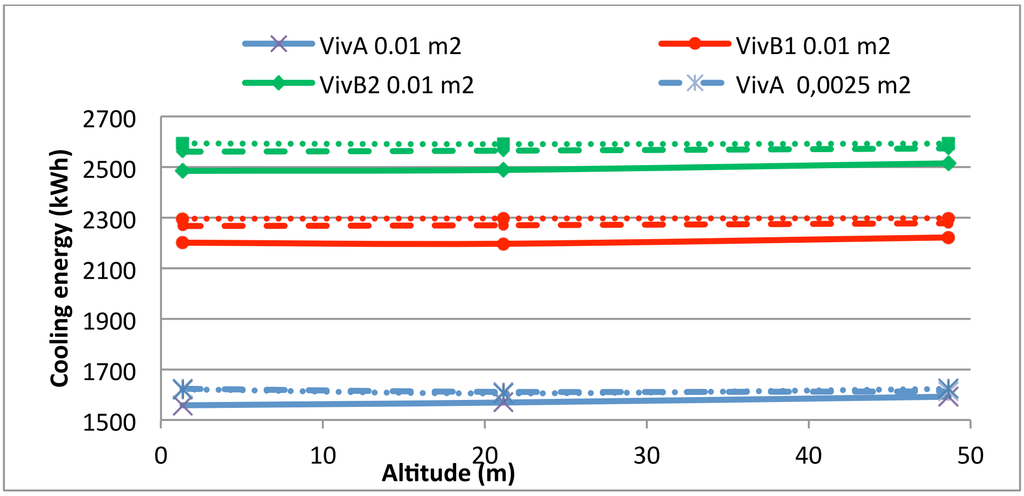
### 2.2.2.4 TESTS CARRIED OUT ON THE MODEL

In the first test the energy demand was calculated, while changing the size of an opening. So by varying the height and size of the opening, the obtained results are shown in *Appendix A: Table 1*.

Results graphically:

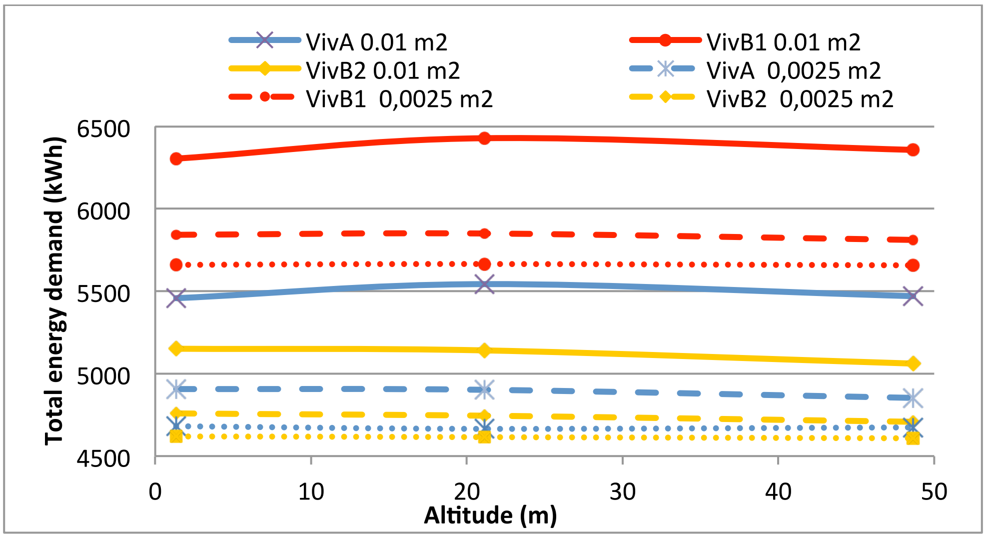


GRAPHIC 2: ANNUAL HEATING DEMAND BY HOUSING TYPE AND HEIGHT



GRAPHIC 3: ANNUAL COOLING DEMAND BY HOUSING TYPE AND HEIGHT

The graphics show the values of cooling and heating demand. It shows the effect of demand in cooling and heating according to the size of the opening. There was also a slight variation in demand according to the height of the houses, but this is negligible for the smallest opening.



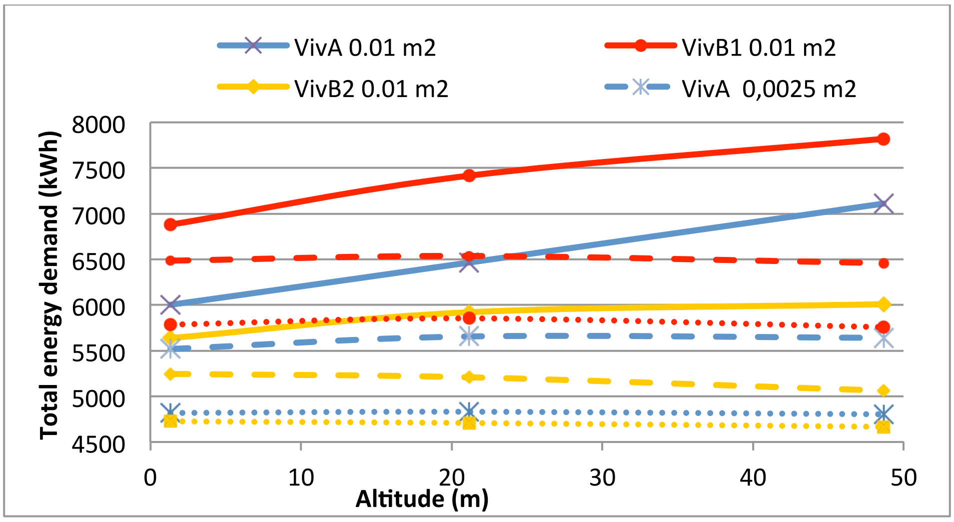
GRAPHIC 4: TOTAL ANNUAL ENERGY DEMAND

Noting the global demand of the building throughout the year, it shows the difference between the different apartments - B1 has the greatest demand for different heights. For this reason it's logical to look at apartment B1 while doing tests on the wind exposure and direction.

The graphic above summarizes the annual energy demand of different apartments according to their height and number of openings. In all cases the demand increases with the number of openings.

| Openings | 0.1x0.1m | 0.05x0.05m | 0.02x0.02m |
|---|---|---|---|
| 1 hole open | 0.01 m$^2$ | 0.0025 m$^2$ | 0.0004 m$^2$ |
| 5 holes open | 0.05 m$^2$ | 0.0125 m$^2$ | 0.002 m$^2$ |

TABLE 7: SURFACE OF DIFFERENT OPENED HOLES



GRAPHIC 5: ENERGY DEMAND FOR 5 OPENINGS

It’s clear that in this case:

- B1 is the apartment with the highest energy demand;
- Apartments B1 and A are the apartments that are the most influenced by their height and size of openings.

In addition to analyzing the size of the openings, it’s also interesting to analyze the influence of the wind speed and direction on apartment B1, because this is the apartment with highest energy demand. More information in 4.3 .

# 3 METHODOLOGY

## 3.1 THE MEASUREMENTS

### 3.1.1 MEASURING EQUIPMENT

TESTO 435

The TESTO 435 (Figure 3-1), a measuring instrument for ambient air conditions (inside and outside of the model), for assessment of indoor air quality and adjusting and testing VAC systems, stands out on account of its efficient measurement process. The IAQ probe (Figure 3-2) measures the indoor and outdoor air quality by measuring the air moisture and air temperature. Clear analysis and archiving ensure practical PC documentation. The special flow protocol professionally documents duct measurements. It is also possible to connect additional temperature and humidity probes. Readings from up to 3 temperature or humidity probes can clearly be displayed in the measuring instrument.

**FIGURE 3-1: TESTO 435-2**

FIGURE 3-2: IAQ PROBE

It is also possible to connect a hot wire probe (Figure 3-3), for measuring a velocity and a temperature, the diameter of this probe is 7.5 mm and it is very sensitive. Data transmission is by radio, i.e. wireless.

FIGURE 3-3: HOT WIRE PROBE

Characteristics of the TESTO equipment:

| | |
|---|---|
| Instrument memory: | 10,000 readings |
| Probes: | IAQ, lux and comfort level probes |
| Protection class: | IP54 |
| Storage temperature: | -30 to +70 °C |
| Operating temperature: | -20 to +50 °C |
| Battery type: | Alkali manganese, mignon, Type AA |
| Weight: | 428 g |
| Dimensions: | 220 x 74 x 46 mm |
| Material/Housing: | ABS/TPE/Metal |

TABLE 8: CHARACTERISTICS OF TESTO 435

| | |
|---|---|
| Meas. Range: | 0 to 100 %RH |
| Meas. Range: | -20 to +70 °C |
| Accuracy of temperature: | ±0.3 °C |
| Accuracy of humidity | ±2 %RH |

TABLE 9: CHARACTERISTICS OF THE IAQ PROBE

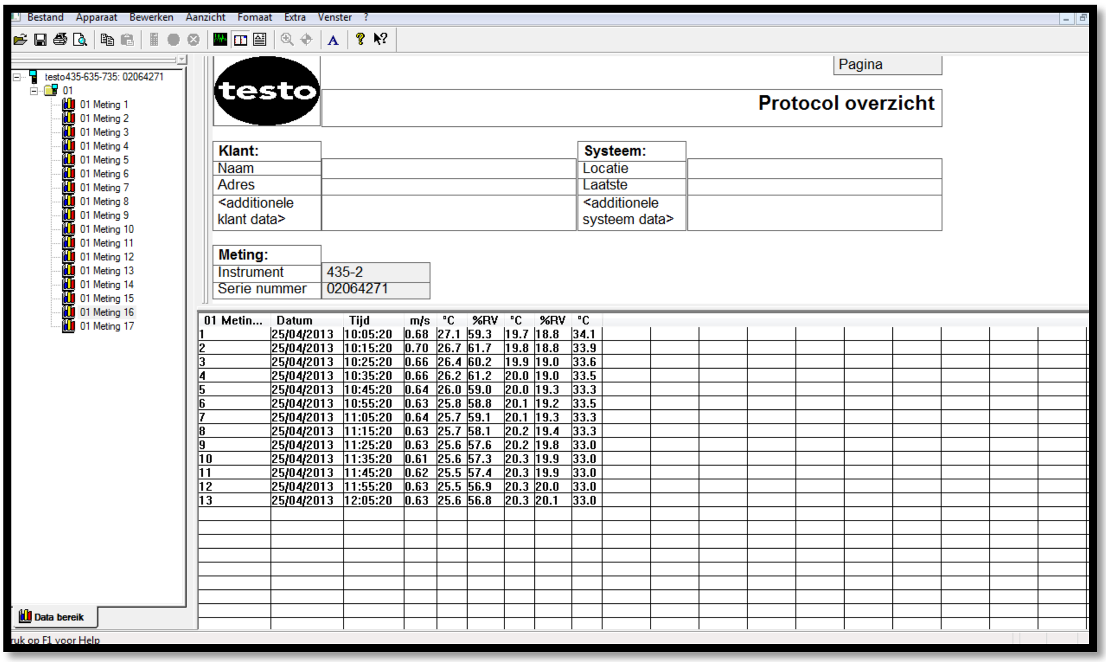
| | |
|---|---|
| Meas. Range: | 0 to +20 m/s |
| Meas. Range: | -20 to +70 °C |
| Meas. Range: | 0 to 100 %RH |
| Accuracy of velocity: | ± 0.03 m/s |
| Accuracy of temperature: | ± 0.3 °C |
| Accuracy of humidity | ± 2 %RH |

TABLE 10: CHARACTERISTICS OF THE HOT WIRE PROBE

### Testo Comfort Software X35

The TESTO equipment is ineffective when there is no software that transfers and saves the data on the computer. The software used during the tests was the TESTO Comfort Software X35.

The TESTO Comfort Software X35 is used to collect data and to extract the maximum value of measurements. Graphical display is the main task of this program but in our research this graphical display is never used because of the benefits of Microsoft Excel. Measured values with the TESTO measuring equipment are transferred to the computer with an USB connection. When there is a connection between the Software and the TESTO measuring equipment all functions of the software become available. All the measurements are shown in a proper table and this table can easily be converted to an Excel-file.



**Protocol overzicht**

**Klant:**
Naam
Adres
<additionele klant data>

**Systeem:**
Locatie
Laatste
<additionele systeem data>

**Meting:**
Instrument 435-2
Serie nummer 02064271

| 01 Metin... | Datum | Tijd | m/s | °C | %RV | °C | %RV | °C |
|---|---|---|---|---|---|---|---|---|
| 1 | 25/04/2013 | 10:05:20 | 0.68 | 27.1 | 59.3 | 19.7 | 18.8 | 34.1 |
| 2 | 25/04/2013 | 10:15:20 | 0.70 | 26.7 | 61.7 | 19.8 | 18.8 | 33.9 |
| 3 | 25/04/2013 | 10:25:20 | 0.66 | 26.4 | 60.2 | 19.9 | 19.0 | 33.6 |
| 4 | 25/04/2013 | 10:35:20 | 0.66 | 26.2 | 61.2 | 20.0 | 19.0 | 33.5 |
| 5 | 25/04/2013 | 10:45:20 | 0.64 | 26.0 | 59.0 | 20.0 | 19.3 | 33.3 |
| 6 | 25/04/2013 | 10:55:20 | 0.63 | 25.8 | 58.8 | 20.1 | 19.2 | 33.5 |
| 7 | 25/04/2013 | 11:05:20 | 0.64 | 25.7 | 59.1 | 20.1 | 19.3 | 33.3 |
| 8 | 25/04/2013 | 11:15:20 | 0.63 | 25.7 | 58.1 | 20.2 | 19.4 | 33.3 |
| 9 | 25/04/2013 | 11:25:20 | 0.63 | 25.6 | 57.6 | 20.2 | 19.8 | 33.0 |
| 10 | 25/04/2013 | 11:35:20 | 0.61 | 25.6 | 57.3 | 20.3 | 19.9 | 33.0 |
| 11 | 25/04/2013 | 11:45:20 | 0.62 | 25.5 | 57.4 | 20.3 | 19.9 | 33.0 |
| 12 | 25/04/2013 | 11:55:20 | 0.63 | 25.5 | 56.9 | 20.3 | 20.0 | 33.0 |
| 13 | 25/04/2013 | 12:05:20 | 0.63 | 25.6 | 56.8 | 20.3 | 20.1 | 33.0 |

FIGURE 3-4: EXAMPLE OF TESTO COMFORT SOFTWARE X35

### 3.1.2 GENERAL METHOD

24 measurements are taken in 3 hours. There were more measurements than necessary because there were a couple of failures so these results couldn't be used. The reason why one test takes 3 hours is that the box is fully heated after 100 minutes and because every test is different, a test duration of 3 hours was enough.

The temperature and %RH were measured on the inside and the outside of the model, the IAQ probe on the inside was in the middle of the box for observing the global temperature and %RH inside the model. At the top of the PVC-tube the hot wire probe was installed that measured the air velocity.

#### 3.1.2.1 ANALYSIS OF THE MEASUREMENTS

The results were shown as follow, e.g. "2 lamps, opening = 100 cm², height of pipe = 2 m", the 23 other measurements were analyzed with the same method:

- # Measurements: each 10 minutes the data was measured (3 hours = 180 minutes)
- Date: the date when the measurements were taken
- Time
- Velocity: this is the velocity at the end of the tube (m/s)
- %RH outside: the relative humidity measured outside
- %RH inside: the relative humidity measured inside
- T outside: Temperature outside (°C)
- T inside: Temperature inside (°C)
- T inside-T outside (Δ temperature): Difference between the inside temperature of the box and the outside temperature in the lab (°C)

| # Measurements | Date | Time | Velocity (m/s) | %RH outside | Toutside (°C) | Tinside-Toutside (°C) |
|---|---|---|---|---|---|---|
| 1 | 23/04/13 | 14:38:45 | 0,45 | 50 | 22,3 | 8 |
| 2 | 23/04/13 | 14:48:45 | 0,47 | 50,2 | 22,4 | 9,3 |
| 3 | 23/04/13 | 14:58:45 | 0,5 | 49,9 | 22,3 | 10,3 |
| 4 | 23/04/13 | 15:08:45 | 0,51 | 50,4 | 22,4 | 10,8 |
| 5 | 23/04/13 | 15:18:45 | 0,53 | 49,7 | 22,4 | 11,5 |
| 6 | 23/04/13 | 15:28:45 | 0,54 | 50,1 | 22,4 | 11,9 |
| 7 | 23/04/13 | 15:38:45 | 0,55 | 50 | 22,5 | 12 |
| 8 | 23/04/13 | 15:48:45 | 0,55 | 50,3 | 22,5 | 12,1 |
| 9 | 23/04/13 | 15:58:45 | 0,56 | 50,1 | 22,5 | 12,3 |
| 10 | 23/04/13 | 16:08:45 | 0,56 | 50,1 | 22,5 | 12,5 |
| 11 | 23/04/13 | 16:18:45 | 0,57 | 49,5 | 22,6 | 12,5 |
| 12 | 23/04/13 | 16:28:45 | 0,57 | 49,8 | 22,5 | 12,6 |
| 13 | 23/04/13 | 16:38:45 | 0,58 | 49,3 | 22,5 | 12,6 |
| 14 | 23/04/13 | 16:48:45 | 0,57 | 50 | 22,5 | 12,7 |
| 15 | 23/04/13 | 16:58:45 | 0,58 | 49,7 | 22,5 | 12,7 |
| 16 | 23/04/13 | 17:08:45 | 0,56 | 49,5 | 22,5 | 12,7 |
| 17 | 23/04/13 | 17:18:45 | 0,57 | 49,5 | 22,5 | 12,7 |
| 18 | 23/04/13 | 17:28:45 | 0,55 | 49,8 | 22,5 | 12,7 |

**TABLE 11: TEST DATA OF 2 LAMPS, 2 M (OUTSIDE + VELOCITY)**

| # Measurements | Date | Time | %RH inside | Tinside (°C) |
|---|---|---|---|---|
| 1 | 23/04/13 | 14:38:45 | 20,3 | 30,3 |
| 2 | 23/04/13 | 14:48:45 | 19,4 | 31,7 |
| 3 | 23/04/13 | 14:58:45 | 19,2 | 32,6 |
| 4 | 23/04/13 | 15:08:45 | 19,2 | 33,2 |
| 5 | 23/04/13 | 15:18:45 | 18,9 | 33,9 |
| 6 | 23/04/13 | 15:28:45 | 18,9 | 34,3 |
| 7 | 23/04/13 | 15:38:45 | 19 | 34,5 |
| 8 | 23/04/13 | 15:48:45 | 19,1 | 34,6 |
| 9 | 23/04/13 | 15:58:45 | 19 | 34,8 |
| 10 | 23/04/13 | 16:08:45 | 19 | 35 |
| 11 | 23/04/13 | 16:18:45 | 19 | 35,1 |
| 12 | 23/04/13 | 16:28:45 | 19,1 | 35,1 |
| 13 | 23/04/13 | 16:38:45 | 19,2 | 35,1 |
| 14 | 23/04/13 | 16:48:45 | 19,2 | 35,2 |
| 15 | 23/04/13 | 16:58:45 | 19,2 | 35,2 |
| 16 | 23/04/13 | 17:08:45 | 19,2 | 35,2 |
| 17 | 23/04/13 | 17:18:45 | 19,3 | 35,2 |
| 18 | 23/04/13 | 17:28:45 | 19,4 | 35,2 |

**TABLE 12: TEST DATA OF 2 LAMPS, 100 CM$^2$, 2 M (INSIDE)**

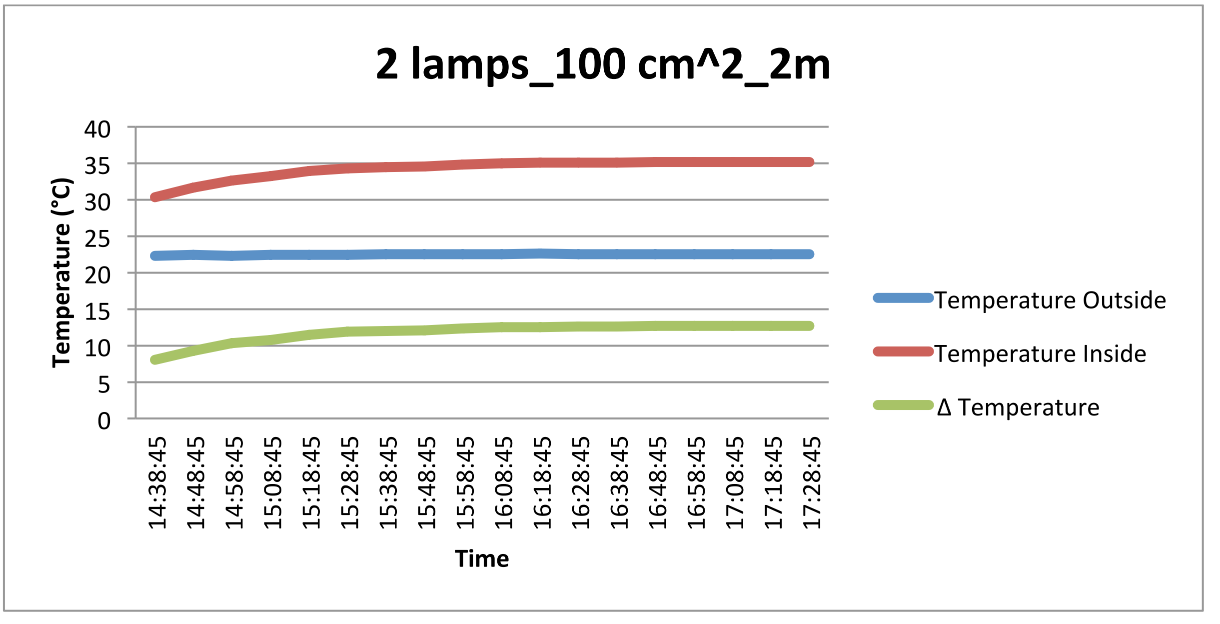
To calculate when the box is totally heated the Δ temperature is determined. When Δ temperature is constant, the box is completely heated. Δ Temperature is used because the outside temperature increases or decreases during the day, that's why the inside temperature isn't used.

- In red: T inside – T outside = not constant
- In green: T inside – T outside = constant

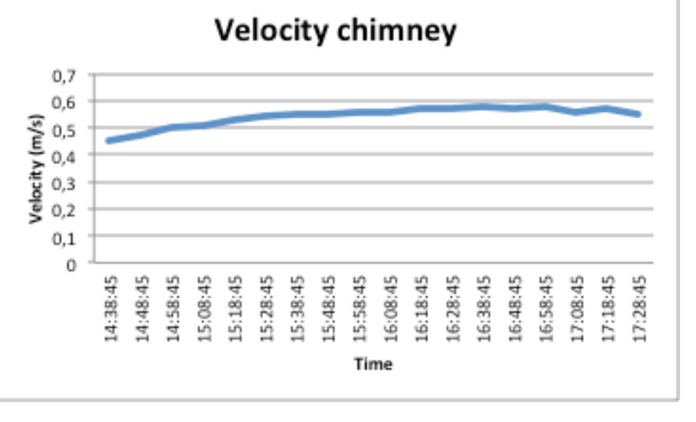
| # Measurements | Date | Time | Velocity (m/s) | %RH outside | Toutside (°C) | Tinside-Toutside (°C) |
|---|---|---|---|---|---|---|
| 1 | 23/04/13 | 14:38:45 | 0,45 | 50 | 22,3 | 8 |
| 2 | 23/04/13 | 14:48:45 | 0,47 | 50,2 | 22,4 | 9,3 |
| 3 | 23/04/13 | 14:58:45 | 0,5 | 49,9 | 22,3 | 10,3 |
| 4 | 23/04/13 | 15:08:45 | 0,51 | 50,4 | 22,4 | 10,8 |
| 5 | 23/04/13 | 15:18:45 | 0,53 | 49,7 | 22,4 | 11,5 |
| 6 | 23/04/13 | 15:28:45 | 0,54 | 50,1 | 22,4 | 11,9 |
| 7 | 23/04/13 | 15:38:45 | 0,55 | 50 | 22,5 | 12 |
| 8 | 23/04/13 | 15:48:45 | 0,55 | 50,3 | 22,5 | 12,1 |
| 9 | 23/04/13 | 15:58:45 | 0,56 | 50,1 | 22,5 | 12,3 |
| 10 | 23/04/13 | 16:08:45 | 0,56 | 50,1 | 22,5 | 12,5 |
| 11 | 23/04/13 | 16:18:45 | 0,57 | 49,5 | 22,6 | 12,5 |
| 12 | 23/04/13 | 16:28:45 | 0,57 | 49,8 | 22,5 | 12,6 |
| 13 | 23/04/13 | 16:38:45 | 0,58 | 49,3 | 22,5 | 12,6 |
| 14 | 23/04/13 | 16:48:45 | 0,57 | 50 | 22,5 | 12,7 |
| 15 | 23/04/13 | 16:58:45 | 0,58 | 49,7 | 22,5 | 12,7 |
| 16 | 23/04/13 | 17:08:45 | 0,56 | 49,5 | 22,5 | 12,7 |
| 17 | 23/04/13 | 17:18:45 | 0,57 | 49,5 | 22,5 | 12,7 |
| 18 | 23/04/13 | 17:28:45 | 0,55 | 49,8 | 22,5 | 12,7 |

**TABLE 13: AFTER ANALYSIS OF CONSTANT Δ TEMPERATURE**

After the analysis of the constant Δ temperature, the following graphs are plotted:

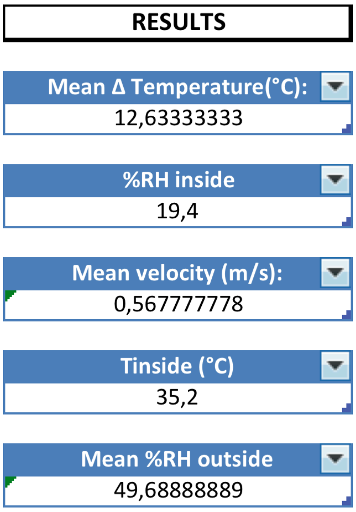


GRAPHIC 6: OUTSIDE, INSIDE AND Δ TEMPERATURE



GRAPHIC 7: AIR VELOCITY AT THE TOP OF THE CHIMNEY

In the shown graphics the same conclusions can be made of Table 14, when Δ temperature is not changing a lot, the box is totally heated. This is a good way to analyse the test data. When the lines of the graphics aren't rising anymore, the velocity at the top of the chimney is in balance.



**RESULTS**

Mean Δ Temperature(°C):
12,63333333

%RH inside
19,4

Mean velocity (m/s):
0,567777778

Tinside (°C)
35,2

Mean %RH outside
49,68888889

**TABLE 14: RESULTS FOR 2 LAMPS, 100 CM$^2$, 2 M**

The values of Table 14 will be used to analyze the measurements:

Mean Δ temperature (°C)

= Mean of T inside-T outside that's marked with a green background in Table 13.

This value is calculated because it is very important to compare it with the other measurements with the same number of lamps but with a different opening and height of the chimney.

%RH inside

= The last value of % RH inside in Table 12.

Mean velocity (m/s)

= Mean velocity that's marked with a green background in Table 13.

Mean velocity is the value that will be compared with the outcome of the TRNSYS-file.

T inside (°C)

= The last value of T inside in Table 12.

This value will be set into the TRNSYS-file as a constant value of the temperature inside.

Mean %RH outside

= Mean %RH outside that's marked with a green background in Table 13.

### 3.1.3 THERMOGRAPH CAMERA

#### 3.1.3.1 GENERAL

The infrared camera is used to measure the surface temperature of the box and the reflected temperature of the environment. These values will be set into the thermal balance and with the thermal balance it's possible to verify the results (See 5.2)

The infrared camera that will be used during the tests is the FLIR B335 (See Figure 3-5). FLIR B335 is a small and light–weight infrared camera with an excellent image quality and high sensitivity, ideal for building diagnostics and energy declaration surveys.

**FIGURE 3-5: INFRARED CAMERA FLIR B335**

Characteristics:

| | |
|---|---|
| Resolution IR Images | 320 x 240 pixels infrared resolution |
| Digital camera | 3.1 Megapixels |
| Temperature range | -20 °C to +120 °C |
| Accuracy | ± 2% |
| Type of lens | 25° lens |
| Zoom | 2x continuous digital |
| Laser pointer | Yes |
| Spectral range | 7.5 – 13 µm |
| Image frequency | 9 Hz |
| Camera weight | 880 g |
| Camera size (L x W x H) | 106 x 201 x 125 mm |

**TABLE 15: CHARACTERISTICS OF THE B335 CAMERA**

### 3.1.3.2 SOFTWARE

The software-program that will be used during the analysis of the pictures, which were taken with the infrared camera, is QuickReport of FLIR. QuickReport allows us to analyze and arrange the radiometric images from the infrared camera and present them afterwards in a full report. The QuickReport software permits us to adapt the level, zoom, span and pan of the infrared camera. The build-in report template allows us to either include two infrared images, or an infrared image and a digital photo.

### 3.1.3.3 METHOD

Before the infrared pictures were taken, the temperature inside had to be saturated. Subsequently for each wall a white sticker label was pasted, this for measuring the emissivity and also for each wall an aluminum stroke was placed (See black spot on Figure 3-6) to gauge the reflected temperature. After these adaptations, the model was photographed and the pictures were set into the QuickReport FLIR, afterwards the infrared pictures were analyzed. The software calculates the minimum and maximum temperature of a specific region on the photo that can be indicated by the researcher (green squares on Figure 3-6). After analyzing the entire surface of the box an average surface temperature is calculated.

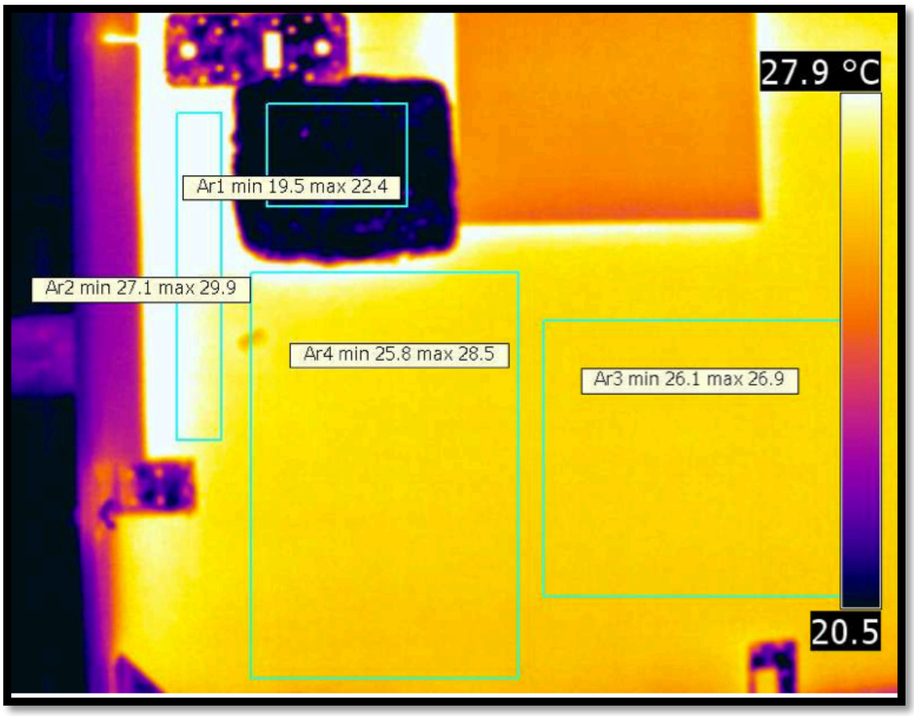


**FIGURE 3-6: EXAMPLE OF AN INFRARED PICTURE OF THE MODEL**

The average temperature will be calculated on the basis of a geometric mean, because the surface of the model is not homogeneous. The average temperatures will be calculated as follow:

- Find the homogeneous zones and draw a green square on this zone.
- The software will calculate the minimum and maximum temperature of this zone.
- Calculate the average temperature of the zone.
- Calculate the surface of the green square.
- Repeat this for the whole surface of the model.
- Calculate the average temperature for the model

## 3.1.4 BLOWER DOOR TEST

### 3.1.4.1 DEFINITION

Window, doors or ventilation systems are provided to ventilate buildings. Unfortunately, indoor air also escapes through openings caused by construction defects, such as joints and connections. Components in the roof that are not tight also cause an uncontrolled air exchange.

Using the blower door test, (the differential pressure measuring procedure for buildings), an overpressure and under pressure of 50 Pa can be used to check the air-tightness of buildings, locate leakages in the building shell and determine the rate of air exchange.

There are many benefits for providing a blower door test: draughts are prevented, sound insulation and living comfort are increased, the energy consumption is decreased, and condensation build-up, moisture damage and mould formation on components are prevented

### 3.1.4.2 TEST

The overpressure and the under pressure will be measured because in reality there is an under pressure in the region of the different kind of openings and an overpressure in the region of the chimney, when it’s compared with the pressure in the chimney. So the under pressure and overpressure of 50 Pa was measured separately.

<u>Equipment for blower door test:</u>

**DM-2 Series 2 Channel Digital Pressure Gauge**

Retrotec’s DM-2, dual channel, digital manometer puts the operator in command of virtually every parameter of interest to the blower door tester. The DM-2 represents a huge advance in building and envelope diagnostic instrumentation.

FIGURE 3-7: DM-2 DIGITAL MANOMETER

What does the manometer measure:

- Measuring pressure on two channels
- Calculating airflow
- Equivalent leakage area
- Air-changes per hour

### The 2200-Serie calibrated fan

It is designed for testing any residential house or enclosure from 0.8 m² of leakage down to tight houses and small enclosures with 15 inch$^2$ (97 cm$^2$).

FIGURE 3-8: THE 2200-SERIE CALIBRATED FAN

### Software Retrotec FanTestic version 5.2.116

It's the latest version of the program provided by the company. Right now it is one of the most advanced programs for the blower door test.

FIGURE 3-9: SOFTWARE RETROTEC

### Range

The ranges that were needed during the tests with an opening of 100 cm$^2$ and 50 cm$^2$ is Range C1 and with an opening of 10 cm$^2$ it's Range L4. The use of a different Range is coming from the different openings that were used during the tests.

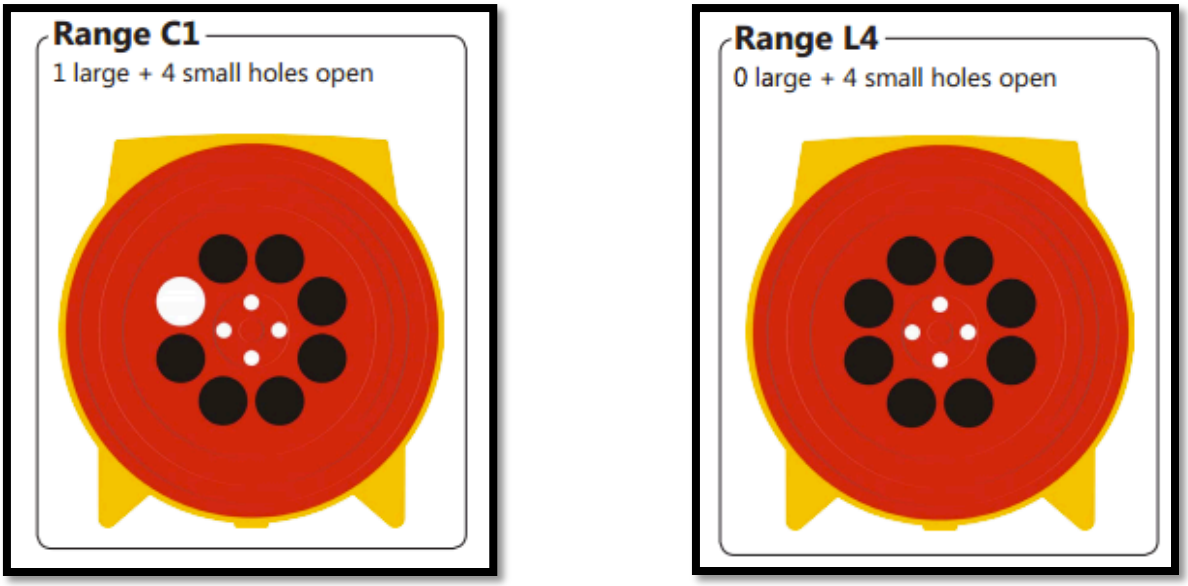


FIGURE 3-10: RANGE C1 AND L4

TEST-DATA

The test was provided in compliance with European Norm EN13829. The next parameters were put into the software of RetroTec:

| | |
|---|---|
| Elevation (m) | 9 |
| Height of building above ground (m) | 1,5 |
| Volume ($m^3$) | 1,2 |
| Total envelope area ($m^2$) | 6,2 |
| Floor area ($m^2$) | 0,8 |
| Norm | European Norm EN13829 |
| Air flow reference #1 (Pa) | 50 |
| Flow/unit area reference pressure (Pa) | 50 |
| Bias pressure (12 measurements) | For 10 sec each. |
| Induced pressures (Pa) (12 measurements) | 20-80 for 20 sec each. |
| Autotest timeout (Sec) | 20 |
| Ramp up delay (Sec) | 30 |
| Allowed error | 5 % or 2 Pa |
| Max change of Pa/sec | 1 |

**TABLE 16: THE DIFFERENT PARAMETERS INTRODUCED IN THE RETROTEC SOFTWARE**

## 3.2 MAKING OF TRNSYS-FILE

### 3.2.1 CREATION OF THE MODEL IN GOOGLE SKETCH-UP™

If you want to use a Multi-Zone Building it's possible to implement a *.IDF file, that's created with TRNSYS3d (TRNSYS) a plugin for Google Sketch-Up™. Instead of entering the surfaces manually in TRNSYS, three-dimensional data created by TRNSYS-3D for TRNSYS can be imported.

So first it's necessary to design the model. The model has the following dimensions: 1.00 x 0.79 x 1.50 m. The next step is saving the model as a "TRNSYS-3D input file", this data will be saved as an IDF-file (IDentification File), where the dimensions of the model are saved.

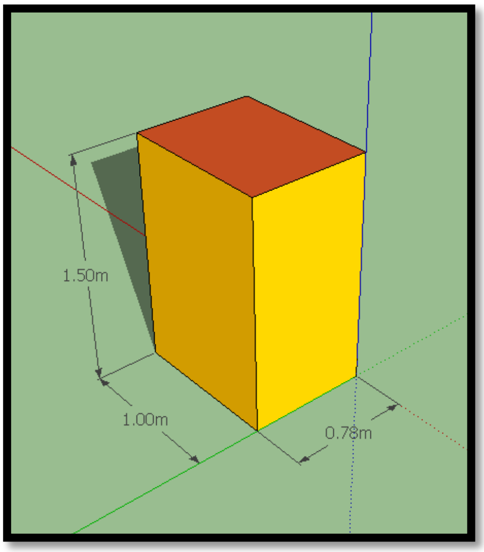
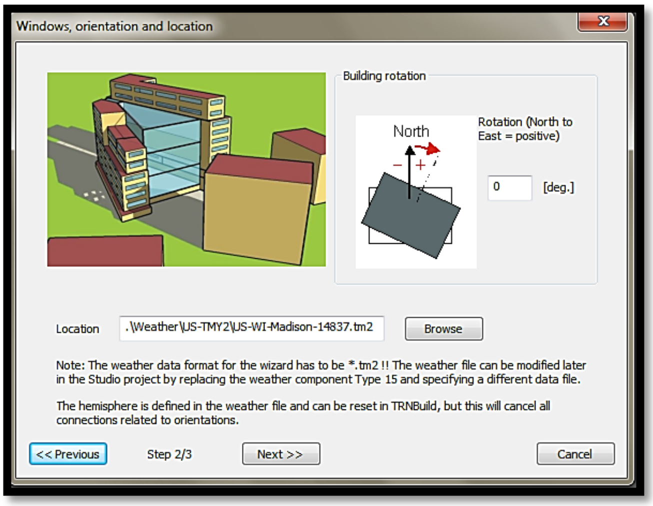


FIGURE 3-11: BOX DESIGNED IN SKETCH-UP™

FIGURE 3-12: TOOLBAR TO SAVE THE PROJECT AS A TRNSYS-3D INPUT FILE

### 3.2.2 IMPLEMENTING THE MODEL IN TRNSYS

Once the IDF file is created, a new building can be implemented in TRNSYS, by creating a new 3D Building Project (Multi-Zone) - Type 56. If the specific weather data is selected (e.g. Valencia) and the desired IDF-file is opened, TRNSYS will display a design of the system with different types connected with each other by several links.



Rotation (North to East = positive) 0 [deg.]

Location .\Weather\US-TMY2\US-WI-Madison-14837.tm2

Note: The weather data format for the wizard has to be *.tm2 !! The weather file can be modified later in the Studio project by replacing the weather component Type 15 and specifying a different data file.

The hemisphere is defined in the weather file and can be reset in TRNBuild, but this will cancel all connections related to orientations.

Step 2/3

FIGURE 3-13: WINDOW TO IMPLEMENT THE WEATHERDATA

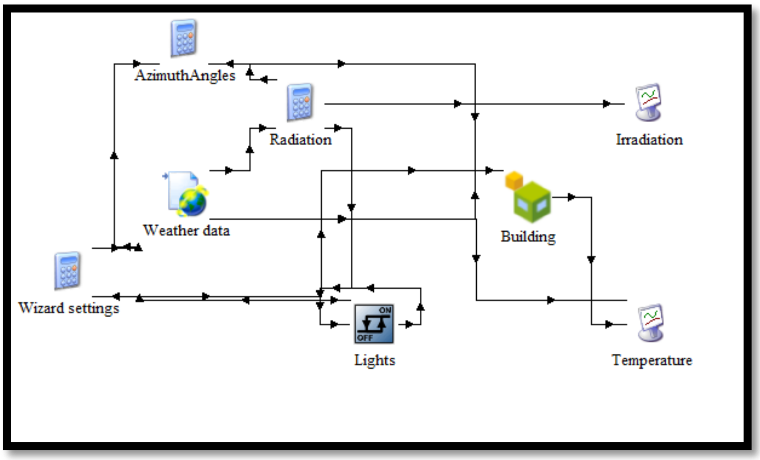


FIGURE 3-14: RESULT AFTER SPECIFYING A SIMPLE MULTI-ZONE BUILDING

Since the model is situated in a laboratory (inside, where there is no sunlight) and there are only lamps inside the model, the irradiation components can be deleted (lights or the ON/OF differential controller, Irradiation, AzimuthAngles, Radiation, Wizard settings). The weatherdata is still required, because TRNSYS recommends indicating a Solar Zenith- and Solar Azimuth Angle otherwise the system doesn't work.

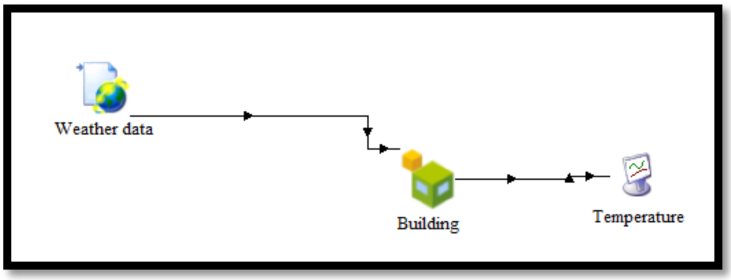


FIGURE 3-15: DESIGN IN THE SIMULATION STUDIO WITHOUT TRNFLOW

Another adaptation that's needed is replacing the Loads and Structures of the Multi-Zone Building into a Multi-Zone Building with AirFlow (TRNFLOW), so it's possible to graph the resulted heat flow through the chimney, window and crack in the Simulation Studio.

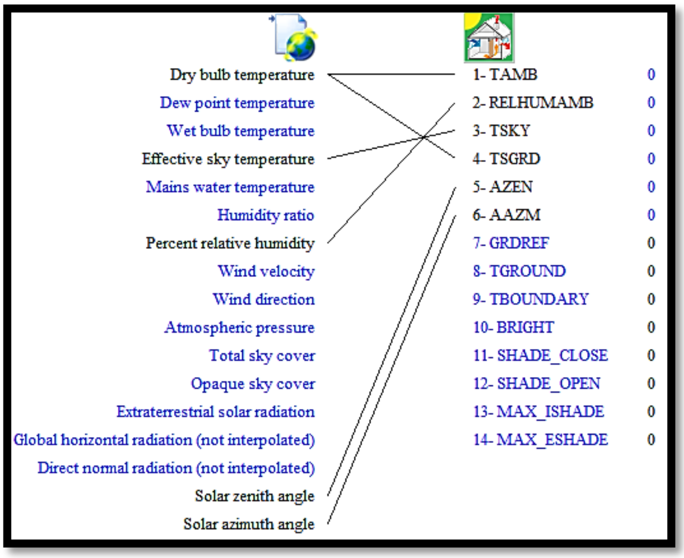


FIGURE 3-16: DESIGN IN THE SIMULATION STUDIO WITH TRNFLOW

The links between the weatherdata and the building are shown on Figure 3-17:

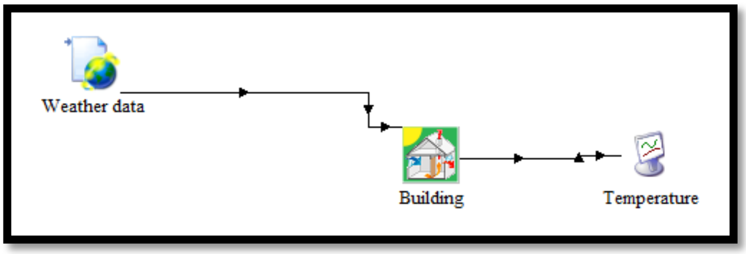


FIGURE 3-17: LINKS BETWEEN THE WEATHERDATA AND THE MODEL

This is the weatherdata for the outside weather in Valencia, but since the model is situated inside a laboratory, some links have to be deleted:

- Dry bulb temerperature → $T_{ambient}$+$T_{surface,ground}$;
- Effective sky temperature → $T_{sky}$;
- Percent relative humidity → Relative Ambient Humidity.

The temperature and humidty inside the laboratory is seen as the weatherdata "outside", in order to make a comparison with the measurements that are made with the TESTO measurement equipment.

The measurements (Temperature outside + Relative Humidity) that are registrated in the lab are copied in a *.txt-file and implemented in the Simulation Studio with the Type 9e.

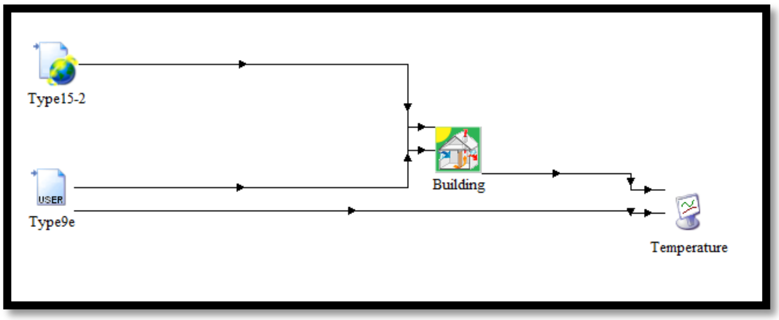
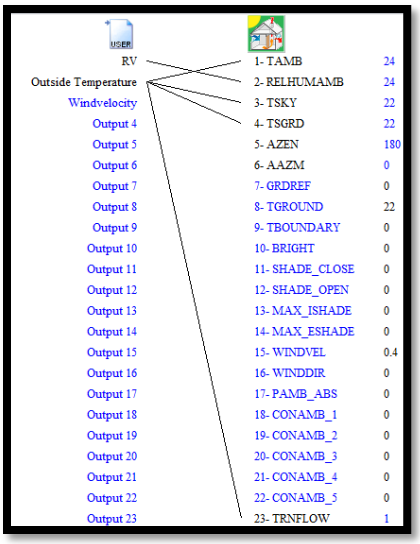


FIGURE 3-18: THE DESIGN WHEN ADDING TYPE 9E

> *Type 9e*
> *"This component serves the purpose of reading data at regular time intervals from a data file, converting it to a desired system of units, and making it available to other TRNSYS components as time-varying forcing functions. This component is very general in nature and can read many different types of files. The data from line to line must be at constant time intervals"*
>
> *Werner Keilholz (2012), TRNSYS 17 Manual 02-Simulation Studio*



| | | |
|---|---|---|
| RV | 1- TAMB | 24 |
| Outside Temperature | 2- RELHUMAMB | 24 |
| Windvelocity | 3- TSKY | 22 |
| Output 4 | 4- TSGRD | 22 |
| Output 5 | 5- AZEN | 180 |
| Output 6 | 6- AAZM | 0 |
| Output 7 | 7- GRDREF | 0 |
| Output 8 | 8- TGROUND | 22 |
| Output 9 | 9- TBOUNDARY | 0 |
| Output 10 | 10- BRIGHT | 0 |
| Output 11 | 11- SHADE_CLOSE | 0 |
| Output 12 | 12- SHADE_OPEN | 0 |
| Output 13 | 13- MAX_ISHADE | 0 |
| Output 14 | 14- MAX_ESHADE | 0 |
| Output 15 | 15- WINDVEL | 0.4 |
| Output 16 | 16- WINDDIR | 0 |
| Output 17 | 17- PAMB_ABS | 0 |
| Output 18 | 18- CONAMB_1 | 0 |
| Output 19 | 19- CONAMB_2 | 0 |
| Output 20 | 20- CONAMB_3 | 0 |
| Output 21 | 21- CONAMB_4 | 0 |
| Output 22 | 22- CONAMB_5 | 0 |
| Output 23 | 23- TRNFLOW | 1 |

FIGURE 3-19: LINKS OF THE MODEL CONNECTED WITH TYPE 9E

Type 9e is now linked with the following inputs of the Multi-Zone Building with Airflow:

- RV→Relative Humidity Ambient
- "Outside" Temperature → $T_{sky}$+ $T_{amb}$+ $T_{surface+ground}$+ TRNFLOW

TRNBUILD only gives the airflows [kg/hr] as output, so to print the air velocity of the opening and duct, an equation is required. (More information about the equation type is found in topic 1.2.2.3 Equations.)

### 3.2.2.1 EQUATIONS BETWEEN THE BUILDING OUTPUT (AIRFLOW) AND THE ONLINE PLOTTER

The following formulas are needed:

$$v\left[\frac{m}{s}\right] = \frac{Heatflow\ [\frac{kg}{h}]}{3600[s] * Area[m^2] * \rho[\frac{kg}{m^3}]}$$

| | **Area** | **From airflow [kg/s] to air velocity [m/s]** |
|---|---|---|
| Pipe | 9,08 cm$^2$ | $v = \frac{Heatflow\_Pipe}{(3600 * 1.293 * 9.08 * 0.0001)}$ |
| Window | 10 cm$^2$ | $v = \frac{Heatflow\_Window}{(3600 * 1.293 * 0.001)}$ |
| | 50 cm$^2$ | $v = \frac{Heatflow\_Window}{(3600 * 1.293 * 0.005)}$ |
| | 100 cm$^2$ | $v = \frac{Heatflow\_Window}{(3600 * 1.293 ** 0.01)}$ |

**TABLE 17: AIR VELOCITY CALCULATION FOR THE DIFFERENT OPENINGS**

### 3.2.2.2 CONCLUSION

This is the final result of the construction in the Simulation Studio:

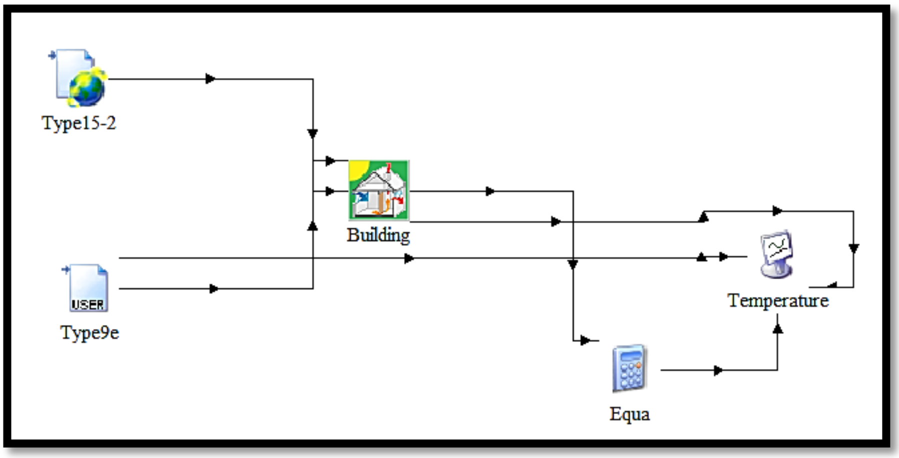


FIGURE 3-20: FINAL RESULT OF THE MODEL IN THE TRNSYS SIMULATION STUDIO

Now the system is mostly made in TRNSYS, the building itself needs some adjustments so it's similar with the real model. These adjustments are made in TRNBUILD, an independent program that interacts with TRNSYS, by using a *.idf-file.

## 3.2.3 DEFINE ADJUSTMENTS IN TRNBUILD AND BUILDING AIR LINKS IN TRNFLOW

In TRNBUILD it's possible to define the type and thickness of the walls, the different and sort of links,... Thanks to Google Sketch-Up™ the area of the model is already calculated. So the next step is to define the thickness and type of walls.

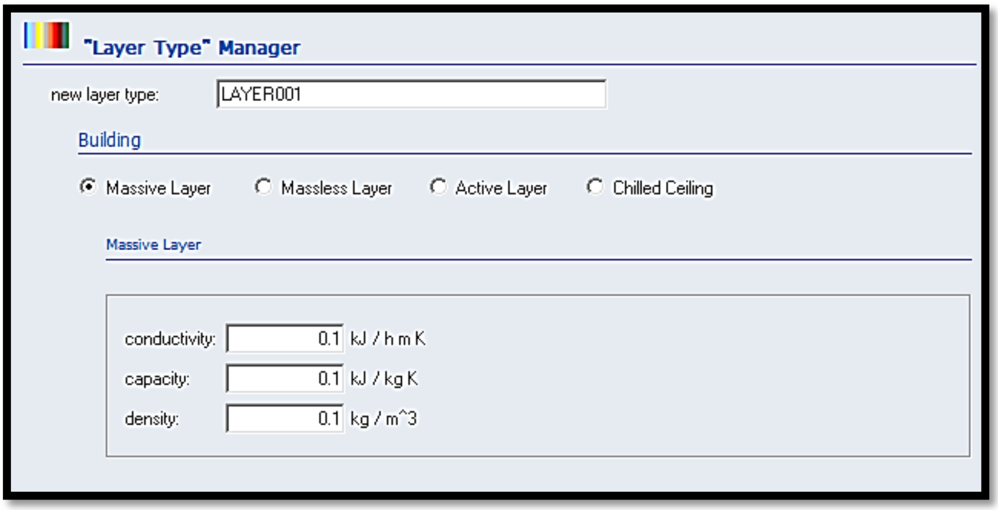
### 3.2.3.1 WALLS

Adjusting the walls occurs in the Zone Airnode Window of TRNSYS (More information about this, see: 1.3.2 The Zone Airnode Window).
The first step is defining the different walls, thereafter the thickness and type of walls.

There are 3 kinds of walls to define:

| | **NAME** | **Thickness [m]** | **Area [m²]** |
|---|---|---|---|
| GROUND_FLOOR | MEDIUMDENSITY (Massive layer) | 0.01 | 1.5/ 1.17 |
| EXT_ROOF | MEDIUMDENSITY (Massive layer) | 0.01 | 0.78 |
| EXT_WALL | MEDIUMDENSITY (Massive layer) | 0.01 | 0.78 |

TABLE 18: SPECIFICATIONS OF THE WALLS



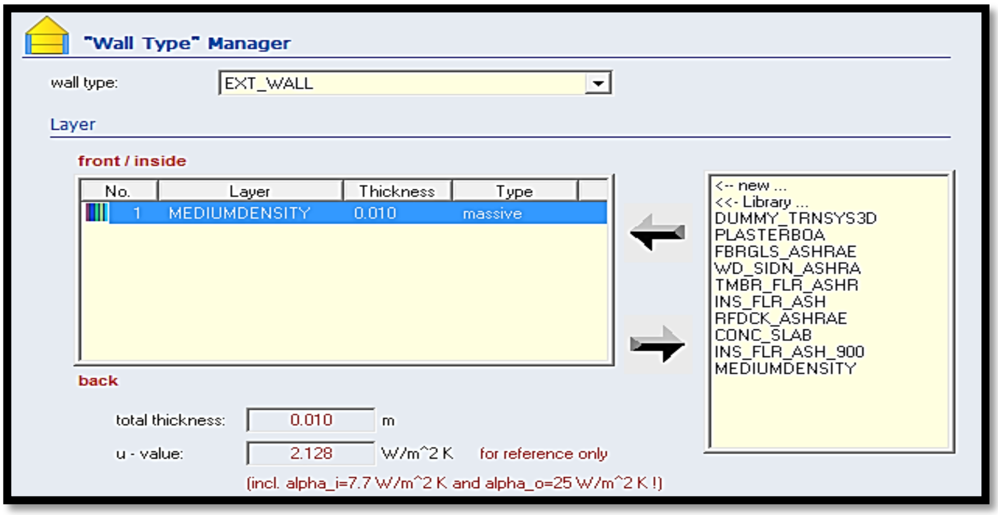
new layer type: LAYER001

● Massive Layer ○ Massless Layer ○ Active Layer ○ Chilled Ceiling

conductivity: 0.1 kJ / h m K
capacity: 0.1 kJ / kg K
density: 0.1 kg / m^3

FIGURE 3-21: THE "LAYER TYPE" MANAGER

The density of this layer is: 760 kg/$m^3$ (see 2.1.3)



wall type: EXT_WALL

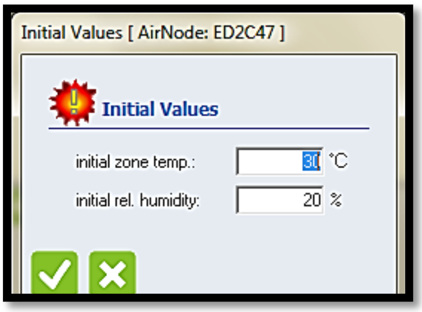
| No. | Layer | Thickness | Type |
|---|---|---|---|
| 1 | MEDIUMDENSITY | 0.010 | massive |

total thickness: 0.010 m
u - value: 2.128 W/m^2 K for reference only
(incl. alpha_i=7.7 W/m^2 K and alpha_o=25 W/m^2 K !)

FIGURE 3-22: THE "WALL TYPE" MANAGER

### 3.2.3.2 OPTIONAL EQUIPMENT

Initial values:

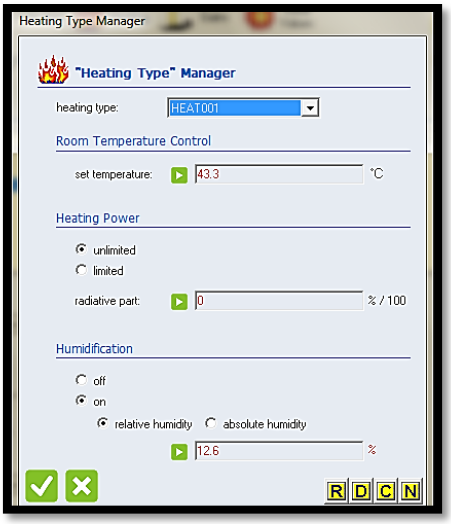


initial zone temp.: 30 °C
initial rel. humidity: 20 %

FIGURE 3-23: INITIAL VALUES IN TRNFLOW

Heating Type manager:

This topic is to define the maximum temperature and the minimum humidity inside the box. These are different for each length of duct, number of halogen lamps that are switched on and window opening. So it's very important to ensure that the results of the TRNSYS-file match with the results of the measurements.



Heating Type Manager

"Heating Type" Manager

heating type: HEAT001

Room Temperature Control

set temperature: 43.3 °C

Heating Power

● unlimited
○ limited

radiative part: 0 % / 100

Humidification

○ off
● on

● relative humidity ○ absolute humidity

12.6 %

**FIGURE 3-24: THE "HEATING TYPE" MANAGER**

### 3.2.3.3 BUILDING AIR LINKS IN TRNFLOW

In this model there are 3 different air links to identify, these links are explained below:

1) DC_PVCPIPE ("Straight Duct" PVC PIPE)

To create an air link it's necessary to first specify the 2 air nodes, where the link comes from and where it goes to (respectively "From-Node" to "To-Node").

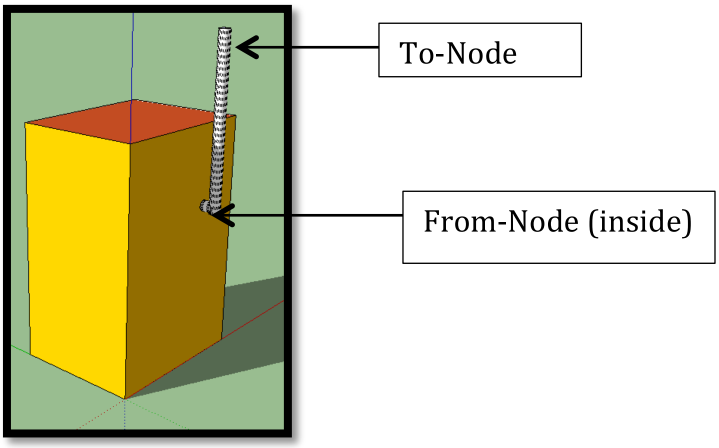
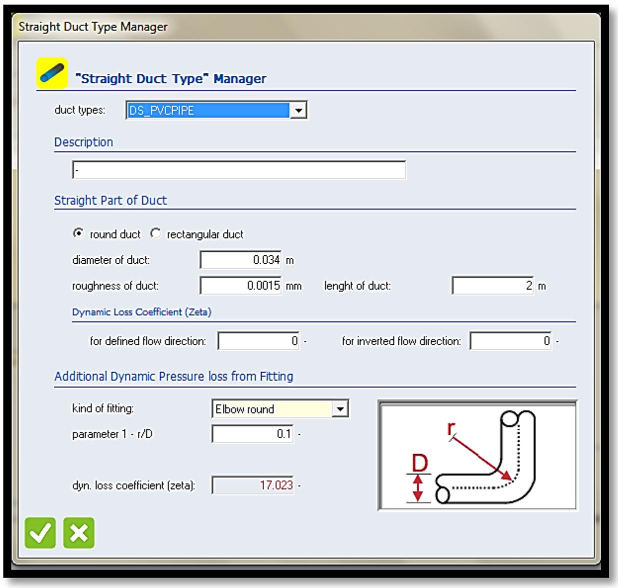


**FIGURE 3-25: VIEW OF THE BOX IN SKETCH-UP™ (WITH CHIMNEY)**

The pipe has the 2 following airnodes:

| | Type | Height of beginning node | Name |
|---|---|---|---|
| From-Node | Thermal Airnode | 1 m | ED2C47 |
| To-Node | External Airnode | 2 m or 3 m (depending on the length of the duct) | EN_PIPE |

TABLE 19: AIRNODES HEIGHTS OF CHIMNEY IN TRNFLOW



duct types: DS_PVCPIPE

-

● round duct ○ rectangular duct

diameter of duct: 0.034 m

roughness of duct: 0.0015 mm

lenght of duct: 2 m

for defined flow direction: 0 -

for inverted flow direction: 0 -

kind of fitting: Elbow round

parameter 1 - r/D 0.1 -

dyn. loss coefficient (zeta): 17.023 -

FIGURE 3-26: THE " STRAIGHT DUCT TYPE" MANAGER

The link is created by using the "Straight Duct Type Manager".

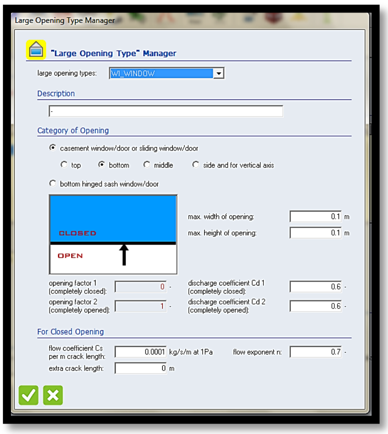
2) WI_WINDOW (varying window opening)

The window has the 2 following airnodes:

| | Type | Height of beginning node | Name |
|---|---|---|---|
| **From-Node** | External Airnode | 0.2 m | EN_WINDOW |
| **To-Node** | Thermal Airnode | 0.2 m | ED2C47 |

TABLE 20: AIRNODES HEIGHT OF WINDOW IN TRNFLOW

The link is created by using the “Large Opening Type Manager”:



large opening types: WI_WINDOW

Description: -

Category of Opening
● casement window/door or sliding window/door
○ top ● bottom ○ middle ○ side and for vertical axis
○ bottom hinged sash window/door

max. width of opening: 0.1 m
max. height of opening: 0.1 m
opening factor 1 (completely closed): 0 -
opening factor 2 (completely opened): 1 -
discharge coefficient Cd 1 (completely closed): 0.6 -
discharge coefficient Cd 2 (completely opened): 0.6 -

For Closed Opening
flow coefficient Cs per m crack length: 0.0001 kg/s/m at 1Pa
flow exponent n: 0.7 -
extra crack length: 0 m

FIGURE 3-27: THE “LARGE OPENING TYPE “MANAGER

3) CR_UNDER (Largest crack in the model)

There are probably more than 10 cracks in the model, but it’s better to specify one particular crack because this is the largest one, so this is also the most decisive one. Only by doing a blower door test with smoke it’s possible to identify all the cracks.

The crack has the 2 following airnodes:

| | Type | Height of beginning node | Name |
|---|---|---|---|
| **From-Node** | Thermal Airnode | 0.685 m | ED2C47 |
| **To-Node** | External Airnode | 0.685 m | EN_CRACK |

TABLE 21: AIRNODES HEIGHT OF CRACK IN TRNFLOW

The crack goes from 0.4 to 0.97 m, so the mean of these 2 values are 0.685 m. It’s more useful to identify the mean for these 2 air nodes instead of the different heights for each air node, because otherwise the program will assume the link is a pipe (because of the 2 different heights).

The link is created by using the “Crack Type Manager”:

crack types: CR_UNDER

Description: -

Air Mass Flow Coefficient Cs: 0.001 kg/s at 1PA

Air Flow Exponent n: 0.61 -

FIGURE 3-28: THE “CRACK TYPE” MANAGER

## 3.3 ADJUSTMENTS ON THE TRNSYS MODEL

This topic will give more information about the different adaptations that are used for each model. Only one example is used to simplify the explanation.

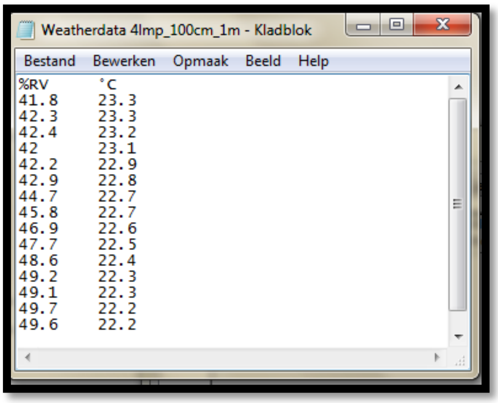
**Example: 4lamps_100cm$^2$_1m**

### 3.3.1 ADJUSTMENTS IN TRNSYS

#### 3.3.1.1 WEATHER DATA

For each measurement, another type of weather data (read: temperature inside the laboratory) is measured. The data is pasted in a *.txt-file, so that Type 9e can easily read the measured values.

Example:



```
%RV     °C
41.8    23.3
42.3    23.3
42.4    23.2
42      23.1
42.2    22.9
42.9    22.8
44.7    22.7
45.8    22.7
46.9    22.6
47.7    22.5
48.6    22.4
49.2    22.3
49.1    22.3
49.7    22.2
49.6    22.2
```

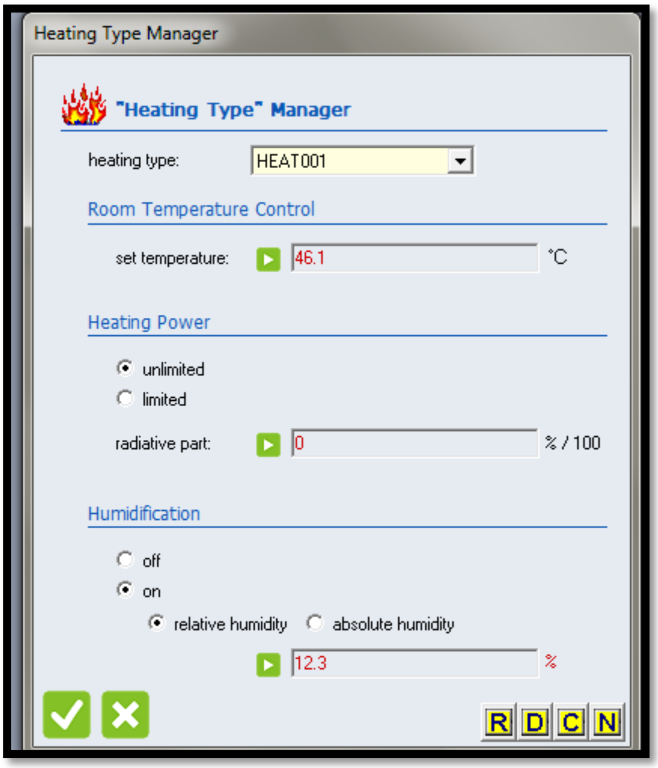
FIGURE 3-29: WEATHERDATA (OUTSIDE) IN NOTEPAD

#### 3.3.1.2 EQUATION

The equation of the window changes 3 times (10 cm$^2$, 50 cm$^2$, 100 cm$^2$). These equations are also shown in Table 17.

## 3.3.2 ADJUSTMENTS IN TRNBUILD

### 3.3.2.1 HEATING TYPE MANAGER



heating type: HEAT001

Room Temperature Control

set temperature: 46.1 °C

Heating Power

● unlimited

○ limited

radiative part: 0 % / 100

Humidification

○ off

● on

● relative humidity ○ absolute humidity

12.3 %

FIGURE 3-30: THE "HEATING TYPE" MANAGER

The only parameters that had to be changed in TRNBUILD, are the set temperature and the humidification in the Heating Type Manager.

## 3.3.3 ADJUSTMENTS IN TRNFLOW

### 3.3.3.1 DUCT LENGTH

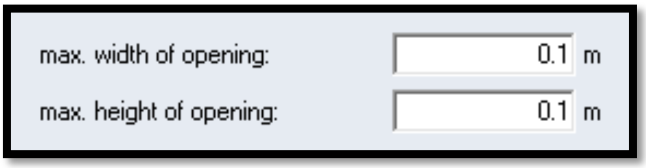
In the Straight Duct Type Manager, only the length of the duct had to be changed. When the duct length varies between 1 m and 2 m, the height of the external node also had to be changed,

lenght of duct: 1 m

FIGURE 3-31: LENGTH OF DUCT

#### 3.3.3.2 WIND OPENING

The window can have 3 different openings: 10 cm², 50 cm², and 100 cm². Only the height of the opening had to be changed.



max. width of opening: 0.1 m

max. height of opening: 0.1 m

**FIGURE 3-32: SURFACE OF THE WINDOW**

## 3.4 ADJUSTMENTS OF THE APARTMENTS' PARAMETERS

This TRNSYS file was developed by:
Gabrielle De Gourcy
Pastor Rafael Royo
Carola Aparicio.

So all the parameters of the building were already set, which is explained in 2.2.
The purpose of this chapter is to identify the heat flow through the chimney (of apartment B1) at 3 different floor levels caused by a specific wind velocity and direction when only 1 of the 5 openings is opened. How these adaptions took place, is explained next page.

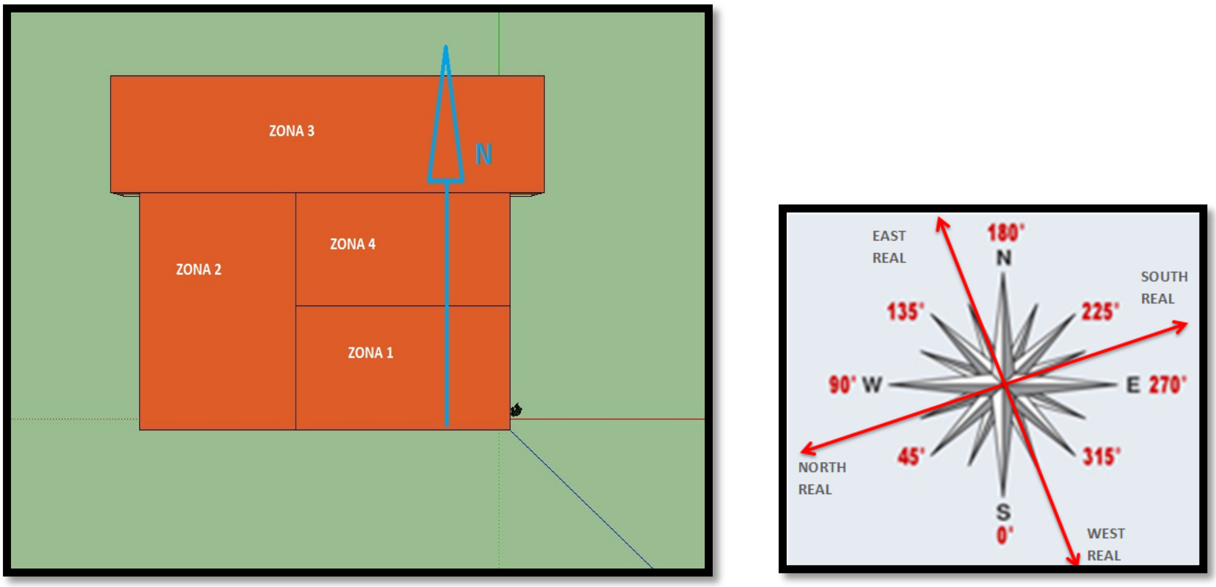


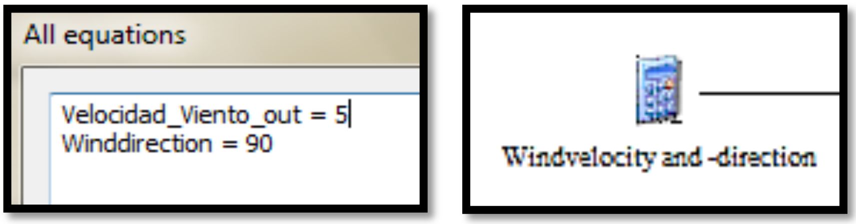
**FIGURE 3-33: COMPARISON BETWEEN THE NORTH IN SKETCH-UP™ AND THE ACTUAL NORTH**

### 3.4.1 ADAPTATIONS OF WIND VELOCITY AND WIND DIRECTION

As you can see on Figure 3-34 and Figure 2-11 (highest red rectangle), an equation is used to change the velocity and direction of the wind. The wind direction of Sketch-Up™ is used in the equation.

| **Wind velocity [m/s]** | **Wind direction [North of Sketch-Up™]** | **Wind direction [Wind direction real]** |
|---|---|---|
| 0 | North (180°) | South-East |
| 3 | East (270°) | South-West |
| 5 | South (0°) | North-West |
|  | West (90°) | North-East |

**TABLE 22: COMPARISON BETWEEN THE NORTH IN SKETCH-UP™ AND THE ACTUAL NORTH**

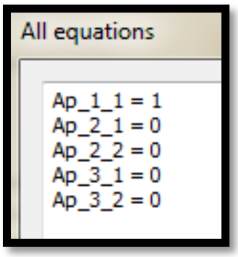


Velocidad_Viento_out = 5
Winddirection = 90

**FIGURE 3-34: EQUATION OF WIND VELOCITY AND -DIRECTION**

### 3.4.2 ADAPTATION OF THE WINDOW OPENING

As you can see on Figure 2-11 (lowest red rectangle) and Figure 3-35, an equation is used to change the velocity and direction of the wind. When the equation is set as followed, Ap_1_1=1, it means that the hole is totally open and 0 means it's closed.



Ap_1_1 = 1
Ap_2_1 = 0
Ap_2_2 = 0
Ap_3_1 = 0
Ap_3_2 = 0

**FIGURE 3-35: EQUATION OF WINDOW OPENING**

There are 3 different wind velocities, 4 different wind directions, 5 different openings and 3 floor levels, and so in total there are 180 results. These calculated results are shown in *Appendix B: Table 2*.

# 4 RESULTS

## 4.1 RESULTS OF MEASUREMENTS

### 4.1.1 GENERAL RESULTS

The two parameters that will be compared with each other are the air velocity and the Δ temperature (explained in 3.1.2).

#### OPENING = 100 CM$^2$

PIPE = 1m

| # Lamps | Mean Δ Temperature(°C) | Surface (cm^2) | %RH inside | Air velocity (m/s) | Tinside (°C) | Mean % RH outside |
|---|---|---|---|---|---|---|
| **1** | 6,83 | 100 | 29,7 | 0,417 | 30,9 | 54,33 |
| **2** | 13,05454545 | 100 | 26,2 | 0,616363636 | 36,1 | 58,0090909 |
| **3** | 18,17 | 100 | 19,3 | 0,693 | 42,7 | 48,89 |
| **4** | 23,57142857 | 100 | 12,3 | 0,73 | 46,1 | 48,7428571 |

**TABLE 23: RESULTS OF 100 CM$^2$ OPENING, 1 M PIPE LENGTH**

PIPE = 2m

| # Lamps | Mean Δ Temperature(°C) | Surface (cm^2) | %RH inside | Air velocity (m/s) | Tinside (°C) | Mean % RH outside |
|---|---|---|---|---|---|---|
| **1** | 7,91 | 100 | 20,4 | 0,453 | 30,2 | 49,54 |
| **2** | 12,63333333 | 100 | 19,4 | 0,567777778 | 35,2 | 49,68888889 |
| **3** | 18,24285714 | 100 | 17,7 | 0,711428571 | 39,8 | 53,67142857 |
| **4** | 23,01 | 100 | 12,6 | 0,844 | 43,3 | 47,76 |

**TABLE 24: RESULTS OF 100 CM$^2$ OPENING, 2 M PIPE LENGTH**

#### OPENING = 50 CM$^2$

PIPE = 1m

| # Lamps | Mean Δ Temperature(°C) | Surface (cm^2) | %RH inside | Air velocity (m/s) | Tinside (°C) | Mean % RH outside |
|---|---|---|---|---|---|---|
| **1** | 4,781818182 | 50 | 26,2 | 0,429090909 | 30,1 | 51,01818182 |
| **2** | 12,54285714 | 50 | 15,7 | 0,598571429 | 34,6 | 41,22857143 |
| **3** | 17,725 | 50 | 14,3 | 0,68 | 40,5 | 42,35 |
| **4** | 21,1 | 50 | 18,8 | 0,745833333 | 45,2 | 55,55833333 |

**TABLE 25: RESULTS OF 50 CM$^2$ OPENING, 1 M PIPE LENGTH**

### PIPE = 2m

| # Lamps | Mean Δ Temperature(°C) | Surface (cm^2) | %RH inside | Air velocity (m/s) | Tinside (°C) | Mean % RH outside |
|---|---|---|---|---|---|---|
| **1** | 8,866666667 | 50 | 24,2 | 0,473333333 | 28,9 | 61,45 |
| **2** | 13,98571429 | 50 | 23,1 | 0,63 | 33,6 | 65,5 |
| **3** | 17,97692308 | 50 | 27,2 | 0,75 | 35,8 | 65,5 |
| **4** | 21,76666667 | 50 | 19,9 | 0,856666667 | 41,2 | 56,9 |

**TABLE 26: RESULTS OF 50 CM$^2$ OPENING, 2 M PIPE LENGTH**

## OPENING = 10 CM$^2$

### PIPE = 1m

| # Lamps | Mean Δ Temperature(°C) | Surface (cm^2) | %RH inside | Air velocity (m/s) | Tinside (°C) | Mean % RH outside |
|---|---|---|---|---|---|---|
| **1** | 7,25 | 10 | 29,9 | 0,445 | 31 | 53,5875 |
| **2** | 11,04285714 | 10 | 27,5 | 0,56 | 36,3 | 48,65714286 |
| **3** | 15,77 | 10 | 25,1 | 0,634 | 39,9 | 53,84 |
| **4** | 21,06 | 10 | 20,6 | 0,683 | 45,9 | 52,02 |

**TABLE 27: RESULTS OF 10 CM$^2$ OPENING, 1 M PIPE LENGTH**

### PIPE = 2m

| # Lamps | Mean Δ Temperature(°C) | Surface (cm^2) | %RH inside | Air velocity (m/s) | Tinside (°C) | Mean % RH outside |
|---|---|---|---|---|---|---|
| **1** | 7,583333333 | 10 | 22,2 | 0,365 | 29,6 | 50,16666667 |
| **2** | 12,05714286 | 10 | 21,9 | 0,578571429 | 34,2 | 50,4 |
| **3** | 17,84444444 | 10 | 18,9 | 0,693333333 | 39,8 | 51,73333333 |
| **4** | 23,55714286 | 10 | 15,5 | 0,784285714 | 44,5 | 54,34285714 |

**TABLE 28: RESULTS OF 10 CM$^2$ OPENING, 2 M PIPE LENGTH**

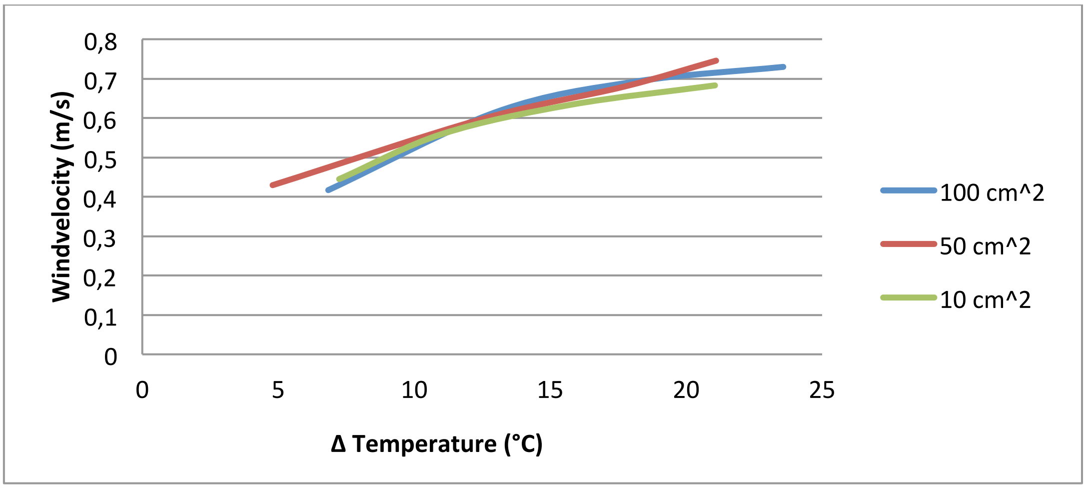
As expected the higher the temperature difference is the higher the air velocity will be through the chimney. The measurements below a temperature difference of 20 °C are not that reliable because in the model there has to be a big difference between the outside and inside temperature. This difference is necessary to notice the effect of the heat flow through a chimney with different heights. The relative humidity inside is decreasing because there is an increase of the temperature inside the model. A remarkable parameter that can't be ignored, is that the wind velocity is 0 m/s in the laboratory so this model has a significant imperfection. Therefore a second model was made videlicet, the apartment model.

### 4.1.2 COMPARING DIFFERENT PARAMETERS

#### 4.1.2.1 FUNCTION OF GAP WIDTH

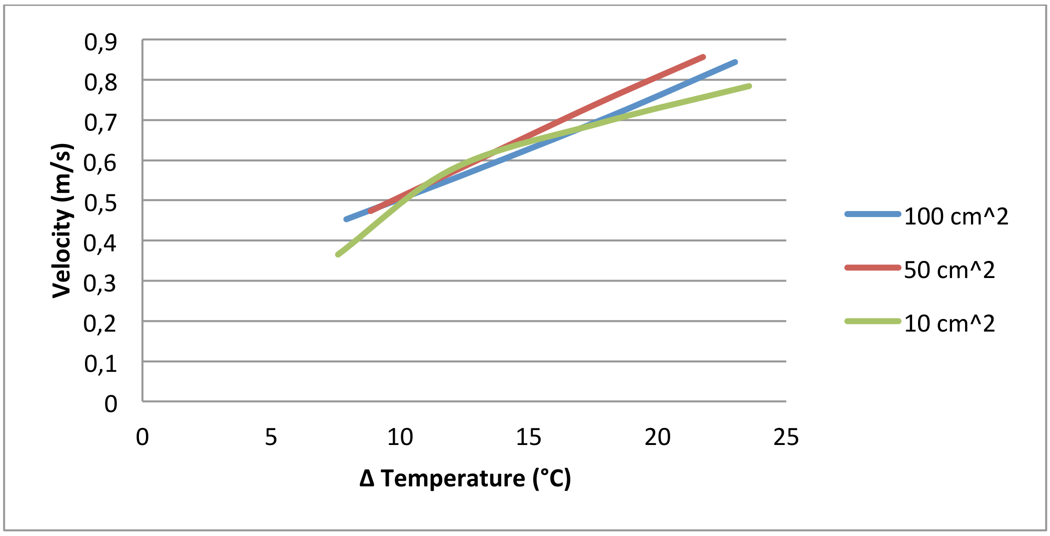
This function is calculated and plotted to know if the gap width has an influence on the airflow through the chimney in the model.

PIPE = 1m



GRAPHIC 8: DIFFERENT GAP WIDTH, 1 M

PIPE = 2m



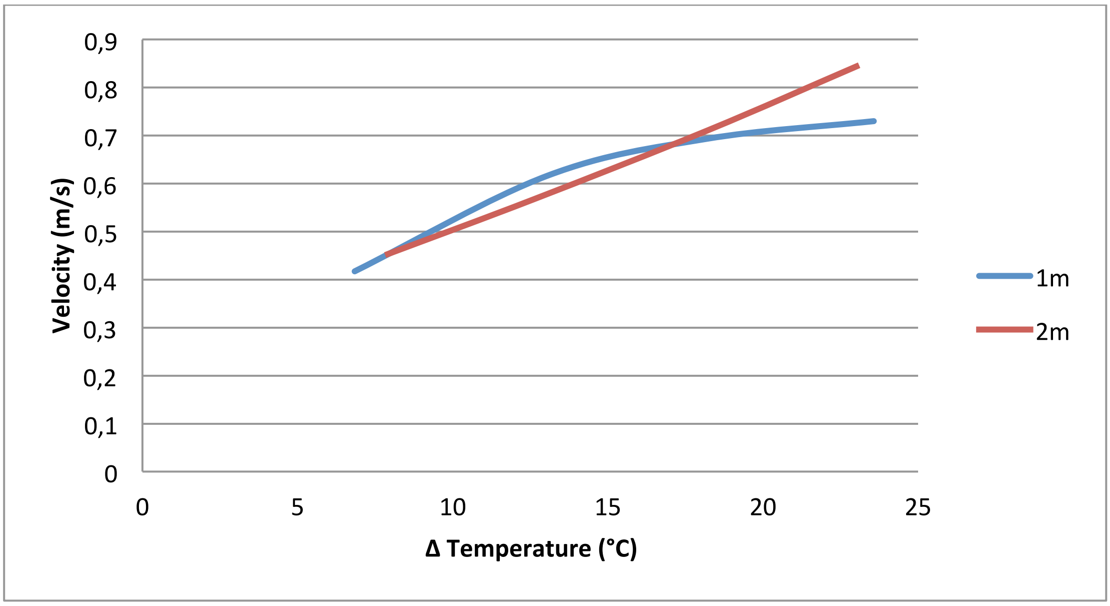
GRAPHIC 9: DIFFERENT GAP WIDTH, 2 M

The air gap width doesn't have much influence on the airflow through the chimney in our model (see Graphic 8 and Graphic 9). Only when the temperature difference is higher than 20 °C, because the velocity begins to divert.

### 4.1.2.2 FUNCTION OF CHIMNEY HEIGHT

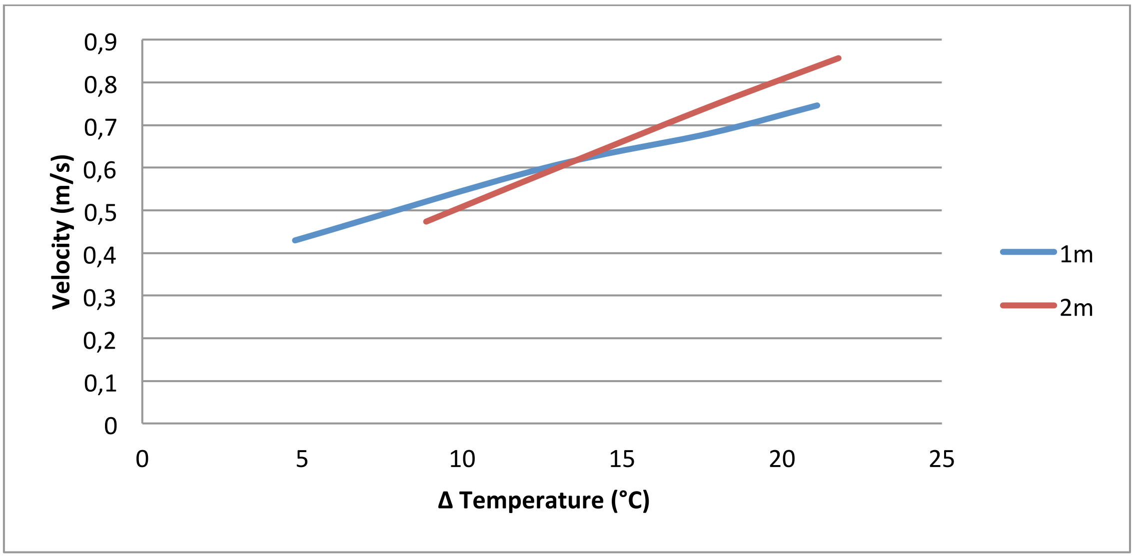
Function of chimney height is the most important function. These results will be used in the comparison with the TRNSYS-program and will be verified with a theoretical background.

Opening 100 cm²



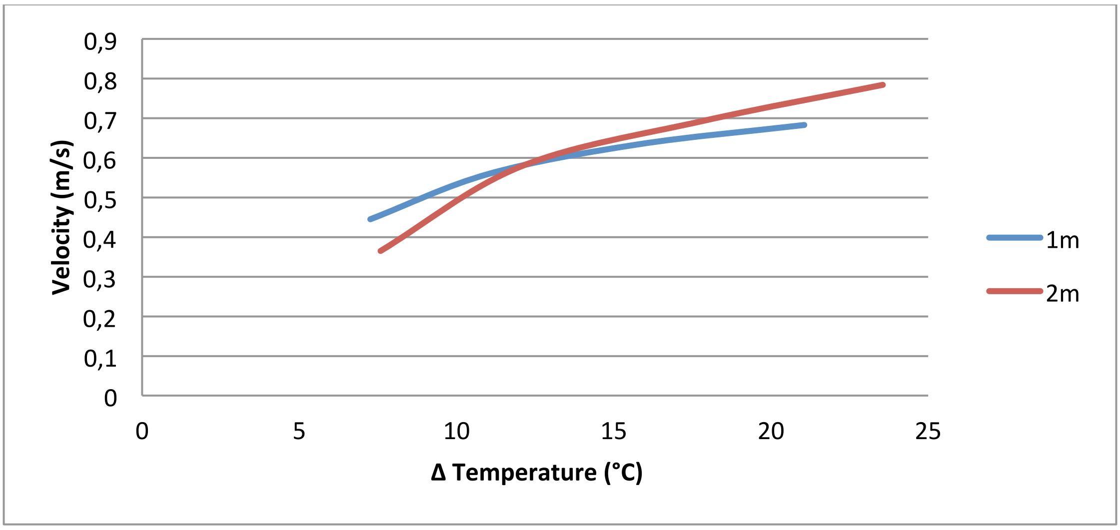
GRAPHIC 10: FUNCTION CHIMNEY HEIGHT, 100 CM²

Opening 50 cm²



GRAPHIC 11: FUNCTION CHIMNEY HEIGHT, 50 CM²

Opening 10 cm²



**GRAPHIC 12: FUNCTION CHIMNEY HEIGHT, 10 CM²**

The height of the chimney (see Graphic 10, 11 and 12) has a big influence from the time that Δ temperature increases to a certain level. The measurements below this level are not that reliable because in the model there has to be a big difference between the outside and inside temperature. The minimum Δ temperature had to be more than ±20 °C before the chimney worked properly. Further conclusions are made in 4.2 (comparison with the TRNSYS-file).

## 4.2 COMPARING TRNSYS OUTPUTS (SIMULATED MODEL) WITH THE MEASUREMENTS

### 4.2.1 TABLE OF RESULTS

In *Appendix B: Table 1* the comparison between the TRNSYS results and the experimental-results are made. For the temperature inside the maximum temperature is taken and for the humidity (inside) the minimum humidity is taken. The most important parameter that causes the heat flow is the temperature difference between the inside and outside temperatures.

Explanation of the parameters:

Error = difference between the TRNSYS and Experimental results (of the air velocity);
Correlation = the relation of the results, for each window opening, between the TRNSYS and Experimental results.

In Graphics 13, 14 and 15 results are represented to compare the 2 results with each other:

- 10 $\text{cm}^2$
- 50 $\text{cm}^2$
- 100 $\text{cm}^2$

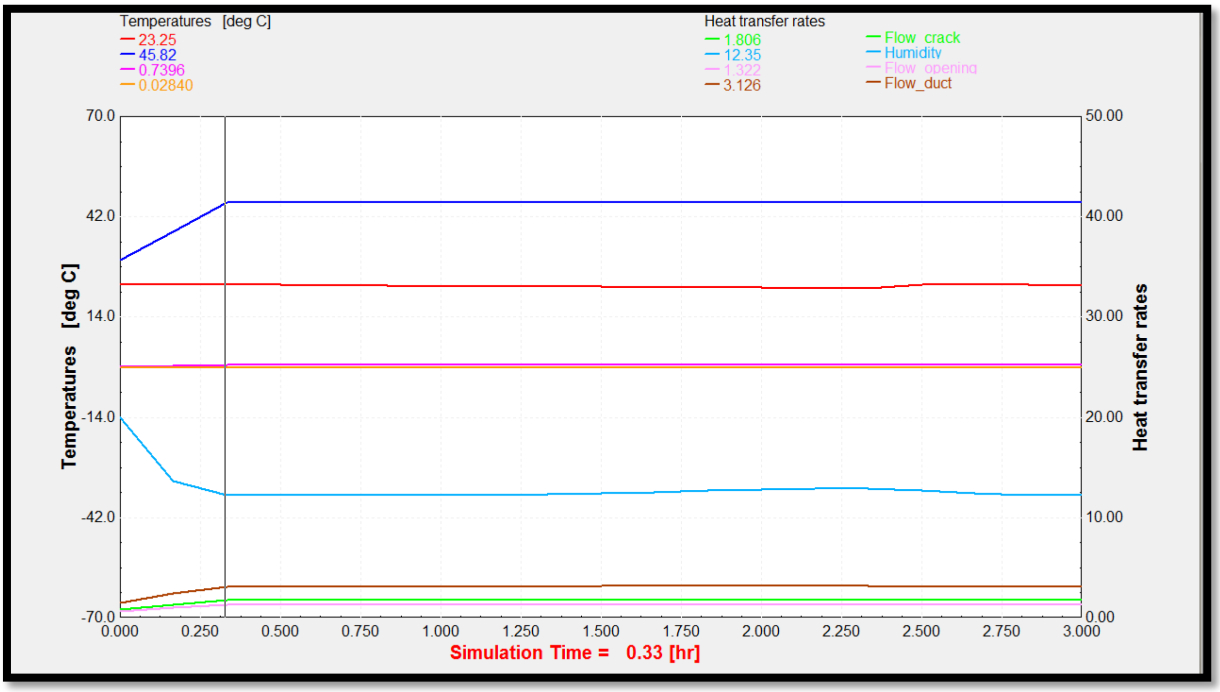


FIGURE 4-1: 1 METER, 100 $\text{CM}^2$ AND 4 LAMPS ON

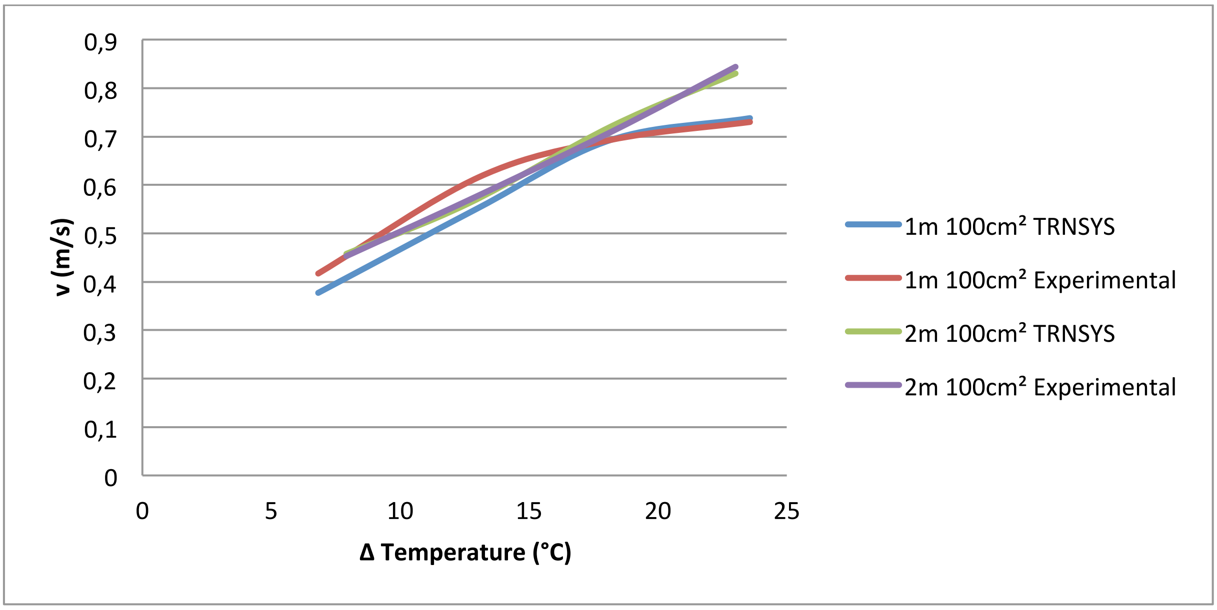
Figure 4-1 is an example of the plot that is shown after TRNSYS simulated the model. This plot is for a pipe length of 1 meter, a window opening of 100 $\text{cm}^2$ and for 4 lamps turned on.

After 20 minutes the temperature inside is clearly saturated and the results are valid to be compared with the measured values. The simulation duration is 3 hours, just like the duration of the measurements.

In the simulation it's clear that the flow through the duct is a summation of the crack-flow and the flow through the opening. It's a logical consequence as the height of the exit of the chimney is the highest one.

### 4.2.2 GRAPHICS OF THE 3 DIFFERENT WINDOW OPENINGS

#### 4.2.2.1 WINDOW OPENING OF 100 CM$^2$



GRAPHIC 13: RESULTS FOR A WINDOW OPENING OF 100 CM$^2$

| | Correlation |
|---|---|
| **1 meter** | 0.986674354 |
| **2 meter** | 0.998118792 |

TABLE 29: CORRELATION OF 100 CM$^2$

Table 29 shows that the correlations between both results are very good. What's already been commented on is that it's important to look at the temperature differences, as this is the most important parameter to generate the heat flow.

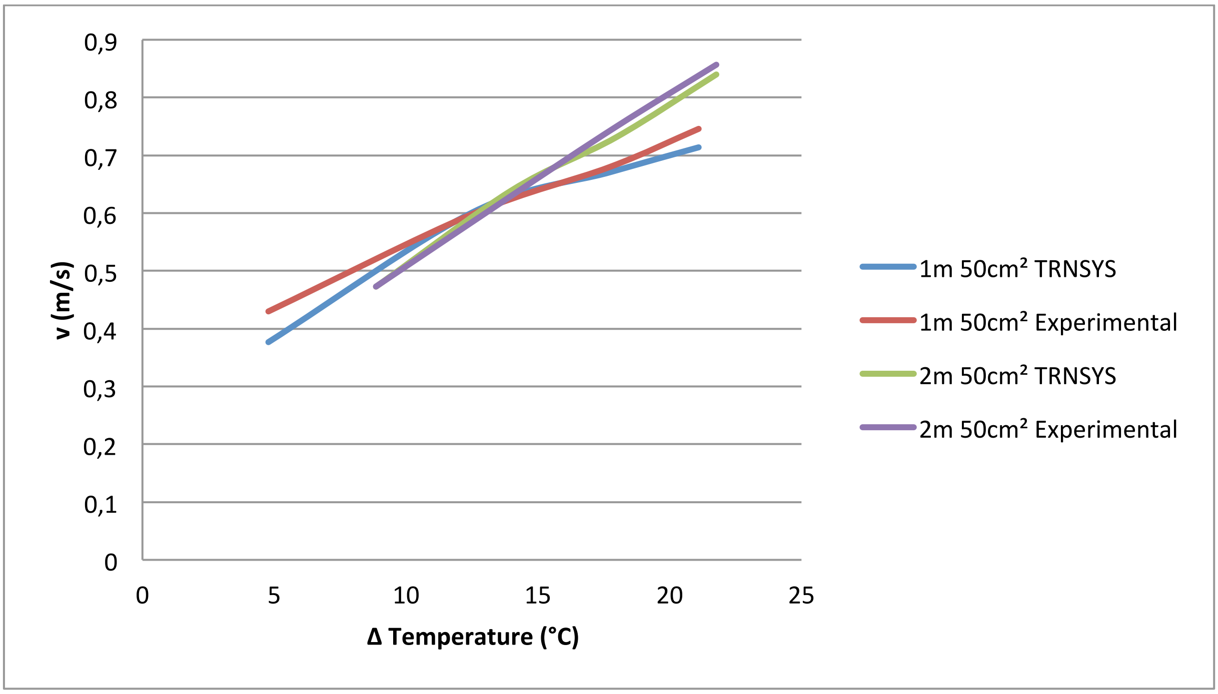
Starting at a temperature difference of 17°C, the flow through the 2 meter chimney goes faster than the flow through the 1 meter chimney. The final difference of air velocity (between 1 meter and 2 meter) is 0.1035 m/s, when the mean between the TRNSYS and manual results are taken.

| | | v [m/s] | | | |
|---|---|---|---|---|---|
| | | ΔT (K) | TRNSYS | Manual | Mean-Difference |
| **1 meter** | 4 lamps | 23.57 | 0.738 | 0.73 | 0.734 |
| **2 meter** | 4 lamps | 23.01 | 0.8303 | 0.844 | 0.8375 |
| | | | | | **0.1035** |

TABLE 30: RESULTS OBTAINED BETWEEN 1 AND 2 METER FOR 100 CM$^2$ OPENING

What's also shown in the Graphic 13, is that with a low temperature difference, the flow between the TRNSYS and manual measurements is not the same. So it's better to look at a high temperature difference, when comparing different results.

### 4.2.2.2 WINDOW OPENING OF 50 CM$^2$



GRAPHIC 14: RESULTS FOR A WINDOW OPENING OF 50 CM$^2$

| | Correlation |
|---|---|
| **1 meter** | 0.989380643 |
| **2 meter** | 0.998220772 |

TABLE 31: CORRELATION OF 50 CM$^2$

The correlations of these measurements are also very good, according to Table 31. Starting at a temperature difference of 13.5°C, the flow through the 2 meter chimney goes faster than the flow through the chimney of 1 meter.

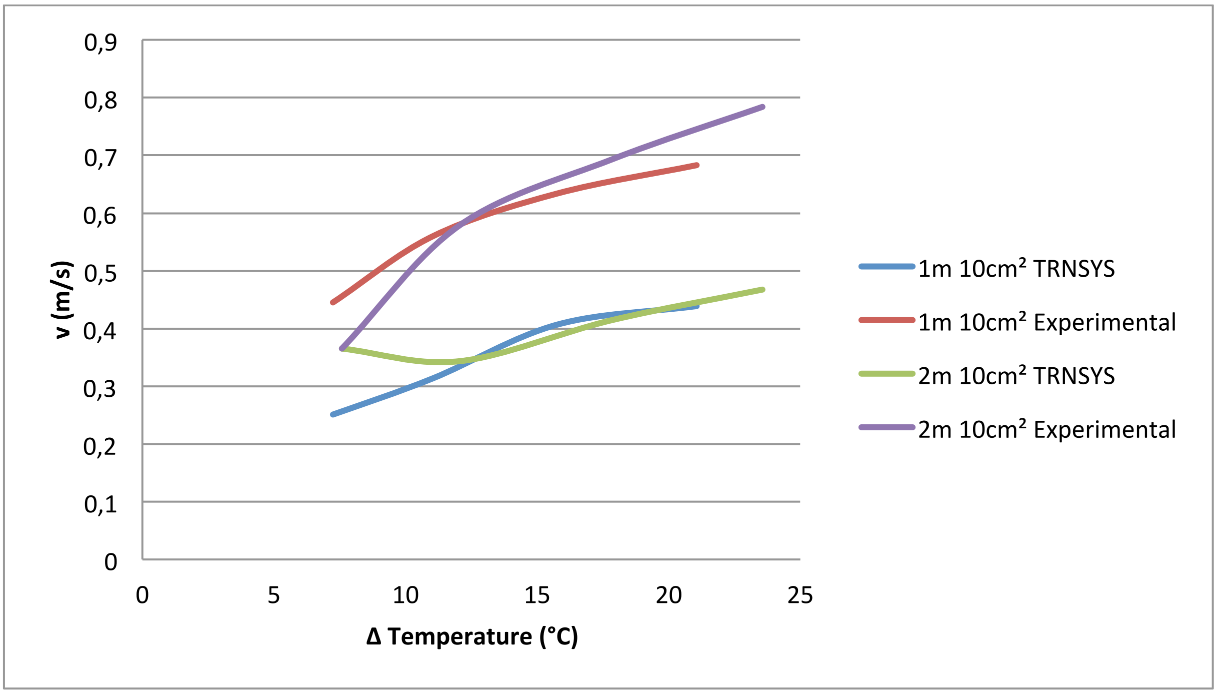
| | | v [m/s] | | | |
|---|---|---|---|---|---|
| | | ΔT (K) | TRNSYS | Manual | Mean-Difference |
| **1 meter** | 4 lamps | 21.1 | 0.714 | 0.746 | 0.73 |
| **2 meter** | 4 lamps | 21.77 | 0.8401 | 0.857 | 0.84855 |
| | | | | | **0.11855** |

TABLE 32: RESULTS OBTAINED 1 AND 2 METER FOR 50 CM$^2$ OPENING

The difference in air velocity is 0.11855 m/s, which is similar to the air velocity difference when the opening is 100 cm$^2$. So the surface of the opening doesn't have a big influence on the air velocity through the chimney.

It's also correct to comment that the flow through the chimney goes faster when the length of the chimney increases.

### 4.2.2.3 WINDOW OPENING OF 10 CM$^2$



GRAPHIC 15: RESULTS FOR A WINDOW OPENING OF 10 CM²

| | Correlation |
|---|---|
| **1 meter** | 0.984686244 |
| **2 meter** | 0.776237037 |

TABLE 33: CORRELATION OF 10 CM²

These values are not valid. It's clear in the graphic and also at the correlations of the 2 groups of values. The cause lies probably in the opening of the window, because when the number of lamps increases, the differences are still high. So when comparing the values of a measurement with the values of TRNSYS, it's better to have an opening larger than 10 cm$^2$.

Starting at a temperature difference of 12.5°C (experimental), the flow through the 2 meter chimney goes faster than the flow through the 1 meter chimney. It's also correct to say that, the smaller the opening is, the lower temperature difference is when the fastest air velocity switches from 1 m to 2 m.

| | | | v [m/s] | | |
|---|---|---|---|---|---|
| | | ΔT (K) | TRNSYS | Manual | Mean-Difference |
| **1 meter** | 4 lamps | 15.77 | 0.4069 | 0.634 | 0.52045 |
| **2 meter** | 4 lamps | 23.56 | 0.4675 | 0.784 | 0.62575 |
| | | | | | **0.1053** |

TABLE 34: RESULTS OBTAINED 1 AND 2 METER FOR 10 CM² OPENING

The difference between the 2 maximum air velocities stays 0.1053 m/s.

## 4.3 RESULTS OF THE ADJUSTMENTS ON THE APARTMENT

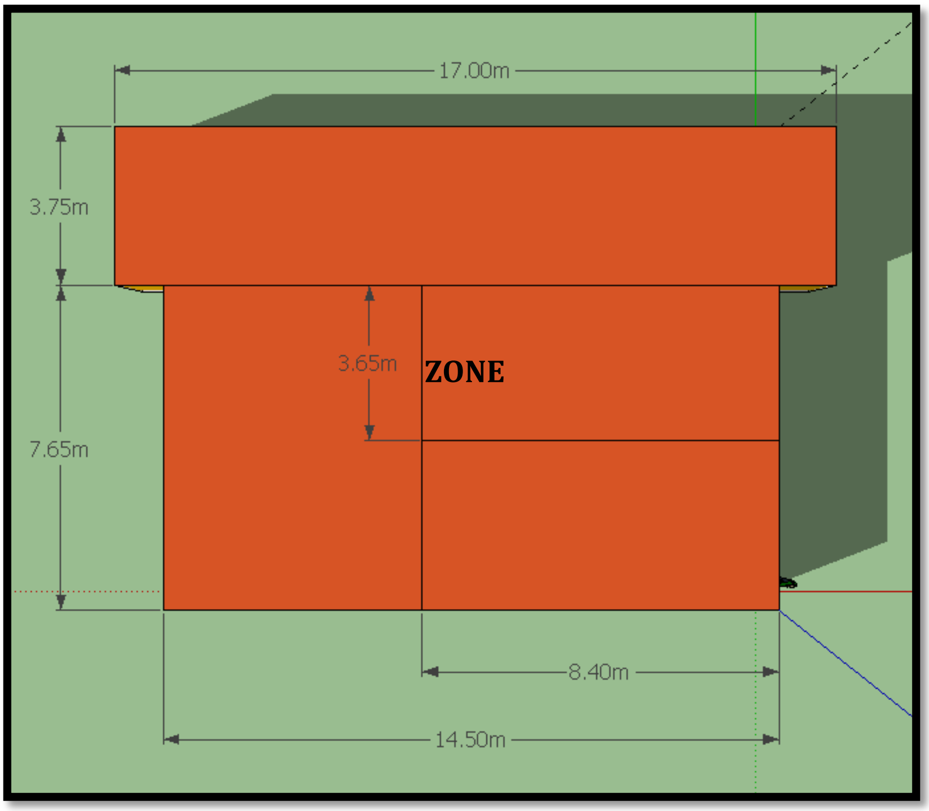
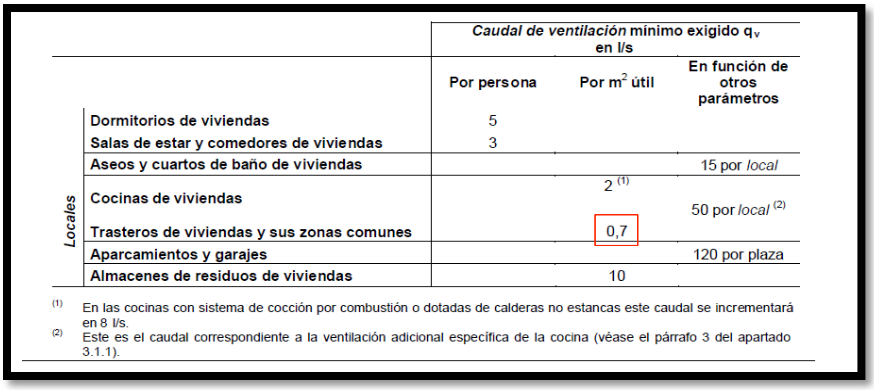


FIGURE 4-2: TOPVIEW OF APARTMENT B1



|  |  | *Caudal de ventilación* mínimo exigido $q_v$ en l/s |  |  |
|---|---|---|---|---|
|  |  | Por persona | Por $m^2$ útil | En función de otros parámetros |
| *Locales* | Dormitorios de viviendas | 5 |  |  |
|  | Salas de estar y comedores de viviendas | 3 |  |  |
|  | Aseos y cuartos de baño de viviendas |  |  | 15 por *local* |
|  | Cocinas de viviendas |  | 2 [(1)] | 50 por *local* [(2)] |
|  | Trasteros de viviendas y sus zonas comunes |  | 0,7 |  |
|  | Aparcamientos y garajes |  |  | 120 por plaza |
|  | Almacenes de residuos de viviendas |  | 10 |  |

(1) En las cocinas con sistema de cocción por combustión o dotadas de calderas no estancas este caudal se incrementará en 8 l/s.

(2) Este es el caudal correspondiente a la ventilación adicional específica de la cocina (véase el párrafo 3 del apartado 3.1.1).

FIGURE 4-3: MINIMUM FLOW FOR NATURAL VENTILATION

$$\text{Surface of the hallway} = 8.4\text{m} * 3.65\text{m} = 30.66\ \text{m}^2 \xrightarrow{2.52*\frac{m^3}{h}/m^2} 77.26\ \boldsymbol{m^3/h}$$

The chimney is situated in zone 4: The Hallway. This room needs a minimum ventilation of 77.26 $\text{m}^3$/h. The results of the measurements are given in *Appendix B: Table 2*. In this table the comparison is made to look if zone 4 (or the whole apartment) could be ventilated by natural ventilation, with no need of mechanical ventilation.

As you can see on *Table 2 in Appendix B*, the results are taken at 120 hours, so on 6th of January. This is the best comparison because it's in the winter so then there's a bigger temperature difference then in the summer.

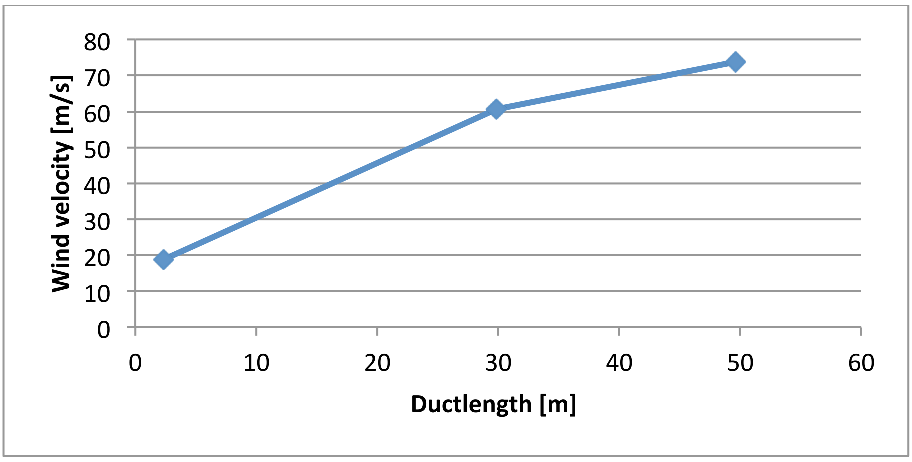
Wind velocity = 0 m/s

What's quite expected is that the results of this velocity (v = 0m/s) stays the same for each window opening on each level, because it's similar with the model in the laboratory where there's also no wind velocity present.

The same phenomenon happens like with the rescaled model. As the chimney length rises, the flow through the chimney also increases.

| | 1e floor | Middle floor | Top floor |
|---|---|---|---|
| **Chimney Length [m]** | 49.62 | 29.85 | 2.35 |
| **Wind velocity [m/s]** | 73.88 | 60.56 | 18.82 |

TABLE 35: RESULTS WHEN WIND VELOCITY IS 0 M/S



GRAPHIC 16: RESULT OF ADJUSTMENTS ON THE APARTMENT FOR 0 M/S WIND VELOCITY

Graphic 16 shows the same curve as in the results of the rescaled model, so it's valid to say that the results of the rescaled model are well measured.

Wind velocity = 3 m/s

The average wind velocity in Valencia is 3 m/s, so this is the most important parameter to look at, when only natural ventilation in the hall is needed (>77 $m^3/h$).

When the wind direction comes from the Southeast, the five openings aren't acceptable, except for Ap_3_1 and the flows of the ground floor. When Ap_3_1 is opened, all the values for the three different floors are higher than 77 $m^3/h$.

For example:

| **Opening open** | **Wind velocity (without Cp-values)** | **Wind direction (real time)** | **Ground floor ($m^3$/h)** | **Air velocity duct** | **Middle floor ($m^3$/h)** | **Air velocity duct** | **Highest floor ($m^3$/h)** | **Air velocity duct** |
|---|---|---|---|---|---|---|---|---|
| **Ap_1_1** | 3 | SOUTH-EAST | 77.27 | 0.953950617 | 44.87 | 0.553950617 | -39.8 | -.491358025 |

TABLE 36: RESULTS FOR A WIND VELOCITY OF 3 M/S AT THE 3 LEVELS

The highest floor has the shortest chimney (2.35m), so the average difference between the top- and lowest level is already 20 $m^3$/h when there's a wind velocity of 3 m/s.

Wind velocity= 5 m/s

A wind velocity of 5 m/s is not so common in Valencia, but it's good to also look at these values, because if there's a wind velocity of 5 m/s outside, the mechanical ventilation can maybe be switched off for that particular room, when there's a flow higher than 77 $m^3$/h.

Almost all values are higher than this minimum on all the floors, so the mechanical ventilation for this room can be switched off then. Only for Ap_1_1 and Ap_2_1 there's a negative value of maximum 70 $m^3$/h, when the wind comes from the South-East, so when this is happening it is best to close these two openings and use another opening for natural ventilation.

What was very interesting is that when the wind velocity goes higher than 3 m/s, the flow through the longest chimney becomes the lowest value and the flow through the shortest chimney becomes the highest value.
So this parameter (wind velocity) is very sensitive for the flow through a chimney.

Results when all the windows are opened

It was also interesting to know what happens when all the windows were opened, because maybe then the whole apartment could be ventilated by only using natural ventilation and not mechanical ventilation

$$\text{Total Surface} = 14.50\text{m} * 7.65\text{m} + 3.75\text{m} * 17\text{m} = 174.675\ \text{m}^2 \xrightarrow{3.6\frac{\text{m}^3}{\text{h}}/\text{m}^2} 628.83\ \text{m}^3/\text{h}$$

To achieve this, the flow had to be higher than 628.83 $m^3$/h. Sadly, there's only 1 value that's above this certain minimum (628.83 $m^3$/h) that was when the wind velocity was 5 m/s.

| **Wind velocity (without Cp-values)** | **Wind direction (real time)** | **Ground floor ($m^3$/h)** | **Air velocity duct** | **Middle floor ($m^3$/h)** | **Air velocity duct** | **Highest floor ($m^3$/h)** | **Air velocity duct** |
|---|---|---|---|---|---|---|---|
| 5 m/s | NORTH-WEST | 181.8 | 2.244444444 | 247 | 3.049382716 | 641.7 | 7.922222222 |

TABLE 37: HIGHEST FLOW WHEN ALL THE WINDOWS ARE OPENED

Present and future solution of this phenomenon

Nowadays, they're already calculating the effect of the wind velocity on the chimney to change the structure and the shape of it. What's shown on Figure 4-4 is that the surface of the chimney increases when the height of the building increases, so that the ventilation of all the apartments stays the same. Because what's also proven in this topic is, when a wind velocity, higher than 3 m/s is present, the flow through the lowest chimney (highest apartment) generates the biggest flow, that's why the surface at this place is the highest in comparison with the lower apartments.

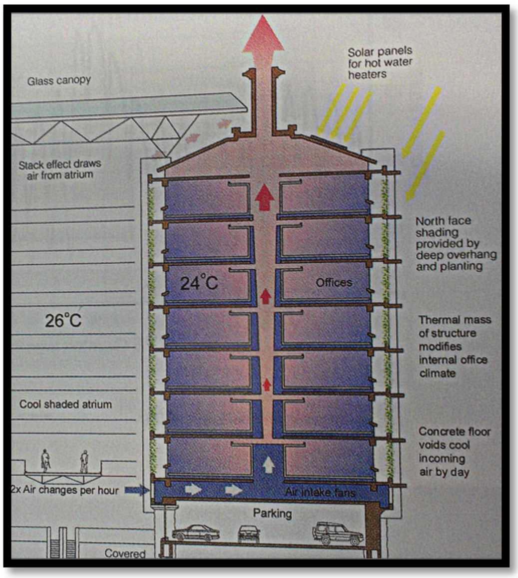


**FIGURE 4-4: FUTURE SOLUTION OF THIS PHENOMENON**

What also could be an improvement in the future is that the surface of the chimney would be automatized, so that the surface of the chimney would change according to the state of the parameters (wind velocity, temperature difference, and height of the chimney). But since this is not yet invented, the costs of these imaginary adaptations are probably bigger than the benefits of it.

# 5 VERIFYING THE RESULTS OF THE EXPERIMENT

## 5.1 PRINCIPLE OF NATURAL VENTILATION

### 5.1.1 LAMINAR STREAM

The Reynolds number can be used to determine if the airflow through the chimney is laminar, transient or turbulent.

Laminar: Re < 2300
Transient: 2300 < Re < 4000
Turbulent: Re > 4000

$$Re = \frac{v \times D_h}{\Upsilon}$$

- v Max velocity through the chimney (m/s)
- $D_h$ Hydraulic diameter of the pipe (m)
- ϒ Kinematic viscosity (300 K) ($m^2/s$)

$$\text{Re} = \frac{1 \times 0{,}034}{15{,}68 \times 10^{-4}} = 2169$$

The airflow is laminar, that means that the flow in the pipe goes as follow:

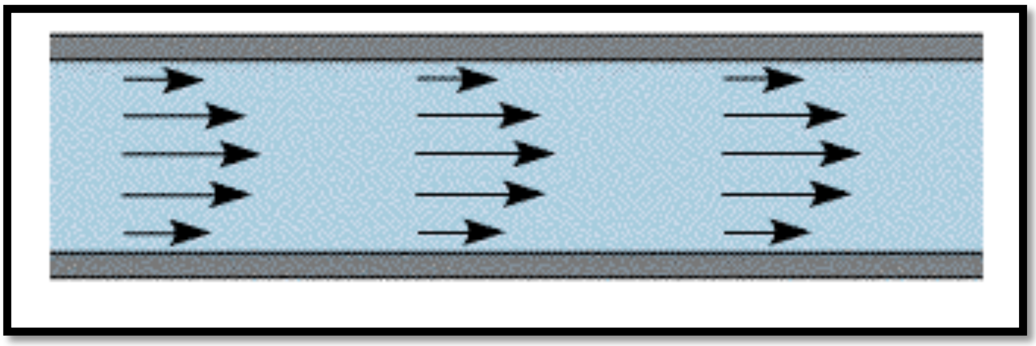


FIGURE 5-1: SHAPE OF LAMINAR STREAM

The problem with the laminar shape of the airflow is that it is very difficult to measure a mean airflow (Figure 5-1). All the measurements were more or less at the centre of the pipe. That means that the values of the measurements were the maximum of the airflow and not the mean. The exact (mean) value of the airflow is very difficult to measure physical because of this problem. In TRNSYS it was possible to solve this problem, because the parameters were defined at the values of the measurements, but for the theoretical part it was impossible to take the shape of the airflow into account.

### 5.1.2 NATURAL VENTILATION

Since the operating forces in natural ventilation are wind and temperature, the outdoor conditions are an important factor when talking about natural ventilation and the airflow through an opening (window or crack) and chimney.

Natural ventilation is driven by pressure differences created by either temperature differences (Thermal Buoyancy), wind on the building or a combination of these two. In the model that was used in this thesis there was no wind so Thermal Buoyancy will be the only factor, which will provide a pressure difference. The derivation of these pressure differences is made in the following sections. From the pressure differences, an airflow rate through the opening of the pipe can be calculated. A detailed presentation of the different expressions for calculations of flow rates caused by Thermal Buoyancy is given in the next paragraph 5.1.3.

### 5.1.3 THERMAL BUOYANCY

Thermal Buoyancy is the air exchange between two or more zones with different air densities due to difference in temperatures and/or moisture content. Ventilation by air exchange expresses openings between the zones and the opening arrangement can either be separate small openings in different levels or horizontal opening or it can be a single large vertical opening. The temperature difference can appear due to heating one or more of the zones.

$$P = P_0 - \rho_0 \times g \times H \qquad \text{(Zhigang L., 2007, p.10)} \qquad (5.1)$$

- $P$ External or internal pressure [Pa]
- $P_0$ Pressure at a reference level (floor) [Pa]
- $\rho_0$ External or internal air density at a reference level [kg/m$^3$]
- g Gravitational acceleration [m/s$^2$]
- H Height above the reference level [m]
- e,i External, Internal

The pressure difference between internal and external air can be found by:

$$\Delta P = P_{e,0} - P_{i,0} - g \times H\,(\rho_e - \rho_i) \qquad (5.2)$$

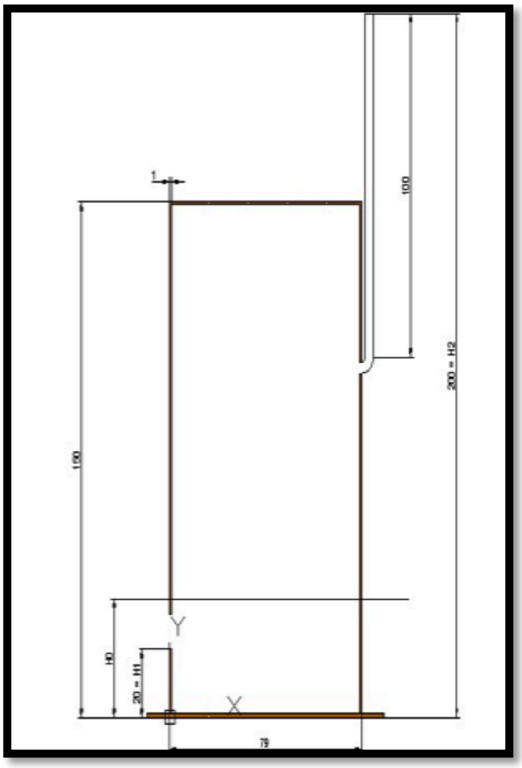


FIGURE 5-2: PRESSURE DIFFERENCE AROUND THE NEUTRAL PLANE IN THE MODEL

Whether the air enters or goes out a building at a certain height depends on the position of the opening compared to the neutral plane ($H_0$) in the building, see Figure 5-2 (the horizontal line on the figure). At the neutral plane the pressure difference ($\Delta P$) is zero. Above this plane an overpressure exists in the building that will generate an outgoing airflow. Below the neutral plane ($H=H_0$) there will be an under pressure in the building compared with outside which will make the air flow into the building.

At the neutral plane where $\Delta P = 0$, expression (5.2) becomes:

$$P_{e,0} - P_{i,0} = (\rho_e - \rho_i) \times g \times H_0 \qquad (5.3)$$

According to the perfect gas law, the density differences and the temperature are related by:

$$\frac{\rho_e - \rho_i}{\rho_i} \cong \frac{T_i - T_e}{T_e} \qquad (5.4)$$

and

$$\frac{\rho_e - \rho_i}{\rho_e} \cong \frac{T_i - T_e}{T_I}$$

- $\rho_e$ External air density [kg/m$^3$]
- $\rho_i$ Internal air density [kg/m$^3$]
- $T_e$ External air temperature [K]
- $T_i$ Internal air temperature [K]

and (5.3) can be rewritten as

$$P_{e,0} - P_{i,0} = \rho \times g \times H_0 \times \frac{Ti-Te}{Te} \quad (5.5)$$

For opening $H_1$ where $\Delta P \neq 0$ we have:

$$\Delta P = P_{e,0} - P_{i,0} - \rho_i \times g \times H_1 \times \frac{Ti-Te}{Te} \quad (5.6)$$

If expression (5.5) is introduced into expression (5.6) the pressure difference in $H_1$ can be expressed only from the internal and external temperatures, the gravitational acceleration (g) and the density of air (ρ) . Positive values of the pressure difference in expression (5.7) ($H_1$ below the neutral plane) shows that the pressure outside the building is higher than inside, so an under pressure is created.

$$\Delta P = \rho_i \times g \times H_0 \times \frac{Ti-Te}{Te} - \rho_i \times g \times H_1 \times \frac{Ti-Te}{Te} \quad (5.7)$$
$$\Delta P = \rho_i \times g \times (H_0 - H_1) \times \frac{Ti-Te}{Te}$$

From (5.7) it is seen that the pressure difference is increased with increasing height difference and/or increasing temperature difference and that's the exact phenomenon that this thesis is about.

It is seen that for openings below the neutral plane the pressure difference is positive (under pressure) and for openings above the neutral plane the pressure difference is negative (overpressure). The airflow rate through an opening can be calculated with the following formula (Heiselberg P., 2003, p.53):

$$q = C_d \times A \times v_{theo} = C_d \times A \times \sqrt{\frac{2|\Delta P|}{\rho}} \times \frac{\Delta P}{|\Delta P|} \quad (5.8)$$

The level of the neutral plane is determined by the mass balance, which means that the amount of inflowing air flow equals the amount of outgoing airflow. If the area of the openings is not equal, the position of the neutral plane can be determined from the mass balance where the position of the neutral plane is the only unknown:

$$\rho_e \times q_{v1} - \rho_i \times q_{v2} = 0 \quad (5.9)$$

$$\rho_e \times C_{d1} \times A_1 \times \sqrt{\frac{2 \times \Delta T \times g \times (H_0 - H_1)}{T_i}} - \rho_i \times C_{d2} \times A_2 \times \sqrt{\frac{2 \times \Delta T \times g \times (H_2 - H_0)}{T_e}} = 0 \quad (5.10)$$

| | |
|---|---|
| • $\rho_e$, $\rho_i$ | Density of outdoor and indoor air (kg/m$^3$) |
| • $q_{v1}$, $q_{v2}$ | Air flow rates through the inlet and outlet (pipe) openings (m$^3$/s) |
| • $C_{d1}$, $C_{d2}$ | Discharge coefficient of inlet and outlet (pipe) openings (-) |
| • $A_1$, $A_2$ | Inlet and outlet (pipe) area (m$^2$) |
| • $\Delta T$ | Temperature difference between the inside and outside (K) |
| • g | Gravitational acceleration (m/s$^2$) |

- $T_i$, $T_e$ Absolute indoor and outdoor temperature (K)
- $H_0$ Height of the neutral plane (m)
- $H_1$, $H_2$ Height of the inlet opening and the height of the pipe (m)

The discharge coefficient $C_d$ is used to take into account the physical effects of flow contraction and friction loss. It depends on the shape of the opening and surrounding conditions. Values from 0.61 for sharp-edged gap to 0.98 for trumpet shaped nozzles can be found in literature. The discharge coefficient that will be used in the calculation is a constant value for both openings, $C_d$ = 0,70.

Simplifications:

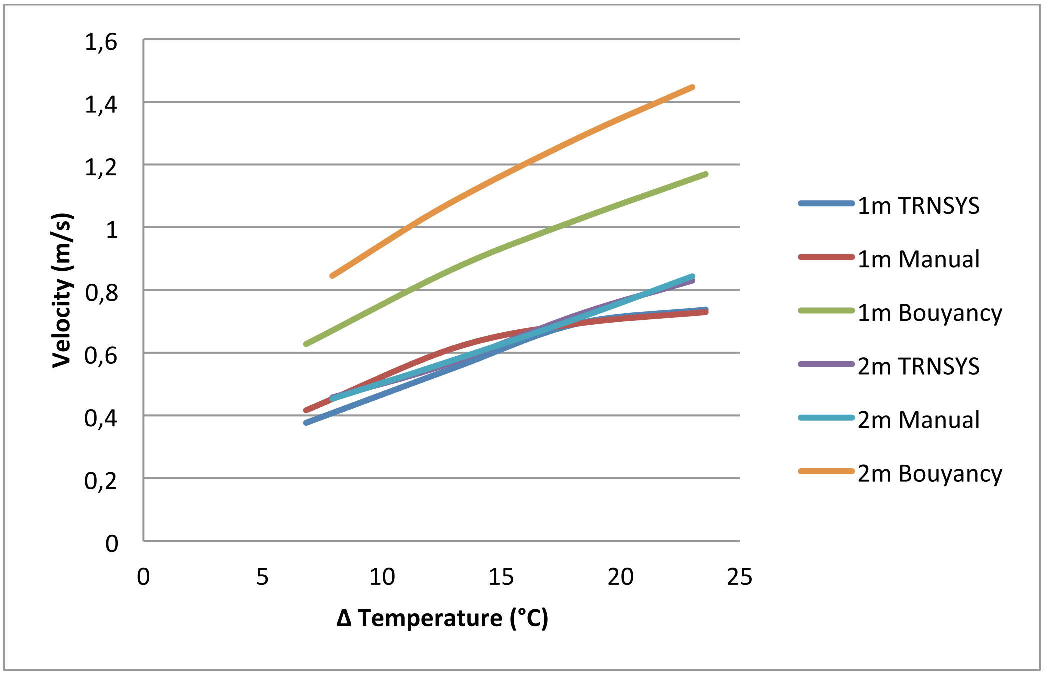
- $C_{d1} = C_{d2} = 0{,}70$
- $\rho_e = \rho_i$
- No cracks

With these simplifications 5.10 is converted into 5.11:

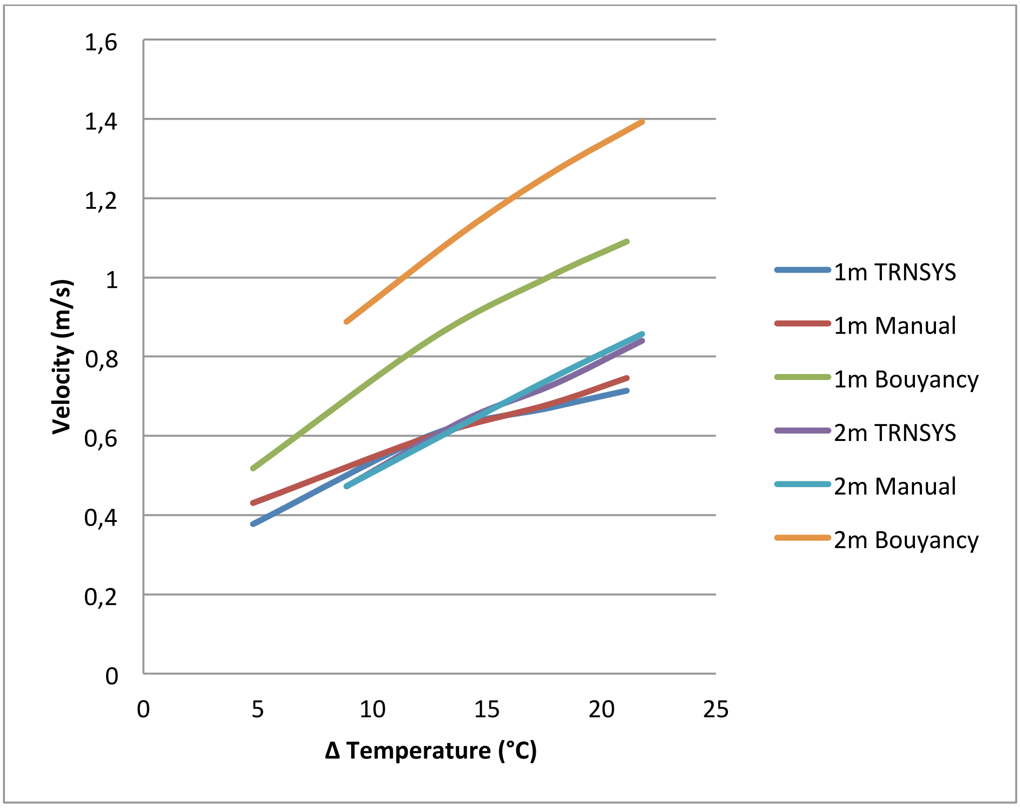
$$A_1 \times \sqrt{\frac{(H_0 - H_1)}{T_i}} - A_2 \times \sqrt{\frac{(H_2 - H_0)}{T_e}} = 0 \qquad (5.11)$$

Outcome of this formula is $H_0$, the final airflow and velocity through an opening will be calculated with (5.8).

Graphic Results:



**GRAPHIC 17: RESULTS WITH THERMAL BUOYANCY, 100 CM² OPENING**



**GRAPHIC 18: RESULTS WITH THERMAL BUOYANCY, 50 CM² OPENING**

For more information about the calculated values see *Appendix C: Table 1.*

Difference between Buoyancy and TRNSYS/Measurements:

| Height pipe | Opening ($m^2$) | Lamps | Buoyancy vs TRNSYS (%) | Buoyancy vs. Measurements (%) |
|---|---|---|---|---|
| **1** | 0,01 | 1 | 66,54448274 | 50,60893151 |
| **1** | 0,01 | 2 | 57,28294582 | 41,17165705 |
| **1** | 0,01 | 3 | 47,7227884 | 47,70147198 |
| **1** | 0,01 | 4 | 58,49952911 | 60,23651025 |
| **1** | 0,005 | 1 | 37,46919922 | 20,46138202 |
| **1** | 0,005 | 2 | 40,15601623 | 40,8345679 |
| **1** | 0,005 | 3 | 49,35747797 | 47,33675915 |
| **1** | 0,005 | 4 | 52,73368687 | 46,18210781 |
| **2** | 0,01 | 1 | 84,76762453 | 86,64385206 |
| **2** | 0,01 | 2 | 90,2499569 | 88,00581128 |
| **2** | 0,01 | 3 | 77,99828985 | 80,80220103 |
| **2** | 0,01 | 4 | 74,26975125 | 71,440965 |
| **2** | 0,005 | 1 | 87,92672439 | 87,72807035 |
| **2** | 0,005 | 2 | 74,61434084 | 77,13654799 |
| **2** | 0,005 | 3 | 73,45741485 | 69,20192627 |
| **2** | 0,005 | 4 | 65,75691665 | 62,48819799 |

TABLE 38: DIFFERENCE BETWEEN CALCULATED RESULTS AND TRNSYS

As the Graphics 17 and 18 show, the velocity (airflow) is too large if we compare it with the results of TRNSYS and the measurements. The reason for these huge differences (see Graphic 17) is that we didn't take the cracks into account, all the air leaks of the model, the laminar stream in TRNSYS and the measurements (5.1.1) and the ventilation losses. This way of calculating the airflow with the effect of Thermal Buoyancy is a simplification of the real situation.

Though, the shape and the behavior of the graphs are quite similar to the results that TRNSYS and the measurements gave us. This means that the phenomenon of Thermal Buoyancy is present in the situation of this experiment.

### 5.1.4 VENTILATION LOSSES OF THE CHIMNEY

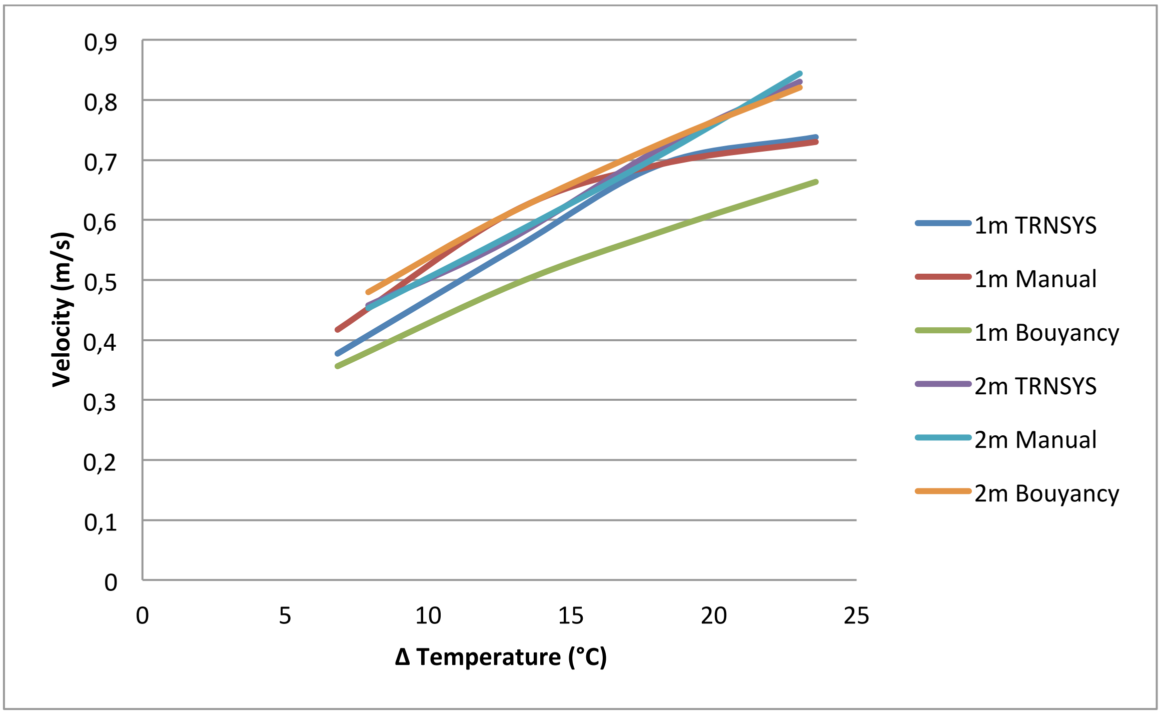
The ventilation loss of the curve (90°) will be taken into consideration. The friction losses of the tube will not be calculated because they are incorporated in the phenomenon of the Thermal Buoyancy.

$$\Delta P = \xi \times \rho \times \frac{v^2}{2} \tag{5.12}$$

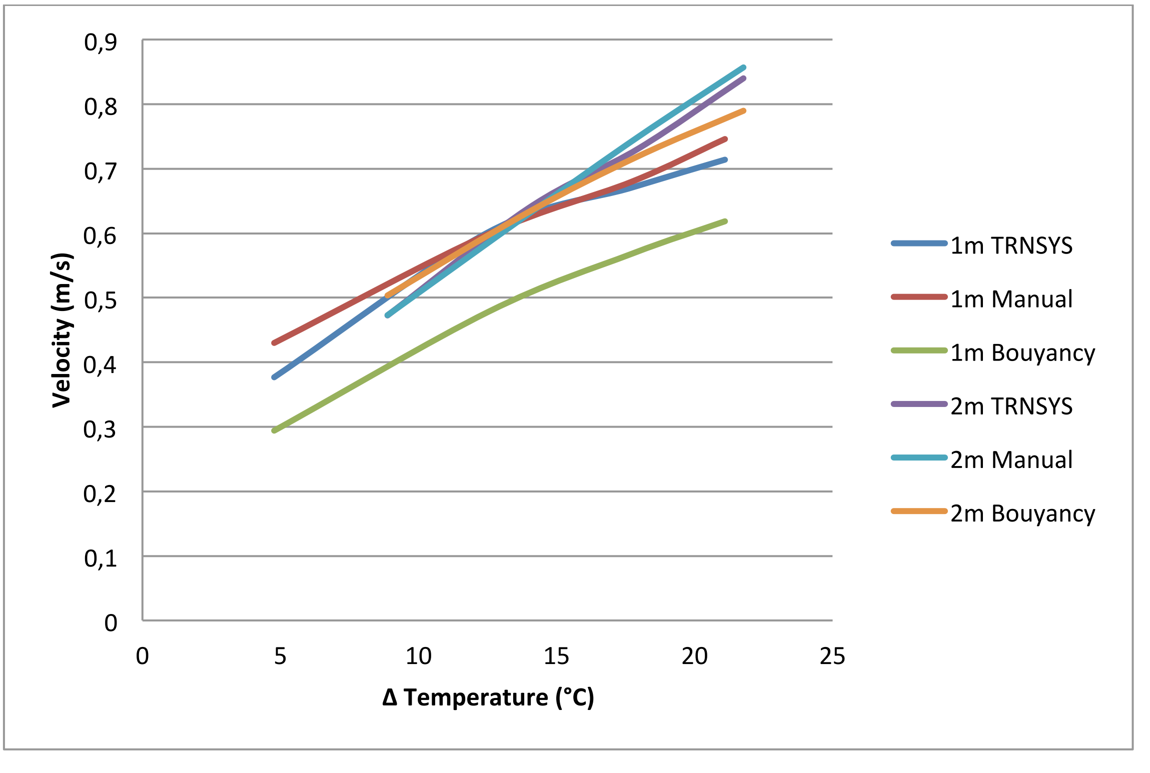
- ξ Drag coefficient (-)
- ρ Air density ($kg/m^3$)
- v Velocity at the end of the chimney without the ventilation losses (m/s)
- ΔP Pressure loss (Pa)

If ΔP is calculated we get ΔQ to invert the solution into equation 5.8.

Graphic Results:



GRAPHIC 19: RESULTS WITH THERMAL BUOYANCY AND VENTILATION LOSSES, 100 CM² OPENING



GRAPHIC 20: RESULTS WITH THERMAL BUOYANCY AND VENTILATION LOSSES, 50 CM² OPENING

For more information about the calculated values see *Appendix C: Table 2.*

Difference between Buoyancy and TRNSYS/Measurements:

| Height pipe | Opening ($m^2$) | Lamps | Buoyancy vs. TRNSYS | Buoyancy vs. Measurements |
|---|---|---|---|---|
| 1 | 0,01 | 1 | 5,540002054 | 14,57826085 |
| 1 | 0,01 | 2 | 10,79292154 | 19,93085442 |
| 1 | 0,01 | 3 | 16,21521134 | 16,2273015 |
| 1 | 0,01 | 4 | 10,10290496 | 9,117731313 |
| 1 | 0,005 | 1 | 22,03079884 | 31,67722094 |
| 1 | 0,005 | 2 | 20,5069013 | 20,12204322 |
| 1 | 0,005 | 3 | 15,288055 | 16,43415778 |
| 1 | 0,005 | 4 | 13,37315106 | 17,08904807 |
| 2 | 0,01 | 1 | 4,795722716 | 5,859873543 |
| 2 | 0,01 | 2 | 7,905168889 | 6,632343834 |
| 2 | 0,01 | 3 | 0,956320001 | 2,546630527 |
| 2 | 0,01 | 4 | 1,158416814 | 2,762835878 |
| 2 | 0,005 | 1 | 6,587487665 | 6,474815902 |
| 2 | 0,005 | 2 | 0,962973942 | 0,467560879 |
| 2 | 0,005 | 3 | 1,619154348 | 4,032764428 |
| 2 | 0,005 | 4 | 5,986690471 | 7,840628547 |

**TABLE 39: DIFFERENCE BETWEEN CALCULATED RESULTS AND TRNSYS (WITH VENTILATION LOSSES)**

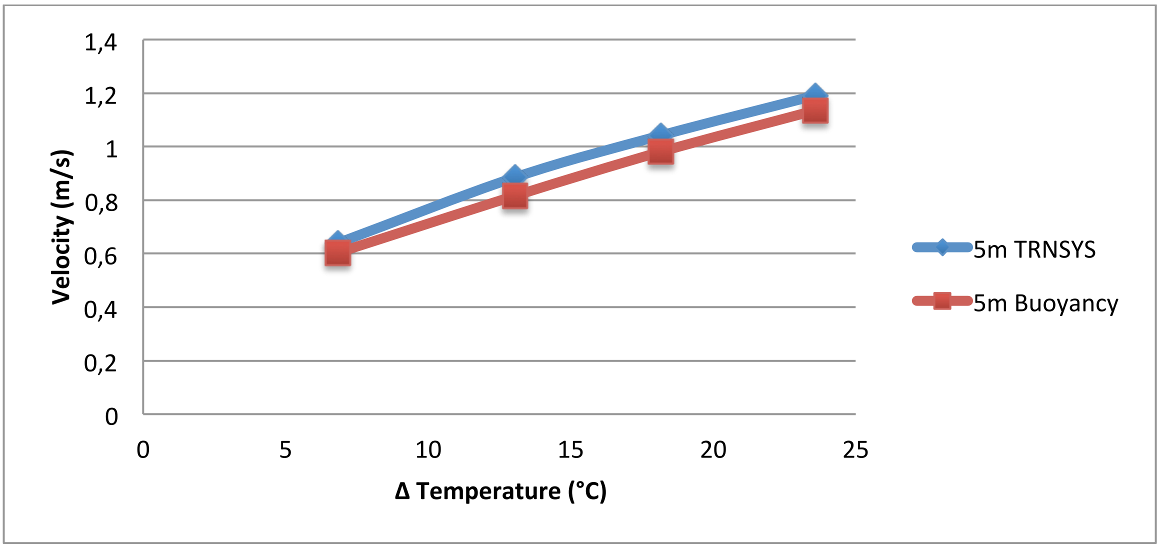
If we assume there are ventilation losses (Graphics 19 and 20) the airflow with the phenomenon of Thermal Buoyancy corresponds more properly with the airflow we get with TRNSYS and the measurements. The difference in percentage is much smaller than when there was no ventilation losses considered. The values for a chimney height of 2 meter are more complementary than those for 1 meter. That means, the higher the chimney, the better this theory of Thermal Buoyancy works (see also 5.1.5).

### 5.1.5 COMPARING BUOYANCY AND TRNSYS WITH A HIGHER CHIMNEY

To verify the model of TRNSYS and the calculations of Thermal Buoyancy a longer chimney was taken with a height of 5 m to look if the results were still similar with each other.

Parameters:

Height = 5 m, opening 100 $cm^2$, 1-2-3-4 lamps



GRAPHIC 21: 5 M, 100 CM²

The results of TRNSYS and the theory of buoyancy look similar but there are still a lot of simplifications that were made in the theory of Thermal Buoyancy. It's normal that those two values are not the same but they do have the same shape. That means that the behavior of the chimney can be explained by the phenomenon of Thermal Buoyancy. For more information about the calculated values see *Appendix C: Table 3.*

## 5.2 THERMAL BALANCE

### 5.2.1 GENERAL

Another way to check the measurements is to compare the results of the measurements with the thermal balance. The balance gives an idea what the heat transfer is through the chimney, heat transfer by convection and heat transfer by radiation.

Heat transfer by convection is caused by a flow of fluids. In applications for construction the relevant fluids are mainly achieved by air and water. The fluid that causes the heat transfer by convection in the case of our model is air, more precisely there will be a heat transfer between the surface of the construction. The impellent of the heat transfer by convection will be natural or free convection, the fluid is caused by density differences because of the temperature differences in the fluid. It is assumed that the inside and outside environment is an isothermal black radiator with a reflected temperature $T_{Reflected}$. The heat transfer coefficient h describes the connection between the differences in temperature and the heat flux between the fluid and the surface of the construction.

For the specific case of heat transfer between a construction and the outside environment (our laboratory) it is practical to express the heat transfer by radiation as a function of a heat transfer coefficient and a reference temperature.

Thermal radiation is a heat transfer because of the electromagnetic waves radiated by the surfaces of materials. We assumed the outside environment (our laboratory) was an isothermal black radiator with a reflected temperature ($T_{reflected}$). Some simplifications were added to the equation: surface of the outside environment (all the walls, racks, …) is much bigger than the surface of the model and a linearization between the thermal radiation and the temperature.

Main equation of the thermal balance:

$$Q_{heating} = \dot{m} \times c_p \times (T_{Box} - T_{Room}) + Q_{Radiation} + Q_{Convection} \tag{5.13}$$

| | |
|---|---|
| $\dot{m}$ | Mass flow rate of air (kg/s), $\dot{m}$ = ρ x Q |
| $C_p$ | Specific heat capacity = 1000 (J/kg*K) |
| $T_{Box}$ | Temperature inside the box (K) |
| $T_{Room}$ | Temperature in the room (K) |
| Q | Air flow through the chimney ($m^3/s$) |
| ρ | Air density ($kg/m^3$) |

$$Q_{Radiation} = e \times \sigma \times A_{ht} \times \left(T^4_{Surface} - T^4_{Reflected}\right), \sigma = 5,67 *10^{-8} \tag{5.14}$$

| | |
|---|---|
| $A_{ht}$ | Surface where heat transfers take place ($m^2$) |
| $T_{Surface}$ | Temperature of the wall of the box (K) |
| $T_{Reflected}$ | Reflected temperature (K) |
| e | Emissivity = 0,95 |

$$Q_{Convection} = A_{ht} \times h \times \left(T_{Surface} - T_{Air}\right) \tag{5.15}$$

| | |
|---|---|
| $A_{ht}$ | Surface where heat transfers take place ($m^2$) |
| h | Heat transfer coefficient ($W/m^2*K$) |
| $T_{Surface}$ | Temperature of the wall of the box (K) |
| $T_{air}$ | Temperature of the air (K) |

$$h = e \times \sigma \times F_t \text{ and } F_t = 4 \times T_m^3 \text{ and } T_m = \frac{(T_{Surface} + T_{Reflected})}{2} \tag{5.16}$$

or h = ±5,2 ($W/m^2*K$)

### 5.2.2 THERMO GRAPHIC RESULTS

The method of calculating the surface and the temperatures is already explained in paragraph 3.1.3.3. The surface of the general region is calculated by the whole surface minus the surface with a special temperature. The following parameters were used: 4 lamps, length of chimney = 1 m and an opening of 100 $cm^2$.

### 5.2.2.1 FRONT (1,185 M²)

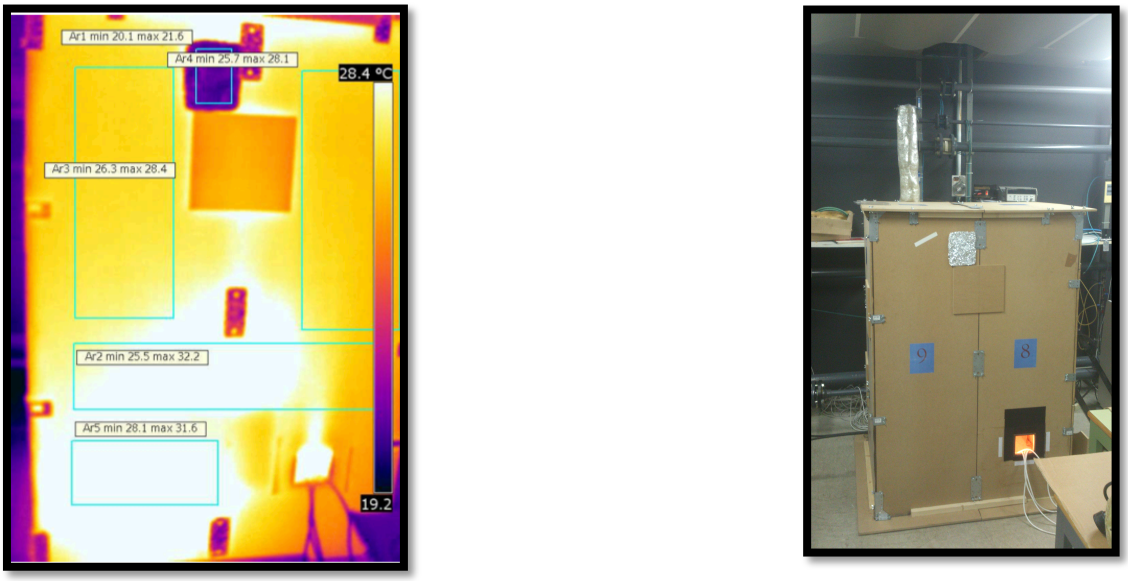


FIGURE 5-3: INFRARED PICTURE + NORMAL PICTURE (FRONT SIDE)

| Front | Tsurface (°C) | Surface (m²) | Tsurface x Surface (°C x m²) |
|---|---|---|---|
| **General** | 28,5 | 0,585 | 16,6725 |
| **Sides** | 28,5 | 0,2 | 5,7 |
| **Focus** | 31,5 | 0,4 | 12,6 |

TABLE 40: WALL TEMPERATURES OF THE FRONT SIDE

### 5.2.2.2 LEFT (0,395 M²)

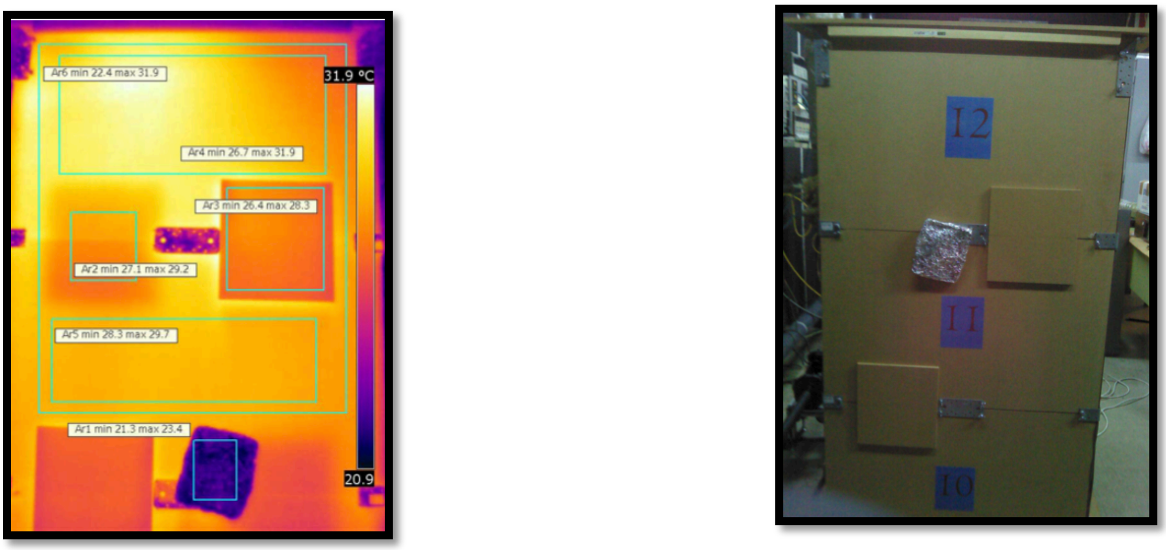


FIGURE 5-4: INFRARED PICTURE + NORMAL PICTURE (LEFT SIDE)

| Left | Tsurface (°C) | Surface (m$^2$) | Tsurface x Surface (°C x m$^2$) |
|---|---|---|---|
| **General** | 28,5 | 0,245 | 6,9825 |
| **Sides** | 28,5 | 0,05 | 1,425 |
| **Focus** | 31 | 0,1 | 3,1 |

TABLE 41: WALL TEMPERATURES OF THE LEFT SIDE

### 5.2.2.3 Right (0,395 m$^2$)

FIGURE 5-5: INFRARED PICTURE + NORMAL PICTURE (RIGHT SIDE)

| Right | Tsurface (°C) | Surface (m$^2$) | Tsurface x Surface (°C x m$^2$) |
|---|---|---|---|
| **General** | 29 | 0,245 | 7,105 |
| **Focus** | 34 | 0,15 | 5,1 |

TABLE 42: WALL TEMPERATURES OF THE RIGHT SIDE

### 5.2.2.4 Back (1,185 m$^2$)

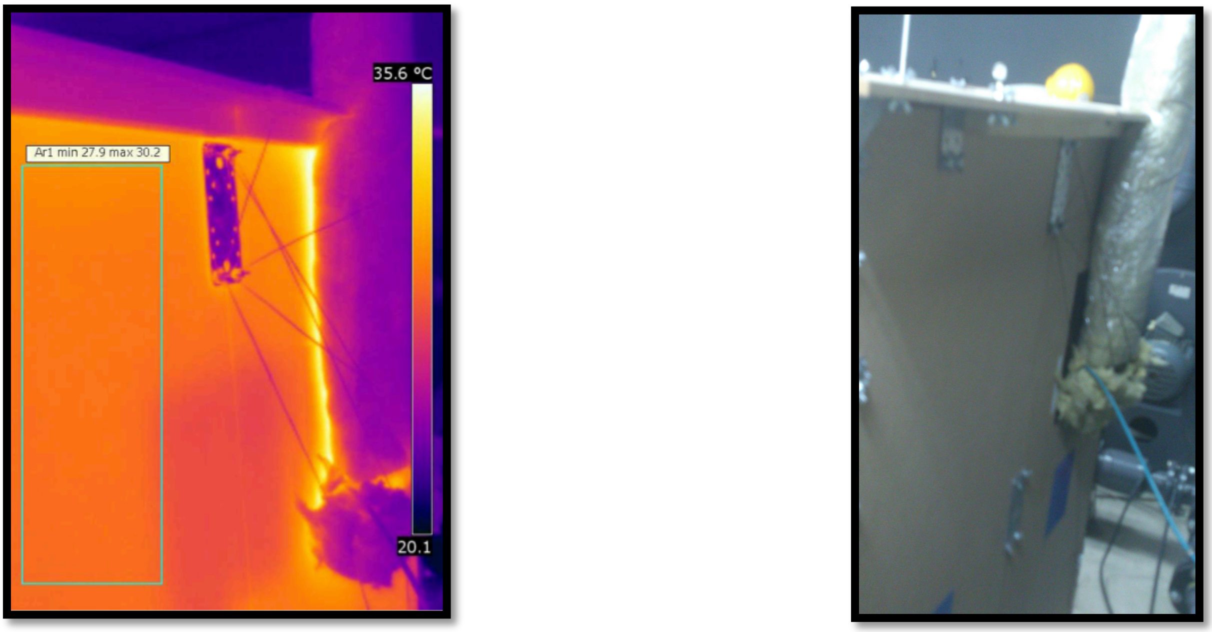


FIGURE 5-6: INFRARED PICTURE + NORMAL PICTURE (BACK SIDE WITH CHIMNEY)

| Back | Tsurface (°C) | Surface (m$^2$) | Tsurface x Surface (°C x m$^2$) |
|---|---|---|---|
| **General** | 28,5 | 0,885 | 25,2225 |
| **Sides** | 28,9 | 0,2 | 5,78 |
| **Focus** | 30 | 0,1 | 3 |

TABLE 43: WALL TEMPERATURES OF THE BACK SIDE

### 5.2.2.5 Top (0,395 m$^2$)

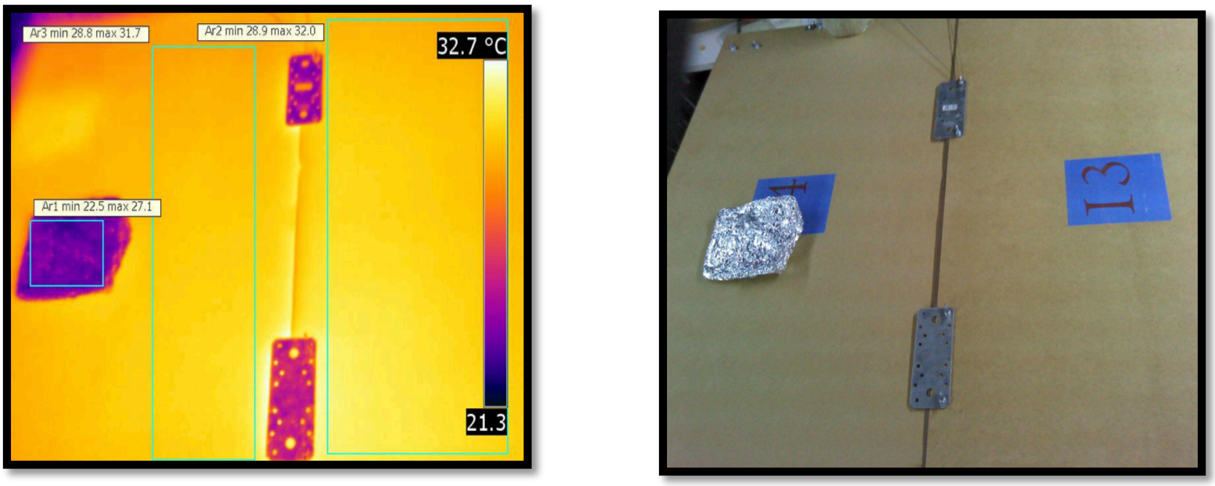


FIGURE 5-7: INFRARED PICTURE + NORMAL PICTURE (TOP)

| **Top** | **Tsurface (°C)** | **Surface ($m^2$)** | **Tsurface x Surface (°C x $m^2$)** |
|---|---|---|---|
| **General** | 30 | 0,295 | 8,85 |
| **Focus** | 31,5 | 0,1 | 3,15 |

**TABLE 44: WALL TEMPERATURES OF THE TOP**

### 5.2.2.6 FINAL CALCULATIONS

a) $T_{surface}$

∑ (Tsurface x Surface) = 105 (°C x $m^2$)

$$\frac{\sum\ (Tsurface\ x\ Surface)}{Total\ Surface} = \frac{105}{3{,}555} = 29{,}54\ (°C) =\ 302{,}69\ K$$

$T_{Surface}$ = 302,69 K

b) Heat transfer coefficient

$T_{Reflected}$ = 293,63 K (From the QuickReport of Flir)

$$h = 0{,}95 \times 5{,}67 * 10^{-8} \times F_t\ and\ F_t = 4 \times T_m^3\ and\ T_m = \frac{(302{,}69 + 293{,}63\ )}{2}$$

➔ h = 5,7 (W/$m^2$*K)

c) Thermal Balance

$$Q_{Radiation} = 0{,}95 \times 5{,}67 * 10^{-8} \times 3{,}555 \times \left(302{,}69^4 \quad - 293{,}63^4\ \right) = 184{,}90\ W$$

$$Q_{Convection} = 3{,}555 \times 5{,}7 \times (302{,}69 - 293{,}13) = 194{,}00\ W$$

$$Q_{heating} =\ 1{,}18 \times 0{,}0006628 \times 1000 \times (23{,}57) + 184{,}90 + 194{,}00 = 396{,}34W$$

## 5.2.3 CONCLUSION

The expected output of theoretically thermal balance is 480 W, because there were 4 lamps of 120 W. The result of the thermal balance that was calculated with the equation of the thermal balance is 397 W. There could be several reasons for the big difference of 83 W: heat losses at the connection between the pipe and the box, not a good measurement of the flow through the chimney, heat losses at the bottom of the model, heat losses in some focuses of lamps,...

Another remarkable result is that $Q_{Radiation}$ and $Q_{Convection}$ are very big compared with the influence of the air mass flow. The cause of this big difference is that the box is not isolated so there are a lot of heat losses through the surface of the model.

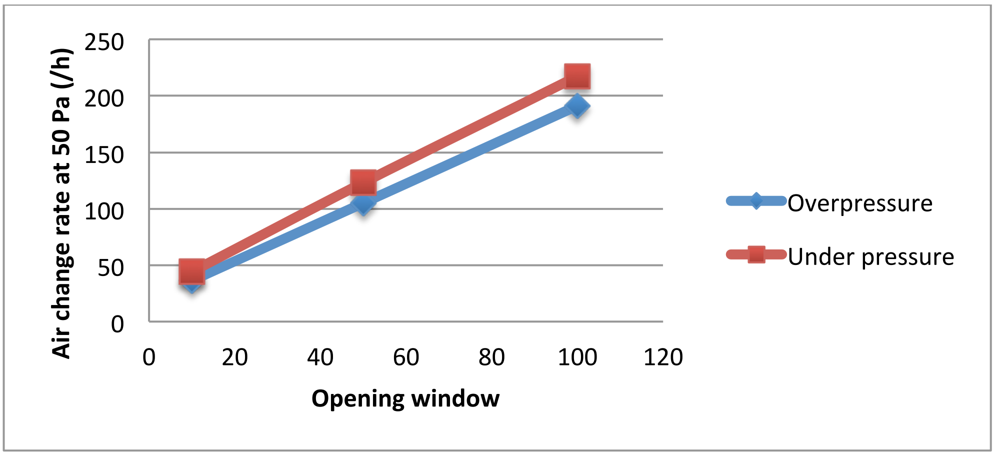
One last comment is that $Q_{Radiation}$ and $Q_{Convection}$ are nearly the same, the reason for this noteworthy outcome is that there is no isolation and that we are working in an inside environment.

## 5.3 BLOWER DOOR TEST

For a final test it was decided to carry out a blower door test, for an overpressure of 50 Pa and an under pressure of 50 Pa as was explained in paragraph 3.1.4.2. A summary of the results is given in Table 45. Further details of the blower door test are available in *Appendix D*.

| | Air flow at 50 Pa ($m^3$/h) | Air changes at 50 Pa (/h) |
|---|---|---|
| **Overpressure 100 $cm^2$** | 229 | 191 |
| **Overpressure 50 $cm^2$** | 127 | 105 |
| **Overpressure 10 $cm^2$** | 43,55 | 36,30 |
| **Under pressure 100 $cm^2$** | 260,5 | 217 |
| **Under pressure 50 $cm^2$** | 148 | 123,05 |
| **Under pressure 10 $cm^2$** | 53.05 | 44,20 |

TABLE 45: SUMMARY OF THE RESULTS



GRAPHIC 22: SUMMARY OF BLOWER DOOR TEST

There is a little difference between overpressure and under pressure and the air change rates are linear with the opening of the window. The air change rates are large (For example: air change rate for a passive house is 0,6 /h) so we can conclude that this box has many air leaks. This was also a conclusion of thermal balance. But what's remarkable is that the air change rates changes by the opening of the window, but not when the flow through the chimney was measured, there the window opening had no influence on the flow.

Air change rates for the under pressure is a little higher than the rates for the overpressure, this is most probably caused by the tape that we placed inside the box, what's shown on Figure 5-8. When there's an overpressure the air wants to get out, but the tape is pushed into the corners of the box, so it's more difficult for the air to get out. When there is an under pressure it's easier for the air to get out.

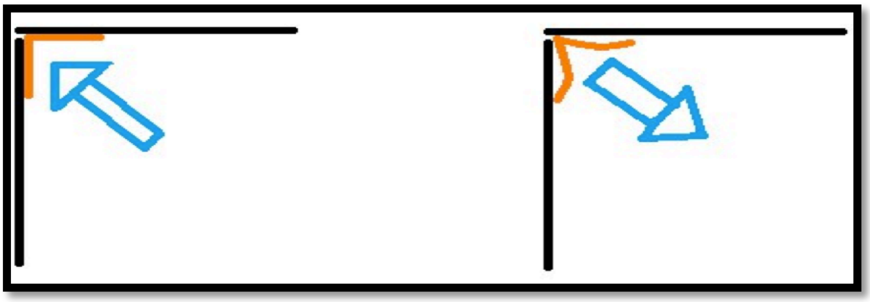


**FIGURE 5-8: SKETCH OF TAPE IN THE BOX IN OVERPRESSURE AND UNDER PRESSURE**

## 5.4 PRESSURE VS. BLOWER DOOR TEST

Another way to measure and verify the air mass flow is with the following method: Pressure difference vs. blower door test.

Methodology:

1. Make the model exactly the same as before (2.2.).
2. The pressure difference between the inside and outside environment (ΔP) will be measured by a manometer during different temperatures created inside the box.
3. Remove the heating source and close the window.
4. The blower door will be installed to create an overpressure.
5. Set the ΔP into the program of the blower door and the blower door can measure the air mass flow perfectly because it was calibrated.
6. Compare the results of the blower door with the results of the air velocity measured with the TESTO equipment.

The measuring equipment used during the test was not reliable because the values of the pressure fluctuated all the time. That's why it was decided not to evaluate these measurements. Although it was a good idea to measure the airflow in a different way rather than just measure the velocity physically (with the TESTO equipment).

The problems we discovered were:

- Appropriate measuring equipment wasn't available (small range).
- The place were the measuring tube should be placed wasn't well known because the pressure inside the box was very versatile.
- The situation had to be exactly the same like the first measurements.

# CONCLUSION

How does the chimney effect actually take place? The lamps cause a temperature rise as well as a density drop in the air inside the chimney. The drop in air density causes air within the thermal chimney to rise and be expelled out of the top of the chimney (see topic Thermal Buoyancy).

By using three methods to illustrate the effect: experimental tests on a rescaled model, tests in TRNSYS of the model and an apartment, and calculations by using the theory of Thermal Buoyancy, conclusions could be drawn. It's appropriate to define these conclusions because the results of these three methods were similar to each other and were also verified with the theory of Thermal Balance.

Four different parameters were manipulated to see how sensitive each parameter was in changing the air velocity through the chimney. The following parameters are defined from the less sensitive to the most sensitive one:

Window opening - this parameter had the lowest influence on the air velocity which was also defined in the following comment: "Air gap width doesn't have much influence, solar influence and chimney height is much higher." (Kwang Ho Lee, Richard K. Strand, 2008, p. 7) It's also correct to say that, the smaller the opening, the lower the temperature difference when the air velocity switches from 1 m to 2 m, see Graphic 13, 14 and 15.

Temperature difference - starting at a baseline temperature difference that changes according to the window opening. The flow through the 2 meter chimney goes faster than the flow through the 1 meter chimney. The minimum Δ temperature had to be more than ± 20 °C before the chimney worked properly. The height has the same sensitivity, since these are the 2 most important parameters in the experiment and are measured at the same time. What's also important is that, "if the discharge air temperature from the top of the thermal chimney is less than the room air temperature, the air velocity through the chimney will be automatically shut down, since the outlet temperature should be greater than the room temperature in order to cause the updraft airflow" (Kwang Ho Lee, Richard K. Strand, 2008, p. 7).

Chimney height - the height of the chimney (see Graphic 10) has a big influence from the time that Δ temperature increases to ± 20 °C in the experimental test. And when there's no influence of the wind velocity on top of the chimney, it's valid to say that the longer the chimney gets, the higher the air velocity through the chimney.

Wind velocity - this is the most sensitive parameter because it can change the whole effect of the chimney that's defined above. When the wind velocity rises above 3 m/s in the test with TRNSYS, the longest chimney has now the lowest air velocity through the pipe in comparison with the shorter chimneys.

Currently architects and building engineers are experimenting with variable sizes of the surface opening of the chimney at each floor level. In the future the surface of the chimney could probably be automatized, so it changes automatically according to the situation of the 4 different defined parameters.

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# APPENDIX

# APPENDIX A: RESULTS OF THE APARTMENT

| | Ap= 0.1x0.1= 0.01m$^2$ | | | Ap= 0.05x0.05= 0.0025m$^2$ | | | Ap= 0.02x0.02= 0.0004m$^2$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | E Heating | E Cooling | **Yearly** | E Heating | E Cooling | **Yearly** | E Heating | E Cooling | **Yearly** |
| VivA_PB | 3898 | 1558 | **5456** | 3284 | 1623 | **4907** | 3059 | 1622 | **4681** |
| VivA_PM | 3974 | 1569 | **5543** | 3291 | 1611 | **4902** | 3060 | 1605 | **4665** |
| VivA_PA | 3878 | 1592 | **5470** | 3240 | 1613 | **4853** | 3051 | 1623 | **4674** |
| VivB1_PB | 4103 | 2201 | **6304** | 3575 | 2267 | **5842** | 3365 | 2296 | **5661** |
| VivB1_PM | 4231 | 2197 | **6428** | 3580 | 2270 | **5850** | 3368 | 2297 | **5665** |
| VivB1_PA | 4135 | 2222 | **6357** | 3533 | 2278 | **5811** | 3359 | 2298 | **5657** |
| VivB2_PB | 2664 | 2486 | **5150** | 2196 | 2561 | **4757** | 2027 | 2593 | **4620** |
| VivB2_PM | 2652 | 2489 | **5141** | 2180 | 2565 | **4745** | 2024 | 2591 | **4615** |
| VivB2_PA | 2546 | 2515 | **5061** | 2134 | 2574 | **4708** | 2015 | 2593 | **4608** |

**TABLE 1: ENERGY DEMAND**

# APPENDIX B: COMPARING TRNSYS OUTPUTS (MODEL) WITH THE MEASUREMENTS

| | | | | | | TRNSYS | Manual | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Ductlength** | Opening | Nr of lamps | $T_{in}$ [°C] | ΔT | Humidity[%] | v [m/s] | | Error | Correlation | Flow crack [$m^3$/h] |
| **1 meter** | 100 $cm^2$ | 1 | 30.9 | 6.83 | 29.7 | 0.3771 | 0.417 | 0.0399 | 0.986674354 | 0.8521 |
| | | 2 | 36.1 | 13.05 | 26.2 | 0.5529 | 0.616 | 0.0631 | | 1.298 |
| | | 3 | 42.7 | 18.17 | 19.3 | 0.6929 | 0.693 | 1E-04 | | 1.666 |
| | | 4 | 46.1 | 23.57 | 12.3 | 0.738 | 0.73 | -0.008 | | 1.786 |
| | 50 $cm^2$ | 1 | 30.1 | 4.78 | 26.2 | 0.3768 | 0.43 | 0.0532 | 0.989380643 | 0.8552 |
| | | 2 | 34.6 | 12.54 | 15.7 | 0.6019 | 0.599 | -0.0029 | | 1.43 |
| | | 3 | 40.5 | 17.73 | 14.3 | 0.6708 | 0.68 | 0.0092 | | 1.611 |
| | | 4 | 45.2 | 21.1 | 18.8 | 0.714 | 0.746 | 0.032 | | 1.725 |
| | 10 $cm^2$ | 1 | 31 | 7.25 | 29.9 | 0.2505 | 0.445 | 0.1945 | 0.984686244 | 0.3745 |
| | | 2 | 36.3 | 11.04 | 27.5 | 0.3138 | 0.56 | 0.2462 | | 0.478 |
| | | 3 | 39.9 | 15.77 | 25.1 | 0.4069 | 0.634 | 0.2271 | | 0.6366 |
| | | 4 | 45.9 | 21.06 | 20.6 | 0.4389 | 0.683 | 0.2441 | | 0.693 |
| **2 meter** | 100 $cm^2$ | 1 | 30.2 | 7.91 | 20.4 | 0.4576 | 0.453 | -0.0046 | 0.998118792 | 0.9741 |
| | | 2 | 35.2 | 12.63 | 19.4 | 0.5613 | 0.568 | 0.0067 | | 1.221 |
| | | 3 | 39.8 | 18.24 | 17.7 | 0.7222 | 0.711 | -0.0112 | | 1.612 |
| | | 4 | 43.3 | 23.01 | 12.6 | 0.8303 | 0.844 | 0.0137 | | 1.88 |
| | 50 $cm^2$ | 1 | 28.9 | 8.87 | 24.2 | 0.4725 | 0.473 | 0.0005 | 0.998220772 | 1.011 |
| | | 2 | 33.6 | 13.99 | 23.1 | 0.6391 | 0.63 | -0.0091 | | 1.409 |
| | | 3 | 35.8 | 17.98 | 27.2 | 0.7316 | 0.75 | 0.0184 | | 1.635 |
| | | 4 | 41.2 | 21.77 | 19.9 | 0.8401 | 0.857 | 0.0169 | | 1.904 |
| | 10 $cm^2$ | 1 | 29.6 | 7.58 | 22.2 | 0.3648 | 0.365 | 0.0002 | 0.776237037 | 0.4421 |
| | | 2 | 34.2 | 12.06 | 21.9 | 0.3435 | 0.579 | 0.2355 | | 0.416 |
| | | 3 | 39.8 | 17.84 | 18.9 | 0.4146 | 0.693 | 0.2784 | | 0.5005 |
| | | 4 | 44.5 | 23.56 | 15.5 | 0.4675 | 0.784 | 0.3165 | | 0.5729 |

**TABLE 1: TABLE OF THE AIR VELOCITY'S OF TRNSYS- AND MANUALRESULTS**

| Opening open | Wind velocity (without Cp-values) | Winddirection (realtime) | Winddirection (SketchUp) | Time [Hr] | Groundfloor (m$^3$/h) | Air velocity duct | Middle floor (m$^3$/h) | Air velocity duct | Highest floor (m$^3$/h) | Air velocity duct |
|---|---|---|---|---|---|---|---|---|---|---|
| **Ap_1_1** | 0 | SOUTH-EAST | NORTH 180° | 120<br>(6 januari 00:00) | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| **EN_001** | | SOUTH-WEST | EAST 270° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | | NORTH-WEST | SOUTH 0° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | | NORTH-EAST | WEST 90° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | 3 | SOUTH-EAST | NORTH 180° | 120 | 77.27 | 0.953950617 | 44.87 | 0.553950617 | -39.8 | -.491358025 |
| | | SOUTH-WEST | EAST 270° | 120 | 87.07 | 1.074938272 | 104.5 | 1.290123457 | 108.6 | 1.340740741 |
| | | NORTH-WEST | SOUTH 0° | 120 | 84.71 | 1.045802469 | 88.82 | 1.09654321 | 86.03 | 1.062098765 |
| | | NORTH-EAST | WEST 90° | 120 | 83.77 | 1.034197531 | 87.23 | 1.07691358 | 83.06 | 1.025432099 |
| | 5 | SOUTH-EAST | NORTH 180° | 120 | 83 | 1.024691358 | -28.29 | 0.349259259 | -70.54 | -.870864198 |
| | | SOUTH-WEST | EAST 270° | 120 | 106.8 | 1.318518519 | 155.4 | 1.918518519 | 176.6 | 2.180246914 |
| | | NORTH-WEST | SOUTH 0° | 120 | 101.3 | 1.250617284 | 124.8 | 1.540740741 | 141.2 | 1.743209877 |
| | | NORTH-EAST | WEST 90° | 120 | 99.13 | 1.22382716 | 121.5 | 1.5 | 136.2 | 1.681481481 |
| **Ap_2_1** | 0 | SOUTH-EAST | NORTH 180° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| **EN_001** | | SOUTH-WEST | EAST 270° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | | NORTH-WEST | SOUTH 0° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | | NORTH-EAST | WEST 90° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | 3 | SOUTH-EAST | NORTH 180° | 120 | 77.27 | 0.953950617 | 44.87 | 0.553950617 | -39.8 | -.491358025 |
| | | SOUTH-WEST | EAST 270° | 120 | 87.07 | 1.074938272 | 104.5 | 1.290123457 | 108.6 | 1.340740741 |
| | | NORTH-WEST | SOUTH 0° | 120 | 84.71 | 1.045802469 | 88.82 | 1.09654321 | 86.03 | 1.062098765 |
| | | NORTH-EAST | WEST 90° | 120 | 83.77 | 1.034197531 | 87.23 | 1.07691358 | 83.06 | 1.025432099 |
| | 5 | SOUTH-EAST | NORTH 180° | 120 | 83 | 1.024691358 | -28.29 | 0.349259259 | -70.54 | -.870864198 |
| | | SOUTH-WEST | EAST 270° | 120 | 106.8 | 1.318518519 | 155.4 | 1.918518519 | 176.6 | 2.180246914 |
| | | NORTH-WEST | SOUTH 0° | 120 | 101.3 | 1.250617284 | 124.8 | 1.540740741 | 141.2 | 1.743209877 |
| | | NORTH-EAST | WEST 90° | 120 | 99.13 | 1.22382716 | 121.5 | 1.5 | 136.2 | 1.681481481 |
| **Ap_2_2** | 0 | SOUTH-EAST | NORTH 180° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| **EN_002** | | SOUTH-WEST | EAST 270° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | | NORTH-WEST | SOUTH 0° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | | NORTH-EAST | WEST 90° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | 3 | SOUTH-EAST | NORTH 180° | 120 | 81.64 | 1.007901235 | 79.61 | 0.982839506 | 69.48 | 0.857777778 |
| | | SOUTH-WEST | EAST 270° | 120 | 84.53 | 1.043580247 | 86.06 | 1.062469136 | 80.13 | 0.989259259 |
| | | NORTH-WEST | SOUTH 0° | 120 | 91.29 | 1.127037037 | 121.1 | 1.495061728 | 131.4 | 1.622222222 |
| | | NORTH-EAST | WEST 90° | 120 | 83.52 | 1.031111111 | 81.52 | 1.006419753 | 74.33 | 0.917654321 |
| | 5 | SOUTH-EAST | NORTH 180° | 120 | 93.52 | 1.154567901 | 105.5 | 1.302469136 | 113 | 1.395061728 |
| | | SOUTH-WEST | EAST 270° | 120 | 100.9 | 1.245679012 | 119.2 | 1.471604938 | 131.4 | 1.622222222 |
| | | NORTH-WEST | SOUTH 0° | 120 | 115.1 | 1.420987654 | 186.3 | 2.3 | 217.2 | 2.681481481 |
| | | NORTH-EAST | WEST 90° | 120 | 98.53 | 1.216419753 | 109.8 | 1.355555556 | 121.6 | 1.501234568 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ap_3_1 | 0 | SOUTH-EAST | NORTH 180° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| **EN_003** | | SOUTH-WEST | EAST 270° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | | NORTH-WEST | SOUTH 0° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | | NORTH-EAST | WEST 90° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | 3 | SOUTH-EAST | NORTH 180° | 120 | 81.63 | 1.007777778 | 78.64 | 0.970864198 | 68.32 | 0.84345679 |
| | | SOUTH-WEST | EAST 270° | 120 | 87.05 | 1.074691358 | 96.92 | 1.19654321 | 99.26 | 1.225432099 |
| | | NORTH-WEST | SOUTH 0° | 120 | 83.29 | 1.028271605 | 83.11 | 1.026049383 | 76.94 | 0.949876543 |
| | | NORTH-EAST | WEST 90° | 120 | 88.98 | 1.098518519 | 112.3 | 1.386419753 | 120 | 1.481481481 |
| | 5 | SOUTH-EAST | NORTH 180° | 120 | 93.93 | 1.15962963 | 103.1 | 1.272839506 | 111 | 1.37037037 |
| | | SOUTH-WEST | EAST 270° | 120 | 106.8 | 1.318518519 | 140.8 | 1.738271605 | 162.9 | 2.011111111 |
| | | NORTH-WEST | SOUTH 0° | 120 | 97.98 | 1.20962963 | 113.2 | 1.397530864 | 126.2 | 1.558024691 |
| | | NORTH-EAST | WEST 90° | 120 | 111.2 | 1.372839506 | 169.9 | 2.097530864 | 197.6 | 2.439506173 |
| **Ap_3_2** | 0 | SOUTH-EAST | NORTH 180° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| **EN_002** | | SOUTH-WEST | EAST 270° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | | NORTH-WEST | SOUTH 0° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | | NORTH-EAST | WEST 90° | 120 | 73.88 | 0.912098765 | 60.56 | 0.747654321 | 18.82 | 0.232345679 |
| | 3 | SOUTH-EAST | NORTH 180° | 120 | 81.64 | 1.007901235 | 79.61 | 0.982839506 | 69.48 | 0.857777778 |
| | | SOUTH-WEST | EAST 270° | 120 | 84.53 | 1.043580247 | 86.06 | 1.062469136 | 80.13 | 0.989259259 |
| | | NORTH-WEST | SOUTH 0° | 120 | 91.29 | 1.127037037 | 121.1 | 1.495061728 | 131.4 | 1.622222222 |
| | | NORTH-EAST | WEST 90° | 120 | 83.52 | 1.031111111 | 81.52 | 1.006419753 | 74.33 | 0.917654321 |
| | 5 | SOUTH-EAST | NORTH 180° | 120 | 93.52 | 1.154567901 | 105.5 | 1.302469136 | 113 | 1.395061728 |
| | | SOUTH-WEST | EAST 270° | 120 | 100.9 | 1.245679012 | 119.2 | 1.471604938 | 131.4 | 1.622222222 |
| | | NORTH-WEST | SOUTH 0° | 120 | 115.1 | 1.420987654 | 186.3 | 2.3 | 217.2 | 2.681481481 |
| | | NORTH-EAST | WEST 90° | 120 | 98.53 | 1.216419753 | 109.8 | 1.355555556 | 121.6 | 1.501234568 |

**TABLE 2 :RESULTS OF THE FLOW THROUGH THE CHIMNEY WHEN CHANGING THE LENGTH OF THE PIPE, THE WIND VELOCITY , THE WINDDIRECTION & WINDOWOPENING**

| Opening open | Wind velocity (without Cp-values) | Winddirection (realtime) | Winddirection (SketchUp) | Time [Hr] | Groundfloor ($m^3$/h) | Air velocity duct | Middle floor ($m^3$/h) | Air velocity duct | Highest floor ($m^3$/h) | Air velocity duct |
|---|---|---|---|---|---|---|---|---|---|---|
| All Open | 1 | SOUTH-EAST | NORTH 180° | 120 | 129.1 | 1.59382716 | 120 | 1.481481481 | 80.37 | 0.992222222 |
| | | SOUTH-WEST | EAST 270° | 120 | 130.5 | 1.611111111 | 128.7 | 1.588888889 | 150.2 | 1.854320988 |
| | | NORTH-WEST | SOUTH 0° | 120 | 130.7 | 1.613580247 | 130 | 1.604938272 | 158.4 | 1.955555556 |
| | | NORTH-EAST | WEST 90° | 120 | 130.2 | 1.607407407 | 126.8 | 1.565432099 | 140.4 | 1.733333333 |
| | 3 | SOUTH-EAST | NORTH 180° | 120 | 138.1 | 1.704938272 | 116.5 | 1.438271605 | 117.5 | 1.450617284 |
| | | SOUTH-WEST | EAST 270° | 120 | 150.1 | 1.85308642 | 184.6 | 2.279012346 | 371.2 | 4.582716049 |
| | | NORTH-WEST | SOUTH 0° | 120 | 150.5 | 1.858024691 | 187.8 | 2.318518519 | 393.3 | 4.855555556 |
| | | NORTH-EAST | WEST 90° | 120 | 147.3 | 1.818518519 | 173.7 | 2.144444444 | 339 | 4.185185185 |
| | 5 | SOUTH-EAST | NORTH 180° | 120 | 151.3 | 1.867901235 | 130.8 | 1.614814815 | 182 | 2.24691358 |
| | | SOUTH-WEST | EAST 270° | 120 | 181.2 | 2.237037037 | 242.3 | 2.991358025 | 604.8 | 7.466666667 |
| | | NORTH-WEST | SOUTH 0° | 120 | 181.8 | 2.244444444 | 247 | 3.049382716 | 641.7 | 7.922222222 |
| | | NORTH-EAST | WEST 90° | 120 | 176.9 | 2.183950617 | 224.2 | 2.767901235 | 549.3 | 6.781481481 |

**TABLE 3: RESULTS OF THE FLOW THROUGH THE CHIMNEY WHEN CHANGING THE LENGTH OF THE PIPE, THE WIND VELOCITY, THE WINDIRECTION & ALL THE WINDOWS ARE OPENENED**

# APPENDIX C: PRINCIPLE OF NATURAL VENTILATION

| Height pipe (m) | Opening ($m^2$) | Lamps | $\Delta T$ (°C) | Toutside (K) | H0 (m) | Q ($m^3/s$) | v (m/s) |
|---|---|---|---|---|---|---|---|
| **1** | 0,01 | 1 | 6,83 | 297,2 | 0,214718999 | 0,00057026 | 0,628039244 |
| **1** | 0,01 | 2 | 13,05 | 296,18 | 0,214718999 | 0,000789613 | 0,869617407 |
| **1** | 0,01 | 3 | 18,17 | 297,66 | 0,214718999 | 0,000929403 | 1,023571201 |
| **1** | 0,01 | 4 | 23,57 | 295,66 | 0,214718999 | 0,001062112 | 1,169726525 |
| **1** | 0,005 | 1 | 4,78 | 298,45 | 0,257466254 | 0,000470329 | 0,517983943 |
| **1** | 0,005 | 2 | 12,54 | 295,19 | 0,257466254 | 0,000765988 | 0,843599062 |
| **1** | 0,005 | 3 | 17,73 | 295,9 | 0,257466254 | 0,000909716 | 1,001889962 |
| **1** | 0,005 | 4 | 21,1 | 297,23 | 0,257466254 | 0,000990191 | 1,090518524 |
| **1** | 0,001 | 1 | 7,25 | 296,88 | 1,01340887 | 0,000436999 | 0,481276524 |
| **1** | 0,001 | 2 | 11,04 | 298,39 | 1,01340887 | 0,000537891 | 0,592391133 |
| **1** | 0,001 | 3 | 15,77 | 297,26 | 1,01340887 | 0,000644095 | 0,709355197 |
| **1** | 0,001 | 4 | 21,06 | 297,97 | 1,01340887 | 0,000743438 | 0,818764601 |
| **2** | 0,01 | 1 | 7,91 | 295,42 | 0,222896221 | 0,000767711 | 0,84549665 |
| **2** | 0,01 | 2 | 12,63 | 295,7 | 0,222896221 | 0,000969629 | 1,067873008 |
| **2** | 0,01 | 3 | 18,24 | 294,69 | 0,222896221 | 0,001167237 | 1,285503649 |
| **2** | 0,01 | 4 | 23,01 | 293,42 | 0,222896221 | 0,001313841 | 1,446961745 |
| **2** | 0,005 | 1 | 8,87 | 293,16 | 0,28939195 | 0,000806262 | 0,887953773 |
| **2** | 0,005 | 2 | 13,99 | 292,74 | 0,28939195 | 0,001013292 | 1,115960252 |
| **2** | 0,005 | 3 | 17,98 | 290,95 | 0,28939195 | 0,001152265 | 1,269014447 |
| **2** | 0,005 | 4 | 21,77 | 292,56 | 0,28939195 | 0,001264412 | 1,392523857 |
| **2** | 0,001 | 1 | 7,58 | 295,15 | 1,465302686 | 0,000558931 | 0,615562447 |
| **2** | 0,001 | 2 | 12,06 | 295,27 | 1,465302686 | 0,00070487 | 0,776288048 |
| **2** | 0,001 | 3 | 17,84 | 295,09 | 1,465302686 | 0,000857561 | 0,944450252 |
| **2** | 0,001 | 4 | 23,56 | 294,07 | 1,465302686 | 0,000987204 | 1,087229406 |

**TABLE 1 : COMPARISON OF THE RESULTS WHEN NO VENTILATION LOSSES ARE CONSIDERED IN THE CALCULTATION**

| Height pipe | Opening ($m^2$) | Lamps | ΔP (Pa) | ΔQ ($m^3/s$) | v (m/s) | TRNSYS | Manual |
|---|---|---|---|---|---|---|---|
| **1** | 0,01 | 1 | 0,063898193 | 0,000246822 | 0,356208652 | 0,3771 | 0,417 |
| **1** | 0,01 | 2 | 0,122509979 | 0,000341763 | 0,493225937 | 0,5529 | 0,616 |
| **1** | 0,01 | 3 | 0,169727077 | 0,000402268 | 0,580544801 | 0,6929 | 0,693 |
| **1** | 0,01 | 4 | 0,221658143 | 0,000459708 | 0,663440561 | 0,738 | 0,73 |
| **1** | 0,005 | 1 | 0,043465793 | 0,00020357 | 0,29378795 | 0,3768 | 0,43 |
| **1** | 0,005 | 2 | 0,115288819 | 0,000331538 | 0,478468961 | 0,6019 | 0,599 |
| **1** | 0,005 | 3 | 0,162612926 | 0,000393747 | 0,568247727 | 0,6708 | 0,68 |
| **1** | 0,005 | 4 | 0,192655366 | 0,000428579 | 0,618515701 | 0,714 | 0,746 |
| **1** | 0,001 | 1 | 0,037523589 | 0,000189144 | 0,272968391 | 0,2505 | 0,445 |
| **1** | 0,001 | 2 | 0,056850215 | 0,000232812 | 0,335989907 | 0,3138 | 0,56 |
| **1** | 0,001 | 3 | 0,081515937 | 0,00027878 | 0,402329092 | 0,4069 | 0,634 |
| **1** | 0,001 | 4 | 0,108600826 | 0,000321778 | 0,464383456 | 0,4389 | 0,683 |
| **2** | 0,01 | 1 | 0,115808063 | 0,000332284 | 0,479545227 | 0,4576 | 0,453 |
| **2** | 0,01 | 2 | 0,184737147 | 0,000419679 | 0,605671713 | 0,5613 | 0,568 |
| **2** | 0,01 | 3 | 0,26770818 | 0,000505209 | 0,729106543 | 0,7222 | 0,711 |
| **2** | 0,01 | 4 | 0,339179123 | 0,000568662 | 0,820681665 | 0,8303 | 0,844 |
| **2** | 0,005 | 1 | 0,127730828 | 0,00034897 | 0,503625879 | 0,4725 | 0,473 |
| **2** | 0,005 | 2 | 0,2017495 | 0,000438577 | 0,632945634 | 0,6391 | 0,63 |
| **2** | 0,005 | 3 | 0,260884422 | 0,000498728 | 0,719754267 | 0,7316 | 0,75 |
| **2** | 0,005 | 4 | 0,314137876 | 0,000547268 | 0,789805813 | 0,8401 | 0,857 |
| **2** | 0,001 | 1 | 0,061384574 | 0,000241919 | 0,349132115 | 0,3648 | 0,365 |
| **2** | 0,001 | 2 | 0,097624948 | 0,000305085 | 0,440291784 | 0,3435 | 0,579 |
| **2** | 0,001 | 3 | 0,144501777 | 0,000371173 | 0,535669314 | 0,4146 | 0,693 |
| **2** | 0,001 | 4 | 0,191494981 | 0,000427286 | 0,616650193 | 0,4675 | 0,784 |

**TABLE 2: COMPARISON OF THE RESULTS WHEN VENTILATION LOSSES ARE CONSIDERED IN THE CALCULATIONS**

| ΔT (°C) | Tout (K) | H0 (m) | Q ($m^3/s$) | v (m/s) | ΔP (Pa) | ΔQ ($m^3/s$) | v (m/s) | TRNSYS |
|---|---|---|---|---|---|---|---|---|
| **6,83** | 297,2 | 0,247427886 | 0,001023647 | 1,127364946 | 0,205894179 | 0,000443059 | 0,639414099 | 0,6032 |
| **13,05** | 296,18 | 0,247427886 | 0,001417398 | 1,561011019 | 0,394754375 | 0,000613484 | 0,885367652 | 0,8163 |
| **18,17** | 297,66 | 0,247427886 | 0,001668329 | 1,837366536 | 0,546898358 | 0,000722093 | 1,04210981 | 0,9811 |
| **23,57** | 295,66 | 0,247427886 | 0,001906549 | 2,099723372 | 0,714231795 | 0,0008252 | 1,190912254 | 1,1353 |

**TABLE 3 : FLOW 5M PIPELENGTH, 100 CM² WINDOWOPENING**

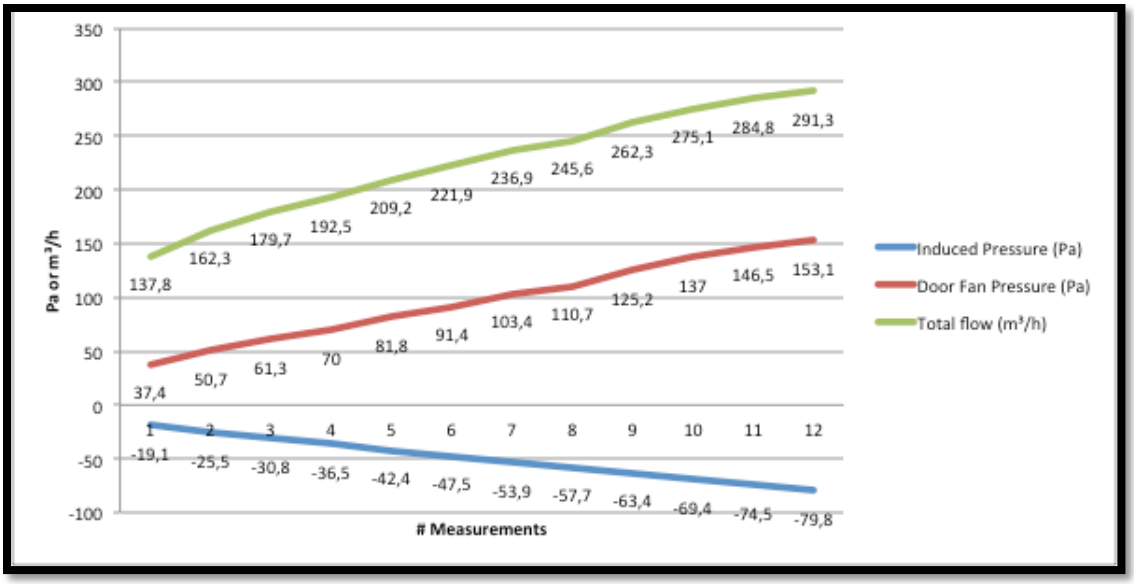
# APPENDIX D: BLOWERDOORTEST

## OVERPRESSURE

### OPENING 100 CM$^2$

| | Results | 95% Confidence Interval | | Uncertainty |
|---|---|---|---|---|
| ***Air flow at 50 Pa, $V_{50}$ $[m^3/h]$*** | **229.0** | **228.0** | **230.5** | **+/-0.6%** |
| ***Air changes at 50 Pa, $n_{50}$ [/h]*** | **191.0** | **189.0** | **192.1** | **+/-0.6%** |
| ***Permeability at 50 Pa, $v_{50}$ $[m^3/h.m^2]$*** | **36.972** | **36.765** | **37.178** | **+/-1.0%** |
| ***Specific Leakage at 50 Pa, $w_{50}$ $[m^3/h.m^2]$*** | **286.531** | **284.931** | **288.131** | **+/-0.6%** |

**TABLE 1: RESULTS FOR 100CM$^2$ OPENING**

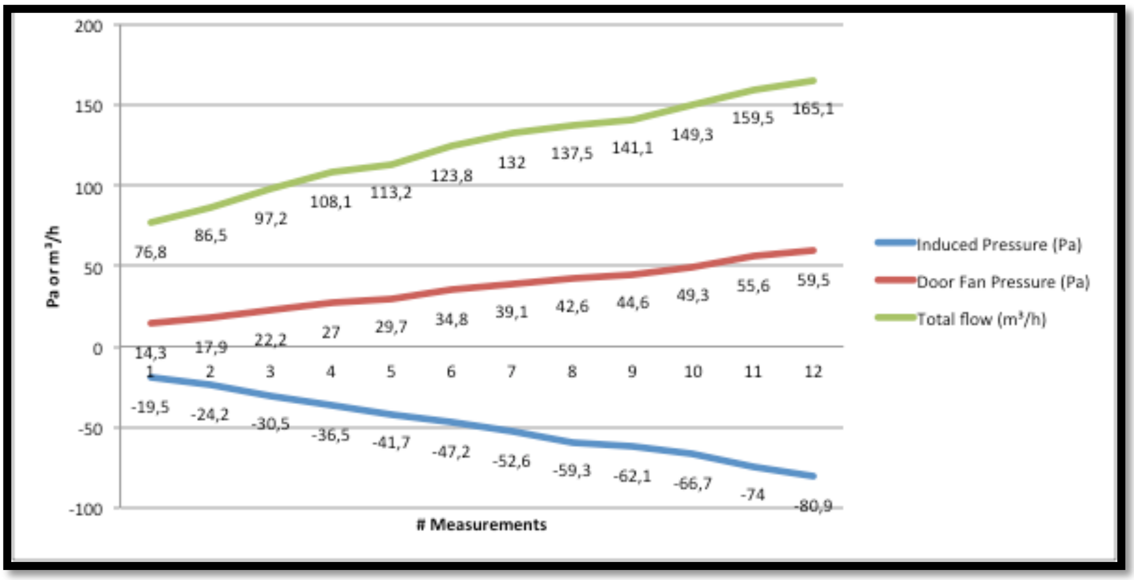


**GRAPHIC 1 : OVERPRESSURE , 100 CM$^2$ OPENING**

## OPENING 50 CM$^2$

| | **Results** | **95% Confidence Interval** | | **Uncertainty** |
|---|---|---|---|---|
| ***Air flow at 50 Pa, $V_{50}$ $[m^3/h]$*** | **127.0** | **126.5** | **128.1** | **+/-0.7%** |
| ***Air changes at 50 Pa, $n_{50}$ [/h]*** | **105.0** | **105.0** | **106.5** | **+/-0.7%** |
| ***Permeability at 50 Pa, $v_{50}$ $[m^3/h.m^2]$*** | **20.515** | **20.370** | **20.661** | **+/-1.0%** |
| ***Specific Leakage at 50 Pa, $w_{50}$ $[m^3/h.m^2]$*** | **158.992** | **157.864** | **160.120** | **+/-0.7%** |

**TABLE 2: RESULTS FOR 50CM$^2$ OPENING**

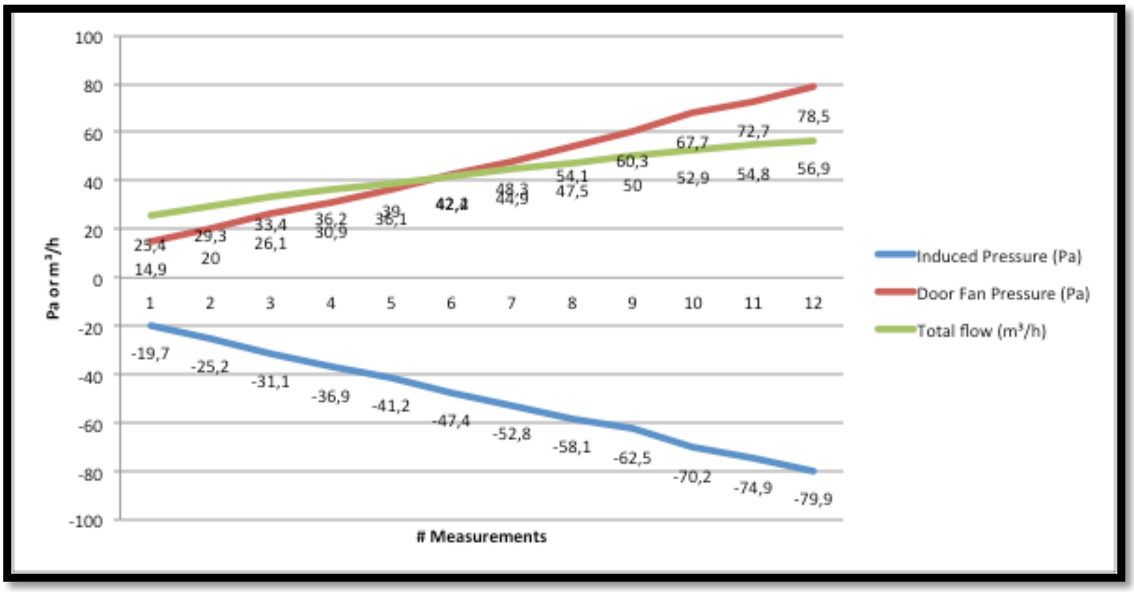


**GRAPHIC 2 : OVERPRESSURE , 50 CM$^2$ OPENING**

## OPENING 10 CM$^2$

| | Results | 95% Confidence Interval | | Uncertainty |
|---|---|---|---|---|
| ***Air flow at 50 Pa, $V_{50}$ [$m^3/h$]*** | **43.55** | **43.40** | **43.70** | **+/-0.3%** |
| ***Air changes at 50 Pa, $n_{50}$ [/h]*** | **36.30** | **36.15** | **36.40** | **+/-0.3%** |
| ***Permeability at 50 Pa, $v_{50}$ [$m^3/h.m^2$]*** | **7.021** | **6.997** | **7.046** | |
| ***Specific Leakage at 50 Pa, $w_{50}$ [$m^3/h.m^2$]*** | **54.416** | **54.229** | **54.603** | **+/-0.3%** |

**TABLE 3: RESULTS FOR 10CM$^2$ OPENING**



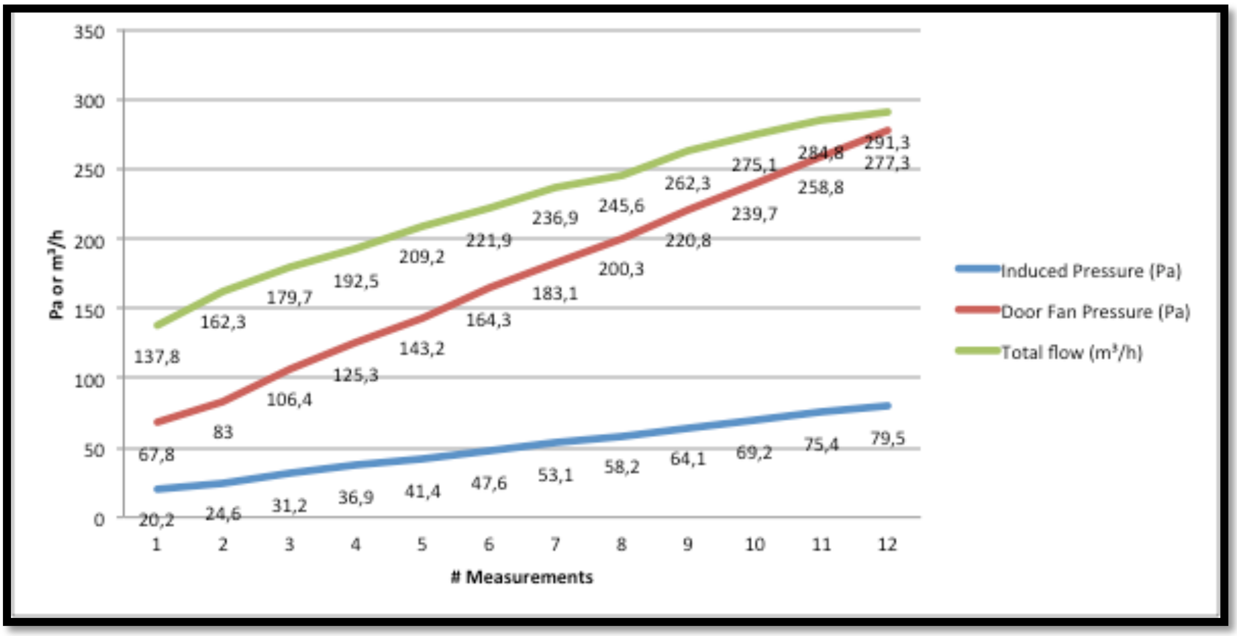
**GRAPHIC 3 : OVERPRESSURE, 10 CM$^2$ OPENING**

## UNDER PRESSURE

### OPENING 100 CM$^2$

| | Results | 95% confidence | | Uncertainty |
|---|---|---|---|---|
| ***Air flow at 50 Pa, V$_{50}$ [m$^3$/h]*** | **260.5** | **259.5** | **261.5** | **+/-0.3%** |
| ***Air changes at 50 Pa, n$_{50}$ [/h]*** | **217.0** | **216.5** | **217.5** | **+/-0.3%** |
| ***Permeability at 50 Pa, v$_{50}$ [m$^3$/h.m$^2$]*** | **42.005** | **41.867** | **42.143** | **+/-0.3%** |
| ***Specific Leakage at 50 Pa, w$_{50}$ [m$^3$/h.m$^2$]*** | **325.539** | **324.468** | **326.611** | **+/-0.3%** |

**TABLE 4: RESULTS FOR 100CM$^2$ OPENING**

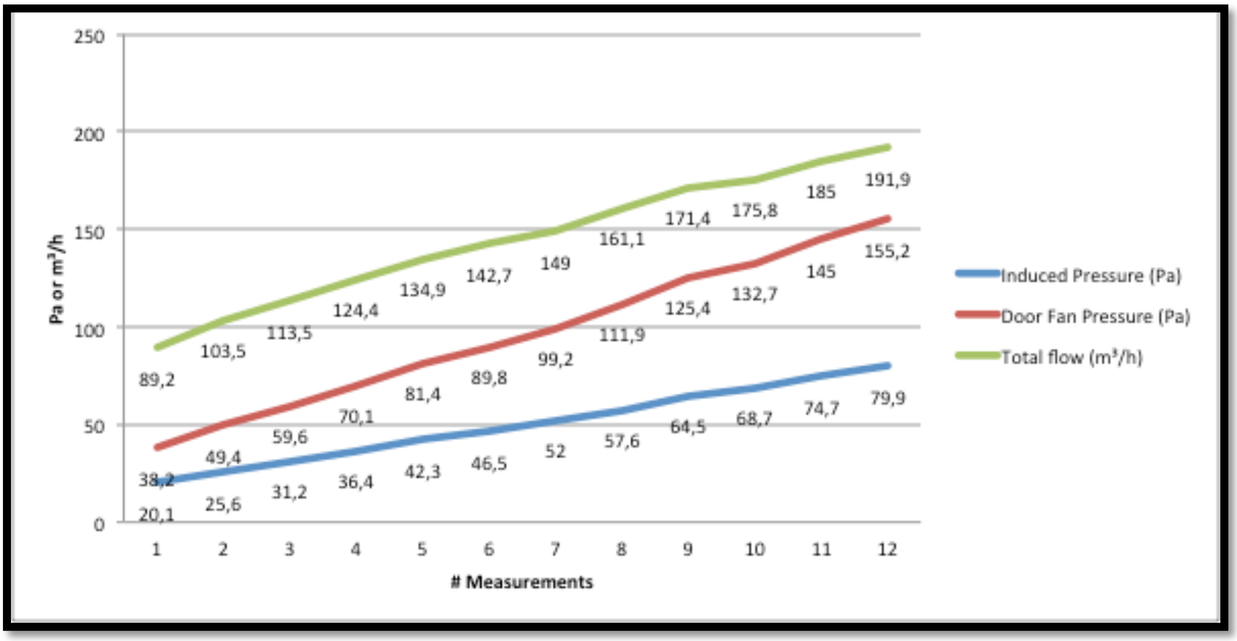


**GRAPHIC 4 : UNDER PRESSURE, 100 CM$^2$ OPENING**

## OPENING 50 CM$^2$

| | Results | 95% confidence | | Uncertainty |
|---|---|---|---|---|
| ***Air flow at 50 Pa, V₅₀ [m³/h]*** | **148.0** | **147.5** | **149.0** | **+/-0.5%** |
| ***Air changes at 50 Pa, n₅₀ [/h]*** | **123.5** | **123.0** | **124.0** | **+/-0.5%** |
| ***Permeability at 50 Pa, v₅₀ [m³/h.m²]*** | **23.900** | **23.786** | **24.014** | **+/-0.5%** |
| ***Specific Leakage at 50 Pa, w₅₀ [m³/h.m²]*** | **185.226** | **184.342** | **186.111** | **+/-0.5%** |

**TABLE 5: RESULTS FOR 50CM$^2$ OPENING**

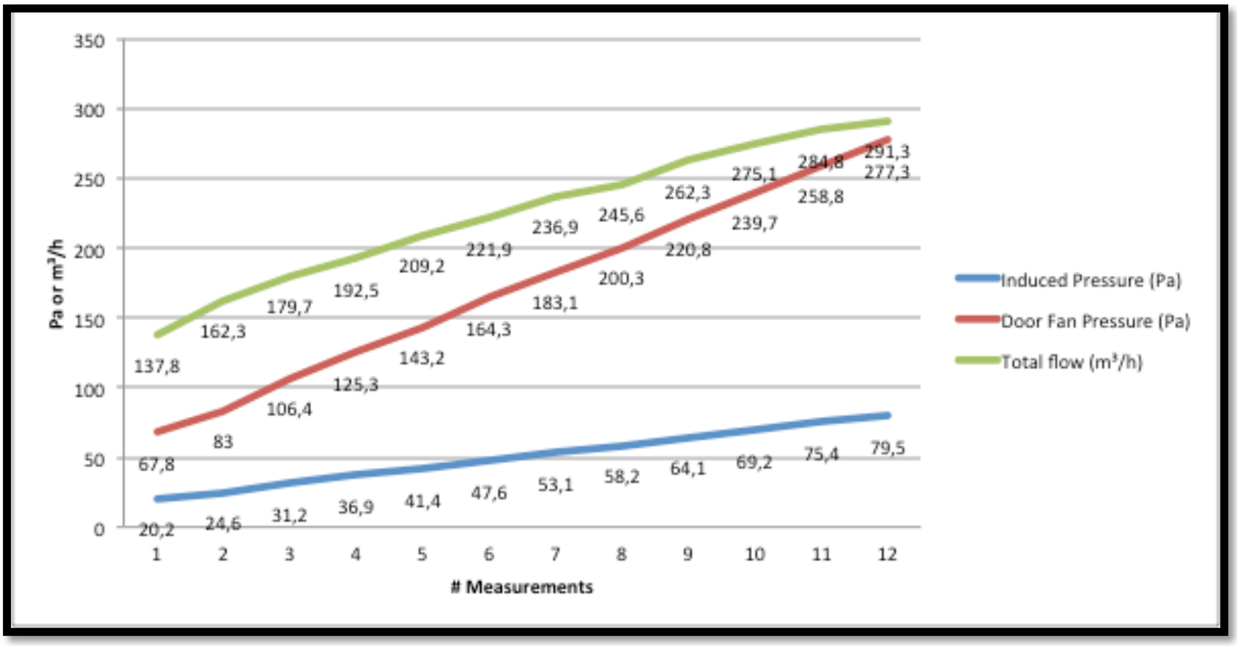


**GRAPHIC 5 : UNDER PRESSURE, 50 CM$^2$ OPENING**

## OPENING 10 CM$^2$

| ***Air flow at 50 Pa, $V_{50}$ [m$^3$/h]*** | **53.05** | **52.90** | **53.21** | **+/-0.3%** |
|---|---|---|---|---|
| ***Air changes at 50 Pa, $n_{50}$ [/h]*** | **44.20** | **44.00** | **44.35** | **+/-0.3%** |
| ***Permeability at 50 Pa, $v_{50}$ [m$^3$/h.m$^2$]*** | **8.559** | **8.535** | **8.582** | **+/-0.3%** |
| ***Specific Leakage at 50 Pa, $w_{50}$ [m$^3$/h.m$^2$]*** | **66.330** | **66.149** | **66.512** | **+/-0.3%** |

**TABLE 6: RESULTS FOR 10CM$^2$ OPENING**



**GRAPHIC 6 : UNDER PRESSURE, 10 CM$^2$ OPENING**