NTNU – Trondheim
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Thermal comfort with simplified heat distribution systems in highly insulated buildings

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MASTER THESIS

for

Student Martine Blomvik Pettersen

Spring 2014

Thermal comfort with simplified heat distribution systems in highly insulated buildings
Termisk komfort med forenklet oppvarmingsløsning i høyisolerte bygninger

Background and objective

The heat distribution system in passive houses is most often simplified in passive houses. In this context where the number of heat emitters in the building is limited, natural convection through internal openings is essential to homogenize the temperature inside the building. Nevertheless, today's simulation models for this physics are a rough estimate of the reality. The objective of this work is to measure the actual flow rate through internal doors and open stairs in passive houses and compare it to theory (i.e. simplified models).

The Master Thesis is in the direct continuation of the work performed by the student during its project work. The student has already performed a literature survey of the different simplified models to evaluate cross-flow through large vertical openings. She has analyzed the different modeling approaches as well as their respective limitations. Based on this knowledge, she has planned the measurement campaign. In parallel, wireless measurement probes and their data-logging equipment have been ordered accordingly so that the required instruments are now available for the campaign.

The objective of the Master Thesis is to perform a short-term measurement campaign in a real passive house and to compare results with the different simplified models analyzed during the project work. A heat source will be placed in a room (essentially the living-room on the first floor but the second floor may also be considered in a second step) while other space-heating emission systems in the building will be switched-off. The resulting flow through the open doors will be measured, especially between the room containing the heat emitter and the main corridor. Different heat source can be investigated, such as electric convectors, radiant or an experimental electric stove. The potential influence of the heat source on the flow through the door will also be investigated and discussed. Finally, the student will pay close attention to the way to the building is constructed. In particular, she will properly report the geometry of the building, the size of the doors as well as the composition of external and partition walls.

The project must be discussed and written in English.

Affiliation: (FME): Zero Emission Buildings – ZEB (www.zeb.no)

The following tasks are to be considered:

1. Test/validation of the measurement material and methodology in the laboratory (i.e. klima room)

2. Measurement campaign in one passive row house using a baseline layout: electric radiator in the living-room and all the internal doors opened inside the building.

3. Measurement campaign in one passive row house using alternative layouts/configurations. Several of the following parameters can be changed:

    a. Change the type of heater in the room (e.g. electric stove or radiant)

    b. Change the location of the heater (e.g. second floor)

    c. Change the number of doors that are opened in the building

    d. Add a complementary heater in the bathroom and check the temperature distribution in the building

    The location of the measurement points has to be adapted to the objectives (a) to (d) and will be discussed with the supervisors.

4. Comparison between the simplified models and the measurement results. The difference should be discussed: for instance, as regards the impact of the accuracy/resolution of the measures, as well as the assumptions done in the simplified models compare to reality.

5. Redaction of the Master Thesis

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☒ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☒ Field work

Department of Energy and Process Engineering, 14. January 2014

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Preface

This thesis was written at the Department of Energy and Process Engineering at NTNU during the spring semester of 2014 and is a continuation of the thesis project I submitted in the fall semester of 2013. This thesis concludes my MSc in Energy and Environmental Engineering.

I would like to thank my supervisor professor Hans Martin Mathisen for guidance throughout the semester and my co-supervisor Laurent Georges for taking time to answer all my questions and for constructive feedback.

I would also like to thank Kristian Stensrud and other employees at Heimdal Bolig for letting us use one of their passive houses for measurements, Runar Kristensen at Aasen Bygg and subcontractors for the help with the retrieval of needed information and the technical staff at the laboratory at the department for assistance in mounting the measurement equipment.

Martine B. Pettersen
Trondheim, June 2014

Summary

The increasing energy consumption and its consequences have led to a major need for energy saving measures. Therefore, the passive house concept has been introduced. Passive houses have a low heating demand, so that it is theoretically possible to simplify the space heating distribution system by for example reduce the number of radiators. It has therefore been investigated if one central heat source can give sufficient thermal comfort in a whole housing unit.

Research shows, with the use of simulations for Belgian climate, that thermal comfort can be obtained in the whole dwelling if the internal doors are open. Thus, the air flows through these doors are central for the thermal comfort in passive houses. Different analytical models for the calculation of velocity and volume flows through large vertical openings are therefore presented and compared. These models, and thus the simulations are based on a set of assumptions which are assessed. Measurements were conducted to investigate if the assumptions are valid and if thermal comfort can be achieved in a real situation. First, laboratory measurements were conducted to see if the planned setup functioned. Then measurements were conducted in an actual passive house; velocity and temperature were measured in a doorway and the air and surface temperatures were measured on both sides of the aperture. Three different heat sources were used and placed in four different positions where one position was on the first floor. There were several factors in the passive house that can have affected the results; the measurements were done in a staircase, a frame was built around the stairs and the measurement equipment all had margins of error.

The measurements gave a velocity profile which deviated some from the theory. While investigating this it was found that many of the central assumptions were invalid. The temperatures in the thermal zones were neither uniform nor with small and similar temperature gradients; the temperatures varied in both zones and the thermal gradients differed for the two rooms and could not be considered small. The results imply that there is heat transfer between the two air streams in the aperture which contradicts the assumption of this not being the case. The passive house also has a ventilation system while the theoretical models assume that there is no supply of ventilation air. The consequence of these assumptions being invalid is that the velocity profile is changed from a symmetric, parabolic shape to a non-symmetric, non-parabolic shape. The position of the neutral plane was also found to be affected by the supplied ventilation air rate. One central assumption was found to be valid; the results showed that there was one neutral plane in the middle of the aperture. The volume flows were calculated based on the measured velocities and neither the velocities nor the volume flows was equal to the analytical calculated values. Thus, it is concluded that the analytical models cannot be used to find exact values for velocity and volume flows. However, the majority of the models can be used to find indications for these magnitudes, especially for the volume flows. The discharge coefficient C_d was found to be varying so that one value cannot be used for all cases.

The deviations from the theory were more evident for the cases with the heat sources located upstairs as the velocity profile and temperature distribution in the aperture differed from the other cases. The neutral plane was located higher up in the aperture and thus none of the central assumptions are valid. The theoretical models are therefore found inapplicable when the heat source is located above the aperture.

Even though the measurement results do not match the theory completely there were no problems with the thermal comfort in the house during the measurement period. The settings for the heat sources are found to be important for the thermal comfort.

Sammendrag

Verdens økende energiforbruk og dets konsekvenser har ført til et stort behov for energibesparende tiltak. Derfor har passivhuskonseptet blitt introdusert. Passivhus har betraktelig lavere oppvarmingsbehov enn konvensjonelle hus og det er derfor mulig å redusere antall varmekilder i huset. Det har derfor blitt undersøkt om man kan oppnå tilfredsstillende termisk komfort i en hel boenhet ved å kun ha én sentral varmekilde. Forskning viser, ved bruk av simuleringer, at termisk komfort i en hel boenhet kan oppnås hvis innvendige dører er åpne. Luftstrømmene gjennom de innvendige dørene er altså svært viktige for den termiske komforten i passivhus. Derfor er analytiske modeller for utregning av hastighet og masse- og volumstrømmer presentert og sammenlignet. Modellene, og simuleringene, er basert på en rekke antagelser som er vurdert. Målinger har blitt utført for å undersøke om antagelsene er gyldige og om termisk komfort kan bli oppnådd i en reell situasjon. Først ble laboratoriemålinger gjort for å se om det planlagte oppsettet fungerte. Deretter ble målinger utført i et passivhus; hastighet og temperatur ble målt i en døråpning og luft- og overflatetemperaturer ble målt på begge sider av åpningen. Tre ulike varmekilder og fire ulike posisjoner ble brukt, hvorav en av posisjonene var i andre etasje. Det var flere faktorer i passivhuset som kan ha påvirket resultatene; målingene ble gjort i en trapp, en lettvegg ble bygd rundt trappen og alt av måleutstyr har en feilmargin.

Målingene ga en hastighetsprofil som avviker noe fra teorien. Da dette ble undersøkt ble det funnet at flere av de sentrale antagelsene var ugyldige. Temperaturene i de to rommene var ikke uniforme eller med små og like temperaturgradienter; temperaturene varierte i begge rommene og gradientene var ulike og kan ikke bli sett på som små. Resultatene tyder på at det er varmeoverføring mellom de to luftstrømmene i eller nær åpningen, dette motstrider antagelsen om at dette ikke er tilfellet. Passivhuset har også et balansert ventilasjonssystem mens de teoretiske modellene antar at det ikke er noe tilførsel av ventilasjonsluft. Konsekvensene av at disse antagelsene er ugyldige er at hastighetsprofile endres fra å være symmetrisk og parabolsk til å være asymmetrisk og ikke-parabolsk. Plasseringen av det nøytrale planet er også funnet å være avhengig av mengde tilført ventilasjonsluft. Én sentral antagelse som er funnet gyldig er antagelsen om ett nøytralt plan i midten av åpningen. Volumstrømmene ble kalkulert basert på de målte hastighetene og hverken hastighetene eller volumstrømmene korresponderte med de analytisk kalkulerte verdiene. Derfor er det konkludert at de analytiske modellene ikke kan brukes for å finne eksakte verdier for hastighet og volumstrømmer, men de kan brukes for å finne indikasjoner på disse størrelsene, spesielt for volumstrømmer. C_d, en koeffisient som tar hensyn til friksjon og andre tap-faktorer ble også regnet ut, koeffisienten varierer mellom casene og én verdi bør derfor ikke brukes som standardverdi for alle tilfeller.

Avvikene fra teorien var tydeligere da varmekildene var plassert i andre etasje, hastighetsprofilen og temperaturfordelingen i åpningen var annerledes enn for de andre casene. Det nøytrale planet var plassert høyere i åpningen, altså var ingen av de sentrale antagelsene gyldige. Derfor er det konkludert at de teoretiske modellene ikke er anvendelige for situasjoner hvor varmekilden er plassert en etasje over døråpningen.

Selv om måleresultatene ikke samsvarer helt med teorien var det ingen problemer med den termiske komforten under måleperioden. For å oppnåtermisk komfort er det viktig at varmekildene er stilt inn slik at temperaturene er behagelige både i stuen og på soverommene.

Nomenclature

A	Area of the aperture [m^2]
a_0	Coefficient in the two-layer hydraulics model [-]
CAV	Constant air volume
C_a	Coefficient in the model of Hensen et al [Pa]
C_b	Coefficient in the model of Hensen et al [Pa]
C_c	Contraction coefficient [-]
C_d	Discharge coefficient [-]
C_t	Coefficient in the model of Hensen et al [Pa]
C_v	Velocity coefficient [-]
f	Function of the pressure difference [Pa]
g	Gravity [m/s^2]
g'	Reduced gravity [m/s^2]
g-value	Value for how much of the solar energy the windows transmit [-]
H	The height of the aperture [m]
H_C	The height of the cold layer, two-layer hydraulics model [m]
H_H	The height of the warm layer, two-layer hydraulics model [m]
H_{rel}	The ratio between the height of the door and the height of the room [-]
k	Coefficient in the two-layer hydraulics model [-]
K	K = Tρ [kgK/m^3]
$\dot{m}$	Mass flow [kg/s]
P	Pressure [Pa]
P_0	Pressure at z =0 [Pa]
q	Volume flow [m^3/s]

Re	Reynolds number [-]
R_{fa}	Specific fan power [Pa]
SFP	Stanton number [-]
St	Temperature [K]
T	Average temperature [K]
$\overline{T}$	Design temperature [K]
T_{av}	Velocity [m/s]
u	Average velocity [m/s]
$\overline{u}$	Maximum velocity [m/s]
u_{max}	Overall heat transfer coefficient [W/m^2K]
U-value	Width of the aperture [m]
W	Height [m]
z	Coefficient in the model of Hensen et al [$m2Pa^{1/2}$]
Z_a	Coefficient in the model of Hensen et al [$m^2Pa^{1/2}$]
Z_b	Height of the bottom of the aperture [m]
z_b	Contraction height of the aperture, sat equal to H [m]
z_c	The height of the neutral plane [m]
z_n	z0 = 0 [m]
z_0	The shift of the neutral plane [m]
Δz	Coefficient in the non-symmetric model of Santamouris [-]
α	Density [kg/m^3]
ρ	Average density [kg/m^3]
$\overline{\rho}$	Reduced density difference [kg/m^3]
$\Delta\rho_r$	

Table of contents

1. Introduction

The increase in energy usage with the resulting shortage of resources and the environmental consequences of fossil fuels have put the need for a reduction of energy consumption in focus during the last decades. The building sector contributes greatly to the energy usage with 26.4 % of final energy consumption in the EU-25 [1]. Therefore, great efforts have been made to reduce the energy consumption in the building sector and low energy buildings and passive houses have been introduced.

Passive houses have a low heating demand compared to conventional houses and too much heat addition can easily lead to overheating. The regular way of heating houses with one heat source, normally a radiator or an electric heater in each room, is too complex and expensive for the low heating demand. The heating system can therefore be simplified to reduce the costs. Georges, Skreiberg and Novakovic [2] have investigated if one central heat source can give sufficient thermal comfort in a whole housing unit, for instance in a detached one-family house. Their results are based on detailed dynamic simulation of the air flow through a dwelling and will be the basis for the analysis of the measuring results obtained in the laboratory and in the passive house.

In this thesis, relevant theory and mathematical models will be presented. The models will be compared and the assumptions they are based on will be assessed. Then, measurements in the laboratory will be prepared and conducted to check if the planned setup is well functioning. The laboratory measurements will then be followed by measurements in an actual passive house. Temperature and velocity of the flow through a doorway as well as air and surface temperatures in the rooms separated by the door will be measured for different cases. Three different heat sources located in four different positions will be used. The volume flow, heat content and the discharge coefficients for the flow in the aperture will be calculated for all cases.

After a presentation and comparison of the measurement results it will be discussed if the results correspond to the theory, if key assumptions are valid and if the obtained temperatures give sufficient thermal comfort. If there are found to be deviations from the theory an explanation will be sought and consequences will be discussed.

Lastly a conclusion will be made based on the discussion of the similarities and inequalities of the theory and the measurements results.

2. The passive house building standard and passive house requirements

According to the Passive House Institute (PHI) passive house is "*a building standard that is truly energy efficient, comfortable and affordable at the same time*" [3]. The goal for passive houses is to provide a comfortable indoor environment with good indoor air quality at the same time as the energy demand and costs are as low as possible.

PHI has identified five areas that demands extra attention for passive house constructions [4]: *Thermal insulation, passive house windows, ventilation heat recovery, air tightness and absence of thermal bridges*. These areas are important as the building envelope is an essential part of the passive house concept and should be highly insulated and airtight so that the heat demand can be provided by a simple and affordable heating system. Efficient heat recovery contributes to ensure good indoor air quality and reduces the energy usage. Requirements subject to these areas and other requirements can be seen in Table 1. In addition to this, effective ventilation must be ensured, and each room should have a minimum of one opening for outdoor air.

Table 1: Passive house requirements identified by PHI [4].

U-values of the envelope, maximum value	0.15 W/m^2K
U-values windows, maximum value	0.80 W/m^2K
g-values, approximately value	0.5 [-]
Maximum share of transparent facades, south oriented facades	25%
Maximum share of transparent facades, west and east oriented facades	15%
Ventilation heat recovery, minimum value	75%
Leakage rate at 50 Pa, maximum value	0.6 [h^{-1}]
Maximum annual heating demand	15 kWh/m^2a
Supply air temperature, minimum value	17 °C
Maximum primary energy for heating, tap water and electrical appliances	120 kWh/m^2a

In Norway, Standard Norge has published two national standards with requirements for passive houses, one for dwellings and one for commercial buildings. Some of the requirements for passive houses in NS 3700:2013 Criteria for passive houses and low energy buildings – residential buildings[1] which differs from PHI's requirements are [5]:

- Maximum values for heat losses and calculated net energy demand for heating depending on the heated floor area.
- Thermal comfort should be obtained without the use of mechanical cooling.
- The heating system should be able to run on non-electric or non-fossil energy goods.
- Thermal bridges: ≤ 0.03 W/m^2K
- Thermal efficiency for heat recovery: ≥ 80%
- SFP-value: ≤ 1.5 $kW/(m^3/s)$

[1] "NS 3700:2013 Kriterier for passivhus og lavenergibygninger – Boligbygninger" for dwellings and "NS3701:2012 Kriterier for passivhus og lavenergibygninger – Yrkesbygninger" for commercial and industrial buildings.

3. Investigation of thermal comfort using detailed dynamic simulations

The paper of Georges, Skreiberg and Novakovic [2], "On the proper integration of wood stoves in passive houses: Investigation using detailed dynamic simulations", looks into the possibility of heating a passive house with a single wood stove located in the living room. Stoves can be a good alternative for space heating, both from economic and environmental perspectives, but the impacts on the thermal comfort in the different rooms in passive houses are unknown. The stove might lead to overheating in the living room at the same time as it is uncertain if the temperature in other rooms will be sufficient to give good thermal comfort. To investigate this the airflows through the building have been simulated both with closed and open internal doors. Simulations were conducted both for design weather conditions and for a typical metrological year.

The article presents three questions that are to be investigated:

1. To investigate how a single heat source located in one thermal zone is able to mainly perform the space heating in a passive house.
2. To investigate how an oversized wood stove can operate with long production cycles in a passive house without generating overheating.
3. To investigate the resulting energy efficiency of a wood stove for the space heating distribution.

Questions one and two are the most relevant for this thesis due to the focus on thermal comfort.

3.1 Conditions, method and assumptions for the simulations

3.1.1 Conditions

The simulations are conducted for a two storey detached single-family house in Belgian climate. The house has balanced mechanical ventilation with heat recovery with a thermal efficiency of 85%. The ventilation system is a CAV cascade system; fresh air is supplied in the living room and in the bedrooms, and exhaust air is extracted in the bathroom and in the kitchen. Additional data for the building can be found in Table 2, and a sketch of the building is given in Figure 1.

Table 2: Additional data for the building used for the simulations.

Data	Value
Number of thermal zones/nodes	10
Net heated surface	152 m^2
Envelope volume	420 m^3
Opaque surfaces	360 m^2
Windows	35 m^2
Set point temperature	20 °C

These data are the same for all the simulations, but the construction mode differs from materials with very heavy inertia to very light inertia; altogether five construction modes are investigated. Even though the inertia differs the insulation level for the envelope stays the same, but the internal insulation differs with the thermal mass. This will affect the heat transfer between the rooms in the dwelling. A high thermal mass will give a high thermal transmittance of internal walls and vice versa [6, 7].

Different types of stoves are investigated; pellet stoves with and without 30% modulation and log stoves with and without 50% modulation. The stoves are first assumed to have no thermal mass, and then it is investigated how a thermal mass affects the results. Different cycle lengths are also investigated.

Figure 1: Sketch of the house used for the simulations. To the left, (a) shows the ground floor where zone 1 is kitchen and living room, zone 2 is an open staircase, zone 3 is laundry room and zone 4 is office. To the right, (b) shows the first floor where zones 5-8 are bedrooms and zone 9 and 10 are bathrooms. Reprinted with permission.

3.1.2 Method

The building is modelled as a multi-zone air flow model[2] and the building is simplified to a network of connected nodes. The airflow rates were found using TRNFLOW[3] where the doors were modelled as large internal openings. This simplification can be done in many ways, this will be looked further into in the following chapters as the flow through internal doors is essential for this investigation.

According to Chen [8], multi-zone models uses a lot of assumptions which make them not very accurate in the individual zones. Despite this, Chen argues that multi-zone models are very well functioning design tools, especially for air flow calculations in large buildings.

3.1.3 Assumptions

The simulations are based on mathematical models with a set of assumptions. The following assumptions are from the applied TRNFLOW model [9]:

[2] The program TRNSYS was used.
[3] The method of TRNFLOW is explained in [9].

- The building is modelled as a network of nodes which are connected by air flow links.
- Each thermal node has a homogeneous temperature, and each node also has a single value for humidity and pressure.
- It is assumed that the flow is strictly horizontal through large vertical openings.
- The pressure difference between two rooms is a function of only the height z which gives a vertical velocity profile.

Other assumptions from the article of Georges, Skreiberg and Novakovic:

- One dimensional heat transfer in the stove envelope is assumed.
- The stove is assumed to be very small compared to the living room, this makes it possible to evaluate the power emitted by radiation analytically.
- The stove is assumed to function as an internal heat gain injected into the building.
- The combustion process is assumed to be instantaneous for the pellet stoves.
- It is assumed that the damping effect of the stove mass is negligible.
- The power delivered by the stoves with zero thermal mass is assumed to be equal to the heat addition to the living room.
- The occupants in the living room are assumed to be at such a distance from the stove that the radiation asymmetry can be neglected, the same applies for direct radiation from the combustion process.
- The following assumptions are made for design weather conditions:
    - $T_{outdoor}$ = -10 ° C
    - No internal gains.
    - No solar gains.
    - Perfect heating in the living room.
- For a typical metrological year, the following assumptions were made:
    - The power of the stove is 8 kW.
    - Perfect heating in the living room.
- For the stoves with thermal mass, and therefore with inertia, it is assumed that heat is only emitted by the external surfaces of the stove.
- The heating is assumed to be constant.
- The doors are either opened or closed, no opening frequencies are considered.

The focus in this thesis will be on the assumption regarding uniform temperature and pressure in the rooms, which entails the assumptions of perfect mixing of the room air and no temperatures gradients, and on the assumptions regarding the shape of the flow. These assumptions will be further discussed in *Chapter 4.4 Assessment of assumptions*.

3.2 Results

3.2.1 Results design conditions

These weather conditions represent the worst case scenario, and it is not realistic to have such a low temperature over long time periods and at the same time having no solar or internal heat gains. The simulations start before simulation time zero and the internal doors are opened at t = 0. The resulting temperatures in the coldest bedroom are shown in Figure 2, the different lines represent different construction modes and different discharge coefficients. The discharge coefficient is explained in *Chapter 4.5 Discharge coefficient*.

The graph shows that opening the internal doors have a strong effect on the temperature in the bedroom and that this depends on the construction modes due to the changes in internal insulation. Still, the obtained temperatures in the bedroom are not sufficient for good thermal comfort and an additional heat system for peak load heating should be installed.

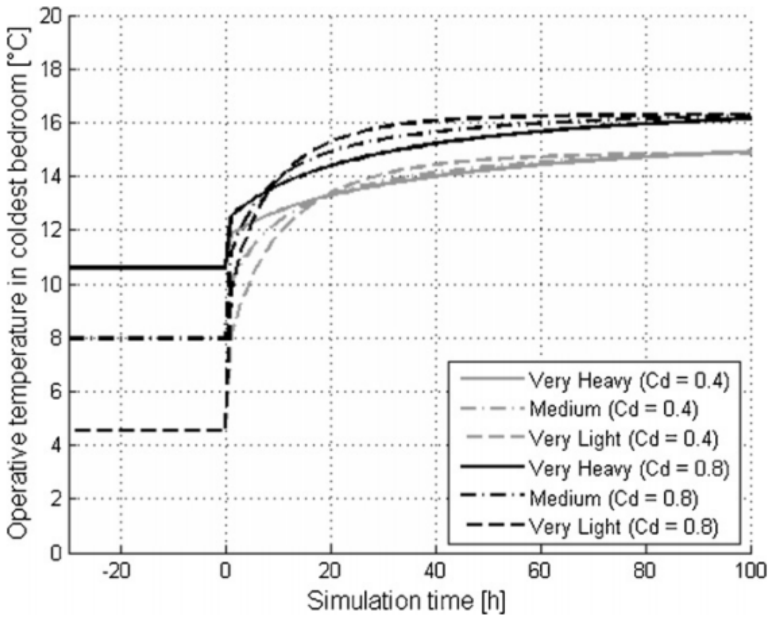

Figure 2: Results for the simulation with design weather conditions. The door is opened at t=0, and the temperature in the coldest bedroom changes as indicated. The results are shown for three construction modes and two values for C_d. Reprinted with permission.

3.2.2 Results typical metrological year (TMY)

Internal and solar heat gains are included for the simulations; these simulations will therefore give a more realistic reflection of a real situation.

3.2.2.1 Pellet stove without inertia

The minimum temperatures in the coldest room with and without modulation as a function of cycle length are showed in Figure 3. The graphs show that opening the internal doors has a huge impact on the thermal comfort and that it is possible to obtain sufficient thermal comfort in the coldest room when the internal doors are open.

At the same time, there is a problem with overheating in the living room; a low thermal mass gives a high level of overheating. The stove without modulation will give unacceptable overheating for all cases except one, but the stove with a 30% power modulation gives satisfying results for almost all cases. Three actions to reduce overheating are identified: a heavy thermal mass, the opening of internal doors and heat emission dominated by radiation.

3.2.2.2 Log stove without inertia

Batch processes are considered for the log stoves; one stove with 50% modulation and one stove without modulation. The results show much of the same as for pellet stoves, but there are some differences:

- There is more overheating; for the stove without modulation it is not possible to maintain maximum temperatures below 24.5 °C in the living room.
- The modulation is less efficient than for pellet stoves.
- Power modulation is not enough to avoid overheating, and it must be combined with at least two of the three actions mentioned above.

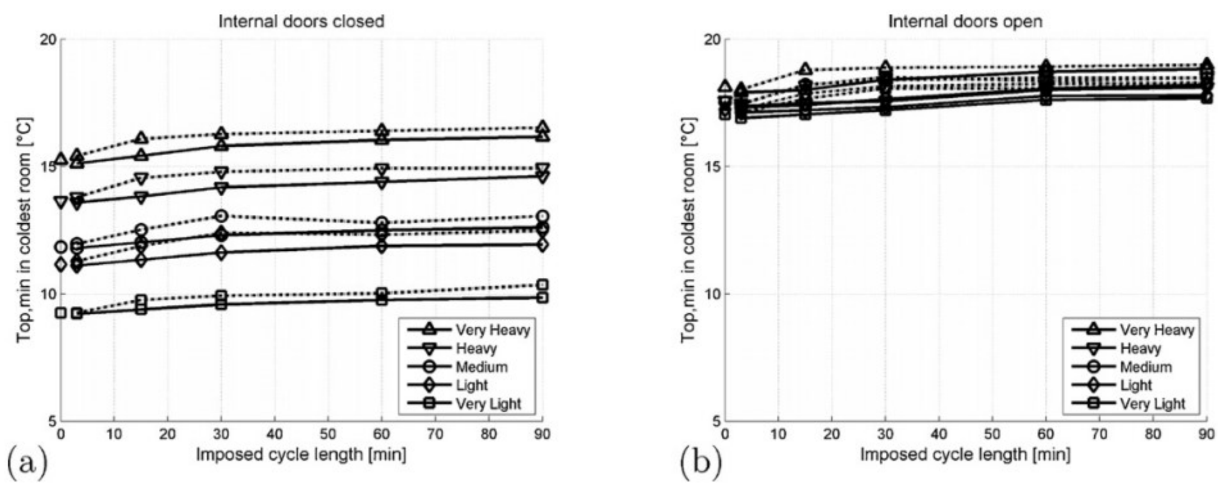

Figure 3: Results for the 8kW pellet stove without inertia for a typical metrological year. (a) shows the results for closed internal doors and (b) for open internal doors. The solid line is the results for the stove with modulation and the dashed line is the result for the stove without modulation. Reprinted with permission.

3.2.2.3 Stoves with inertia

The inertia of the stove can reduce the overheating in the living room as the thermal mass will store some of the released heat. Two thermal masses were investigated: 50 kJ/K and 150 kJ/K. The lightest thermal mass did not affect the results significantly. For pellet stoves with the large thermal mass the maximum temperature in the living room was reduced by a few degrees, but it is not sufficient for the stove without modulation. The inertia was almost negligible for the log stoves.

3.2.2.4 Energy efficiency

The efficiency depends on temperature zoning in the building and on the overheating in the living room. Increased temperature zoning increases the energy efficiency, thus, the yearly energy demand for space heating increases when the internal doors are open. This increased efficiency is obtained at the expense of the thermal comfort.

3.3 Conclusions

The simulations led to the following conclusions for the three questions from the article:

- Conclusion question one:
    - It is not possible to obtain sufficient space heating in a passive house with a single heat source placed in one of the thermal zones under steady state design weather conditions.
    - It is possible to obtain sufficient space heating in a passive house with a single heat source placed in one of the thermal zones during a TMY if the internal doors are open.
    - In practice the internal doors cannot be open at all times, it can therefore be interesting to investigate the influence of the opening frequency.
- Answer question two:
    - Results depend on the stove properties, the building thermal mass, architectonic properties and opening of internal doors.
    - Power modulation is necessary to avoid overheating.
    - Thermal inertia can reduce overheating.
    - Hydro-stoves can be an alternative.
- Answer question three:
    - Energy efficiency depends strongly on temperature zoning, and a strong temperature zoning can give a reduced energy demand, but it will also give a lower thermal comfort.
    - Overheating increases the energy demand.
- Heat transport in the house is dominated by natural convection for all the simulations with open internal doors.

Feist et al. [10] reach similar conclusions regarding thermal comfort in passive houses: *"The Passive House Concept allows for good thermal comfort and indoor air quality, and at the same time allows for a substantial reduction of the primary energy demand compared with requirements of current regulations in the EU"*.

The opening of the internal doors is a key factor for the thermal comfort, both for the coldest bedroom and for the living room. Thus, the air flows through these doors have great influence on the thermal comfort. This is the motivation for looking further into this.

3.4 Investigations for cold climate

Following the above presented research Georges, Skreiberg and Novakovic have made further investigations for passive houses in cold climates [7]. In this article the climates of Oslo, Bergen and Karasjok were used to represent cool, cold and subarctic climates, respectively. The simulations are done for a typical Norwegian detached single-family house.

Again, overheating in the living room is one of the important objects of the article. This was investigated for different power, modulations and TMY and SDC for each climate. The results for pellet stoves are shown in Figure 4; pellet stoves with a maximum power of 8 kW, either with 30% modulation or in combination with architectural measures will prevent overheating in all three climates. Architectural measures are needed for most cases with log stoves. If one want to avoid this dependence on architectural conditions ovens with power lower than 4 kW needs to be developed, better power modulations should be obtained or the cycle lengths need to be reduced. This makes the integration of log ovens more critical than of pellet ovens.

Qualitative performance against overheating of pellet stoves equipped with 50 kJ/K thermal inertia and using τ_{min} between 60 and 90 min: function of the stove nominal power, $P_{d,n}$, and power modulation [%] computed for different locations and weather conditions.

Location	Oslo			Bergen			Karasjok		
Weather	TMY	CTMY	SDC	TMY	CTMY	SDC	TMY	CTMY	SDC
6 kW, 30%	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
6 kW, 100%	⊙⊙	⊙⊙	⊙	⊙⊙	⊙⊙	⊙	⊙⊙	⊙⊙	⊙
8 kW, 30%	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
8 kW, 100%	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙
12 kW, 30%	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙
12 kW, 100%	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖

⊕: good control independent of the architectural measures.
⊙: control if one set of architectural measures is taken.
⊙⊙: control if complete set of architectural measures taken.
⊖: overheating whatever the architectural measures taken.

Figure 4: Results for investigating overheating for pellet stoves. TMY is Typical Metrological Year, CTMY is the cold hours of the TMY and SDC is Standard Design Conditions. Reprinted with permission.

The oven's potential for providing thermal comfort in the whole house is also investigated. The thermal comfort in the coldest room is found to be decreasing with colder climates. For the cool climate in Bergen one centrally placed heat source can cover a large part of the heating needs as long as the internal doors are open. One oven cannot provide sufficient thermal comfort in the whole housing unit for the climates in Oslo and Karasjok.

4. Mathematical models

Different mathematical models for flow through large internal openings will be presented in this chapter. The openings are mostly referred to as doors, but the models apply to all large vertical internal openings. The models refer to the neutral level, which is the height in the aperture where the pressure difference between the two rooms is zero, and therefore the velocity is also zero. The dense, cold air will flow below the neutral level and the warmer and lighter air will flow above the neutral level.

The different models operate with different symbols and names for the same parameters. To make it easier to compare the models the same symbols and names are used for all the models. Zone 1 is taken as the warm zone and zone 2 is taken as the cold and dense zone for all models. Thus, the subscript 12 indicates flow from the warm to the cold zone, and 21 indicates the opposite.

All models, except for the two-layer hydraulics model and the non-symmetrical models, assume a flow pattern as depicted in Figure 5.

The models will be presented and compared, assumptions will be assessed and an example will be given. First, there will be a brief review of analytical models.

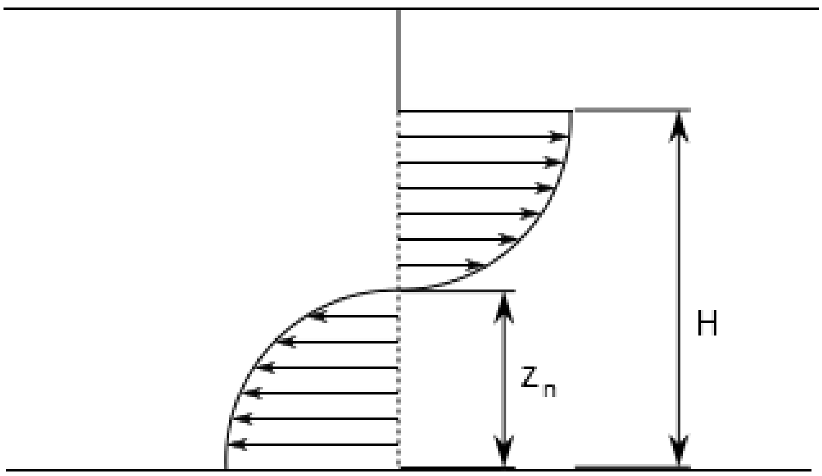

Figure 5: The flow pattern for the majority of the models where H indicates the height of the aperture and z_n indicates the height of the neutral plane.

4.1 Analytical models

A review of different methods used for calculating ventilation efficiency is given by Chen [8]. Although this is not the topic for this project many of the same things apply to the analytic models.

Analytical models are derived from fundamental balances and equations. The analytical models are often results of simplifications and approximations and should only be applied to basic and simple problems. These simplifications can also result in models that are only directly applicable for the specific case they are developed for. Some of the approximations may be valid for similar cases, and models may be used for different cases with some modifications [8].

Even though analytical models have these disadvantages they can still be useful in many situations. Analytical models can give good qualitative, and sometimes also quantitative, indications and predictions, and may be used to check if more advanced models can be applied. Another advantage is that the simplicity of the models lead to less resource demanding calculations [8].

According to this the differences in the following models may be based on different simplifications and approximations used for the case of flow through large vertical openings. This can lead to some of the models may being better for certain conditions and opening geometries. The models may only be applicable for simplified situations, such as in the following calculation example. The obtained values are not necessary exact values for the real situations, but should be a good indication.

4.2 Equations for velocity

Four different models describing the velocity are found, where three of the expressions are almost identical. The assumptions are mostly the same and are explained in the following. The assumptions from the different literature are described more in detail in *Chapter 4.3 Equations for mass and volume flows*. The equations for the four models are shown in Table 3.

The starting point for the expression in the article of Hensen et al. [11] is Bernoulli's equation for the maximum velocity in large vertical openings connecting two zones where friction losses are ignored. It is also assumed that ΔT only depends on the height.

Almost identical expressions as the one from Hensen et al. are obtained in Heiselberg's lecture notes [12] and in the book of Etheridge and Sandberg [13], but the expressions are not simplified as in the last part in equation 1. The velocities are given for the flow in both directions. Besides giving an expression for the maximum theoretical velocity Heiselberg also gives expressions were the effects of friction and contraction is included: C_v is the velocity coefficient which incorporates the friction loss and z_c is the height of the velocity profile due to contraction. These considerations are not included by Etheridge and Sandberg, and the equations are presented in a different way.

These three models give equations which describe the velocity in an internal door in the same way, although it is expressed slightly different in the different literature. The only difference that has any physical meaning is that contraction and friction loss is only included in one of the models. This effect must be included in the other equations too to adapt to a real, non-theoretical situation.

the International Energy Agency gives a different expression for the velocity in Annex 20 [14]; instead of expressing the velocity as a function of Δz, it is expressed using ΔP. As for two of the models above the effects of contraction and friction should be included in the equation. An expression for the pressure difference must be inserted to solve this equation. Using the expression given in *Chapter 4.6.1 Calculating velocities* the equation is transformed to the same type of equation as equations 5 and 6.

Table 3: Equations for velocity.

Equations for velocity		
Reference for the model	**Equation [m/s]**	
Hensen et al.[11]	$u(z) = \sqrt{\frac{2\Delta P}{\rho}} = \sqrt{\frac{2\Delta\rho}{\rho} g(z-z_n)} = \sqrt{\frac{2g}{T}\Delta T(z-z_n)}$	(1)
Heiselberg [12]	$u_{12}(z) = C_v\sqrt{\frac{2g}{\rho_1}(\rho_2-\rho_1)(z-z_n)} \quad (z \geq z_n)$	(2)
	$u_{21}(z) = C_v\sqrt{\frac{2g}{\rho_2}(\rho_2-\rho_1)(z_n-z)} \quad (z \leq z_n)$	(3)
	$u_{max} = \sqrt{\frac{2g}{\rho_1}(\rho_2-\rho_1)(z_c-z_n)} = \sqrt{\frac{2g\Delta T}{\bar{T}}(z_c-z_n)}$	(4)
Etheridge and Sandberg [13]	$u_{21}(z) = \sqrt{2g_1'(z-z_n)} \; (z \geq z_n)$	(5)
	$u_{12}(z) = \sqrt{2g_2'(z_n-z)} \; (z \leq z_n)$	(6)
	$g_i' = g\frac{\Delta\rho}{\rho_i} \; [\frac{m}{s^2}]$	(7)
International Energy Agency [14]	$u(z) = \sqrt{\frac{2}{\rho}\left(\left(P_{1,0}-P_{2,0}\right) - gz(\rho_1-\rho_2)\right)}$	(8)

4.3 Equations for mass and volume flows

4.3.1 Orifice-based models

Many of the models are based on the orifice model as explained in e.g. [13] and [14]. This model treats flow through small openings as a jet encircled by room air, so that the pressure distribution in the flow is determined by the pressure distribution in the room the flow enters. The model is then extended to be valid also for large openings. These common assumptions apply:

- There is no interaction between the two flows in and close to the door, this means no mixing or heat transfer between the two flows.
- The Bernoulli equation is valid, thus, the flow is assumed to be non-viscous, incompressible and stationary.
- The pressures in the two zones are the same at the neutral level.
- The models assume zero supply of ventilation air.
- The neutral plane is in the middle of the door.
- The streamlines are parallel and horizontal in the opening.
- The buoyancy forces dominate the viscous forces, and Gr is assumed so large that the flow does not depend on it.
- When the flow enters the new zone, the pressure is equal to the hydrostatic pressure in this zone.
- The two rooms are assumed to be semi-infinite reservoirs with constant temperature differences.
- Air flow is driven by density fields in the two rooms and there is no boundary layer flow.

The equations for the orifice-based models can be found in Table 4. The model in Heiselberg's lecture notes [12] are originally for external openings, but the same model can be used for internal openings. Equations 9 and 10 gives the volume flow per unit width, so it is important to note that these equations should be multiplied with the width of the door if one wants to know the mass flows in the whole aperture. The three models of Heiselberg, Etheridge and Sandberg [13] and IEA [14] give the same equation written in different ways. Realizing that A = H*W and that $H\text{-}z_b$ equals H since z_b is zero, including C_d in all the equations, substituting for g' and replacing T_1 in the denominator in equation 12 gives three identical equations. To go from mass flow to volume flow, the equation must be divided by the density.

4.3.2 The two-layer hydraulics model

The two-layer hydraulics model is presented in the book of Etheridge and Sandberg [13]. This model differs from the orifice-based models as the streamlines are not assumed to be horizontal. The flow is divided into two layers of air; a dense layer with height H_C and a less dense layer with height H_H, as shown in Figure 6. This approach of dividing the room air into two layers are sometimes used in conjunction with ventilation and fire safety, see for instance [15].

Etheridge and Sandberg give the following assumptions for this model:

- Every cross-section is assumed to have uniform density and velocity, which gives a discontinuity at the interface.

- The flow is assumed to have a Froude number equal to unity which makes the flow critical.

Bernoulli is applied in both layers in a way that allows for hydraulic jumps. This means that the flow through the door does not affect flows through other openings in different rooms. The following expression for the flow rate is given in Table 5.

Table 4: Orifice based models.

Equations for orifice based models		
Reference for the model	**Equation**	**Unit**
Heiselberg [12]	$$q_{12} = \int_{z_n}^{H} u_{12}(z)dz = \sqrt{\frac{2g}{\rho_1}(\rho_2 - \rho_1)}\frac{2}{3}(H - z_n)^{3/2} \quad (9)$$	[m³/s] per unit width
	$$q_{21} = \int_{H_b}^{H_n} u_u(z)dz = \sqrt{\frac{2g}{\rho_2}(\rho_2 - \rho_1)}\frac{2}{3}(z_n - z_b)^{3/2} \quad (10)$$	[m³/s] per unit width
	$$q_{tot} = \frac{1}{3}A\sqrt{\frac{g(T_1 - T_2)(H - z_b)}{T_1}} \quad (11)$$	[m³/s]
Etheridge and Sandberg, orifice based model [13]	$$q = \frac{1}{3}A\sqrt{g'H} \quad (12)$$	[m³/s]
	$$g' = g\frac{\Delta\rho_r}{\bar{\rho}} \quad (13)$$	$[\frac{m}{s^2}]$
	$$\Delta\rho_r = \frac{\Delta T}{\bar{T}}\bar{\rho} \quad (14)$$	$[\frac{kg}{m^3}]$
International Energy Agency [14]	$$\dot{m} \approx \frac{1}{3}C_d\bar{\rho}WH^{\frac{3}{2}}\Delta T^{\frac{1}{2}}\sqrt{\frac{g}{\bar{T}}} \approx 0.04WH^{\frac{3}{2}}\Delta T^{\frac{1}{2}} \quad (15)$$	[kg/s]

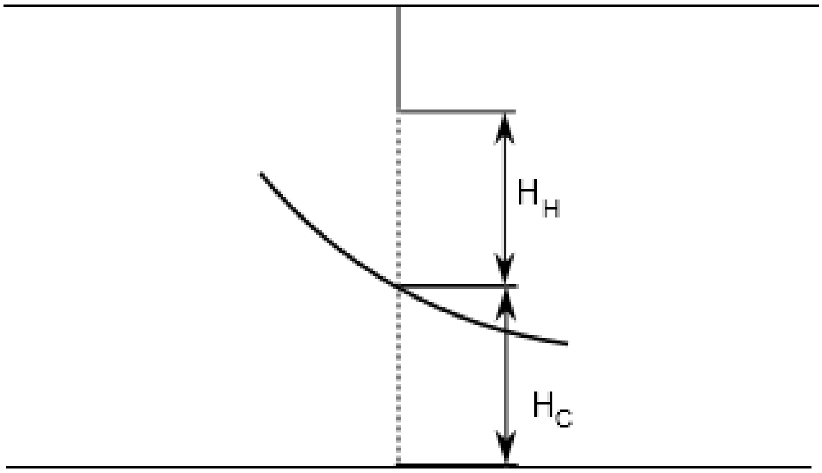

Figure 6: The flow pattern for the two-layer hydraulics model, H_C indicates the height of the dense layer and H_H indicates the height of the uniform warm layer.

If the neutral plane is assumed to be in the middle of the doors, a_0 in equation 18 is zero and k in equation 17 will have a value of 0.25.

This model is hard to compare with the other models as it is fundamentally different. One thing it has in common with the other models is the use of Bernoulli's equation, so some of the assumptions related to this equation are common for the models. Etheridge and Sandberg compare the two-layer hydraulics model with the orifice based model [13]:

- This model, unlike the orifice based model, accounts for the effect the opening geometry has on the streamline pattern.
- This model is more realistic due to the allowance of flow separation, but the assumption of uniform densities and velocities is less realistic than the profile of the orifice based model.
- The two-layer hydraulics model is harder to apply.

Table 5: Equations for the two-layer hydraulics model

Two-layer hydraulics model		
Reference for the model	**Equation**	**Unit**
Etheridge and Sandberg [13]	$q = k\sqrt{g'H}$ (16)	[m³/s]
	$k = \sqrt{\frac{\left(\frac{1}{2}+a_0\right)^3 \left(\frac{1}{2}-a_0\right)^3}{\left(\left(\frac{1}{2}+a_0\right)^3 + \left(\frac{1}{2}-a_0\right)^3\right)}}$ (17)	[-]
	$a_0 = \frac{H_C - \frac{H}{2}}{H}$ (18)	[-]

4.3.3 Other models

Some of the models do not state if they are based on the orifice model or other theory. This compared with varying assumptions makes is different to state the background for these models. But there are indications that at least some of them are based on the orifice model. The equations for these models are given in Table 6.

In the TRNFLOW manual [9] no explicit equation for the mass flow is given, but integrals that must be solved in order to find the mass flow are given. The assumptions for this model are mentioned in *Chapter 3.1.3 Assumptions*. The mass flows are found by conducting numerical integration of equations 19 and 21. For both mass flows, w(z) is equal to the width of the door. The manual do not say anything about how to solve the integrals.

The article of Hensen, van der Maas and Roos [11] present the same integral as TRNFLOW, but a way of solving the integrals is also presented. The following assumptions are given:

- ΔT, which is the temperature difference between the two rooms separated by the door, is assumed to be independent of z; this means that the temperature gradients are small and equal.
- The temperature profiles are assumed to be linear in both zones: $T_i(z) = a_i + b_i z$.
- It is assumed that the conditions give bidirectional flow.
- First, the net volume flow between the rooms is assumed to be zero which means that the neutral level will be in the middle of the door: $z_n = H/2$.
- Then, it is assumed that the two rooms have different vertical temperature profiles which give different temperature gradients, these temperature gradients are also assumed to be small.
- Density variations resulting from pressure differences are assumed to be negligible.

This model does not necessary assume that the flow pattern is always as in figure 4, but argues that the flow can also be unidirectional. It is showed that the pressure difference varies linearly with z when the zones have different temperatures and that the temperature gradients only affect ΔP as a second order term. The error for ignoring this second order contribution is small (~1% for a ΔT of 6K) so that the term can be ignored. A linear expression for ΔP is obtained, but this derivation will not be rendered here. Inserting this into the integrals gives the expressions given inTable 6.

There are two cases where the neutral plane is in the opening and bidirectional flow occurs; if $\Delta P(z_b)>0$ and $\Delta P(z_b + H)<0$, or if $\Delta P(z_b)<0$ and $\Delta P(z_b + H)>0$. In words; the pressure differences at the bottom and top of the aperture must have opposite signs. If this is not the case, there will only be flow in one direction. Equations 23 to 29 assume that the neutral plane is in the opening. Since the pressure difference at the top of the opening is negative, C_a is negative and $\dot{m}_{12}$ is imaginary. The mass flow can be kept real by taking the absolute value of C_a. The net mass flow can be written as a complex number where the imaginary part is the flow from the warm zone and the real part is the flow from the cold zone, see equation 29.

Santamouris et al. [16] gives the following assumptions in their article:

- Inviscid and incompressible flow.
- The pressure variations depend on the height.
- The neutral level is in the middle of the door and the same mass flow therefore occurs in both directions.
- There is no stratification in the two zones.

The mass flow rate is given by equation 30.

4.3.4 Non-symmetrical models

Non-symmetrical models are presented by Hensen et al. [11], Etheridge and Sandberg [13] and Santamouris et al. [16], where the equations from Hensen et al. are applicable also for symmetrical cases. The equations for these models are shown in Table 7.

The same assumptions as above apply for the equations from Hensen et al. The only difference is that this model is also valid when the neutral plane is outside the opening.

For the non-symmetrical model in Etheridge and Sandberg's book [13], it is assumed that ventilation air is provided in the warm zone and discharged in the cold zone, so that there is a net flow through the doorway. This shifts the neutral plane, so that it is no longer located in the middle of the aperture. g'_C, g'_H and g' are assumed to be equal. Equation 36 can be solved for z_n. If the supplied air flow is large enough, the neutral plane will be placed outside the opening, and the flow through the door will be unidirectional. If the density of the supplied air and the room air in the warm zone are assumed to be equal, an estimate of the required supplied air flow to obtain unidirectional flow is given by equation 38.

Using the equations given by Santamouris et al., the displacement of the neutral plane can be found.

Table 6: Equations for other models

Equations for other models		
Reference for the model	**Equation**	**Unit**
TRNFLOW [9]	$$\dot{m}_{12} = C_d \int_0^H \sqrt{2\rho(z) f_{12}(z)} * w(z) * dz \quad (19)$$	[kg/h]
	$$f_{12}(z) = \begin{cases} \Delta p(z) & , if\ \Delta p(z) > 0 \\ 0 & , if\ \Delta p(z) < 0 \end{cases} \quad (20)$$	[Pa]
	$$\dot{m}_{21} = C_d \int_o^H \sqrt{2\rho(z) f_{21}(z)} * w(z) * dz \quad (21)$$	[kg/h]
	$$f_{21}(z) = \begin{cases} -\Delta p(z) & , if\ \Delta p(z) < 0 \\ 0 & , if\ \Delta p(z) > 0 \end{cases} \quad (22)$$	[Pa]
Hensen et al. [11]	$$\dot{m}_{12} = \frac{2}{3} C_d W \sqrt{2\rho_1} \frac{H}{C_t} C_a^{3/2} \quad (23)$$	[kg/s]
	$$\dot{m}_{21} = \frac{2}{3} C_d W \sqrt{2\rho_2} \frac{H}{C_t} (-C_b^{3/2}) \quad (24)$$	[kg/s]
	$$C_t \equiv HgK \left(\frac{1}{T_1(z_0)} - \frac{1}{T_2(z_0)} \right) = C_a - C_b \quad (25)$$	$[Pa]$
	$$C_a \equiv \Delta P(z_b + H) \quad (26)$$	[Pa]
	$$C_b \equiv \Delta P(z_b) \quad (27)$$	[Pa]
	$$K = \rho_i T_i \quad (28)$$	$[\frac{kgK}{m^3}]$
	$$\dot{m}_{net} = \dot{m}_{12} + \dot{m}_{21} = \frac{2\sqrt{2}}{3} C_d W \frac{H}{C_t} * \left(\sqrt{\rho_1} C_a^{\frac{3}{2}} - \sqrt{\rho_2} C_b^{\frac{3}{2}} \right) \quad (29)$$	[kg/s]
Santamouris et al. [16]	$$\dot{m} = W \int_0^{Z_n} \rho(z) u_{1,2}(z) dz = \frac{2}{3} C_d \bar{\rho} W Z_n^{3/2} \sqrt{g \frac{\Delta T}{\bar{T}}} \quad (30)$$	[kg/s]

Table 7: Equations for non-symmetrical models.

Equations for non-symmetric models		
Reference for the model	**Equation**	**Unit**
Hensen et al. [11]	$\dot{m}_{net} = \dot{m}_{21} + \dot{m}_{12}$ (31)	[kg/s]
	$\dot{m}_{21} = -\sqrt{\rho_2}\mathrm{Im}(Z_a - Z_b) \leq 0$ (32)	[kg/s]
	$\dot{m}_{12} = -\sqrt{\rho_1}\mathrm{Re}(Z_a - Z_b) \geq 0$ (33)	[kg/s]
	$Z_a \equiv \frac{2\sqrt{2}}{3}\frac{HC_dW}{C_t}C_a^{\frac{3}{2}}$ (34)	$[m^2Pa^{1/2}]$
	$Z_b \equiv \frac{2\sqrt{2}}{3}\frac{HC_dW}{C_t}C_b^{\frac{3}{2}}$ (35)	$[m^2Pa^{1/2}]$
Etheridge and Sandberg [13]	$q_n 2^{\frac{3}{2}}(\rho_1\left(1-\left(\frac{z_n}{H}\right)\right)^{\frac{3}{2}} - \rho_2\left(\frac{z_n}{H}\right))^{\frac{3}{2}} = \rho_s q_s$ (36)	
	$q_n = A\frac{1}{3}\sqrt{g'h}$ (37)	$[\frac{m^3}{s}]$
	$q_s = 2^{3/2}q_n \approx 0.94\sqrt{g'h}$ (38)	$[\frac{m^3}{s}]$
Santamouris et al. [16]	$\dot{m} = \frac{2}{3}C_{1,d}\bar{\rho}_1W[z_n - \Delta z]^{1.5}\sqrt{2g\frac{\Delta T}{\bar{T}}} = \frac{2}{3}C_{2,d}\bar{\rho}_2W[z_n + \Delta z]^{1.5}\sqrt{2g\frac{\Delta T}{\bar{T}}}$ (39)	[kg/s]
	$\Delta z = z_n\left(\frac{1-\alpha}{1+\alpha}\right)$ (40)	[m]
	$\alpha = \left(\frac{C_{2,d}\bar{\rho}_2}{C_{1,d}\bar{\rho}_1}\right)^{2/3} = \left(\frac{C_{2,d}\bar{T}_1}{C_{1,d}\bar{T}_2}\right)^{2/3}$ (41)	[-]

4.3.5 Comparison of the models

The models have been commented and compared continuously in the above. This is summarized in this subsection:

- Most of the models have the assumptions of no or similar temperature gradients in the two rooms. It seems like this assumption is also applied when this is not stated explicitly. This assumption is further investigated in *Chapter 4.4 Assessment of assumptions*.
- The majority of the models refer to Bernoulli or mention the same assumption as this equation assumes.
- The models which are symmetrical are based on the assumption that the flow is as in Figure 5.
- Three out of the four models giving equations for the velocity use the same starting point and give approximately the same equations.
- The three orifice based models give the same equation for the mass flows, although the equations are written slightly different.
- The two-layer hydraulics model is hard to compare with the other models because it is very different, but it is still based on Bernoulli's equation. This model accounts for other factors than the orifice based model and is more difficult to apply.
- Some of the models that do not state what they are based on have many similarities with the orifice based models and are probably also based on this model. Two of the models put up the same integral, but only one shows how to solve the integral which can lead to different results.

How the differences between the models come to show in practice is showed in calculations made in *Chapter 4.6 Analytical calculations*.

4.4 Assessment of assumptions

Using assumptions that are not acceptable for the situation they are applied to can give significant errors [17]. Generally, it is difficult to determine when assumptions are valid and not, but there are some known limits.

4.4.1 Assumptions regarding temperature gradients

The rooms separated by the door are considered as semi-infinite reservoirs with either uniform temperatures or with small and equal temperature gradients. The former assumption is, according to Etheridge and Sandberg [13], valid when the temperature difference between the top and the bottom of the opening is small compared to the temperature difference between the rooms. According to Hensen et al. [11], the latter is highly accurate when the same temperature difference is small compared to the absolute temperature. Chen states that the assumption of uniform temperature can be acceptable for small rooms such as offices and bedrooms [8]. It is also stated in Annex 20 [14] that assuming a larger horizontal than vertical temperature difference doesn't allow for normal behaviour associated with large vertical openings.

Temperature gradients affect the heat transfer between the rooms [11, 14], but the main consequence is a change in the position of the neutral plane. This shifts the velocity profile from a symmetric parabolic shape to a non-symmetric and non-parabolic profile [13, 14]. Thus, the position and the number of neutral planes are closely linked to the temperature gradients. This will be further explained in the following.

Research shows different temperature gradients for different heating systems. Krajcik, Simone and Olesen [18] found that the vertical temperature difference for a room with floor heating is zero. For warm air heating, the temperature difference was found to increase with increased heat demand, and the maximum value was found to be 0.8 K.

The research from the Desys test cell at CSTB presented in Annex 20 [14] concludes that for the assumption of isothermal air temperature in both rooms, the mass flows and the position of the neutral plane can be calculated with accuracy. For the assumption of linear air temperature profiles in the rooms, the velocities in the door can be calculated with accuracy. The same report also state that if a non-linear temperature profile is approximated as a linear temperature profile, the corresponding heat flows can have significant errors.

The assumption of uniform temperature is a well-mixing assumption, and the effect of local variables in the flow is neglected. The accuracy of this kind of assumptions has been investigated by Wang and Chen [17]. First, an example with a staircase was investigated, and then a case with a four-zone chamber. The difference between simulated and measured results was up to 38% for the first case, thus, the mixing assumption is not valid. The differences were under 10% for the second case, and the assumption is valid. The different results from the two examples show that there is a need to quantify when the well- mixing assumption is valid or not. To do so the temperature gradient is defined as:

$$\frac{\Delta T}{T_{av}} = \frac{|T_t - T_b|}{T_{av}} \tag{42}$$

where T_{av} is the design room temperature. The temperature gradient can also be written as a dimensionless quantity:

$$\tau = Re^{1/3} St^{2/3} \sim \frac{\Delta T}{T_{av}} \tag{43}$$

where

$$Re = \frac{m_{in}}{L\nu} \tag{44}$$

$$St = \frac{Q_{in}}{\rho C_p T_{av} A (gh)^{1/2}} \tag{45}$$

Using this dimensionless quantity, demands of accuracy can be translated into demands of maximum values of τ. For instance, a maximum error of 20% corresponds to a maximum τ-value of 0.03.

4.4.2 The assumption of symmetric, bidirectional flow

The majority of the presented models assume that the flow is symmetric with one neutral plane positioned in the middle of the door. First, the flow need not be bidirectional; dwellings and houses in general have ventilation systems where fresh air is extracted in the building. As mentioned, this can result in an asymmetric flow through the door or even in unidirectional flow. An experiment presented by Hensen et al. [11] shows that bidirectional flow only occur in a small range of ΔP. A small temperature difference will give unidirectional flow similar to the jet flow through an orifice, and a larger temperature difference smoothens out the transition between the two flow directions so that bidirectional flow occurs.

An intersection between the temperature profiles in the two rooms gives rise to an additional neutral plane; the total number of neutral planes is equal to the number of intersections plus one [13, 14]. Thus, the assumptions treated in the above section limits the number of neutral planes.

The position of the neutral plane was investigated in Liège University's experimental programme, for these experiments the neutral plane was in the middle of the opening only two out of five times [14].

4.4.3 The assumption of no mixing between the flows in the aperture

A common assumption is that there is no mixing between the two flows in or near the door, but if such a mixing occur it will lead to a modified velocity profile close to the intersection between the two flows [14].

4.5 Discharge coefficient

The discharge coefficient C_d has been mentioned a lot in the above and will be further explained in this section. It has been mentioned that one need to include this coefficient for real non-theoretical situations. This is due to the fact that the flow is contracted when it flows through an opening and there is also friction that will give losses, C_d includes these factors [12]. Additional factors affecting the flow can also be included in the discharge coefficient, e.g. other flows in the room [9].

C_d can be defined as the ratio between the real and the theoretical flow rate [12]:

$$C_d = \frac{q_{real}}{q_{theo}} = \frac{C_c A C_v u_{theo}}{A u_{theo}} = C_v C_c \tag{46}$$

where C_v is the velocity coefficient which accounts for the friction loss and C_c is the contraction coefficient.

The value of the coefficient depends on the shape and characteristics of the flow, the opening it flows through and the conditions in the surrounding areas[9, 12, 14]. It is difficult to find an exact value, even for almost equal cases since so many factors affect C_d. Many experiments have been conducted to evaluate the discharge coefficient, but the values vary between the experiments [14]. Therefore, it is normal to operate with a range for C_d. However, there are also different ranges that are used for the same kind of openings. In Georges, Skreiberg and Novakovic [2] a range of 0.4 to 0.8 is used for internal doors, and in Annex 20 [14] 0.25 to 0.75 is presented as a common range for large openings. In the TRNFLOW manual [9] the following correlations for the discharge coefficient are presented for internal doors:

$$C_d = 0.609H_{rel} - 0.066 \quad if\ 0.2 \leq H_{rel} \leq 0.9$$

$$C_d = 0.0558 \quad if\ H_{rel} < 0.2$$

$$C_d = 0.4821 \quad if\ 0.9 < H_{rel}$$

where H_{rel} is the ratio between the height of the door and the height of the room.

In Etheridge and Sandberg [13], different values for the discharge coefficient is used for different geometries, and a contraction coefficient of 0.65 is used for all cases.

4.6 Analytical calculations

The mathematical models presented above were used to analytically calculate the velocities and volume flows. For simplicity only the models for symmetric flow were used and some further simplifications were made; these will be explained in the following. The calculations were done using MATLAB and the script is given in *Attachment 1: MATLAB Script for analytical calculations*. The used parameter values are given in Table 8, the temperatures chosen are normal temperatures that can be found in dwellings and the corresponding densities are from the Engineering Toolbox [19] which uses the ideal gas relation at standard atmospheric pressure. In addition to this, the size of the door is equal to the used doors in the two cases.

For these simplified calculations it is assumed that the flow is as in Figure 5; bidirectional flow with the neutral plane in the middle of the door. As for all models, the rooms are assumed to be large reservoirs with uniform temperatures and densities and the pressure is assumed to vary only with the height. C_d is added to all the equations except for the two-layer hydraulics model so that the calculations reflect a real situation and are easier to compare.

Table 8: Parameters used for the analytical calculations.

Parameter	Value
Temperature heated room [K]	298.15
Temperature unheated room [K]	293.15
Density heated room [kg/m³]	1.184
Density unheated room [kg/m³]	1.204
Height of neutral plane [m]	Half of the height
Discharge coefficient [-]	0.4
Gravity [m²/s]	9.81

4.6.1 Calculating velocities

The first model that gives an equation for the velocity is the one of Hensen et al., see equation 1. The first term in the equation includes a T without any subscript, and the model is therefore solved once for T_1 and once for T_2. The first gives the velocity of the flow from zone 1 to zone 2 and vice versa.

For the model from IEA, equation 4, the pressure difference at z=0 is simplified to

$$P_{1,0} - P_{2,0} = P_1 + \rho_1 gz - (P_2 + \rho_2 gz) \tag{47}$$

Evaluating P_1 and P_2 at $z=z_n$ gives:

$$P_{1,0} - P_{2,0} = gz_n(\rho_1 - \rho_2) \tag{48}$$

Inserting this will give a negative value under the square root for the mass flow from zone two to zone one. To avoid a complex result, the absolute value is used.

4.6.2 Calculating volume flows

Some of the models give the mass flows in kg/s, for these models the equation is divided by the density to obtain the volume flow inn m^3/s.

In the TRNFLOW-model, equations 19 to 22, the integrals are simplified by putting $\sqrt{2\rho}$ outside the integrals. Again, a simplification is used to calculate the pressure difference:

$$\Delta P(z) = gK\left(\frac{1}{T_1} - \frac{1}{T_2}\right) * (z - z_0) - \Delta P(z_0) \tag{49}$$

This equation is from Hensen et al. [11] and is also used for the pressure difference in equations 26 and 27.

4.6.3 Calculations corresponding to the laboratory measurements

The specifications for the door in the laboratory are given in Table 9. Running the MATLAB code with these values gives the results given in Table 10 and Table 11.

Table 9: Specifications for the door in the laboratory measurements.

Height [m]	2.05
Width [m]	0.84

The results given in Table 10 show that there are only minor differences between the different models. Based on these simulations, the expected maximum velocity for the laboratory measurements is 0.23 m/s. There are some limitations for the models which are further discussed in section *4.2 Equations for velocity*.

Table 10: The analytical calculated velocities for the door in the laboratory measurements.

Model	Velocity
Hensen et al, flow from zone 1 to zone 2	0.23229 m/s
Hensen et al, flow from zone 2 to zone 1	0.23427 m/s
Heiselberg, maximum velocity	0.23327 m/s
Etheridge and Sandberg, flow from zone 1 to zone 2	0.23314 m/s
Etheridge and Sandberg, flow from zone 2 to zone 1	0.23119 m/s.
IEA, flow from zone 1 to zone 2	0.23314 m/s
IEA, flow from zone 2 to zone 1	0.23119 m/s

There are larger differences between the models when it comes to volume flow, this is further discussed in *Chapter 4.3 Equations for mass and volume flows*. Based on the results shown in Table 11, the expected size of the volume flow in the laboratory is between 0.10 and 0.15 m^3/s.

Table 11: The analytical calculated volume flows for the door in the laboratory measurements.

Model	Volume flow
TRNFLOW, flow from zone 1 to zone 2	0.12092 m^3/s
TRNFLOW, flow from zone 2 to zone 1	-0.12092 m^3/s
Hensen et al, flow from zone 1 to zone 2	-0.13447 m^3/s
Hensen et al, flow from zone 2 to zone 1	0.13335 m^3/s
Heiselberg, flow from zone 1 to zone 2	0.15736 m^3/s
Heiselberg, flow from zone 2 to zone 1	0.15604 m^3/s
Heiselberg, total volume flow	0.13334 m^3/s
Santamouris et al.	0.094681 m^3/s
Etheridge and Sandberg, orifice based model	0.1339 m^3/s
Etheridge and Sandberg, two-layer hydraulics model	0.1458 m^3/s
IEA	0.1339 m^3/s

4.6.4 Calculations corresponding to the passive house measurements

The specifications for the door in the measurements in the passive house are given in Table 12. Running the code with these values gives the results given in Table 13 and in Table 14.

Table 12: Specifications for the door in the passive house measurements

Height [m]	2.35
Width [m]	0.90

Table 13 shows that there are only minor differences between the results from the different models. Based on these simulations, the expected maximum velocity for the passive house measurements is 0.25 m/s. There are some limitations for the models which are further discussed in *Chapter 4.2 Equations for velocity*.

Table 13: The analytical calculated velocities for the passive house.

Model	Velocity
Hensen et al, flow from zone 1 to zone 2	0.24871
Hensen et al, flow from zone 2 to zone 1	0.25082
Heiselberg, maximum velocity	0.24976
Etheridge and Sandberg, flow from zone 1 to zone 2	0.24961
Etheridge and Sandberg, flow from zone 2 to zone 1	0.24573
IEA, flow from zone 1 to zone 2	0.24961
IEA, flow from zone 2 to zone 1	0.24573

As for the laboratory values, there are larger differences for the volume flow than for the velocity. Based on the results shown in Table 14, the expected size of the volume flow in the laboratory is between 0.13 and 0.18 m^3/s.

Table 14: The analytical calculated volume flows for the passive house.

Model	Volume flow
TRNFLOW, flow from zone 1 to zone 2	0.15902
TRNFLOW, flow from zone 2 to zone 1	-0.15902
Hensen et al, flow from zone 1 to zone 2	-0.17683
Hensen et al, flow from zone 2 to zone 1	0.17535
Heiselberg, flow from zone 1 to zone 2	0.18038
Heiselberg, flow from zone 2 to zone 1	0.17888
Heiselberg, total volume flow	0.17534
Santamouris et al.	0.12451
Etheridge and Sandberg, orifice based model	0.17608
Etheridge and Sandberg, two-layer hydraulics model	0.1561
IEA	0.17608

5. Preparation for the laboratory and passive house measurements

5.1 Risk analysis

A risk analysis had to be conducted before the laboratory measurements could be started. During the risk analysis, the following safety hazards were found:

- Heat source: Fire hazard if used improperly.
- Measuring probes: Risk of electrical faults if the electrical mounting is done improperly.

The following safety rules were specified:

- Protective goggles should be used as this is mandatory for students.
- Only the laboratory technicians can alter the electrical mounting.
- Emergency shutdown: The heat source must be switched off, and the measurements should be stopped.

The complete risk analysis with attachments is found in *Attachment 2: Risk analysis*.

5.2 Calibration of velocity probes

Before the measurements could be conducted, the four probes which had already been used in laboratory needed to be calibrated. This was done to check if the probes give useable results. When calibrating it is important to have the error connected to the probes in mind:

- ± 3% of reading
- ±1 % of selected full scale range

To reduce the effect of these errors the full scale range was selected as 0-0.5 m/s as the velocities will be within this range according to the analytical calculations. The calibration was done using a calibration drum where the air velocity can be set by controlling the air intake and the speed (rpm). These settings are done manually which can lead to error; for example if the opening is not exactly at the level it should be or if the set value is not read accurately enough of the graphs .

The air velocity was measured at six different values with the same settings on all of the probes. The measured values varied some from the set values, but including the margin of error and calculating the minimum and maximum velocities showed that all the set value lay within this margin. The calibration results are shown in both tabular form and as graphs in *Attachment 3: Calibration of velocity probes*.

5.2.1 Time constants

Different time constants were used while calibrating. This was done to see which effect the time constant has on the measured values. It was found that a time constant of one second could be applied to low velocities, but it gave a lot of fluctuations for higher velocities. There were still some fluctuations for the maximum time constant of ten seconds, but in most cases the fluctuations decreased some when the time constant was increased. A time constant of one second can be applied as the analytically calculated velocities are low.

5.3. The setup of the laboratory measurements

The temperature and the velocity of the air flow in the opening, the air and surface temperatures in both rooms are to be measured. Pictures of the setup can be seen in *Attachment 4: Pictures*.

5.3.1 Measurements in the doorway

The temperature and the velocity probes will be mounted to a vertical bar. The measurements should be conducted in the whole width of the opening, so the bar needs to be moved manually. These positions will be marked so that the same positions are used for all measurements. In the experiments presented in Annex 20 by the International Energy Agency [14] five, eight and 13 measuring points are used in the width of the doors. Based on this, it was decided to use eight measuring positions for both the laboratory and the passive house measurements. This gives a total of 80 measuring points for both velocities and temperature. The distribution of the vertical positions can be seen in Table 15 and Table 16.

Table 15: The horizontal distribution of the measuring points for the laboratory measurements.

Laboratory measurements	
Width [cm]	84
Numbers of measuring points	8
Distance from door frames [cm]	3
Spacing between positions [cm]	11

Table 16: The horizontal distribution of the measuring points for the passive house measurements.

Passive house measurements	
Width [cm]	90
Numbers of measuring points	8
Distance from door frames [cm]	3
Spacing between positions [cm]	12

5.3.1.1 Measuring the velocity

Ten velocity probes of type 8475 will be mounted to the vertical bar in movable fasteners using plastic strips. The fasteners should be movable so that the placement of the measuring points can be changed. This is important since the location of the neutral plane is unknown.

The probes will be connected to a sensor of type WS-DLXa which transmits the signals wirelessly to the base station.

5.3.1.2 Measuring the temperature

Accurate temperature measurements are needed due to the change over time. Thermocouples will therefore be used; ten thermocouples of type T will be attached to the velocity probes.

The thermocouples will be connected to a sensor of type WS-DLTh which transmits the signals wirelessly to the base station.

5.3.2 Measurements in the two rooms

The air temperatures in the two rooms are measured to investigate if the commonly used assumption of uniform temperature in the rooms separated by the door is valid. Surface temperatures will also be measured on both sides of the aperture.

The temperatures will be measured with PT-100 temperature sensors which are connected to WS-DLTa sensors which transmit the result wirelessly to the base station.

5.3.2.1 Measuring the air temperatures

The air temperatures in the two rooms need to be measured throughout the whole height of the room. The temperature sensors will therefore be mounted to telescopic vertical bars; one bar with five probes in each room. The bars need to be moved to different locations in the rooms to check if there are any differences throughout the rooms. The fasteners do not need to be movable.

5.3.2.2 Measuring the surface temperatures

The surface temperatures in the two rooms need to be measured to see if this temperature differs from the air temperature. The sensors need to be isolated from the environment so that the measured temperature will not be affected by the air temperature. This is done by attaching the probes to the wall using tack-it as this will not damage the walls in the passive house. The temperature will be measured at ten points; six measuring points in the ground floor, one in the staircase and three in the first floor.

5.4 Additional preparations for the passive house measurements

The living room in the passive house is connected to the other rooms via an open stairway and a wide opening to the entrance hall. This means that there are no doorways directly connected to the living room where measurements can be conducted. A wall will therefore be built around the open stairway so that the opening to the stair will get the shape of a door. The frame will be made of wood with two centimetres of expanded polystyrene. EPS has a low thermal conductivity (the exact value depends on the quality and the manufacturer, but the λ-values are in the range 0.032-0.041 W/mK [20-22]) and isolate well Detailed measurements of the staircase were made before the construction of the frame could be started.

The surfaces in the passive house need to be undamaged by the experiments, this need to be taken into consideration when placing the measurement equipment. The bars should be placed on mats which prevents the surfaces from being scratched.

Since the measurements are to be done in a staircase the original plan of using two poles with 5 PT-probes each had to be changed as there is no room for a pole in the stair case.

Instead, the measurements in the staircase will be conducted using a thread suspended in the staircase.

5.5 WiSensys

As mentioned earlier, a wireless system from WiSensys will be used for the measurements. The components of the system are presented in the following. A software called SensorGraph is delivered with the system and all settings for the sensors and the results are chosen in SensorGraph. These settings are sent from the base station to the sensors in the same way as the measurement results are sent wirelessly from the sensor to the base station.

The results are displayed as graphs in SensorGraph which are updated every 30^{th} second. These graphs contain a lot of data and are not easy to read. The results can also be logged in tabular forms and with different step sizes. One data point will be drawn per step [23]. The results presented in the following are logged in tabular form and new, more readable graphs are made in excel.

5.6 Equipment list and specifications

5.6.1 Equipment list

The following equipment will be used:

- 1 WiSensys Base station WS-BU with Ethernet output module
- 10 TSI omnidirectional air velocity transducer, type 8475
    - 6 transducers of length 15 cm
    - 4 longer transducers
- 20 WiSensys PT-100
- 10 Thermocouple, type T
- 10 WiSensys WS-DLTh
- 20 WiSensys WS-DLTa-P100
- 10 WiSensys WS-DLXa
- Temperature coins
- 1 Electric oven, 2000 W
- 2 Air tight electric radiators of type Dimplex Classic 2NW5, 800 W

5.6.2 Specifications

The specifications for the equipment are presented in Table 17.

Table 17: Specifications for the measurement equipment.

Base station [24]	
Operating limits	-20 °C - + 60 °C
Power	8 – 30 V DC
Network	100 sensors
Air Velocity Transducer 8475 [25]	
Accuracy	± 3.0 % of reading
	± 1.0 % of selected full scale range
Response time to flow	5 s
Velocity range	0.05 m/s – 2.5 m/s
Temperature compensation range	0 °C - 60 °C
Thermocouple type T[4]	
Measurement range	-185 °C - +300 °C
Positive conductor	Cu
Negative conductor	Cu-Ni
Accuracy at 0 °C [26]	0.5 °C
PT-100 [27]	
Measurement range	-150 °C - + 200 °C
Accuracy	± 0.1 °C
WS-DLTh [24]	
Measurement range	Depends on sensor type
Accuracy	± 0.1 % ± 0.5 °C
Measurement resolution	0.1 °C
WS-DLTa-P100	
Measurement range	-150 °C - + 200 °C
Accuracy	± 0.1 °C from 0 °C to 100 °C, ± 3 °C otherwise
Measurement resolution	0.1 °C
WS-DLXa	
Accuracy	± 0.25 % of range
Measurement resolution	25 µA
Operating limits	-20 °C - + 80 °C

[4] Information is given by technical staff in the laboratory at the Department of Energy and Process Engineering

6. Laboratory measurements

The laboratory tests are primarily conducted to check if the equipment and the setup are functioning. The laboratory measurements are therefore simpler than the passive house measurements. The ventilation system in the climate laboratory was turned off during the whole test period.

The velocity probes and the thermocouples are both referred to as probes one to ten. Both types of probes are numbered by descending order; probe one is the upper probe and probe ten is the lowest probe.

An electric convector was used as heat source for the laboratory tests. The convector can be used with both natural and forced convection by turning on or off a fan. The convector cannot be set by exact temperature, but by numbered temperature levels. The oven was set on maximum power and maximum temperature for all the laboratory tests.

The sensors the probes are mounted to needed the settings for the transducers to be different than during the calibration. The following settings were used for all laboratory and passive house measurements:

- Full scale velocity: 0.5 m/s.
- Zero flow output current signal: 0 mA.
- Full scale current output: 20 mA.

The results from the measurements can be found in the zip-file that is submitted with the thesis. The velocities in the tables are calculated from currents using the following formula:

$$V = \left(\frac{I_{measured} - I_{output,min}}{I_{output,max} - I_{output,min}}\right) * V_{full\ range,max}\ [\frac{m}{s}] \tag{50}$$

6.1 Full-scale laboratory experiments

Chen [8] investigated the use of full-scale experiments, which he divided into laboratory experiments and in-situ measurements. The first will be presented here and the latter in section *7.3 In-situ measurements*. In general, it was found that full-scale experiments are mostly used to validate numerical models, for instance CFD models.

Further, Chen found that full-scale laboratory tests are normally conducted in environmental chambers which imitate real rooms or houses. A consequence of this is that boundary conditions and other factors are often approximated, which can be a source of error. There will also be errors associated with the measurement equipment. Although there are several sources of error Chen found full scale experiments to give the most realistic predictions compared to other methods. On the other hand, full scale laboratory experiments can be both costly and time consuming [8].

6.2 First laboratory measurements: Natural convection

Only the velocity and temperature probes for the doorway were tested in this first test. The probes were distributed evenly on the bar with the first bar 15 cm above the floor and approximately 20 cm between the probes. The pole with the sensors was placed in one of the ends of the doorway in the beginning of the measurements, and while measuring the pole was moved every 10th minute. The horizontal measuring points were distributed as explained in the above. The last measuring position could not be used due to the door covering a part of the opening.

6.2.1 Results

6.2.1.1 Velocity

The upper velocity probe measured the largest velocity and fluctuated around 0.350 m/s. Probes two and three also measured large velocities with values between 0.250 and 0.300 m/s and 0.200 and 0.250 m/s, respectively. These velocities are very large and exceed the limit for when draught can be felt [28, 29]. Probe 4 measured a lower velocity than the other upper probes. The lowest velocities are found for the middle probes; probe 5 gave the lowest velocity and fluctuated between right over zero velocity and 0.05 m/s, probe 6 measured a velocity around 0.05 m/s for most of the time. The neutral plane seems to be located between these two probes. The lower probes measured much lower velocities than the upper probes and the order is not the same as for the upper probes. According to the theory, the lower probes should have approximately the same velocity as the upper probes, this is not the case here. This will be discussed in *Chapter 6.6 Comparison*.

There were no significant changes when the bar was moved horizontally, only disturbances from moving the pole. The average velocity for each probe is therefore calculated for the whole test period. The average velocities shown in Figure 7 give a clear picture of the large differences between the velocities in the upper and lower part of the door.

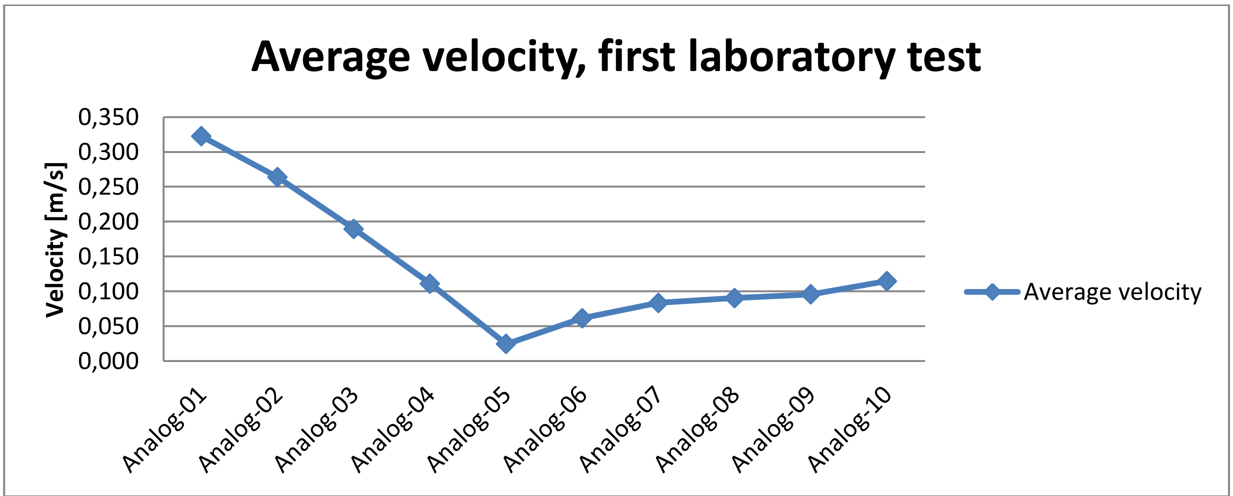

Figure 7: Average velocity for the first laboratory test with natural convection.

6.2.1.2 Temperature

There is a clear distinction between the heated and unheated air. The results showed a slightly higher temperature for the upper probe than for probes two and three and probe four was a bit colder than the other upper probes. The rest of the probes, probes five to ten, only measured a small temperature increase during the measuring period. Again, there were no significant differences between the horizontal measuring positions. The average temperature is therefore calculated for the whole period and can be seen in Figure 8.

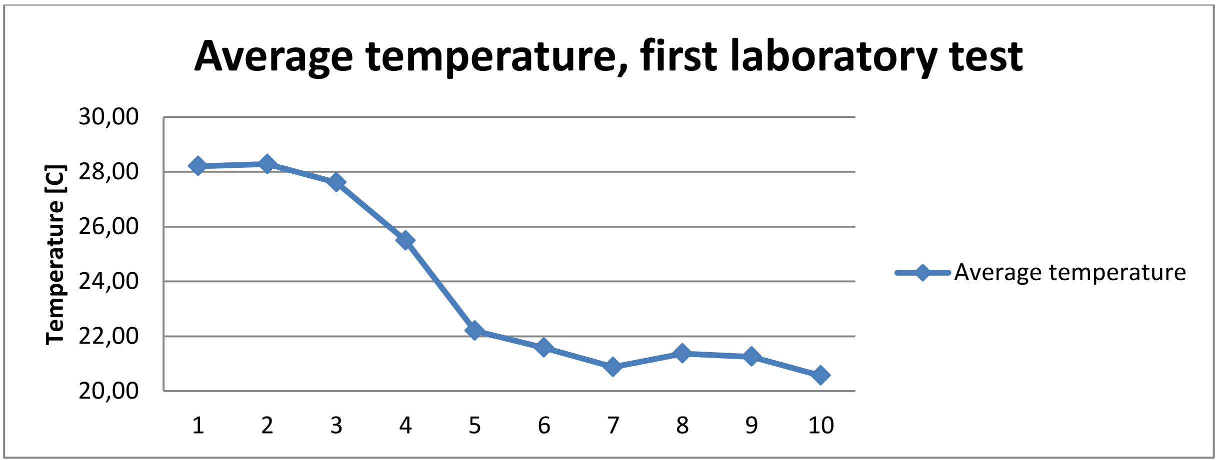

Figure 8: Average temperature for the first laboratory test with natural convection.

6.2.2 Smoke test

A smoke test was conducted after the completion of the first test with the measuring pole standing in the middle of the aperture. The following was observed:

- The air had a visible maximum velocity in the upper part of the aperture.
- The air did not move as fast in the bottom half of the door.
- It was easy to spot a division where the air changed from leaving the heated room to entering the heated room.
- The air moved more close to the door than in the rest of the room where it was almost stagnant.
- There was a small down draught by the windows.

6.3 Second laboratory test: Forced convection

As for the first test, measurements were only done in the doorway. The probes were distributed with decreasing spacing further from the centre of the pole; in the ends the gap was 15 cm, then 20 cm and 25 cm before the mid gap of 30 cm. The pole with the sensors was moved in the same way as in the first laboratory measurements.

6.3.1 Results

6.3.1.1 Velocity

The upper probe, probe one, measured the highest velocity with a value of 0.3-0.35 m/s. There was a small gap down do probes two and three which both measured velocities between 0.2 m/s and 0.25 m/s most of the time. Probe four had a lower velocity than this with 0.15-0.20 m/s. Unlike the measurements above it is not a clear distinction between the lower probes and the probe with the lowest velocity. Probe five to ten all measured quite similar velocities, but probe six had a more varying and a slightly lower velocity than the others. The neutral plane seems to be located closer to probe 6.

There were no significant changes when moving the pole vertically this time either and the average velocity is calculated from the whole measuring period. The average velocities in Figure 9 show that the velocity was a bit lower for the middle probes than for the rest of the probes.

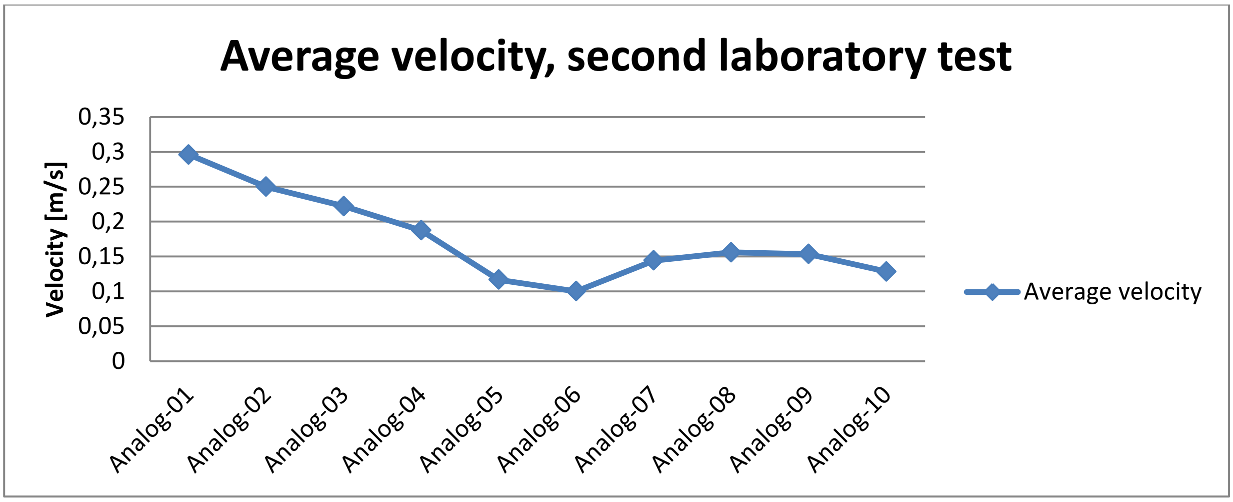

Figure 9: Average velocity for the second laboratory test with forced convection.

6.3.1.2 Temperature

Probe two measured the warmest temperature followed by probes one, three, four and five. Then, there was a gap down to probe 6, followed by a new gap down to the remaining probes. The five lowest probes measured temperatures which were much closer to each other compared to the five upper probes. As for the velocity, the average is calculated for the whole measuring period, see Figure 10.

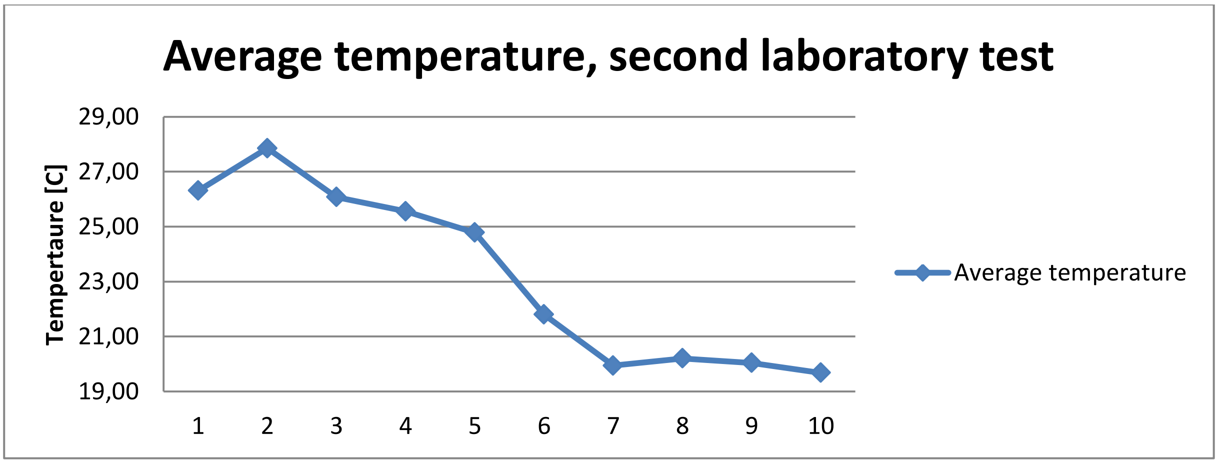

Figure 10: Average temperature for the second laboratory measurements with forced convection.

6.4 Third laboratory test: Natural convection

The oven was put on the same settings as for the first measurements; full power and natural convection. The probes were kept in the same positions as for the second measurements. Again, the pole was moved horizontally every 10th minute.

6.4.1 Results

6.4.1.1 Velocity

The results for the upper probes were approximately the same as for the first measurements: The upper velocity probe measured the largest velocity and fluctuated around 0.350 m/s. Probes two and three also measured large velocities with values between 0.250 and 0.300 m/s and 0.200 and 0.250 m/s, respectively. These velocities are very large and exceed the limit for when draught can be felt [28, 29]. Probe 4 measured a velocity that was slightly above the velocity of the lower probes. The lowest velocity was measured by probe five. As for the first test, the lower probes have much lower velocities than the upper probes and the order is not the same as for the upper probes. The neutral plane seems to be located close to probe 5. The average velocity for each probe, calculated for the whole measuring period, is shown in Figure 11.

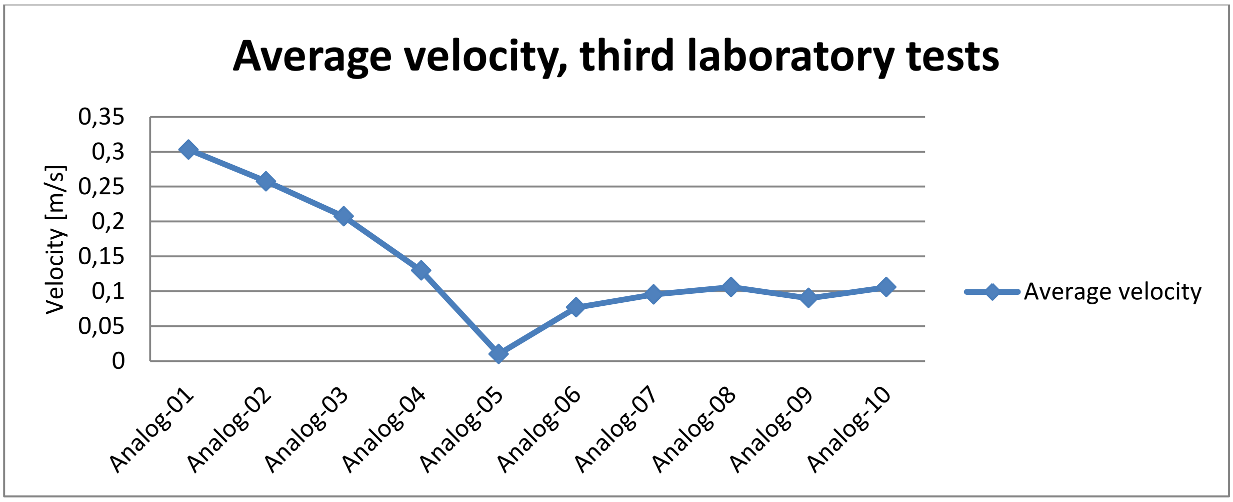

Figure 11: Average velocity for the third laboratory measurements with natural convection.

6.4.1.2 Temperature

There was a clear distinction between the heated and unheated air. Probe two measured the warmest temperature followed by probes 1, 3 and 4. There was a gap of almost 5 °C down to probe 5, followed by a smaller gap down to probes 6-10. The lower probes measured more similar temperatures than the upper probes. The average temperature in Figure 12 gives a clear picture of this.

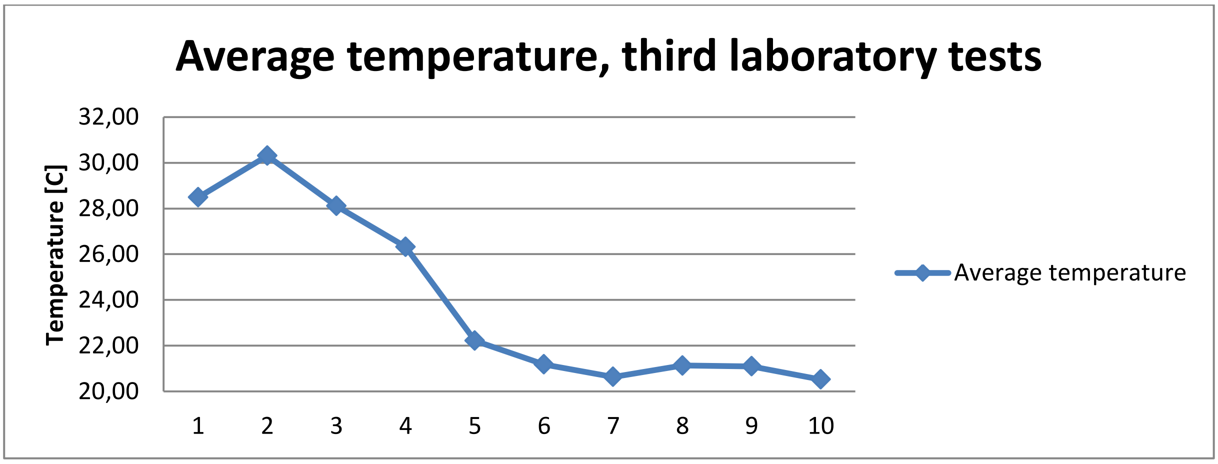

Figure 12: Average temperature for the third laboratory test with natural convection.

6.5 Testing the PT-100 probes

This test was done to check if the mounting of the PT-100 probes on the telescopic pole functioned. The oven was therefore not turned on; it was turned off right before the test started. Five PT-100 probes were taped to a telescopic bar as explained in section *5.3.2.2 Measuring the surface temperatures*.

Due to the test taking place right after the electric oven was turned off, the temperatures were decreasing throughout the test period. The upper sensor, PT1, measured the warmest temperature followed by PT2 to PT5. Thus, the temperature increases with the height.

The difference between the upper and lower temperature, the temperature stratification, declined when the temperatures decreased, see Figure 13. There was still a clear vertical temperature stratification even though the temperatures evened out with time.

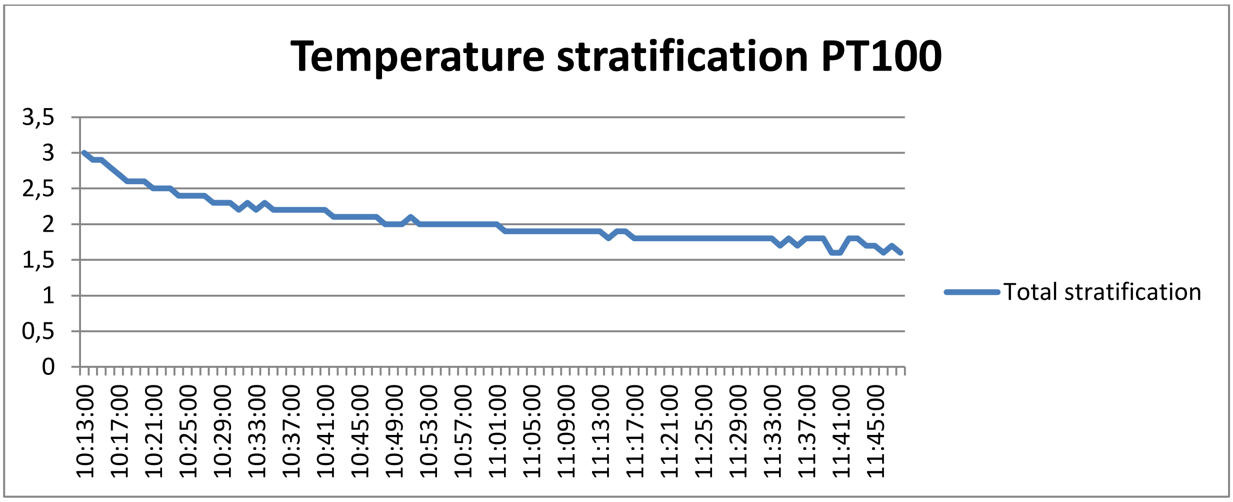

Figure 13: Temperature stratification for the PT-100-sensors.

6.6 Comparison and short discussion

The conditions at the laboratory differ greatly from those in a passive house and the results will therefore only be discussed briefly after the comparison.

In a large laboratory such as at the one at Energy and Process Engineering there might occur processes that can affect the air flow. This might affect the results of the laboratory measurements. Another source of error can be the different length of the velocity transducers.

Tests one and three are both conducted with natural convection, one should therefore expect similar results for these two tests.

A source of error that can influence the results is the fact that there was not a steady state situation when the measurements were done. Therefore, averaging the velocities and temperatures as have been done in the above can result in error.

6.6.1 Velocity

The two tests with natural convection gave similar results; the tendencies are the same, but the magnitude of the velocity varied slightly. For both tests the upper probe measured the largest velocity, the velocity thereafter decreased until a minimum was reached at probe five and the velocity increased again. Test one had a slightly larger velocity for the upper probes than test three, test one also had a lower minimum velocity. It was a clear distinction between the upper and lower velocities for both cases. The differences can be partly due to the different location of the probes.

This divide between the upper and lower probes is less clear for the test with forced convection; the transition is smoother than for the cases with natural convection. The magnitudes are about the same as for the other cases. It is not very clear from the graphs from SensorGraph which probe that measured the lowest velocity for the second test, but from the average velocity displayed in Figure 9 one can see that probe 6 measured the lowest velocity. This differs from both cases with natural convection and might be an indication that the neutral plane is located lower for the case with forced convection.

The graphs showing the average velocity show that the curve is flatter for the forced convection that for the natural convection: The velocity decreases slower and the minimum velocity is larger than for natural convection. This coincides well with the observations from the velocity graphs. The graphs showing the average velocity for the two cases with natural convection has approximately the same shape. Quantitatively, the maximum velocity for the upper probes was larger for the first test and the maximum velocity for the lower probes was larger for the second test. Test one had a lower minimum velocity than the two other tests.

The neutral plane seems to be located close to the middle of the opening for the two tests with natural convection. For the test with forced convection, it seems to be located a bit lower in the aperture. The difference is pretty small so this can be due to the error sources mentioned below.

All three cases have very large velocities compared with the recommended maximum velocities for thermal comfort [28, 29]. At the same time the cases also have apparent discrepancies from the theory; the lower half of the doorway had a clearly lower maximum velocity compared with the upper half. The variable velocity also deviates from the two-layer hydraulics model.

It is difficult to find the exact reasons for the large velocities and deviations from the theory, but some factors that are likely to affect the results are:

- Before mentioned factors such as processes in the lab affecting the air flow.
- The oven is set on maximum power and maximum temperature, this will create a large temperature difference between the heated and unheated air which again will lead to larger velocities.
- A heated plume will be created above the convector. This makes the air in the upper part of the room warmer than the lower air. This will give larger temperature differences between the rooms in the upper part of the aperture than in the lower part which again will lead to larger velocities.
- Deviations from assumptions the mathematical models are based on, such as the two rooms not having uniform temperatures: The test of the PT-100 probes shows that there is considerable temperature stratification in the unheated room. It is likely that this is also the case in the heated room.

The differences in maximum and minimum velocities for the three cases can be due to small differences caused by external circumstances. The different maximum and minimum velocities for the two tests with natural convection may suggest this.

The difference between the velocities for the upper and lower part of the door indicates that the mass flows in and out of the room differ. As the mass flow in and out of the room should be equal and the ventilation system is off this imply that there must be mass transfer in other locations than the door, for instance leakages around the window.

6.6.2 Temperature

As for the velocity, one can see a clear distinction between the heated and unheated air for the cases with natural convection. As mentioned, the transition between the two layers seems to be smoother for the forced convection.

For the first test probe one measured the warmest temperature, but for the two other cases probe two measured the warmest temperature. Thus, the two tests with natural convection do not give corresponding results. Again, this can be partly due to the different vertical location of the probes.

Quantitatively, test two showed the coldest maximum temperature and test three had the warmest maximum temperature.

The graphs for the average temperature shows much of the same as described above. The curve is more rounded for test one as the first probe has the highest temperature. The temperature starts to decrease further up for the two cases with natural convection than for the forced convection case, the slope is also steeper for these two cases.

As for the velocity, the results deviate from the theory: The temperatures are not uniform in the two flows. Since the temperatures are closely linked to the velocities these results are likely to be affected by the same factors as listed above.

When the fan is on the warm air will rise immediately, this may lead to the heated air being able to mix with the room air before reaching the door. The air will not rise as fast for natural convection, and this may lead to less mixing with the room air before the air reaches the door. If this is the case, this can be the reason why the maximum temperature in the door is higher for natural convection.

7. Passive house measurements

7.1. Miljøbyen Granåsen

Miljøbyen Granåsen, developed by Heimdal Bolig, is a major investment in passive houses in Trondheim, Norway and is a part of the EU initiative Concerto Eco-City[30]. It is the largest area with passive houses in Scandinavia and is currently regulated for 310 housing unit, but it has been requested to increase this to 430[5]. In addition to building passive houses with balanced ventilation and heat recovery [31], environmental measures like district heating and no thoroughfare are also applied [32].

7.2 The passive house

The measurements will be conducted in a three storey townhouse built after NS3700[6]. The house has an open staircase and one radiator on the ground and first floor as the only heat source (and comfort heating in the bathroom floor, 700 W[7]). The floor plans of the house can be seen in Figure 14.

The U-values for the outer surfaces are shown in Table 18. The U-values for the windows varies between 0.65 and 0.87 W/m^{2}K, and have an average value of 0.79 W/m^{2}K [33] which is within the requirements presented in *Chapter 2. The passive house building standard and passive house requirements*. The U-values for the walls and floor in the basement, which are underground, will have a lower heat loss than surfaces that border to air, therefore the U-values are converted to equivalent values [34].

The SIMIEN file where the U-values are gathered from do not give any information about the U-values of the internal walls and the floor stands, but the following information is given about their thermal mass:

- Heat storage inner layer, ceiling basement: 2.4 Wh/m^{2}K.
- Heat storage inner layer, floor ground floor: 41.0 Wh/m^{2}K.
- Heat storage inner layer, ceiling ground floor: 2.4 Wh/m^{2}K.
- Heat storage inner layer, floor first floor: 41.0 Wh/m^{2}K.

Table 18: U-values for the outer surfaces. Except for the U-values for windows, the values are from [35].

U-values [W/m^{2}K]	Walls	Floor	Walls, equivalent	Floor equivalent	Windows	Door	Veranda door	Roof
Basement	0.25	0.12	0.19	0.10				
Ground floor	0.15				0.79	0.59	0.80	
First floor	0.15				0.79			0.06

[5] Numbers are given orally by Kristian Stensrud, project manager in Heimdal Bolig.
[6] NS 3700 is the Norwegian standard for «Criteria for passive houses and low-energy buildings – residential buildings”.
[7] This information is given by e-mail by Runar Kristensen in Aasen bygg.

To check if the tightness of the building was satisfactory, a "blower door" test was done[8].

The house has a balanced ventilation system of type Flexit. Air is supplied from two air terminal devices (ATD) in the living room, one ATD in each bedroom, and one ATD in the upstairs living room and in the basement. The exhausts ATDs are located in the kitchen, the bathroom, the staircase and the basement. The supplied, extracted and net air flow in the different storeys are shown in Table 19 [36]. The deficit of air in the basement and the ground floor gives a net air flow from the first floor with the sizes given in the table. A layout of the system can be seen in *Attachment 5: Layout for ventilation system*.

Table 19: The amounts of supplied and extracted air in the basement, ground floor and first floor.

Floor	Supplied ventilation air [m3/h]	Extracted air [m3/h]	Net air flow [m3/h]
Basement	41	56	-15
Ground floor	31	64	-33
First floor	130	82	48

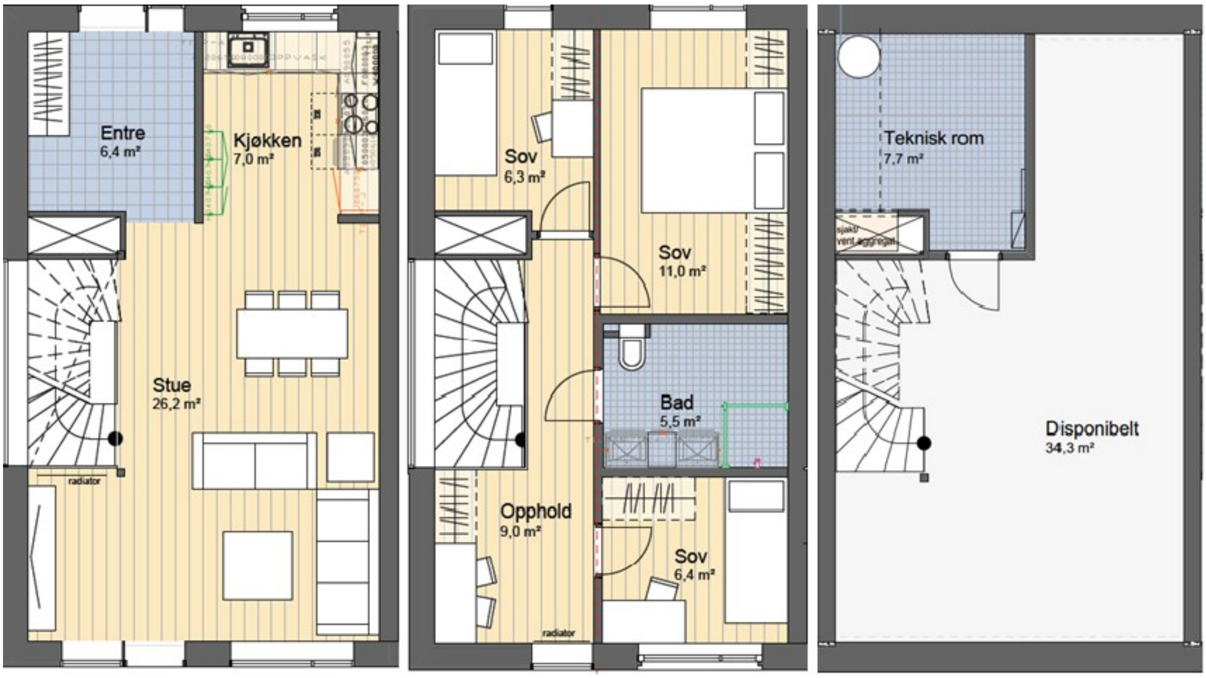

Figure 14: Floor plan for the passive house. The ground floor is to the left: Entre is the entrance, kjøkken is the kitchen and stue is the main living room. The first floor is in the middle: Sov are bedrooms, bad is bathroom and opphold is living room. The basement is to the right: Teknisk rom is technical room and disponibelt is available room.

7.2.1 Comparison with the house used by Georges, Skreiberg and Novakovic

The passive house used in this thesis differs from the house used in the work of Georges, Skreiberg and Novakovic in many areas:

- In this thesis a townhouse is used, and not a detached house. The floor plan of the two houses also differs, but both houses have an open staircase.

[8] This information is given by e-mail by Runar Kristensen in Aasen bygg.

- The house from the article has more zones used for simulation than the zones the air exchange is measured between in this thesis.
- The simulation is done using actual doors and not a frame build to create the shape of a doorway.
- The climate is different: In the paper a house in Belgian climate is used compared to the climate of Trondheim which is used in this thesis. The climates used in the newer work with cold climates are more comparable with the climate in this thesis.
- Both houses have a mechanical cascade ventilation system.

7.3 In-situ measurements

In-situ measurements are, according to Chen [8], to use measurements in one building to predict equivalent results for a similar building, for instance if the results from these passive house measurements are used as valid for passive houses in general. Chen states that boundary conditions are not controllable in such measurements; this can make it difficult to use in-situ measurements. Also, the results obtained from one building is not necessary applicable in other similar buildings.

The same applies to in-situ measurements as full-scale laboratory experiments when it comes to errors and level of predictability, see section *6.1 Full-scale laboratory experiments*.

7.4 Method and procedure

7.4.1 Locations of measurements

The measurements were done using the setup explained in *Chapter 5.3. The setup of the laboratory measurements*. The location for heat sources and the PT-100 sensors measuring the stratification can be seen in Figure 15. Position 1 to position 4 is the location for the heaters, and the red spots mark the location for the PT-100 bar. Location 5 for the PT-100 bar is split into two positions: 5a is used when the heat source is placed in position 1 and 5b is used when the heat source is in the other positions. The red line in the left part of the figure marks the location for the measurements in the doorway. For the stair case, the stratification was measured by suspending a thread with five PT-100 sensors in the stair case. The upper sensor was on level with the third floor, the next two was in the staircase between the first floor and the ground floor, the two lowest probes were in the staircase between the ground floor and the basement, this way the whole height of the staircase is covered. This thread was moved once so that the measurements were done at two locations in the staircase, this is marked in the right part of Figure 15.

Besides the stratification, the temperatures of some surfaces were also measured. This is marked in Figure 16. PT7 measures the air temperature in the first floor, PT8 measures the surface temperature of the floor in the living room, PT13 and PT14 measure the surface temperatures of the floor in the first floor and the remaining probes measures the surface temperatures of walls.

7.4.2 Procedure

The measurements in the passive house were conducted with three different cases:

1. The convector with the fan off, giving natural convection.
2. The convector with the fan on, giving forced convection.
3. Two panel heaters with a higher percentage of radiative heating than the convector

The internal doors on the first floor will be open, except for the door to the bathroom.

The measurements were initially planned to also include a radiative heat source in form of a terrace heater. But this did not arrive in time to be used for the measurements.

As there were few changes for the results in the laboratory measurements when the bar was moved horizontally in the door it have been decided to reduce the number of horizontal positions to three. Moving the bar fewer times will give fewer disturbances.

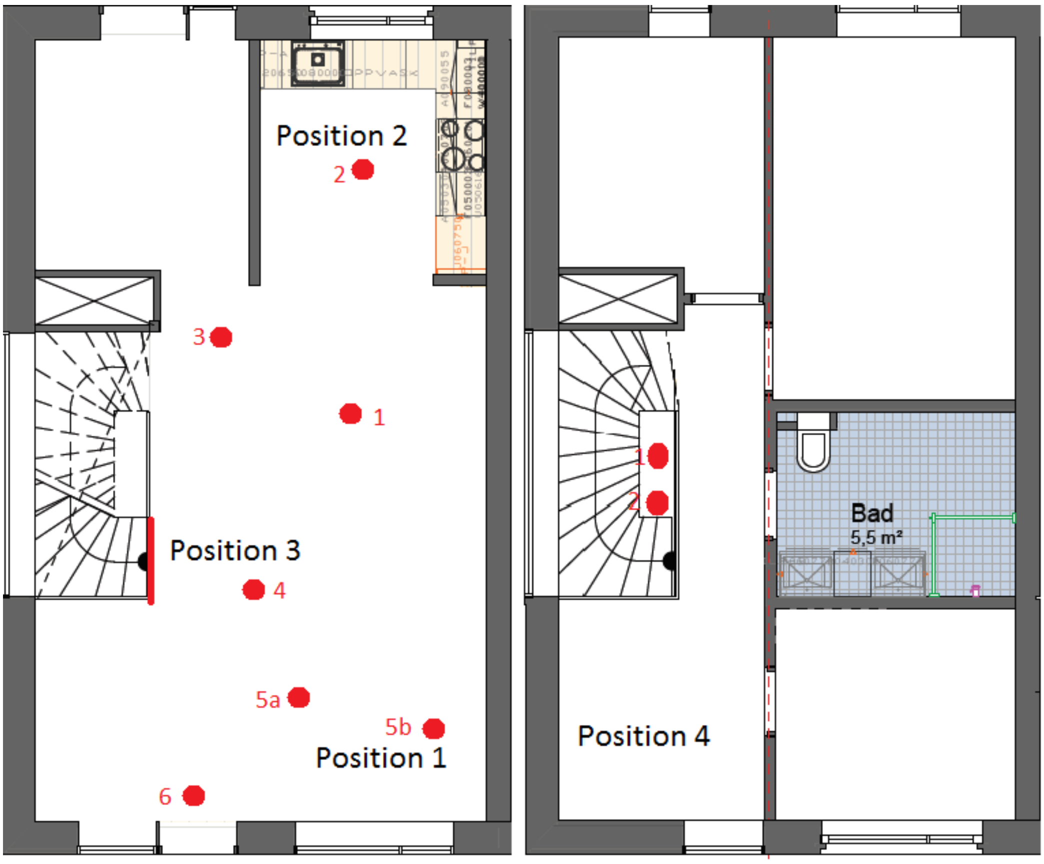

Figure 15: The positions for the heat sources are marked with black and the location for the temperature measurements are marked with red. The red line to the left marks the location for the measuring of velocity and temperatures in the aperture.

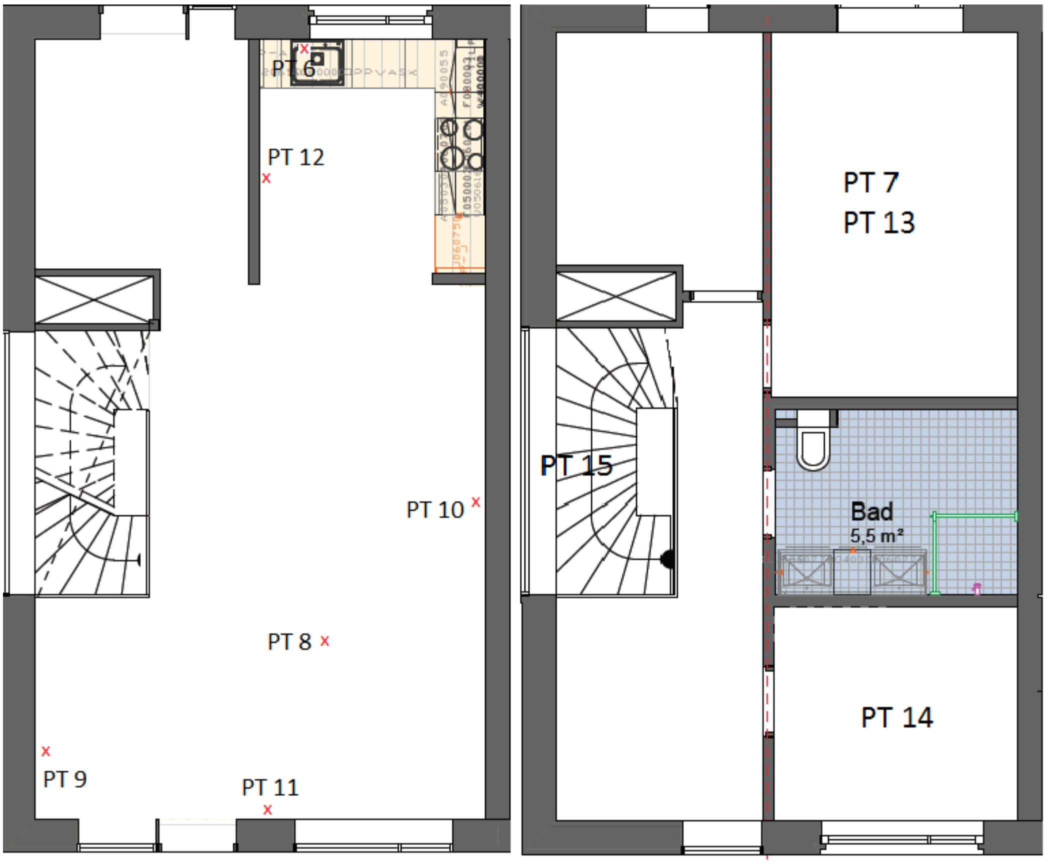

Figure 16: The locations for the measurements of the surface temperatures. PT7 is not measuring a surface temperature, but is measuring the air temperature in the first floor.

It takes many hours to reach a steady state in the house as passive houses react slowly. Due to this, most of the measurements are conducted in a state close to steady state and not in a complete steady situation. The average temperature on both sides of the aperture is needed for calculations that will be made based on the measurement results. This is the motivation for moving the PT-100 bar and thread. With this in mind, this is how the measurements were conducted for all three cases:

- The heat source was on overnight, located in position 1, so that the basis for the measurements was as close to steady state as possible.
- After measuring for 30 minutes, the PT-100 bar was moved to position 2. After this it was moved every five minutes, and it was moved back to the nominal position after 55 minutes.
- The bar in the doorway was moved to the left side of the opening after 35 minutes, ten minutes later it was moved to the right of the opening and after ten more minutes it was moved back to the initial position.
- The thread with PT-100 sensors in the staircase was moved to position 2 after 40 minutes and was located there the rest of the measurements. Moving the thread to position 2 changes the position of PT18, PT19 and PT20; they are moved a bit higher and to the right. PT16 and PT17 are left in the same positions.

- The measurement lasted for one hour per oven-position. After the hour had passed, the thread in the staircase was moved back and the oven was moved to position 2. The measurements were resumed after waiting one hour and conducted in the same way as described above.
- The same procedure was also used for position 3.
- For the measurements with the heat source in position 4, the heaters were again on overnight. Then the same procedure as described above was used. Position 4 was not used for the case with forced convection.

Some additional measurements were conducted in a slightly different manner than the main measurements which were done as described above. These measurements include tests with different ventilation rates and a test with closed doors on the first floor. The procedures for these measurements are explained in *Chapte*r *8. Other measurements*.

The temperatures in different locations in the house have also been measured with temperature coins. These coins have been measuring constantly for a month with a data point every tenth minute. This gives a lot of data and it is not reasonable to render all this data with the measurement results; the locations of the temperature coins and the average temperatures with standard deviations can be found in *Attachment 6: Temperature coins*.

As the measurements were conducted during the winter which can be very cold, the floor heat in the bathroom was kept at 16 °C to be certain that it would not be too cold for the piping.

7.5 Smoke test

A smoke test was conducted in the passive house when the convector was set on natural convection and located in the nominal position. The test revealed the following:

- The air did not flow through the small gap between the frame that was built and the ceiling and walls.
- There was one neutral plane in the aperture and one could clearly see that the air moved in different directions under and above this plane.
- The air flow in the staircase was so that the warm air followed the curve of the stairs, therefore there was a layer of unheated air in the middle of the stair case.

7.6 Measurement results

The results of the passive house measurements will be given in this chapter. The tables and graphs with the results can be found in the zip-file that is submitted with the thesis. Equation 50 was used to calculate the velocities. There were differences in velocities for the horizontal positions for all cases, but this is only graphed for the first case.

7.6.1 Natural convection, oven-position 1

7.6.1.1 Velocity

- Initial position: The velocity measured by probe 1 was clearly the largest velocity followed by probes 7-10. These were closely followed by probes 2 and 3. Probes 5 and 6 measured the clearly lowest velocities; probe 5 had a slightly lower velocity than probe 6. Probes 1-4 and 6 had a lot of variations between the measuring points, probes 5 and 7-10 fluctuated less.
- Moving the bar to the left side of the doorway: The velocity of probes 1 and 3 dropped and the velocity of probes 2, 9 and 10 increased significantly. Probes 5-8 also measured a slightly increasing velocity. Some of the probes measured less fluctuation compared to the initial result.
- Moving the bar to the right side of the aperture: Probe 3 measured a larger velocity and probe 2 had a decreasing velocity. Besides this, the rest of the probes measured velocities in the same level as above.
- Moving the bar back to the initial position: The velocities moved towards the initial levels. The average velocities for the three different horizontal positions are given in Figure 17; there are clear differences between the three positions.
- Average velocities: The average velocities of the probes are calculated for the whole measuring period even though there were some differences for the horizontal movement of the bar. This is the case for all the measurements. Probe 1 had the largest average velocity followed by probes 7-10 which had approximately the same average velocities. Probes 2-4 had a lower average velocity than the lower probes, and probes 5 and 6 had the overall lowest velocities. The lower probes have a higher average velocity than the upper probes if one calculates the average velocity of the four upper and lower probes. The average velocities are shown in Figure 18.
- Average velocities with standard deviation: The average velocity was plotted with the velocities in the lower half of the door being negative to investigate how the velocity profile of the average velocity looks compared to the theoretical profile in Figure 5. The average plus and minus the standard deviation was also plotted in the same figure, see Figure 19. This is done for all cases. The graph reveals that the shape of the velocity profile is not completely as in the literature: The velocities in the lower half do not decrease closer to the middle of the aperture, and the shape is therefore flatter. The shape of the upper half is closer to the theory; the main deviation here is that probes 4 and 3 had larger average velocities than probe 2. The standard deviations show that the deviations from the average values are larger for the upper probes than for the lower and middle probes.
- These observations indicate that the neutral plan is likely to be placed between probe 5 and probe 6, closer to probe 5.

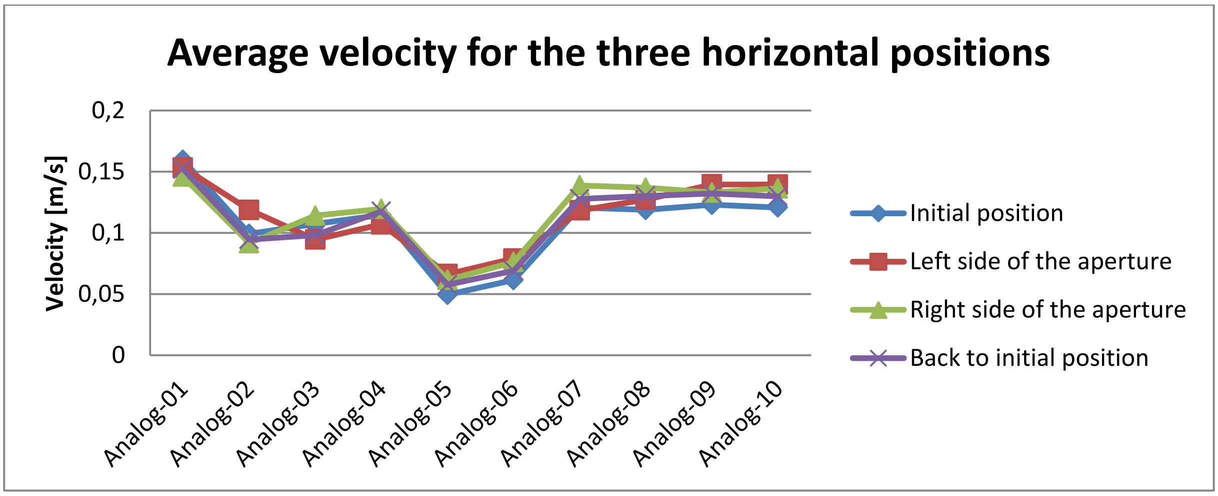

Figure 17: The average velocity per probe for the three different horizontal positions.

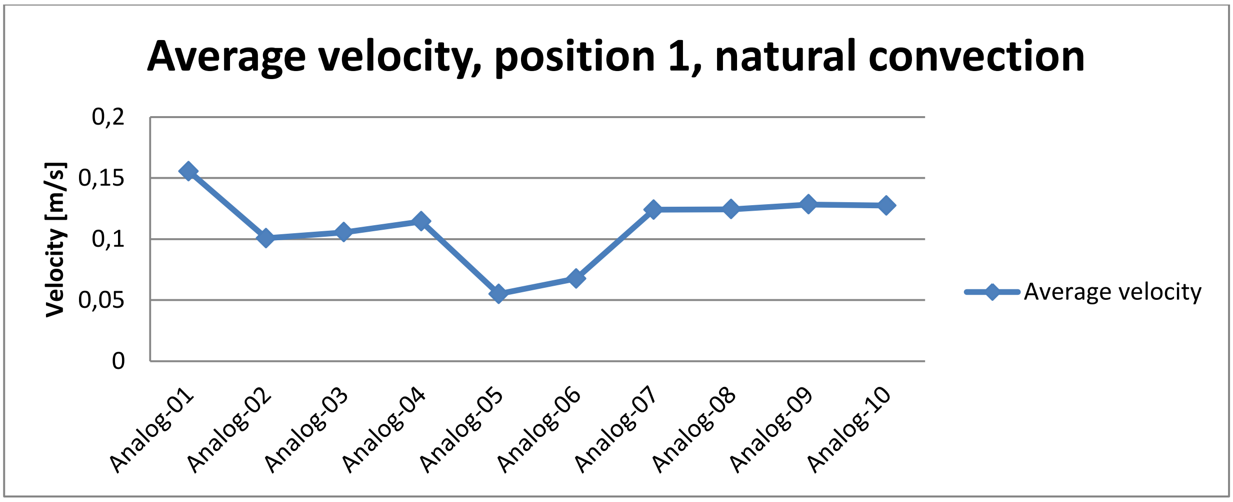

Figure 18: Average velocity per probe for natural convection when the oven is in position 1.

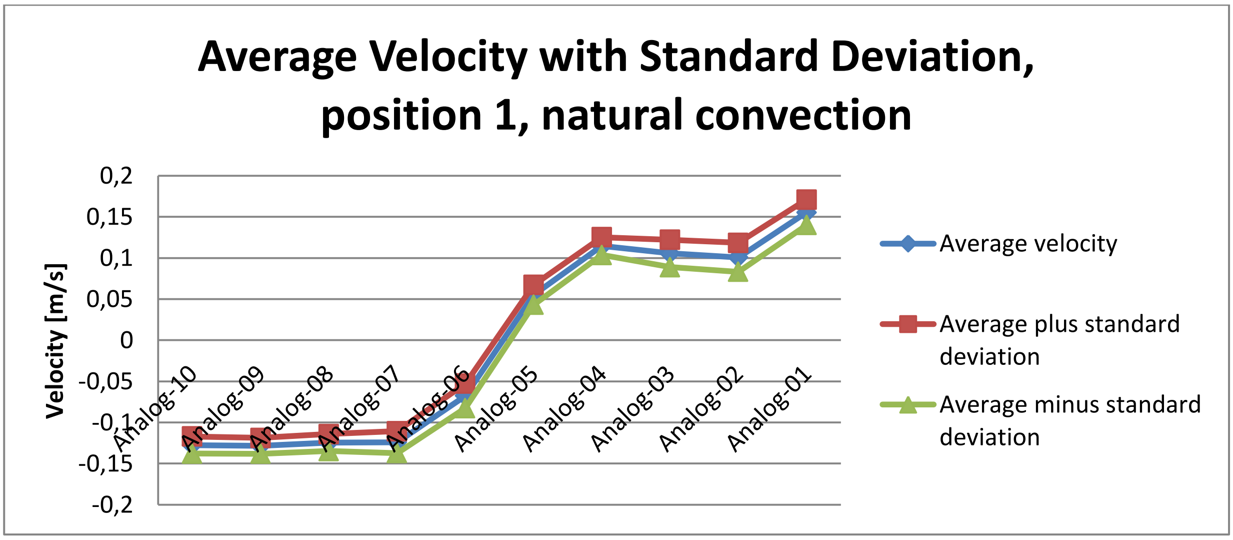

Figure 19: Average velocity with standard deviations for natural convection when the oven is in position 1.

7.6.1.2 Temperature in the aperture

- Initial position: Probe 1 measured the warmest temperature followed by probes 2-6 which all had a small gap between each other. After probe 6 there was a small gap down to probes 7-10 which all measured quite similar temperatures. Probe 10 appeared to have a slightly lower temperature than the rest of the lower probes.
- Moving the bar to the left side of the aperture: Slightly increased temperatures for probes 2, 3 and 7-10. Besides this, there were no visible changes.
- Moving the bar to the right side of the doorway: The temperatures that increased slightly earlier all changed back to the initial level of temperature.
- Moving the bar back to the initial position: No visible changes.
- Altogether there were only minor changes when the bar was moved horizontally. The lower probes measured similar temperatures while the upper probes had more varying temperatures. This makes the transition from the warmest air to the cold air a gradually transition.
- Average temperature: The average temperature for the whole period is shown in Figure 20 which shows the same trends as described above.

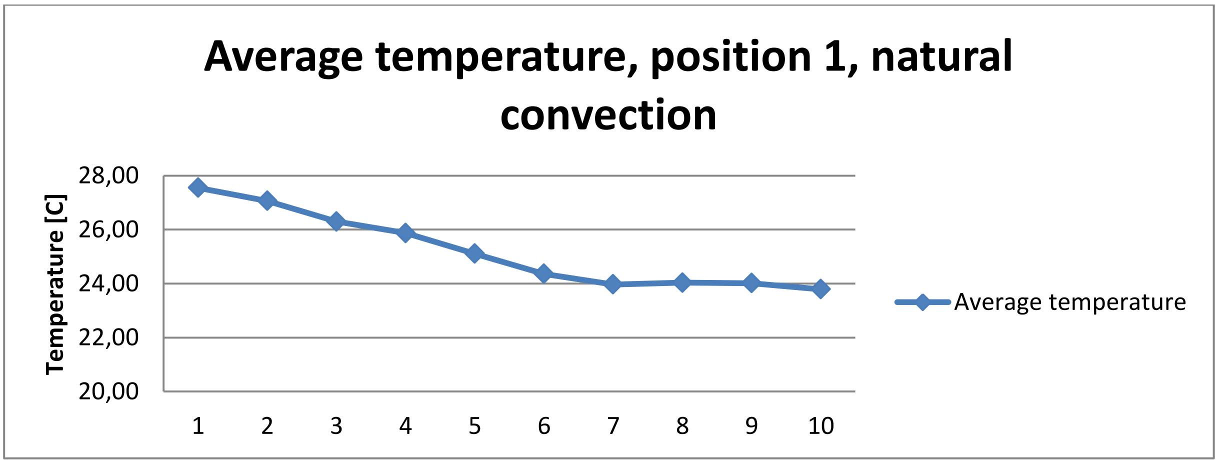

Figure 20: Average temperature per probe for natural convection when the oven is in position 1.

7.6.1.3 Stratification and surface temperatures

Stratification in the living room:

- The temperatures and the stratifications only varied slightly in the initial position. The stratification was fluctuating between 2.3 and 2.4 °C.
- There were approximately the same temperatures in position 2; this is not surprising as the position is close to the nominal position. PT2 measured a decrease of 0.2 °C, which was the largest temperature drop. The stratification was at the same level as for the initial position.
- Many of the sensors measured a temperature increase of 0.1 °C when the bar was moved to position three. The stratification was 0.1-0.2 °C lower than in the above.
- Moving the bar to position 4 gave an increased temperature for PT1 and a decreased temperature for PT5, the rest of the temperatures were unchanged. This led to a large increase in the stratification of 0.9 °C.

- PT1 and PT2 measured a small decrease in temperature when the bar was moved to position 5a, and the three lower sensors measured a small increase in the temperature which made the stratification decrease.
- The temperatures increased in position 6; most for the upper sensor and less for the lower sensors. This gave a clear increase in stratification.
- Moving the bar back to the initial position resulted in lower temperatures for all sensors except PT3. The two upper sensors had the largest decrease so the stratification decreased significantly.
- The average temperature for all the measurements in the living room during the measuring period was 26.06 °C.

Surface temperatures:

- Most of the surfaces only had a minor temperature increase of 0.1-0.2 °C.
- There was some sun in the last part of the measuring period; PT8, PT9 and PT14 were affected by the solar radiation and the measured temperatures increased more during the last minutes of the measuring period.
- The wall temperatures on the ground floor had approximately the same values and the floor was a bit colder. The surface temperatures on the first floor also had similar values, and the air temperature increased with only 0.1 °C.

Stratification in the staircase:

- There were even temperatures in the staircase when the thread was in the initial position. PT17, PT19 and PT20 measured lower temperatures than PT16 and PT18 due to the air flow in the staircase. The stratification, which was calculated as the maximum temperature minus the minimum temperature, fluctuated between 3.8 and 4.0 °C
- Moving the thread to position 2 did not affect PT16 and PT17, but PT18 was moved up to the layer of unheated air and measured a decrease in temperature. The two lowest sensors were moved up from the colder basement air and measured a clear temperature increase. Thus, moving the thread resulted in a significant reduction of stratification.
- The average temperature in the staircase was 23.53 °C.

7.6.2 Natural convection, oven-position 2

7.6.2.1 Velocity

- Initial position: There were a lot of fluctuations, especially for probes 1 and 3. When these probes were at the maximum value of the fluctuations they alternated on measuring the maximum velocity. When this was not the case probes 9 and 10 measured the largest velocities closely followed by probes 7 and 8. These probes also had less fluctuating velocity. Probe 4 varied with probe 3, but measured a lower velocity. Probe 2 measured a velocity which was in between the largest and smallest velocities, and probes 5 and 6 had the lowest velocities.

- Moving the bar to the left side of the aperture: Many of the probes measured increasing velocities; probes 9 and 10 measured a large increase in velocity, probes 7 and 8 measured a slight increase and probes 3 and 6 measured increasing velocity.
- Moving the bar to the right side of the aperture: The four lower probes measured decreased velocities, but they still measured the largest velocities. The rest of the probes moved towards the initial velocity level.
- Moving the bar back to the initial position: The results were approximately the same as when the bar was moved to the right side of the aperture.
- Average velocity: The graph showing average velocities, see Figure 21, shows much of the same as described above; the average velocities of the lower probes were higher than for the upper ones, probe 2 had a lower average velocity than the rest of the upper probes and probes 5 and 6 had the lowest average velocities.
- Average velocity with standard deviation: Again, the shape of the velocity profile deviates some from the theory; the shape is flatter for the lower probes, and probe 2 having a low velocity makes the profile deviate for the upper probes. The standard deviation increased with increasing velocity, this is shown in Figure 22.
- Again, the observations indicate that the neutral plan is likely to be placed between probe 5 and probe 6, a bit closer to probe 5.

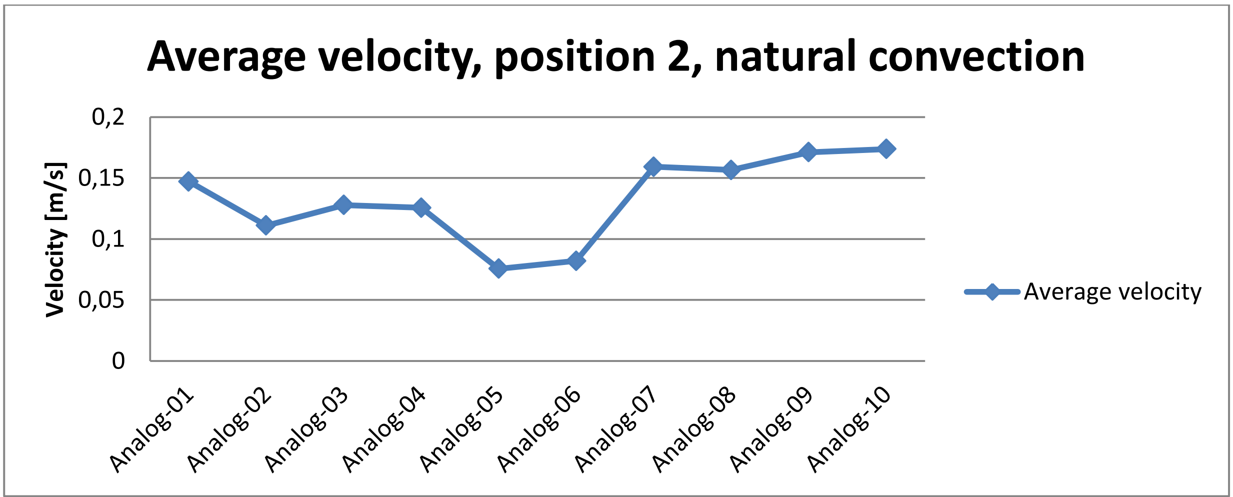

Figure 21: The average velocity per probe for natural convection when the oven is in position 2.

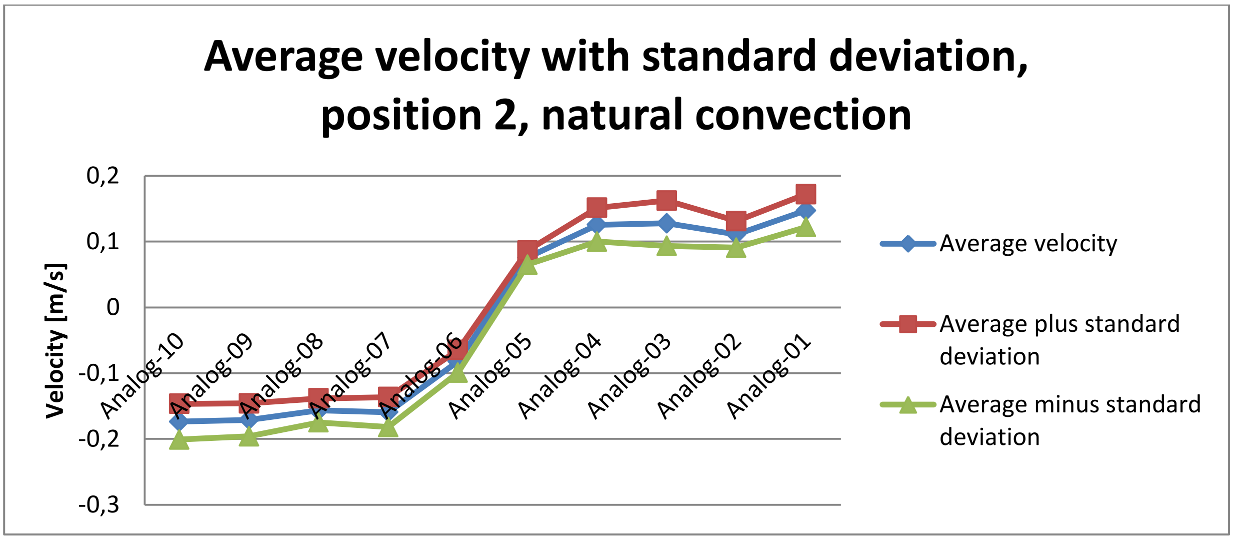

Figure 22: The average velocity with standard deviations for natural convection when the oven is in position 2.

7.6.2.2 Temperature in the aperture

- Initial position: The temperatures were warmest for the upper probes and decreased with decreasing height. After probe 4 there was a gap down to probe 5, after another gap probes 6-10 followed closely after each other.
- Moving the bar to the left side of the aperture: Some of the probes measured minor temperature increases and probe 10 had a more significant temperature increase.
- Moving the bar to the right side of the aperture: The temperatures moved towards the initial values.
- Moving the bar back to the initial position: The temperatures changed back to the initial values.
- Average temperature: The average temperatures for the whole period are shown in Figure 23 which shows the same trends as described above

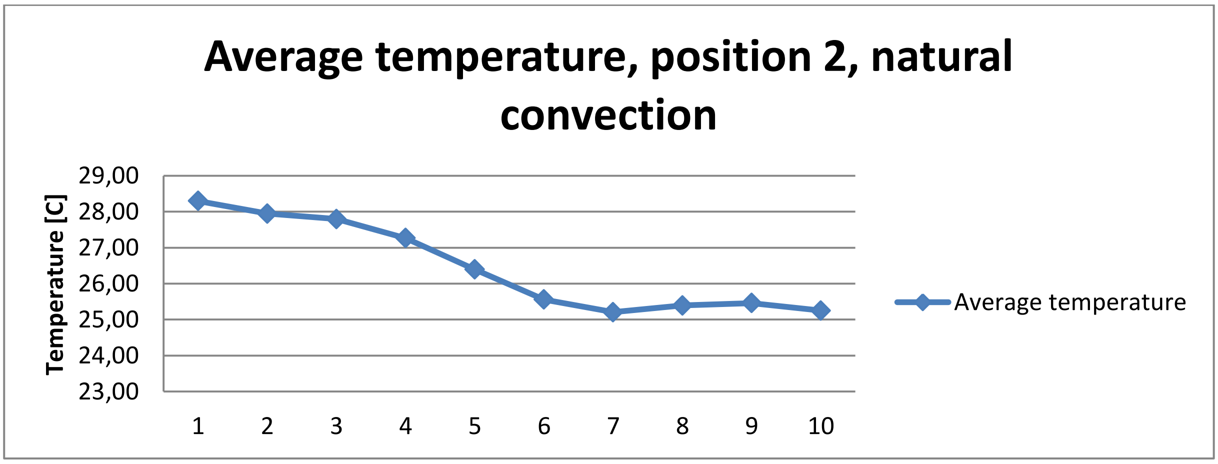

Figure 23: Average temperature for natural convection and oven-position 2.

7.6.2.3 Stratification and surface temperatures

Stratification in the living room:

- The temperatures varied some in the initial position and the stratification was around 3 °C.
- When the bar was moved to position 2 it was placed right next to the heat source, but the temperatures only increased 0.1-0.2 °C. The stratification was still at the same level as in the initial position.
- Small increases were measured for most sensors when the bar was moved to position three and the stratification increased with 0.1 °C.
- Moving the bar to position 4 resulted in a small decrease in temperature for PT1. The rest of the sensors measured small increases in temperature. The stratification was kept at the same level as in position 3.
- PT1 measured a small temperature decrease and the rest of the probes measured small temperature increases when the bar was moved to position 5b. This resulted in a decreased stratification.
- All sensors measured temperature increases when the bar was moved to position 6, the lower probes increased the most and the stratification was therefore decreased.
- Moving the bar back to the initial position resulted in temperature decreases for all probes. The stratification was kept constant at a slightly lower level than for position 6.
- The average temperature in the room was 27.42 °C.

Surface temperatures:

- The surface temperatures increased with 0.3-1.2 °C.
- There was solar radiation on some of the probes during the whole measuring period; this led to larger surface temperature increases.
- The surfaces on the same floors had similar temperatures, but the floor on the ground floor was colder than the walls. The air temperature upstairs changed with 0.5 °C during the whole measuring period.

Stratification in the staircase:

- There was solar radiation in the stair throughout the whole measuring period. This led to increasing temperatures when the thread was in the initial position. The stratification varied between 4.8 and 5.1 °C.
- Moving the thread did not affect PT16 and PT17, but PT18 measured a decreasing temperature and PT19 and PT20 measured temperature increases. This gave a significant reduction of the temperature stratification to 2.9 °C.
- The average temperature in the staircase was 24.31 °C.

7.6.3 Natural convection, oven-position 3

7.6.3.1 Velocity

- Initial position: The four lower probes alternated on having the clearly largest velocity. There was a gap down to probes 1, 2 and 4. Probes 3, 5 and 6 measured the lowest velocities after, with probe 3 being slightly above the two others.
- Moving the bar to the left side of the aperture: Probe 7 measured a decreased velocity and probe 3 measured an increased velocity. The remaining probes seemed to be unaffected.
- Moving the bar to the right side of the aperture: The velocity measured by probe 7 increased, and the velocity measured by probe 3 decreased again. The upper probes all measured slowly declining velocities.
- Moving the bar back to the initial position: The results follow the same trends as for the right side.
- Average velocity: The average velocity is given in Figure 24 which shows the same as described in the above.
- Average velocity with standard deviation: Again, the shape of the velocity profile deviates some from the theory; the shape is flatter both for the lower and upper probes. The standard deviation increased with increasing velocity and was largest for the lower probes, see Figure 25.
- These observations indicate that the neutral plane is likely to be located between probe 5 and probe 6.

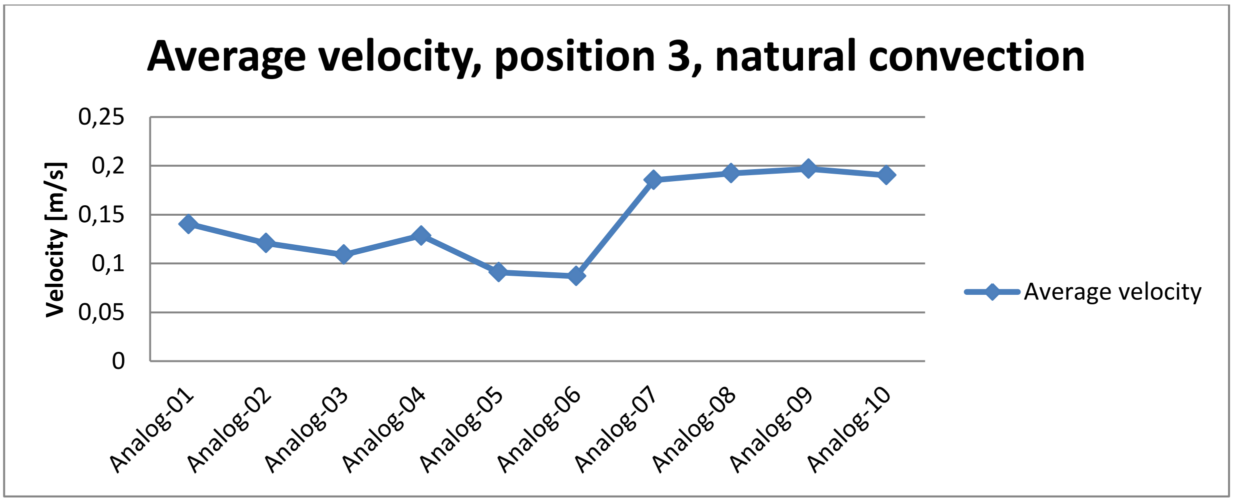

Figure 24: Average velocity per probe for natural convection and oven-position 3.

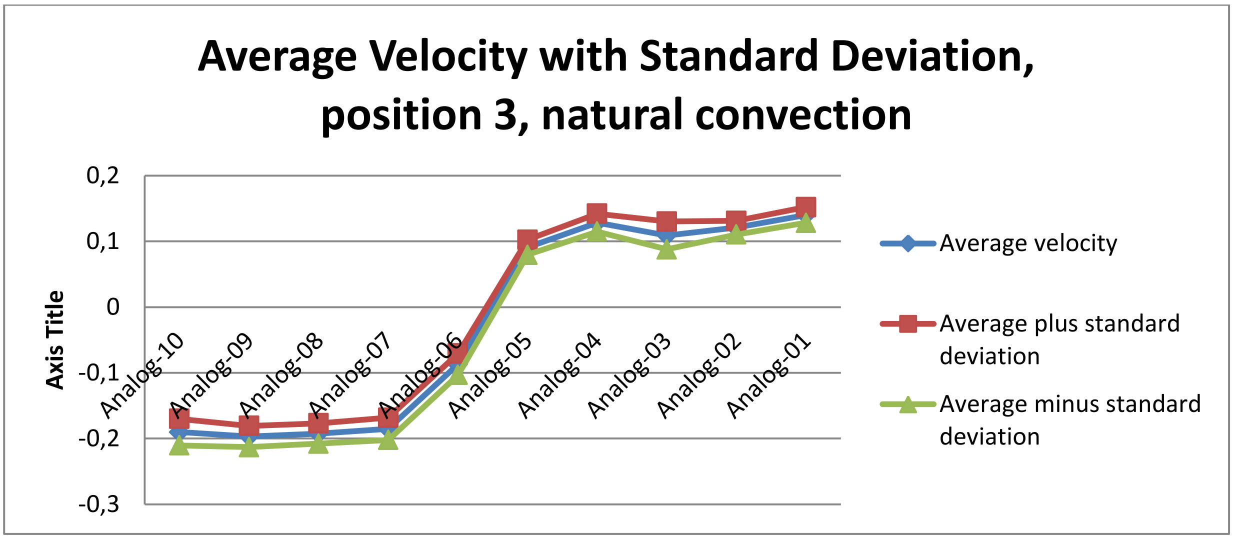

Figure 25: Average velocity with standard deviations for natural convection when the oven is in position 3.

7.6.3.2 Temperature in the aperture

- Probe 1 measured the largest temperature and also fluctuated a lot. The lower parts of the fluctuations were closely followed by probes 2-4. Probe 5 was slightly colder than probe 4, and was followed by a gap down to the rest of the probes. The five lowest probes measured more similar temperatures than the five upper probes.
- There were no visible changes when the bar was moved horizontally in the doorway.
- The average temperature given in Figure 26 shows the same as explained in the above.

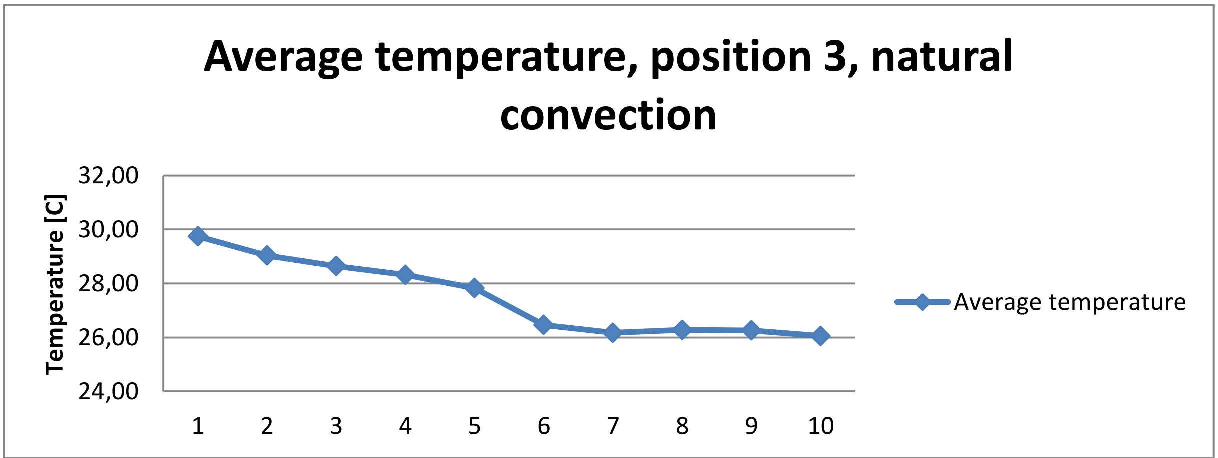

Figure 26: Average temperature for natural convection and oven-position 3.

7.6.3.3 Stratification and surface temperatures

Stratification in the living room:

- The temperatures were increasing when the bar was in the initial position due to solar radiation. PT4 and PT5 increased the most which gave a decrease in stratification.

- Moving the bar to position 2 resulted in slightly increasing temperatures for the three upper sensors. PT4 measured a constant temperature and PT5 measured a temperature decrease. Thus, the stratification increased.
- All sensor measured small temperature decreases when the bar was moved to position 3. The stratification was constant.
- Position 4 was located right next to the oven and a temperature increase was measured for all sensors. The stratification decreased slightly.
- Moving the bar to position 5 resulted in small increases for the three upper sensors. PT4 measured a temperature decrease of 0.6 °C and PT5 measured a drop of 1 °C, this led to increased stratification.
- There was some solar radiation on the middle of bar when it was moved to position 6; this resulted in 0.5 °C temperature increases for PT3 and PT4. PT1 had the same temperature as above, PT2 measured a small temperature increase and the temperatures measured by PT5 were kept almost at constant value. The stratification dropped with 0.1 °C.
- All temperatures declined when the bar was moved back to the initial position. The decrease was largest for the upper probes, so the stratification decreased with 0.6 °C.
- The average temperature in the living room was 29.02 °C.

Surface temperatures:

- The solar radiation led to increased surface temperatures.
- Most of the surfaces increased with 0.3-0.5 °C.
- PT8 measured a decreasing temperature as there was sun on the probe during the whole period except for the last part. Calculating the increase as a function of maximum and minimum temperature gave an increase of 1.4 °C.
- PT14 was also greatly affected by the solar radiation and measured an increase of 0.9 °C.
- The air temperature in the first floor increased with 0.4 °C.

Stratification in the staircase:

- The solar radiation affected the temperatures in the staircase; PT16, PT18 and PT19 measured increasing temperature the whole time the thread was in the initial position. PT17 measured an increasing temperature in the beginning of the period, then, due to the lack of sun the temperature decreased. The stratification was large due to the solar radiation: 5.7 °C.
- Again, moving the thread did not affect PT16 and PT17. PT18 measured a temperature decrease after the thread was moved, and PT19 and PT20 measured large temperature increases. Due to these large changes the stratification declined to 3.6 °C.
- The average temperature in the staircase was 25.11 °C.

7.6.4 Natural convection, oven-position 4

7.6.4.1 Velocity

- Initial position: Probes 1 and 2 measured the largest velocities followed by a gap down to probes 3 and 6-10. These probes measured a lot of fluctuations and therefore had alternating order. Probes 4 and 5 measured the lowest velocities.
- Moving the bar: Since the velocities fluctuated a lot it is hard to recognize differences in velocities when the bar was moved. Probes 3 and 6 appeared to measure larger velocities when the bar was moved to the left side of the aperture and lower velocities when the bar was moved to the right side.
- The graph showing the average velocity, Figure 27, shows the same as explained in the above. Figure 28 shows that the velocity profile is different compared to the other measurements. The standard deviations were large for all probes except the three upper probes, this shows that the middle and the lower probes fluctuated more than the upper probes.
- The velocities were very low, which makes fluctuations and disturbances more apparent.
- Some of the measured velocities were negative; this is due to the error margin of the equipment.
- The above explained observations indicate that the neutral plane is located between probes 4 and 5, closer to probe 5.

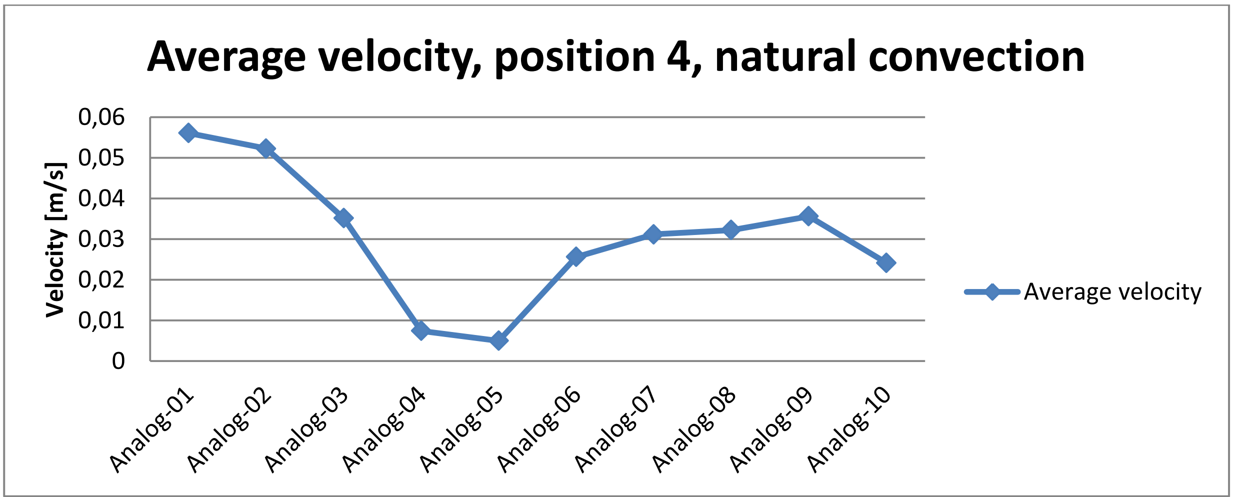

Figure 27: The average velocity for each probe whit natural convection and oven-position 4.

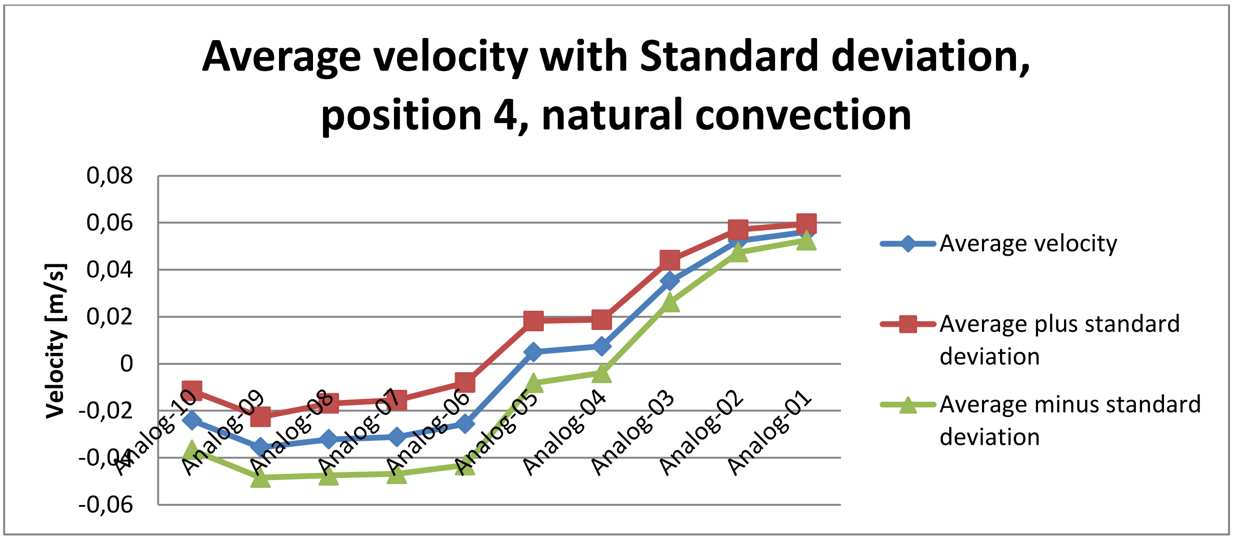

Figure 28: average velocity with standard deviation for natural convection and oven-position 4.

7.6.4.2 Temperature in the aperture

- Probe one measured a temperature approximately 2 °C warmer than the one measured by probe 2. The rest of the probes followed closely after probe 2 with probe 10 measuring the lowest temperature.
- There were no visible changes in temperature when the bar was moved horizontally.
- The graph with the average temperatures per probe shows the same as explained above, see Figure 29.

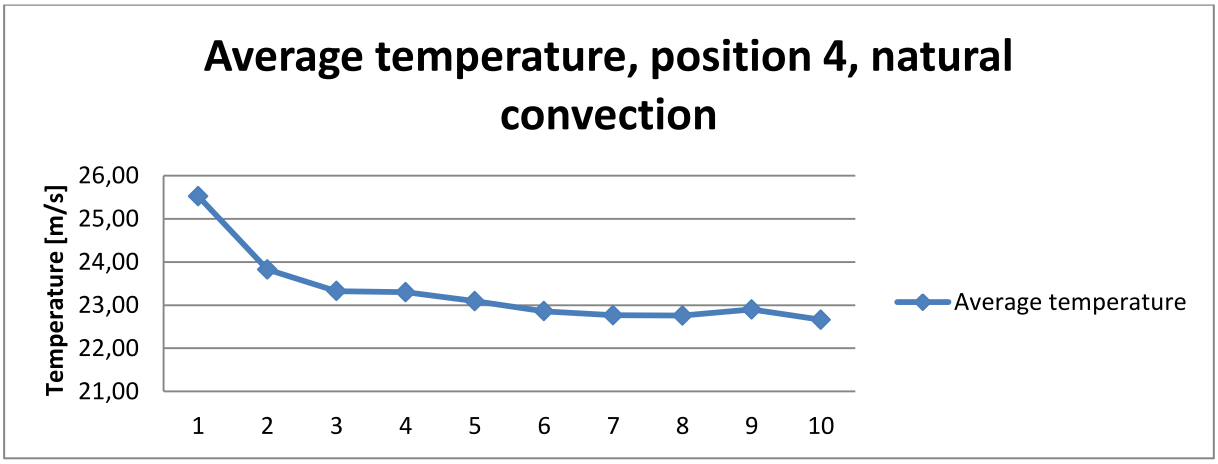

Figure 29: The average temperature for natural convection and oven-position 4.

7.6.4.3 Stratification and surface temperatures

Stratification in the living room:

- The temperatures and the stratification were stable when the bar was in the initial position. The stratification was 0.4 °C.
- The temperature measured by probes 1, 2 and 4 increased with 0.1-0.2 °C when the bar was moved to position 2 and the stratification increased with 0.1 °C.

- The upper temperature increased with 0.1 °C and the lowest temperature decreased with the same magnitude when the bar was moved to position 3 which gave an increase in stratification.
- Moving the bar to position 4 resulted in minor temperature increases for the upper probes, therefore the stratification increased.
- In position 5 the upper temperature decreased slightly, leading to less stratification.
- The temperatures and the stratification were stable when the bar was moved to position 6.
- The temperatures and the stratification were stable when the bar was moved back to the initial position.
- The average temperature in the living room was 23.10 °C.

Surface temperatures:

- There was no solar radiation on any of the surfaces during the measurements.
- The surfaces in the living room all had quite similar temperatures, this also applied to the surfaces on the first floor. The air temperature upstairs changed with 0.2 °C.
- The surface temperatures changed with 0.1-0.3 °C which were relatively small changes.

Stratification in the staircase:

- The probes only measured changes when the thread was in the initial position. PT16 measured the clearly warmest temperature which was about 2.5 °C warmer than the temperature measured by PT17. PT18 measured a temperature which was about 3 °C lower than the one measured by PT17 and 1 °C warmer than the temperature of PT19. PT20 had the lowest temperature. The stratification was large with a value of 8.2-8.4 °C.
- Moving the thread did not affect PT16 and PT17, but PT18, PT19 and PT20 all measured warmer temperatures after the thread was moved. This resulted in a reduction in stratification of about 1 °C.
- The average temperature in the staircase was 24.82 °C.

7.6.5 Forced convection, oven-position 1

7.6.5.1 Velocity

- Initial position: Probe 1 measured the largest velocity followed by probes 7-10, probes 2 and 4 and probe 3. After probe 3 there was a gap down to probes 5 and 6 which measured the lowest velocities. The lower probes had much more similar velocities than the upper probes.
- Moving the bar to the left side of the aperture: The lower probes and probe 2 measured velocity increases.
- Moving the bar to the right side of the aperture: The velocities changed towards the initial values.

- Moving the bar back to the initial position: The velocities were back to the initial levels.
- Average velocity: Figure 30 shows the same as explained in the above; the lower probes had similar velocities and the upper probes had more varying velocities. Probes 5 and 6 measured the lowest velocities and had approximately the same average velocity.
- Average velocity with standard deviation: Again, the shape of the velocity profile deviates some from the theory; the lower probes have a flatter curve, but the shape of the upper part is closer to the theory. The only deviation here is that probe 4 had a larger average velocity than probe 3. The standard deviation increased with increasing velocity.
- The neutral plane seems to be located between probes 5 and 6.

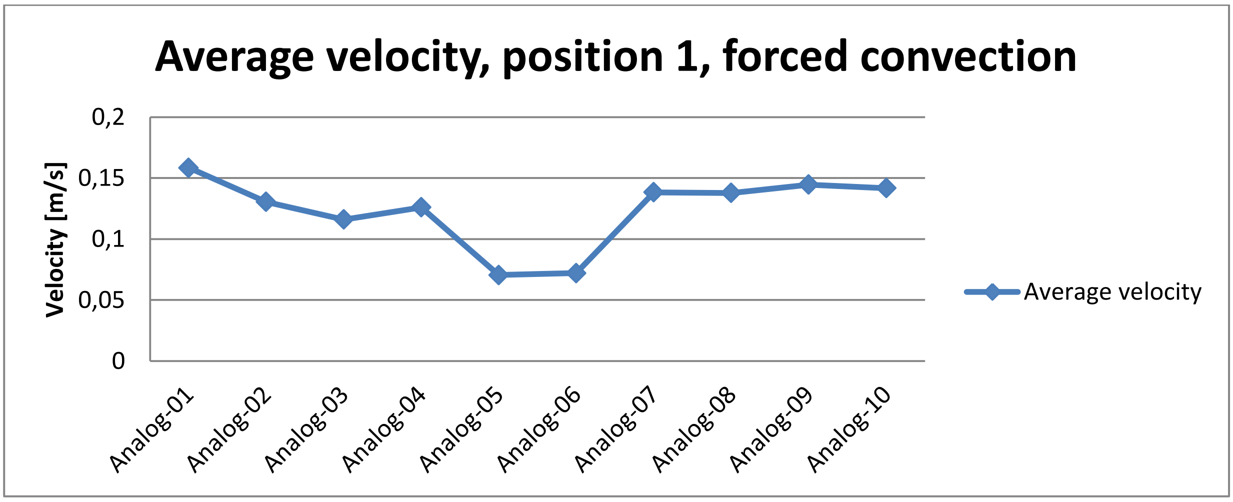

Figure 30: Average velocity per probe for forced convection and oven-position 1.

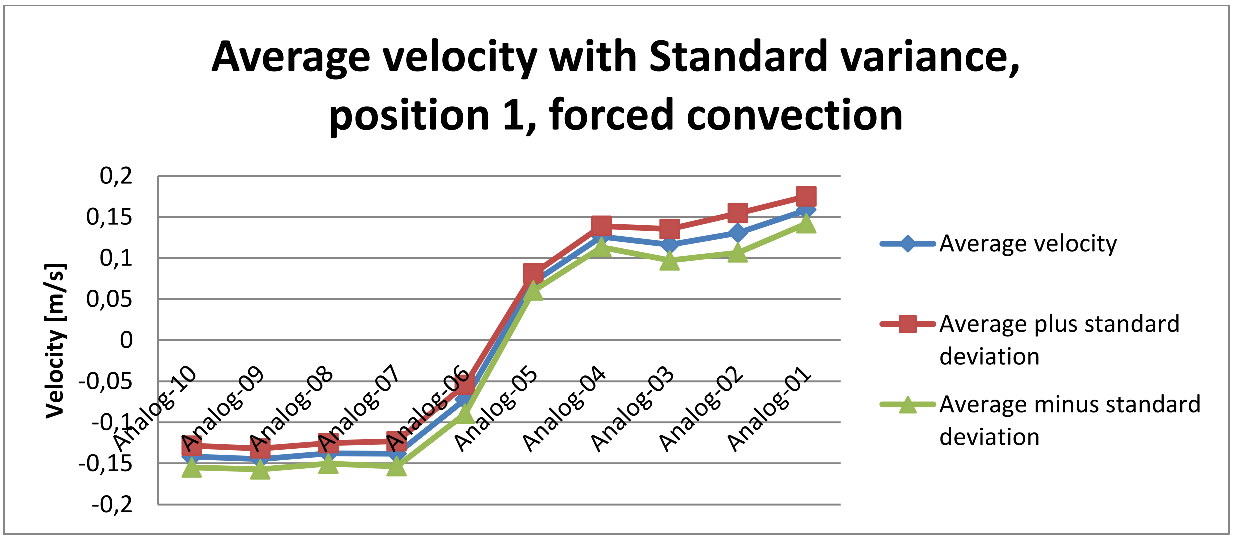

Figure 31: Average velocity with standard deviation for forced convection and oven-position 1.

7.6.5.2 Temperature in the aperture

- The probes were divided into two groups with similar temperatures: One group with probes 1-4 which measured the warmest temperatures and one group with probes 6-10 which measured less warm temperatures. Probe 5 measured a temperature between the temperatures of the two groups, but was closer to the upper grouping.
- There were no visible changes in the temperatures when the bar was moved horizontally in the doorway.
- Figure 32 shows the same as explained above: The upper and lower probes measured similar temperatures and probe 5 was in the middle of the transition between the warm and less warm layers.

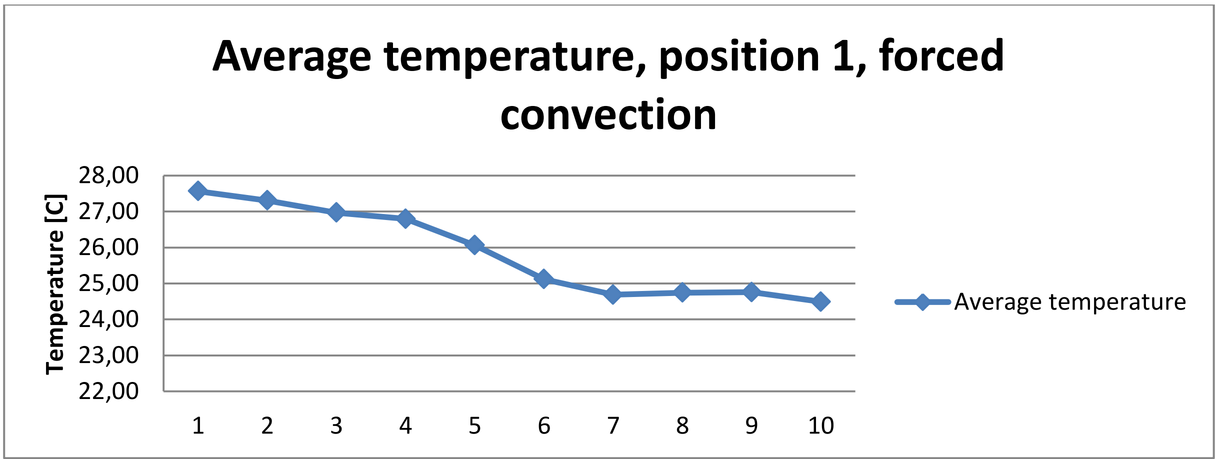

Figure 32: The average temperature for the probes with forced convection and oven-position 1.

7.6.5.3 Stratification and surface temperatures

Stratification in the living room:

- There were stable temperatures with minor variations when the bar was located in the initial position. The stratification decreased during the period and had a value of 1-1.4 °C.
- The upper sensor measured a temperature increase which led to increased stratification when the bar was moved to position 2.
- The same behaviour as in position 2 was measured in position 3 and the stratification increased again.
- Moving the bar to position 4 resulted in a temperature increase for PT1 and in a minor temperature decrease for PT3 and PT4. This gave an increase in stratification from 1.7 to 2.2 °C.
- Only minor changes in temperatures and stratification were measured when the bar was located between the oven and the staircase.
- Moving the bar to position 6 did not result in significant changes compared to position 5a.
- The two upper probes measured lower temperatures when the bar was moved back to the initial position, so the stratification decreased from 2.2 to 1.4 °C.

- The average temperature in the living room was 26.68 °C.

Surface temperatures:

- There was no solar radiation on the surfaces during the measuring period and there were only minor changes in surface temperatures.
- The air temperature upstairs changed with only 0.2 °C during the whole period.
- The walls on the ground floor had approximately the same temperatures and the floor was a bit colder. The surfaces on the first floor also had similar temperatures.

Stratification in the staircase:

- The temperatures were stable with only minor variations when the thread was in the initial position and the stratification varied slightly from 4.4 to 4.7 °C.
- Moving the thread did not affect PT16 and PT17, but PT18 measured a temperature decrease. PT19 and PT20 both measured temperature increases and the stratification declined to 2.3 °C.
- The average temperature in the stair case was 24.14 °C.

7.6.6 Forced convection, oven-position 2

7.6.6.1 Velocity

- Initial position: Probes 1-4 and 7-10 all measured similar velocities; probe 1 measured a slightly larger velocity than the rest. The lower probes were closer to each other than the upper probes. Probes 5 and 6 measured the lowest velocities.
- Moving the bar to the left side of the aperture: The three lowest probes measured larger velocities and probe 4 measured a slightly lower velocity.
- Moving the bar to the right side of the aperture: Probes 1-4 measured larger velocities and the velocities of the lower probes started to decline slowly.
- Moving the bar back to the initial position: Probes 1-4 changed towards the initial velocities and the lower probes continued to measure a slow temperature decline.
- Average velocity: Figure 33 shows that the average velocities of the upper and lower probes are not that far from each other. The variations were larger between the upper probes than for the lower probes.
- Average velocity with standard deviation: The shape of the graph in Figure 34 deviates some from the theory as the lower half is too flat and the average velocities of probes 3 and 4 were larger than that of probe 2. The standard deviations were larger for the upper probes than for the lower probes.
- These observations indicate that the neutral plane is located between probes 5 and 6 and that it might be closer to probe 6.

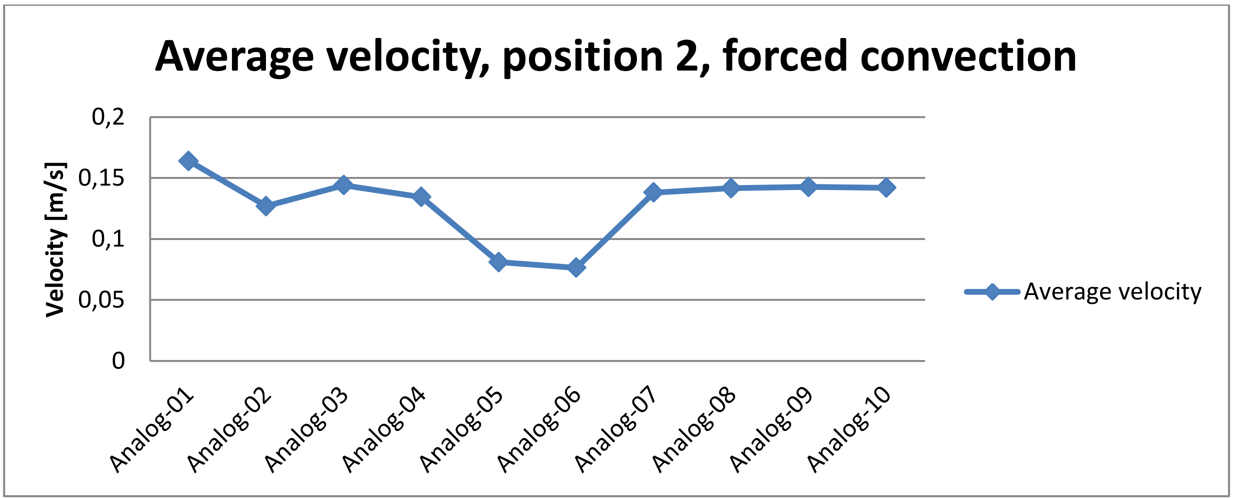

Figure 33: Average velocity with forced convection and oven-position 2.

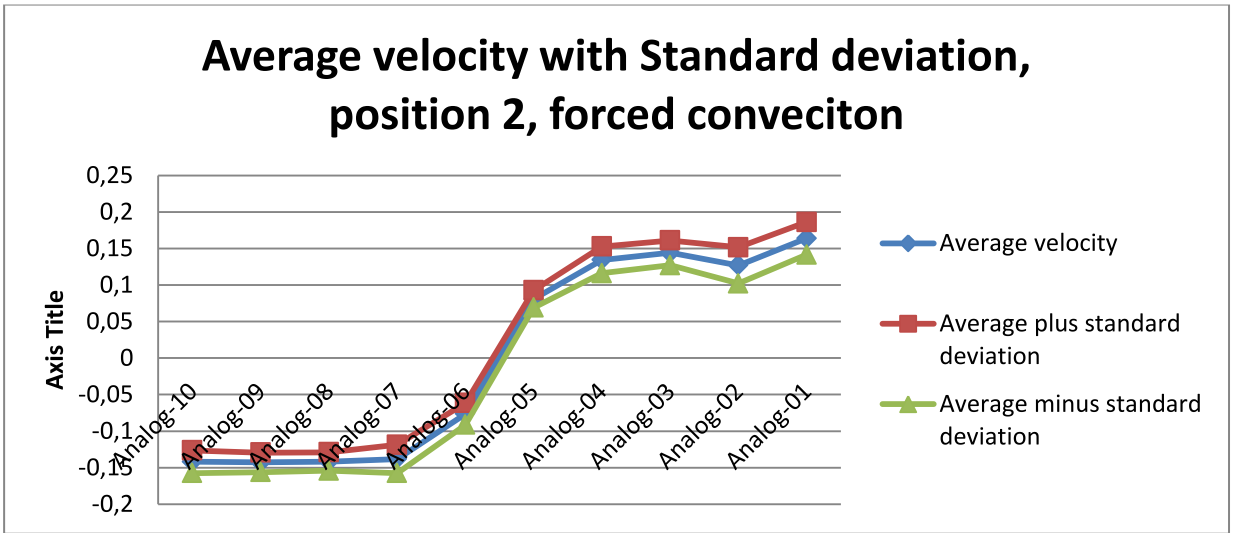

Figure 34: Average velocity with standard deviation for forced convection and oven-position 2.

7.6.6.2 Temperature in the aperture

- The temperatures were divided into a warm and a less warm group, but the two groups were not far from each other. The warm group consisted of probes 1-4 in ascending order and the less warm group was compromised by probes 6-10, where probe 6 was slightly warmer than the rest of the group. Probe 5 measured a temperature which was in between the temperatures of the two groups.
- There were no visible temperature changes when the bar was moved horizontally in the aperture.
- The average temperatures, which are graphed in Figure 35, show the same as explained in the above.

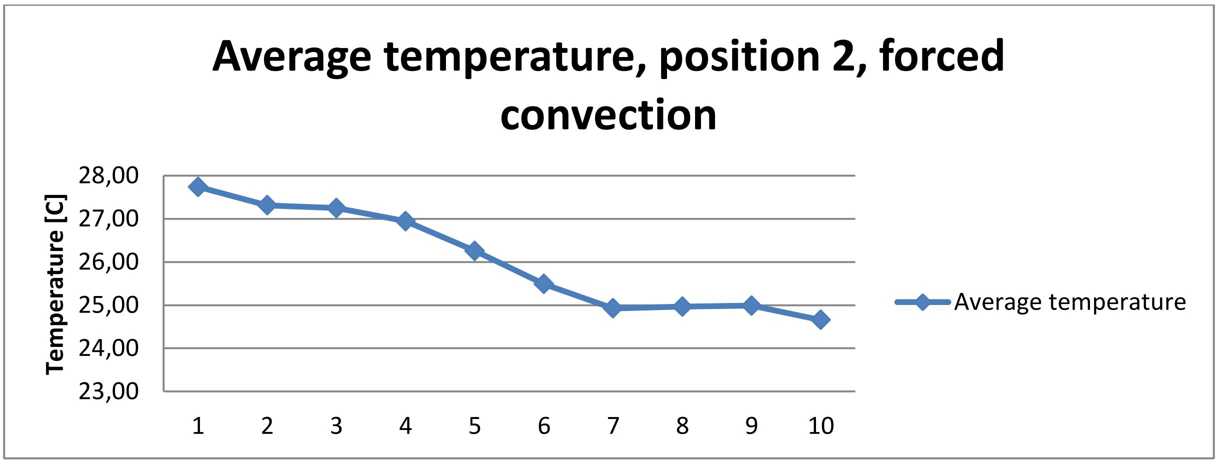

Figure 35: Average temperature with forced convection and oven-position 2.

7.6.6.3 Stratification and surface temperatures

Stratification in the living room:

- The temperatures and the stratification were stable when the bar was located in position 1. The stratification was 2.1-2.3 °C.
- Moving the bar to position 2, which is right next to the convector, resulted in temperature increases for all probes. PT5 measured the largest temperature increase followed by PT1 and PT2. The temperature increase measured by PT5 was so large that the stratification turned negative; the temperature measured by PT5 was 1.1 °C warmer than that measured by PT1.
- The upper probes measured stable temperatures when the bar was moved to position 3, but the lower probes had large temperature decreases. This led to the stratification turning positive again; the stratification was 1.5 °C in the end of the period.
- PT1 and PT5 measured temperature declines when the bar was moved to position 4, but the temperature declined most for the lower probe. Thus, the stratification continued to increase.
- Moving the bar to position 5 led to minor temperature decreases for PT1, PT2 and PT3. The two remaining probes had stable temperatures and the stratification therefore decreased.
- The three lower probes measured increasing temperatures so the stratification decreased further when the bar was moved to position 6.
- The upper temperatures increased slightly when the bar was moved back to the initial position. The lower temperatures were constant, thus, the stratification increased slightly.
- The average temperature in the living room during the whole measuring period was 27.13 °C.

Surface temperatures:

- There was no solar radiation on the surfaces during the measuring period and there were only minor changes in surface temperatures.

- The air temperature upstairs only changed with 0.1 °C during the whole period.
- The walls on the ground floor had approximately the same temperatures, but the kitchen walls were slightly warmer and the floor was a bit colder. The surfaces on the first floor also had similar temperatures.

Stratification in the staircase:

- The temperatures were stable with only minor variations when the thread was in the initial position and the stratification varied slightly from 4.8 to 5 °C.
- Moving the thread did not affect PT16 and PT17, but PT18 measured a temperature decrease and PT19 and PT20 both measured temperature increases. The stratification declined to 2.5 °C.
- The average temperature in the stair case was 24.28 °C.

7.6.7 Forced convection, oven-position 3

7.6.7.1 Velocity

- Initial position: Probes 1 and 7-10 measured the largest velocities with alternating order. Then follows probes 2-4 followed by probed 5 and 6 which measured the lowest velocities. Again, the lower probes had more similar velocities than the upper probes.
- Moving the bar to the left side of the aperture: All probes except probe 1 measured a velocity increase when the bar was moved. The velocity of probes 7-10 increased the most and probes 2-4 increased the least. Probe one measured a velocity decline.
- Moving the bar to the right side of the aperture: The velocity changed towards the initial velocity levels.
- Moving the bar back to the initial position: The trends from the above continued.
- Average velocity: Figure 36 shows that the lower probes had the highest average velocities. Probe 2 had the lowest average velocity of the upper probes and probes 5 and 6 had the lowest average velocities.
- Average velocity with standard deviation: The velocity profile is flatter in the lower part than it should be according to theory. The shape of the upper part deviates from the theory as the average velocity of probes 3 and 4 were larger than that of probe 2. The standard deviations were larger for the lower probes than for the upper probes and increased with increasing velocity.
- The above presented observations indicate that the neutral plane is located between probes 5 and 6.

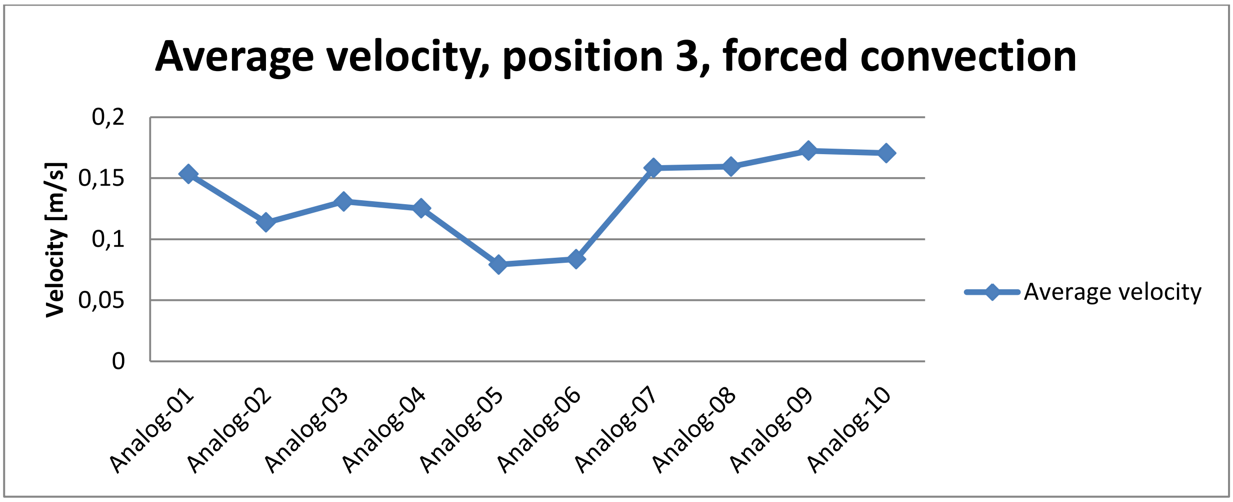

Figure 36: Average velocity per probe for forced convection and oven-position 3.

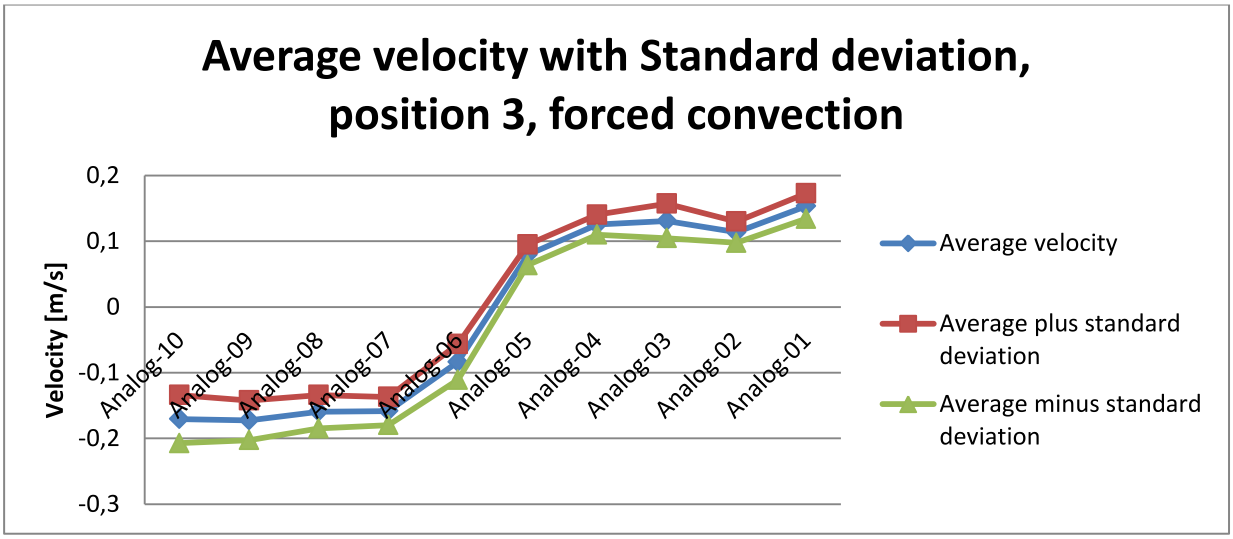

Figure 37: Average velocity with standard deviation for forced convection and oven-position 3.

7.6.7.2 Temperature in the aperture

- Probe 1 measured the clearly warmest temperature followed by probe 2, these temperatures fluctuated a lot compared to the rest of the temperatures. Probe 2 was followed by probes 3 and 4, then probe 5 followed after a small gap. Then, after another gap were probe 6, followed by a small gap and probes 7-10.
- There were no clear temperature differences when the bar was moved horizontally, except from large variations in the temperature of the lower probes due to disturbances.
- The average temperatures in Figure 38 show the same trends as explained above. There was no clear gap between the temperatures of the heated and unheated air flows, but a more gradual transition. The real average temperatures of probes 7-10 may be slightly higher due to the disturbances.

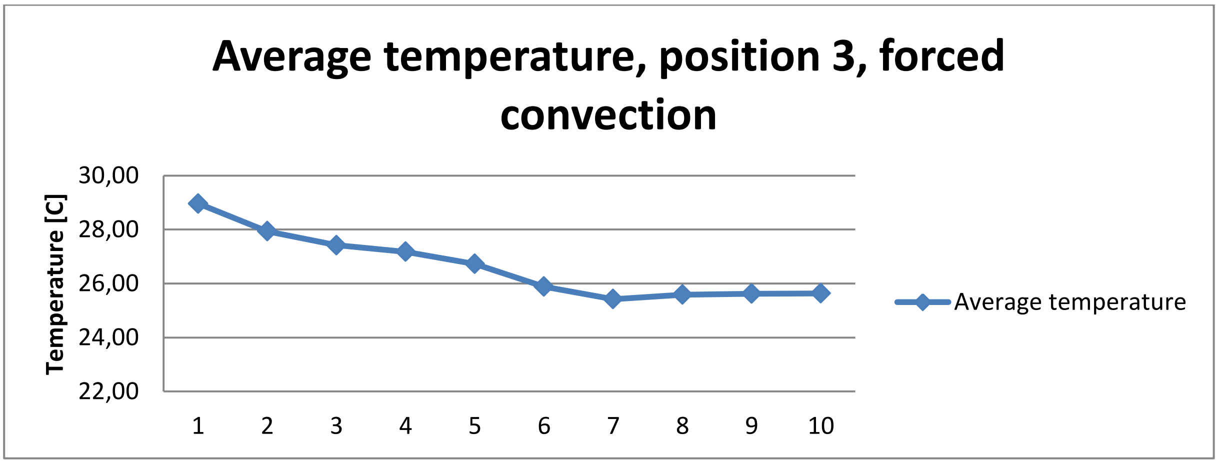

Figure 38: The average temperatures in the aperture for forced convection and oven-position 3.

7.6.7.3 Stratification and surface temperatures

Stratification in the living room:

- The temperatures and the stratification were stable when the bar was located in position 1, the stratification varied from 0.9 to 1.2 °C.
- Moving the bar to position 2 did not result in any significant changes.
- The stability continued in position 3.
- All probes measured small temperature increases when the bar was moved to position 4 and the stratification increased slightly.
- Moving the bar to position 5b led to minor temperature increases for PT1-PT4, this gave increased stratification.
- All of the temperatures increased when the bar was moved to position 6. The lower probes measured larger temperature increases than the upper probes, thus, the stratification declined.
- The upper temperatures declined and the lower temperatures increased when the bar was moved back to the initial position. This gave a reduction in stratification from 1 to 0.4 °C.
- The average temperature in the living room during the whole measuring period was 27.34 °C.

Surface temperatures:

- There was some solar radiation on the surfaces during the measuring period, and many of the surfaces experienced only small changes in surface temperatures. There was solar radiation on PT8, PT14 and PT15.
- The air temperature upstairs only changed with 0.2 °C during the whole period.
- The walls on the ground floor had approximately the same temperatures, the floor was a bit colder in the beginning of the period, but the temperature increased due to the solar radiation. The surfaces on the first floor also had similar temperatures, but PT14 had a larger temperature increase due to the solar radiation.

Stratification in the staircase:

- There was some solar radiation from time to time in the staircase.
- The temperatures were stable with only minor variations when the thread was in the initial position and the stratification was 5.2-5.3 °C.
- Moving the thread did not affect PT16 and PT17, but PT18 measured a temperature decrease. PT19 and PT20 both measured temperature increases and the stratification declined to 2.7-2.8 °C.
- The average temperature in the stair case was 24.52 °C.

7.6.8 Panel heaters, oven-position 1

7.6.8.1 Velocity

- Initial position: Probes 1-4 and 7-10 measured approximately the same velocities, probes 2 and 3 measured a slightly lower velocity than the rest and probes 5 and 6 measured the lowest velocities where the velocity of probe 6 fluctuated more than that of probe 5.
- Moving the bar to the left side of the aperture: Probes 6-10 all measured an increased velocity when the bar was moved. The velocities measured by probes 1-4 seemed to decline slightly.
- Moving the bar to the right side of the aperture: The increased velocities declined and the ones that decreased in the above increased. Then, probes 8-10 measured new velocity increases.
- Moving the bar back to the initial position: The velocities moved towards the initial values.
- Average velocity: Figure 39 show that the average velocities of the upper and lower probes were at approximately the same level. For the upper part the average velocity declined for probes 2 and 3 and for the lower part the average velocity decreased for probe 10. Probes 5 and 6 had the lowest average velocities.
- Average velocity with standard deviation: Probe 4 having a larger average velocity than probes 2 and 3, and probes 7 and 8 having larger average velocities than probes 9 and 10 makes the shape of the velocity profile deviate from the theory. The standard deviations were small for the middle probes and increased with increasing velocity.
- The above mentioned observations indicate that the neutral plane is located between probes 5 and 6.

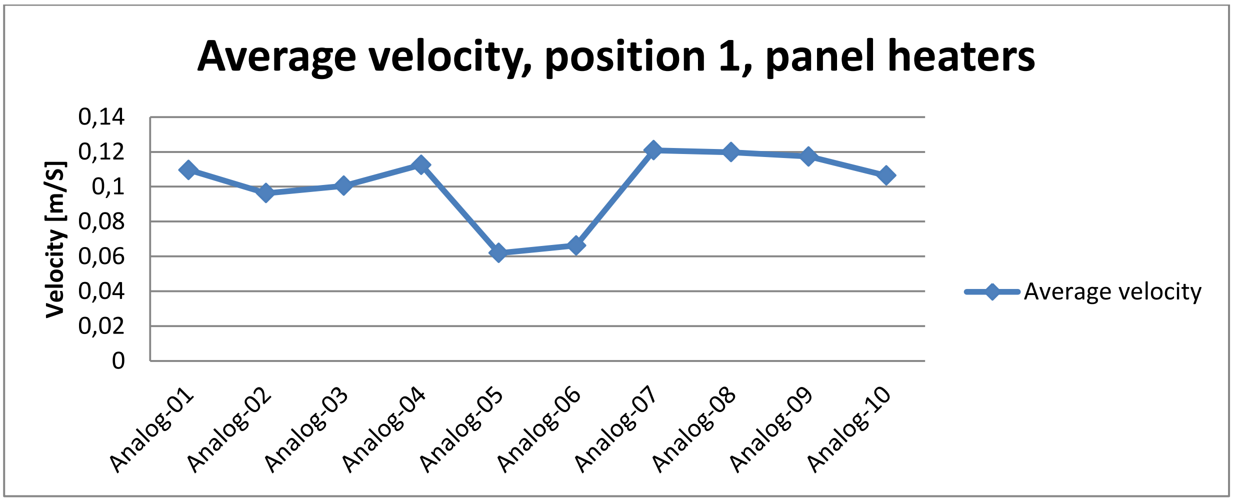

Figure 39: Average velocity for each probe with the panel heaters and oven-position 1.

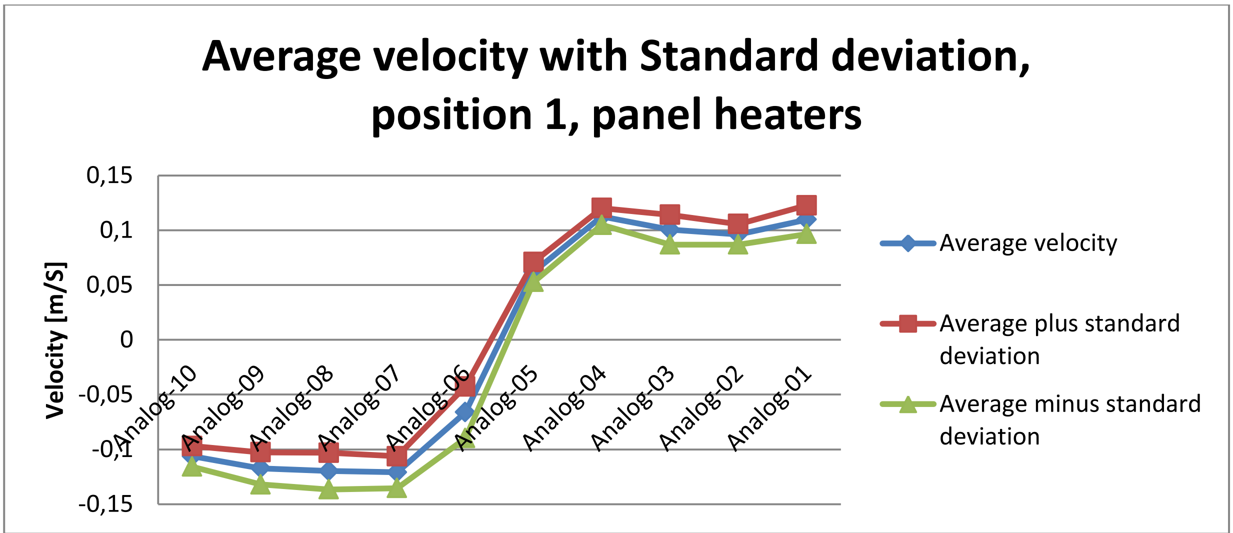

Figure 40: Average velocity with standard deviation for panel heaters placed in position 1.

7.6.8.2 Temperature in the aperture

- Probes 1 and 2 measured the warmest temperatures in alternating order followed by probes 3 and 4 which were followed by a gap down to probe 5 and a new gap down to the remaining probes. The lower probes had more similar temperatures than the upper probes.
- There were no visible changes in temperature when the bar was moved horizontally in the doorway.
- The average temperatures per probe shown in Figure 41 reveal the same as explained above: From the two upper probes the temperature declined with decreasing height, and this decline flattens out after probe 6.

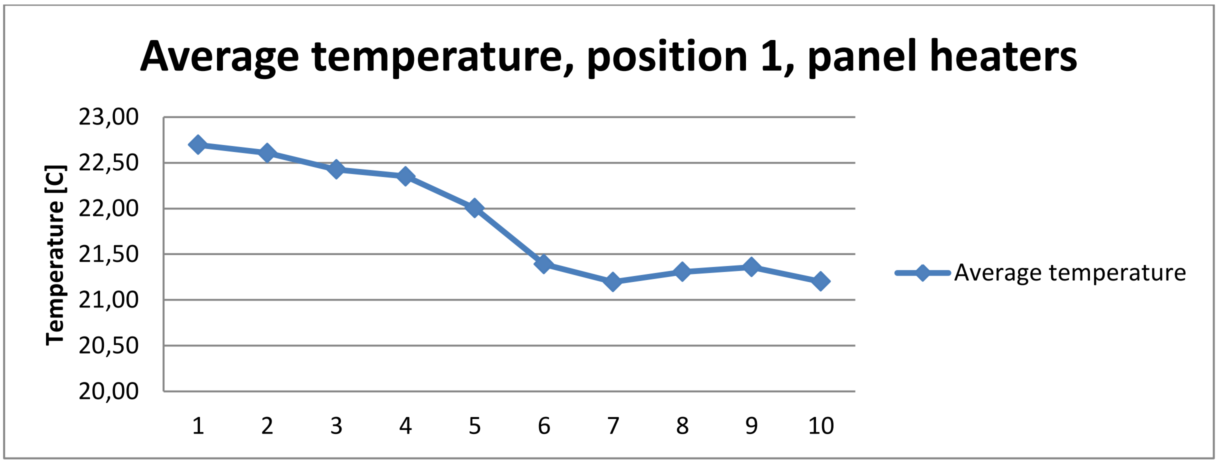

Figure 41: Average temperature per probe for panel heaters located in position 1.

7.6.8.3 Stratification and surface temperatures

Stratification in the living room:

- Both the temperatures and the stratification were stable when the bar was located in position 1, the stratification was 0.7-0.8 °C.
- The stability continued when the bar was moved to positions 2, 3 and 4.
- The stratification increased to 0.9 °C when the bar was moved to position 5a and position 6. All the temperatures increased with 0.1 °C in these positions.
- Moving the bar back to the initial position did not result in any large changes; the sensors measured changes of 0.1 °C and the stratification was 0.9 °C.
- The average temperature in the living room during the whole measurement period was 22.43 °C.

Surface temperatures:

- There was no solar radiation on any of the surfaces during the measurement period so the surfaces had only small temperature increases.
- The air temperature on the first floor varied with only 0.1 °C.
- The surfaces on the ground floor had around the same temperature, this also applied for the surfaces on the first floor.

Stratification in the staircase:

- The temperatures and the stratification were stable when the thread was placed in the initial position. The stratification was 1.1-1.3 °C.
- Moving the thread to position 2 did not affect PT16 and PT17, as it should not do. PT18 was also not affected, PT19 only measured a temperature increase of 0.1 °C and the temperature measured by PT20 increased with 0.6 °C. The stratification was reduced to 0.6-0.7 °C.
- The average temperature was 21.21 °C.

7.6.9 Panel heaters, oven-position 2

7.6.9.1 Velocity

- Initial position: Probe 1 measured the clearly largest velocity followed by probes 2 and 4, these probes measured a lot of variations in velocity. Then, probes 7-10 and 3 followed and probes 5 and 6 measured the lowest velocities. The upper probes varied a lot more than the lower probes, they were also more spread.
- Moving the bar to the left side of the aperture: Probes 1-4 measured velocity drops when the bar was moved, the drops were of varying sizes and the velocity measured by probe 1 declined the most. The lower probes measured small velocity increases.
- Moving the bar to the right side of the aperture: The velocities that declined in the above except for the one measured by probe 3 increased so that the velocities changed back to the initial level. The obtained velocity for probe 3 was larger than the initial velocity.
- Moving the bar back to the initial position: The velocity measured by probe 3 also changed back to the initial velocity level.
- Average velocity: The graph showing the average velocity of the probes, Figure 42, reveals the same as presented in the above.
- Average velocity with standard deviation: The shape of the velocity profile given in Figure 43 deviates some from the theoretical model: The lower half of the graph is too flat and the average velocity of probe 4 should have been lower than that of probe 3. The standard deviations were large for the upper probes and increased with the velocity.

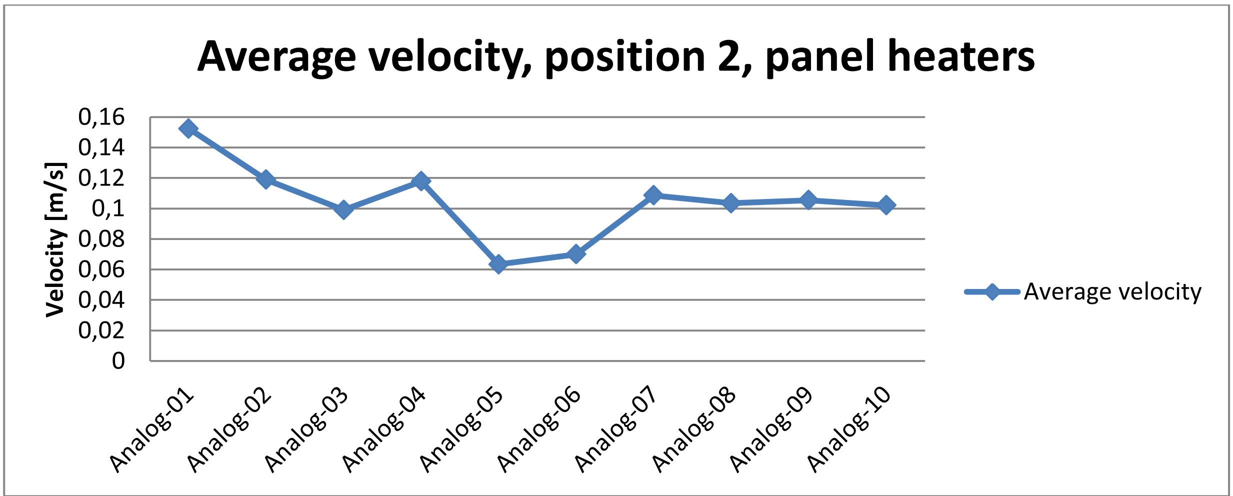

Figure 42: Average velocity per probes for the panel heaters placed in position 2.

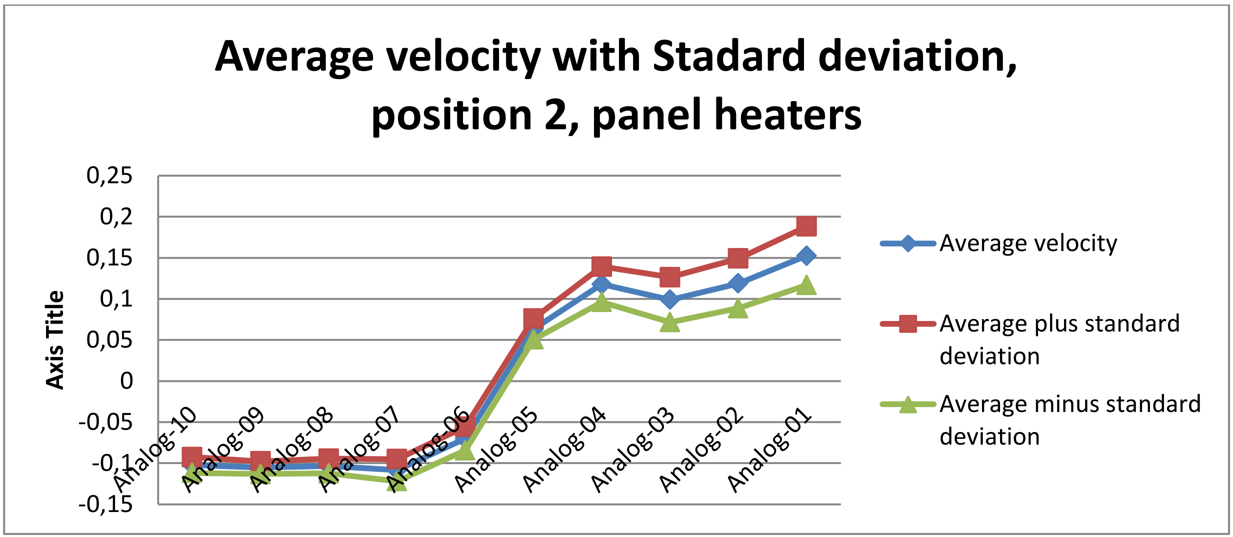

Figure 43: Average velocity with standard deviation for the panel heaters in position 2.

7.6.9.2 Temperature in the aperture

- The temperatures were divided into two distinct groups: Probes 1-4 measured warmer temperatures and probes 6-10 measured less warm temperatures with probe 5 in the middle of the two groups. The temperatures in the two groupings were close to each other.
- Moving the bar horizontally in the opening did not lead to any visible temperature changes.
- The average temperatures, graphed in Figure 44, do not reveal anything that is not already presented in the above.

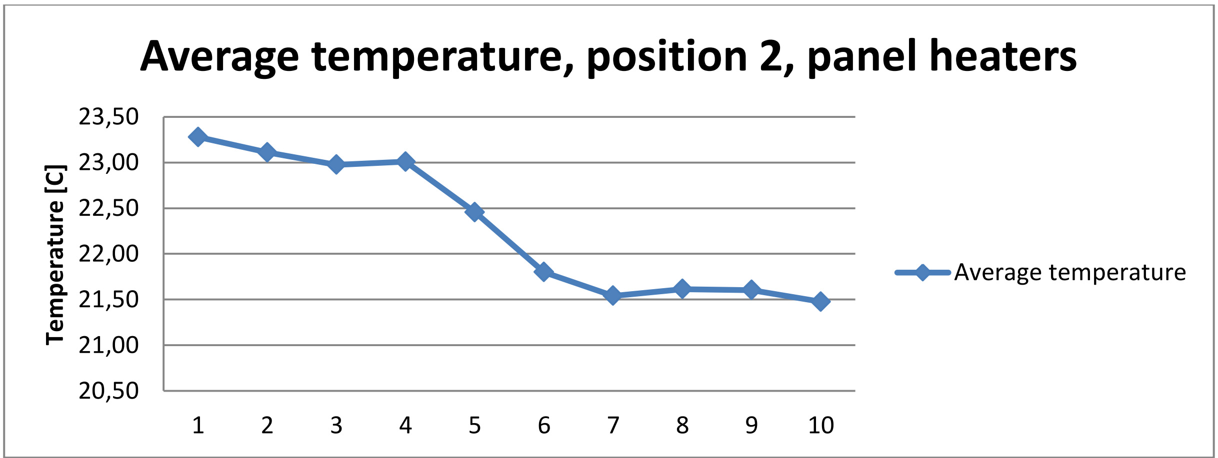

Figure 44: Average temperature for the panel heaters located in position 2.

7.6.9.3 Stratification and surface temperatures

Stratification in the living room:

- Both the temperatures and the stratification were stable when the bar was located in the initial position. The stratification was 1.5-1.7 °C.
- The same stability continued when the bar was moved to positions 2 and 3.

- Moving the bar to position 4 led to a temperature decrease for PT1, the stratification therefore declined.
- The temperatures varied with 0.1-0.2 °C in position 5 and the stratification varied between 0.9 °C and 1.2 °C.
- All temperatures, and therefore also the stratification, were stable in position 6.
- Moving the bar back to the initial position resulted in an increased temperature for PT1-PT4. PT5 measured a constant temperature and the stratification increased from 1°C to 1.3 °C.
- The average temperature in the living room during the whole measurement period was 22.92 °C.

Surface temperatures:

- There was no solar radiation on any of the surfaces during the measurement period, so the surfaces only had small temperature increases.
- The air temperature on the first floor varied with only 0.1 °C.
- The surfaces on the ground floor had approximately the same temperature, this also applied for the surfaces on the first floor.

Stratification in the staircase:

- The temperatures and the stratification were stable when the thread was placed in the initial position, the stratification was 1.7-1.8 °C.
- Moving the thread to position 2 did not affect PT16 and PT17 as expected, PT18 registered a temperature drop after the thread was moved and PT19 measured a temperature increase of 0.1 °C. PT20 measured an increase of 0.6 °C and the stratification was reduced to 0.6-0.7 °C.
- The average temperature in the stair case was 21.49 °C.

7.6.10 Panel heaters, oven-position 3

7.6.10.1 Velocity

- Initial position: Probes 7-10 alternated on measuring the largest velocity. Probes 1-4 followed after a small gap. Probes 5 and 6 alternated on measuring the lowest velocity. The lower probes had more similar and less fluctuating velocities than the upper probes.
- Moving the bar to the left side of the aperture: All probes except probes 2 and 5 measured a temperature increase when the bar was moved.
- Moving the bar to the right side of the door: The velocities of the lower probes continued at the same level, probe 6 measured a velocity decline.
- Moving the door back to the initial position: The velocities continued at the same level as in the above and the upper probes continued to fluctuate.

- Average velocity: Figure 45 shows that the lower probes have quite similar and largest average velocity. The average velocity increased in the upper half as the height declines. Probes 5 and 6 had the lowest average velocities.
- Average velocity with standard deviation: The shape of the velocity profile deviates some from theory as the average velocity in the upper half of the aperture declined with the height. The lower half also deviates from the theory as the curve is too flat. The standard deviations were large for probe 6 and for the probes with the largest velocities, see Figure 46.

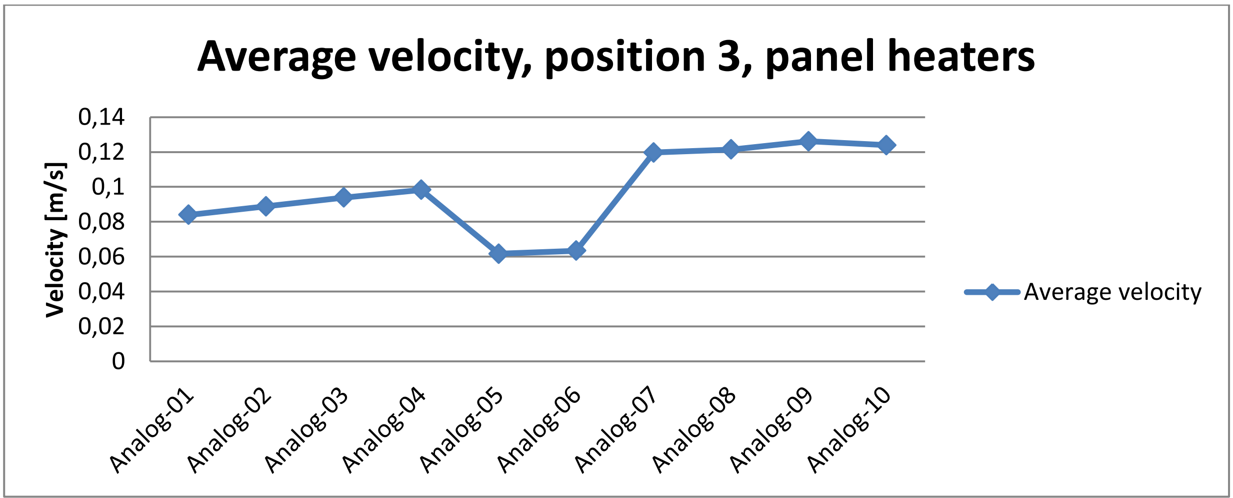

Figure 45: Average velocity for panel heaters located in position 3.

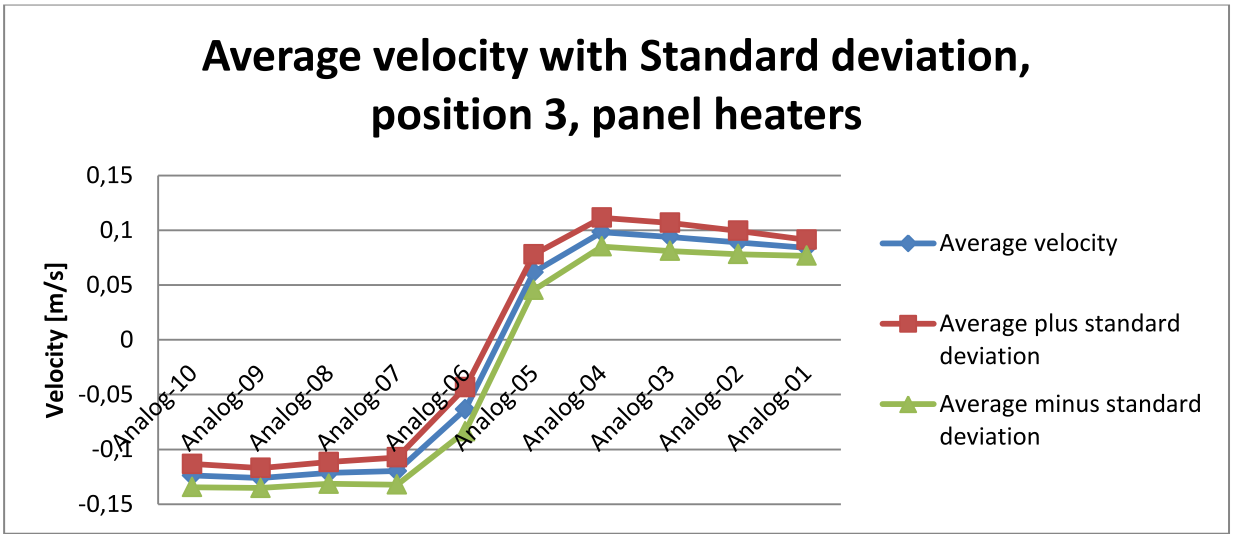

Figure 46: Average velocity with standard deviation for the panel heaters in position 3.

7.6.10.2 Temperature in the aperture

- Probes 1 and 2 alternated on measuring the warmest temperature and were followed by probes 3-5. Probes 6-10 followed after a gap; probe 6 measured a warmer temperature than the rest of the lower probes and probe 10 measured a slightly lower temperature. The temperatures of the upper probes varied more than that of the lower probes.

- There were no significant changes in the temperatures when the bar was moved horizontally in the doorway.
- Figure 47 gives the average temperature of the probes and shows the same temperature distribution as explained in the above.

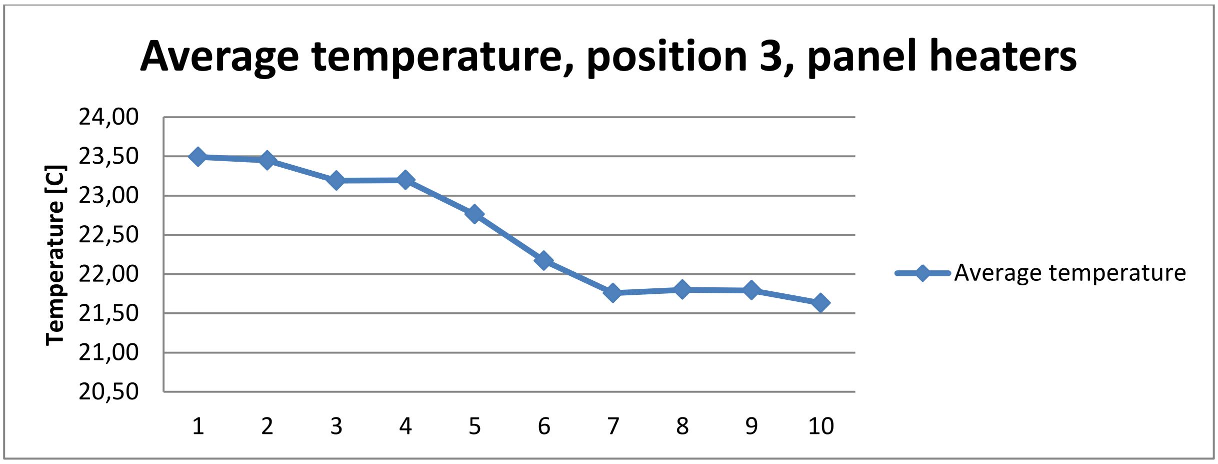

Figure 47: Average temperature for the panel heaters in position 3.

7.6.10.3 Stratification and surface temperatures

Stratification in the living room:

- Both the temperatures and the stratification were stable when the bar was located in the initial position. The stratification was 0.8-1 °C.
- The temperatures increased slightly when the bar was moved to position 2, but the stratification continued being stable. This also applies to positions 3, 4 and 5.
- The probes continued to only measure small temperature changes when the bar was moved to position 6 and the stratification was 0.9-1 °C. This also applies when the bar was moved back to position 1.
- The average temperature in the living room during the whole measurement period was 23.20 °C.

Surface temperatures:

- There was no solar radiation on any of the surfaces during the measurement period, so the surfaces only had small temperature increases.
- The air temperature on the first floor varied with only 0.1 °C.
- The surfaces on the ground floor had approximately the same temperature, this also applied for the surfaces on the first floor.

Stratification in the staircase:

- The temperatures and the stratification were stable when the thread was placed in the initial position and the stratification was 1.8-2.1 °C.
- Moving the thread to position 2 did not affect PT16 and PT17, as it should not do. PT18 registered a temperature drop after the thread was moved, PT19 measured a

temperature increase of 0.2 °C, the temperature measured by PT20 increased with 0.7 °C and the stratification was reduced to 0.8 °C.

- The average temperature was 21.53 °C.

7.6.11 Panel heaters, oven-position 4

7.6.11.1 Velocity

- Initial position: Probe 1 measured the largest velocity and was followed by a gap down to probe 2. Then the rest of the probe followed in an order that was hard to decide due to a lot of variations.
- Moving the bar to the left side of the door: Due to all the fluctuations it was difficult to see any distinct changes, but probes 1 and 2 had increasing velocities and there were more disturbances affecting the rest of the probes.
- Moving the bar to the right side of the aperture: The velocity measured by probed 1 and 2 decreased and there were fewer disturbances.
- Moving the bar back to the initial position: The velocities behaved as when the bar was in the right side of the opening.
- Average velocity: Figure 48 shows that probe 1 had the highest average velocity, followed by probe 2 and probe 9. After probe 2 the average velocity declined until it started to increase again after probe 4 and after probe 9 the average velocity decreased again.
- Average velocity with standard deviation: The shape of the velocity profile deviates from the theory, but is close to the right shape in the upper half. The standard deviation was large for all probes except from probe 1 which did not vary as much as the rest of the probes.
- The velocities were low.
- The above presented observations indicate that the neutral plane is between probes 4 and 5, closest to probe 4.

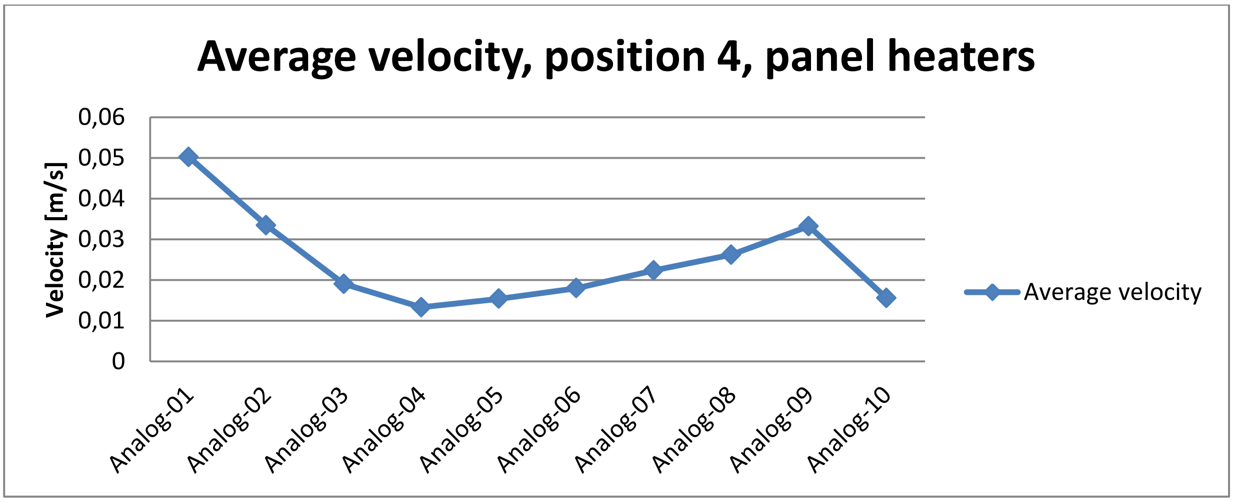

Figure 48: The average velocity for the panel heaters in location 4.

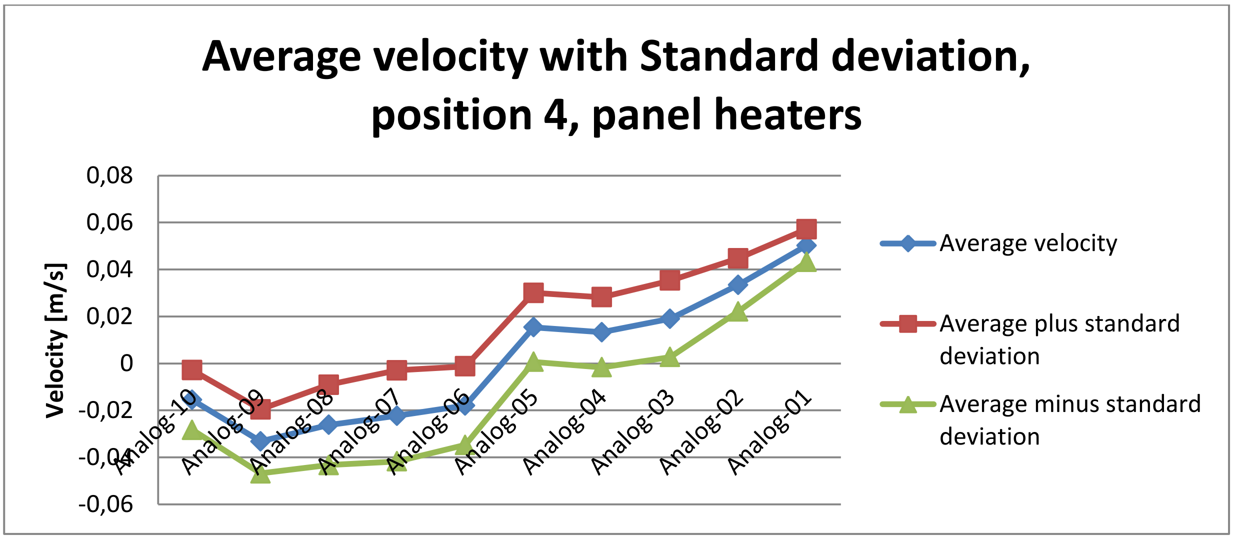

Figure 49: Average velocity with standard deviation for the panel heaters in position 4.

7.6.11.2 Temperature in the aperture

- Probe 1 measured a temperature that was clearly warmer than the rest of the measured temperatures, probe 2 followed after a gap followed by a small gap down to probes 3-5. Then, after another small gap, probes 6-10 measured the lowest temperatures.
- The temperatures of probes 2-10 started to increase slowly after the bar was moved to the left in the aperture. This behaviour continued when the bar was moved to the right side of the aperture and when it was moved back to the initial position.
- Figure 50 shows that probe 1 had the highest average temperature followed by probe 2. Probes 3-5 had approximately the same average temperature, the same was the case for probes 6-10.

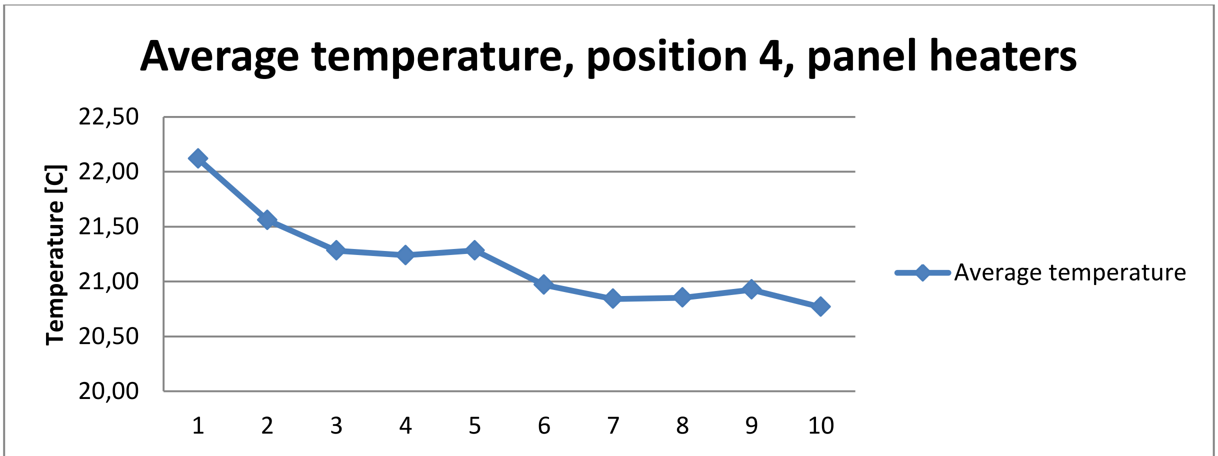

Figure 50: Average temperature in the aperture per probe when the panel heaters is in position 4.

7.6.11.3 Stratification and surface temperatures

Stratification in the living room:

- Both the temperatures and the stratification were stable when the bar was located in the initial position, the stratification was 0.3-0.5 °C.

- The temperatures increased slightly when the bar was moved to position 2, but the stratification continued to be stable. This also applies to position 3, 4 and 5.
- The probes continued to only measure small changes when the bar was moved to position 6. The stratification was 0.3-0.4 °C.
- The temperature changes continued being small when the bar was moved back to position 1 and the stratification was 0.2-0.3 °C.
- The average temperature in the living room during the whole measurement period was 21.30 °C.

Surface temperatures:

- There was direct solar radiation on PT9 and PT14 during the measurement period, so these surfaces had the largest temperature increases. Other surfaces might have been indirectly affected by the solar radiation.
- The air temperature on the first floor varied with only 0.2 °C.
- The surfaces on the ground floor had around the same temperature, this also applies for the surfaces on the first floor.

Stratification in the staircase:

- The thread was first in position 2, and then it was moved to position 1.
- The temperatures and the stratification were stable when the thread was placed in position 2, the stratification was 2.7-2.9 °C.
- Moving the thread to position 1 did not affect PT16 and PT17, as expected. PT18-20 registered temperature drops after the thread was moved. The stratification increased to 3.3 °C.
- The average temperature in the staircase was 21.81 °C.

7.6.12 The velocity profiles

In the previous section it is mentioned that the velocity profiles deviate some from the theoretical velocity profile. The significance of these deviations is investigated by plotting the measurement based average values in the same graphs as the theoretical velocity profiles for each case. The theoretical velocity profile is calculated using the above calculated discharge coefficients and densities using the following equations:

$$u_{z>z_n} = C_D \sqrt{\frac{2\Delta p}{\rho_1}} = C_D \sqrt{\frac{2 * (\rho_2 g(z - z_n) - \rho_1 g(z - z_n))}{\rho_1}} \tag{51}$$

$$u_{z<z_n} = C_D \sqrt{\frac{2\Delta p}{\rho_2}} = C_D \sqrt{\frac{2 * (\rho_1 g(z - z_n) - \rho_2 g(z - z_n))}{\rho_2}} \tag{52}$$

The resulting graphs are given in *Attachment 7: Comparison of the measurements based and the theoretical velocity profiles* and shows that the majority of the velocity profiles have similar shape to the theoretical one, but that they do not follow the shape completely. The deviations from the theory are largest for the upper and lower probes. The deviations are more evident for the two cases with the heat sources located upstairs; the velocity profiles do not follow the same shape as the theory, this is more evident for the upper half.

7.6. 13 Temperature differences between the living room and the stair case

Using the average temperatures of the two rooms, the temperature differences are a shown in Table 20.

7.6.14 Thermal comfort in the living room and in the bedrooms

The main objective of the research presented in *Chapter 3. Investigation of thermal comfort using detailed dynamic simulations* is to investigate if thermal comfort can be achieved with one central heat source. The average air temperatures in the living room and in one of the bedrooms are given in Table 20 to check if there was sufficient thermal comfort in the passive house during the measurements. The numbers show that using the convector with the given settings resulted in overheating in the living room, both for natural and forced convection. The corresponding temperatures in the upstairs bedroom were above what is needed for thermal comfort. This is due to the imposed temperature in the living room is warmer than necessary, thus, if the convector is set on a lower temperature level the overheating in the living room will be reduced and the thermal comfort might still be sufficient in the bedrooms. Using the panel heaters, which were set on 23 °C, led to comfortable temperatures both in the living room and in the bedrooms. Placing the heat sources upstairs gave equivalent results for both heat sources.

The temperatures in the passive house are affected by the outdoor temperatures and the mild winter makes it difficult to analyse the temperature distribution between the rooms as almost no heat addition was needed.

Table 20: Average temperatures for the two rooms separated by the aperture, and temperature difference.

Measurement	Temperature living room [°C]	Temperature staircase [°C]	Temperature difference [°C]
Natural convection			
Position 1	26.06	23.53	2.53
Position 2	27.42	24.31	3.11
Position 3	29.02	25.11	3.91
Position 4	23.10	24.82	-1.72
Forced convection			
Position 1	26.68	24.14	2.54
Position 2	27.13	24.28	2.85
Position 3	27.34	24.52	2.82
Panel heaters			
Position 1	22.43	21.21	1.22
Position 2	22.92	21.49	1.43
Position 3	23.20	21.53	1,67
Position 4	21.30	21.81	-0.51

7.7 Comparison for the measurement results

The results presented in the last chapter will be compared in the following way after some general comments:

- Comparison of the results for the different positions for the same heat source.
- Comparison of the results for the different heat sources for the same position.

7.7.1 General comments

7.7.1.1 Velocity

The following observations were made:

- The lower probes (probes 6-10) had more similar velocities than the upper probes. The upper probes were more spread and the velocities measured in the upper half also varied more.
- The measured velocities alternated on having the largest value.
- There is no clear pattern in how the velocities changed when the bar was moved horizontally in the doorway, but most of the times the lower probes measured larger velocities and the upper probes measured declined velocities when the bar was moved to the left. The velocities often changed back towards the initial velocity levels when the bar was moved to the right.
- The shape of the velocity profile deviated some from the theoretical one in Figure 5 for all the measurements. This deviation is clearly larger for the two cases with the heat source located upstairs.
- The standard deviation increased with the velocity for the majority of the cases.
- The neutral plane seemed to be located between probes 5 and 6 for the cases with the oven positioned on the ground floor, and for the two cases with the heat source

located on the first floor the neutral plane seemed to be located between probes 4 and 5.

7.7.1.2 Temperature in the aperture

The following general observations were made:

- The temperatures were more similar for the lower probes than for the upper probes, the temperatures also varied more for the upper probes.
- The order of the probes measuring the warmer to the less warm temperatures was approximately the same for all the measurements, but the distance between the measured temperatures varied.
- There were small or no visible temperature changes when the bar was moved horizontally in the aperture.

7.7.1.2 Stratification and surface temperatures

The following observations were made for the measurements in the living room:

- The temperatures were less warm and more stable for the panel heaters.
- The temperatures increased throughout the day and were therefore a bit warmer for the measurements conducted later in the day.
- There were mostly small changes in PT-positions 1 to 3, except for in position 2 when the oven with forced convection was located in oven-position 2.
- There were some more significant temperature changes in PT-positions 4 to 6.
- The temperatures for all cases moved towards the initial values when the bar was moved back to the initial position.
- The temperatures were lower when the heat sources were located on the first floor.

The following observations were made for the surface temperatures:

- The surfaces on the same floor had similar temperatures as long as there was no solar radiation.

The following observations were made for the measurements in the stair case:

- The temperatures and the stratification were stable before the thread was moved for all cases. By stable it was not meant that the temperatures were constant, but that the variations were small.
- Moving the thread did not change the position for probes 16 and 17 and the temperatures measured by these probes should therefore not be affected when the thread was moved, which is the case. Probe 18 measured a temperature decrease for the majority of the cases with the heat source on the ground floor. Probes 19 and 20 measured temperature increases for all cases. The stratification declined for all cases when the thread was moved.
- There was another air flow pattern in the staircase when the heat source was located on the first floor. There was not a layer of unheated air in the middle of the staircase such as for the other cases.

7.7.2 Comparison of the result for the different positions for the same heat source
The results from the different positions for the same heat source will be compared in this section.

7.7.2.1 Natural convection
The velocities measured for the cases with position 1 and 2 followed each other from the maximum to the minimum velocity without any large gaps, but for case 3 there was a gap between the velocities measured by probes 7-10 and probes 1-6. There was also a gap after the two probes measuring the largest velocities for position 4, but there were large fluctuations so the gap was less apparent. The velocities measured by the upper probes fluctuated more for position 2 than for position 1.

The cases with natural convection reacted differently when the bar was moved horizontally in the aperture. Many of the probes measured increased velocities for positions 1 and 2 when the bar was moved to the left side of the aperture and then changed back towards the initial values when the bar was moved further. The velocities measured for positions 3 and 4 were less affected when the bar was moved.

Figure 51 shows the average velocity per probe for all four positions when natural convection was applied. Even though there are many differences between the graphs, they all follow the same pattern; probes 5 and 6 measured the lowest velocities and the lower probes had higher average velocity than the upper probes. The three cases with the convector located on the ground floor had similar average velocities for the upper probes, but there were more variations for the lower probes. The case with the oven on the first floor stands out from the rest as the velocities were lower, the variations were smaller and the neutral plane seems to be located further up in the aperture.

The velocity profiles had the same shape for the three cases with the oven on the ground floor, but there were some differences, especially for the ends of the graphs. The velocity profile for position 4 had a different shape than for the other cases.

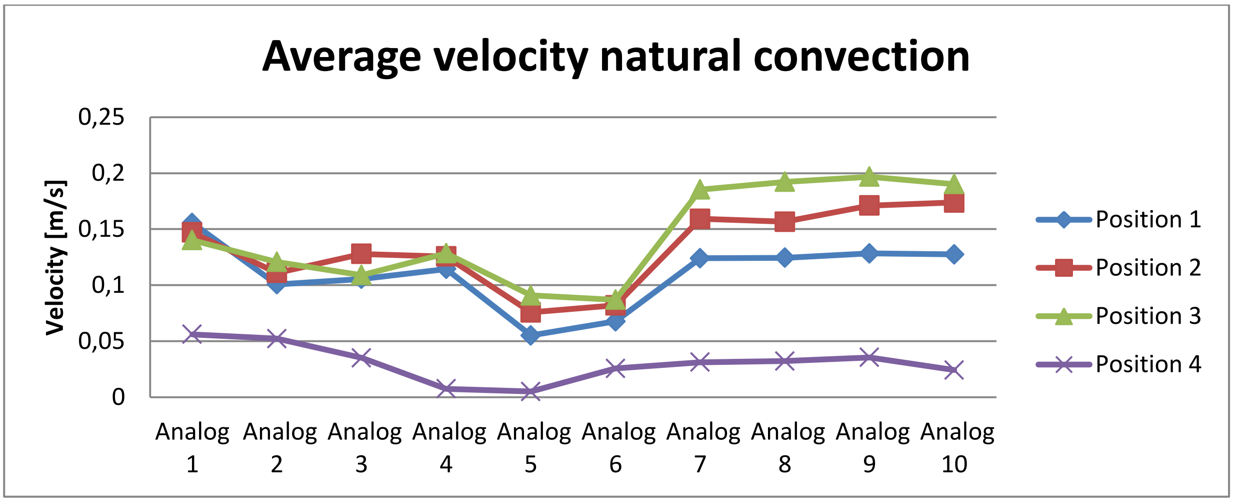

Figure 51: The average velocities per probe for all four cases with natural convection.

The temperatures measured for position 1 had a smoother transition from the warm to the less warm layer than for positions 2 and 3 where the probes were divided into two groupings; one group with the upper probes measuring warmer temperatures and one group with the lower probes measuring less warm temperatures. The temperatures measured by probe 5 were in between the temperatures of the two groupings.

Figure 52 shows the average temperatures per probes for all four cases with natural convection. The graphs reveal the same as explained in the above and shows that the temperatures in the doorway were much lower when the convector was located upstairs. The difference between the temperatures measured by probe 1 and probe 2 was larger for this case.

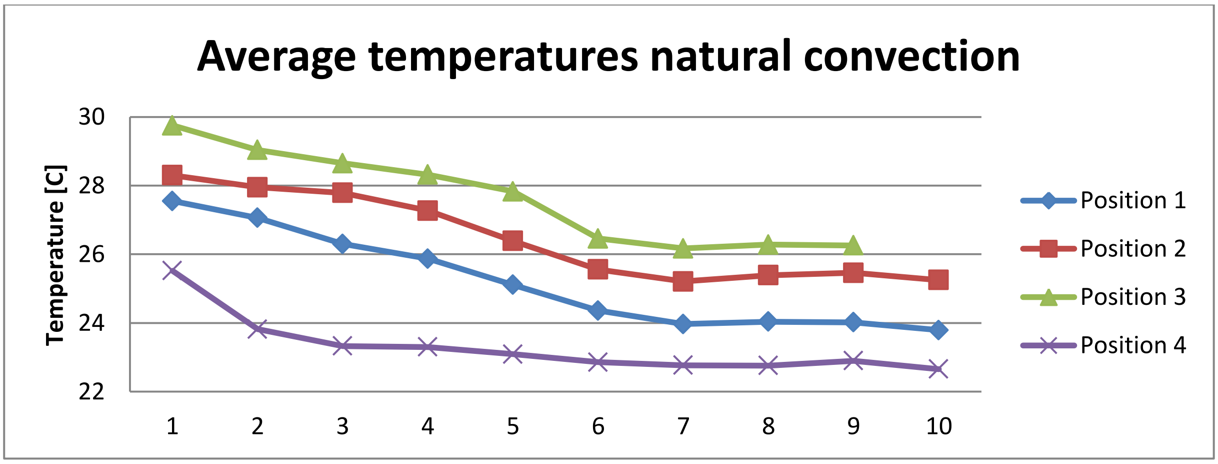

Figure 52: The average temperatures in the aperture per probe for all four cases with natural convection.

In the following, the oven-positions are referred to as positions 1-4 and the positions for the bar with the PT-100 probes in the living room is referred to as PT-positions. The temperatures and the stratification in the living room were stable in the initial PT-position for the cases with positions 1, 2 and 4, the temperatures were less stable for position 3 due to solar radiation. There was more stratification for position 2 than for position 1 and the stratification was significantly lower when the convector was in position 4. The changes in temperatures were different for the four cases when the bar with the PT-probes was moved:

- PT-position 2: There were only small changes for the cases with positions 1, 2 and 4. The changes were larger for the case with position 3 due to the lack of solar radiation compared to the initial PT-position.
- PT-position 3: There were only small changes for cases in this PT-position.
- PT-position 4: The cases with positions 2 and 4 only had small changes, the cases with positions 1 and 3 had more temperature differences. This was due to the PT-bar being close to the oven for position 3.
- PT-position 5: The stratification declined for the cases with positions 1 and 2, the two other cases only measured small changes.
- PT-position 6: The cases with positions 1 and 2 both measured temperature increases, but this gave increased stratification for the first case and reduced stratification for the second case. The cases with positions 3 and 4 only had small changes.
- The cases reacted differently when the PT-bar was moved back to the initial position, but there were mostly small changes.

The surface temperatures behaved somewhat differently for the four cases due to solar radiation affecting different probes. There was no solar radiation during the test with position 4.

The temperatures and the stratification in the staircase were stable in the initial position for all cases. There was more stratification for positions 2, 3 and 4 than for position 1 and the stratification was largest when the convector was in position 4. The temperature changes when the thread was moved were the same for the three cases with the convector on the ground floor, but the changes had different magnitudes, this also applied to the stratification. The temperature changed differently for the case with position 4 compared to the three other cases; PT18, PT19 and PT20 all measured a temperature increase. The stratification decreased when the thread was moved, as was also the case for the other positions.

7.7.2.2 Forced convection

The most important characteristics of the measured velocities were also there for the average velocities; the velocities followed the same magnitudes for all three cases, but there were some differences for the upper and lower probes as shown in Figure 53.

The velocities changed some for all cases when the bar was moved horizontally in the opening, but the velocities changed back to the initial values when the bar was moved further.

The three cases had similar velocity profiles, but with some differences for the upper probes.

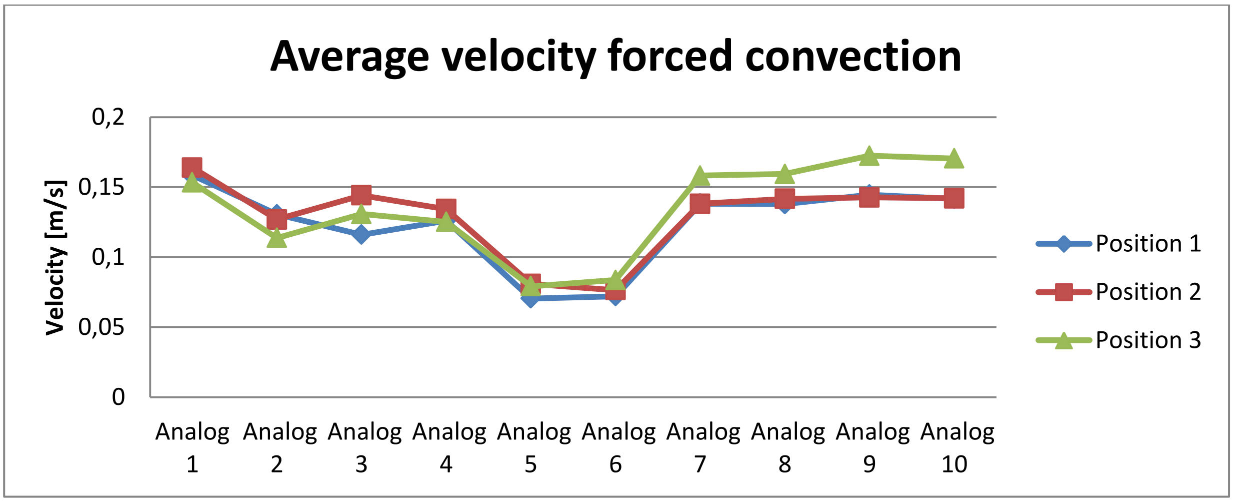

Figure 53: The average velocity per probe for all the cases with forced convection.

The measured temperatures were divided into a warm and a less warm group with probe 5 in the middle for positions 1 and 2. This was not the case for position 3 where the transition from the warm to the less warm temperatures was without any large gaps. The average temperatures for all three cases are shown in Figure 54; the graphs have the same shape, but with different values.

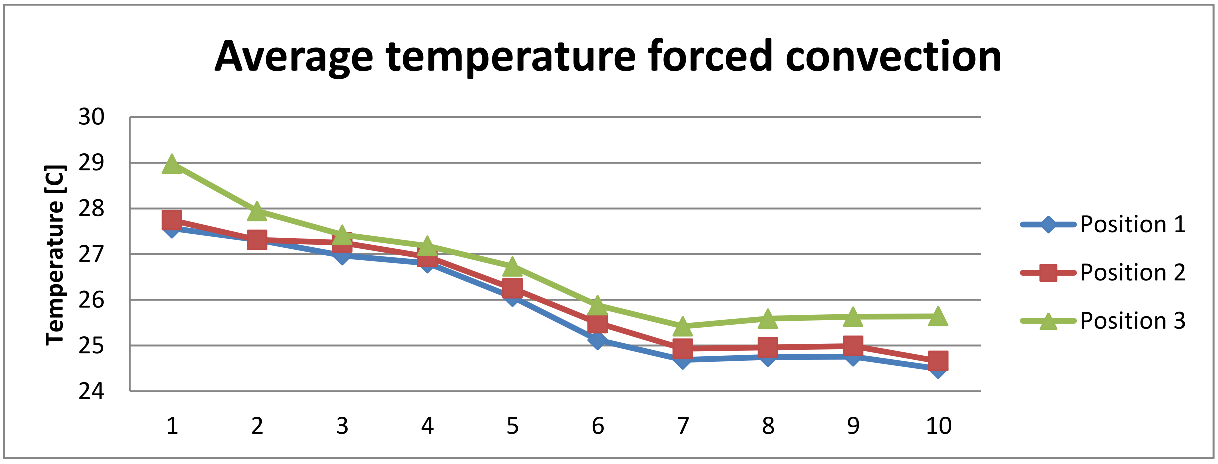

Figure 54: The average temperatures per probe for all the cases with forced convection.

The oven-positions are referred to as positions 1-4 and the positions for the bar with the PT-100 probes in the living room is referred to as PT-positions in the following section. The temperatures and the stratification in the living room were stable in the initial position for all cases. There were more stratification for position 2 than for position 1 and the stratification was slightly lower when the convector was in position 3. The changes in temperatures were different for the four cases when the bar with the PT-probes was moved:

- PT-position 2: The temperatures and the stratification increased for the case with position 1. The temperatures also increased for position 2, but mostly for the lower probes which were close to the oven, this led to a negative stratification. Only small changes were measured when the oven was in position 3.

- PT-position 3: The negative stratification for the case with position 2 was changed back to being positive. The cases with positions 1 and 3 only measured small changes.
- There were only small changes for all of the cases in the rest of the PT-positions.

The surface temperatures behaved similarly, but there were some differences for some of the probes due to solar radiation during the time the oven was in position 3.

The temperatures and the stratification in the staircase were stable in the initial position for all cases. There was larger stratification for positions 2 and 3 than for position 1. The temperature changes when the thread was moved were the same for the three cases, but the changes had different magnitudes, this also applied to the stratification.

7.7.2.3 Panel heaters

The velocities measured when the panel heaters were in positions 1 and 2 followed each other without any large gaps, but there were more fluctuations for position 2. There was a small gap between the four largest velocities and the rest for position 3, and the velocities measured by probes 5 and 6 fluctuated a lot for this case. The measured velocities when the heaters were in position 4 were also divided by a gap after the largest velocities, the velocities were also lower than for the other cases and fluctuated a lot.

The four cases reacted differently when the bar was moved horizontally in the aperture, but the velocities moved back to the initial positions for the two first cases when the bar was moved further. There were still some differences from the initial velocities when the bar was moved back to the initial location for the cases with positions 3 and 4.

The average velocity per probe for the four cases is shown in Figure 55. The graphs have the same shape for the middle and lower probes for the three cases with the heaters on the ground floor, but the case with position 2 had a clearly larger average velocity for probes 1 and 2. The average velocities were clearly lower when the heaters were located upstairs, and the shape of the graph is different than for the three other cases.

The velocity profiles had similar shapes for the three cases with the heaters on the ground floor, but the velocity profile was different when the heaters were located upstairs.

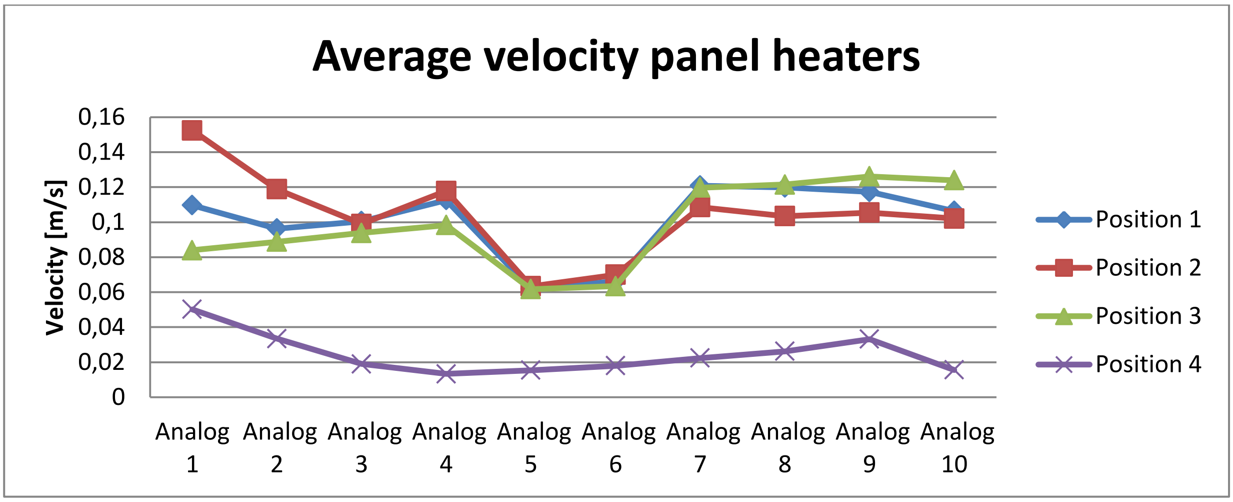

Figure 55: The average velocity per probe for all cases with the panel heaters.

The measured temperatures were divided into a warm and a less warm group for all four cases, the groupings consisted of the upper and lower probes with probe 5, and also probe 6 for position 3, in the middle for the cases with the heaters on the ground floor. The warm group was composed by only probe 1 for the case with the heaters upstairs; probe 2 and the rest followed after a large gap.

The average temperatures per probe for all four cases are given in Figure 56. The graphs with the average temperatures have similar shapes, but different values. The temperatures for position 4 were clearly lower for the upper half, but they were closer to the other cases for the lower probes.

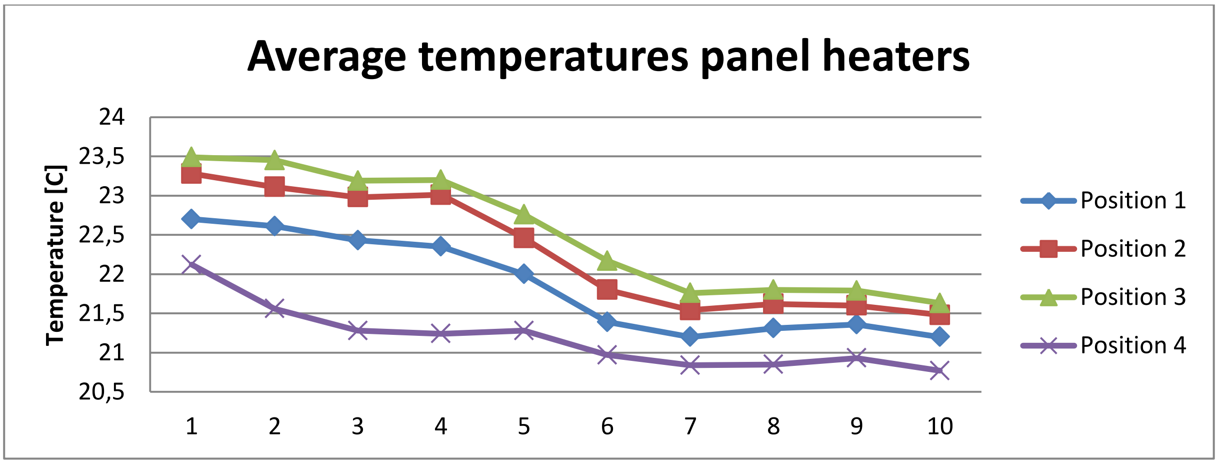

Figure 56: The average temperature in the aperture for the four cases with the panel heaters.

The temperatures and the stratification in the living room were stable in the initial position for all cases. There was more stratification when the heaters were in positions 2 and 3 than for position 1, and the stratification was lower when the panel heaters were in position 4. There were mostly small changes in temperatures and stratification for all cases when the PT-bar was moved.

The surface temperatures behaved similarly for the four cases, but there was some solar radiation when the oven was in position 4 which led to temperature increases for some of the surfaces.

The temperatures and the stratification in the staircase were stable in the initial position for all cases. There were larger stratification for the cases with positions 2, 3 and 4 than for position 1, the stratification was largest when the heaters were in position 4. The temperature changes when the thread was moved were the same for the cases with positions 2 and 3, but the changes had different magnitudes, this also applied to the stratification. The temperature changed differently for the case with positions 4 and 1; the temperature measured by PT18 did not change for the case with position 1 and PT18, PT19 and PT20 measured a temperature increase for the second thread position when the heaters were in position 4. The stratification decreased when the thread was moved, as was also the case for the other positions.

7.7.3 Comparison of the results for the different heat sources for the same position

In this section the results from the different heat sources for the same position will be compared.

7.7.3.1 Position 1

The order of the probes measuring the largest to the lowest velocities was approximately the same for all cases, but the variations in velocity were slightly lower for the case with the panel heaters. There were also more fluctuations for this case.

The three cases reacted differently when the bar was moved horizontally in the opening, but the velocities were as good as back to initial values when the bar was moved back to the initial position.

Figure 57 shows that the average velocities were following the same shape for all cases, but there were some differences of magnitude for the lower and upper probes. The three cases also had velocity profiles with similar shapes.

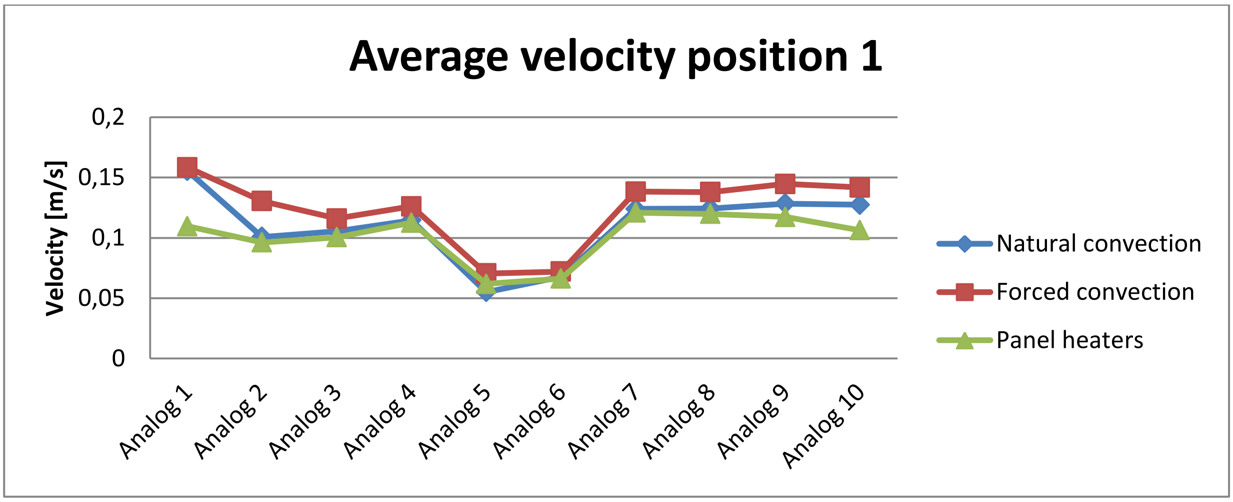

Figure 57: The average velocities for all three heat sources in position 1.

The order of the probes measuring the warmest to the less warm temperature was the same for all cases and the temperatures for the lower probes were more even than the upper ones. The transition between the warm and less warm layer was smoother for natural convection than for the two other cases were the temperatures were divided into two groups with the temperature measured by probe 5 in the middle.

The average temperatures per probe are shown in Figure 58. The graphs show that the temperatures were significantly lower for the panel heaters, but also that the shapes of the graphs were similar for all cases.

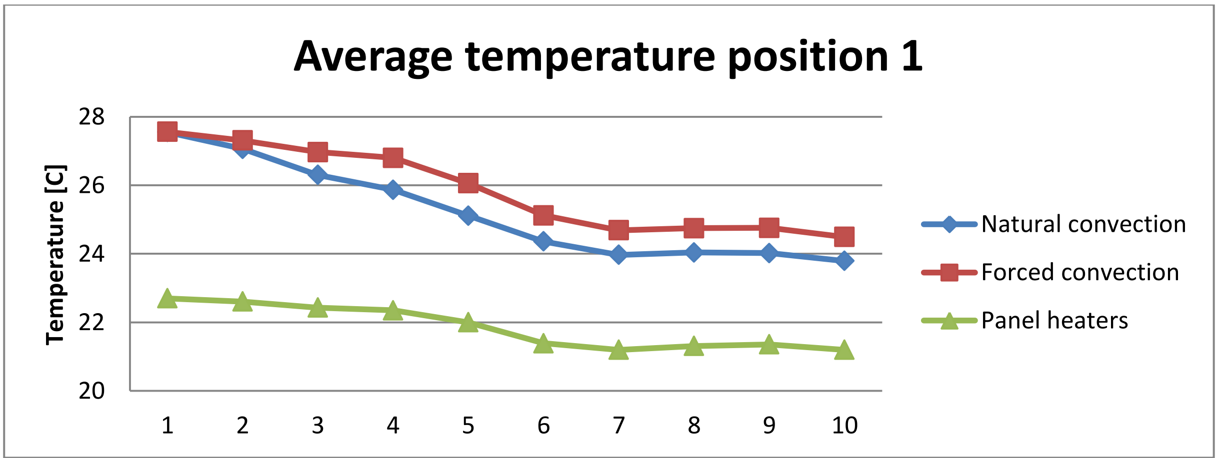

Figure 58: Average temperatures in the aperture for all three heat sources in position 1.

The temperatures and the stratification in the living room were stable in the initial PT-positions for all three heat sources. The initial stratification was approximately 1 °C lower for forced convection and 1.6 °C lower for the panel heaters compared with when natural convection was applied.

There were mostly small changes when the bar with the PT-probes was moved, but the variations in temperature were more apparent for the two cases with convection.

The surface temperatures behaved in similar ways for all cases, but there were some differences due to the solar radiation affecting the temperatures when natural convection was applied.

The initial temperatures and the stratification in the staircase were stable for all three cases, the stratification was largest for the case with forced convection and lowest when the panel heaters were used. The changes when the thread was moved were similar, but with different magnitudes for the two cases with convection; PT18 measured a temperature drop, PT19 and PT20 measured increased temperatures and the stratification declined. PT18 was not affected when the thread was moved when the panel heaters were applied, but the rest of the changes were similar to the two other cases.

7.7.3.2 Position 2

The order of the probes measuring the largest to the lowest velocities was approximately the same for all cases, but there were more fluctuations for the cases with natural convection and panel heaters. The three cases reacted differently when the bar was moved horizontally in the aperture.

The average velocities per probe for the three cases are shown in Figure 59. The graphs in the figure have similar shapes, but there were differences for probe 3 and for the lower probes. The case with the panel heaters had the lowest average velocity for the lower half of the door. The velocity profiles for the three cases had similar shapes.

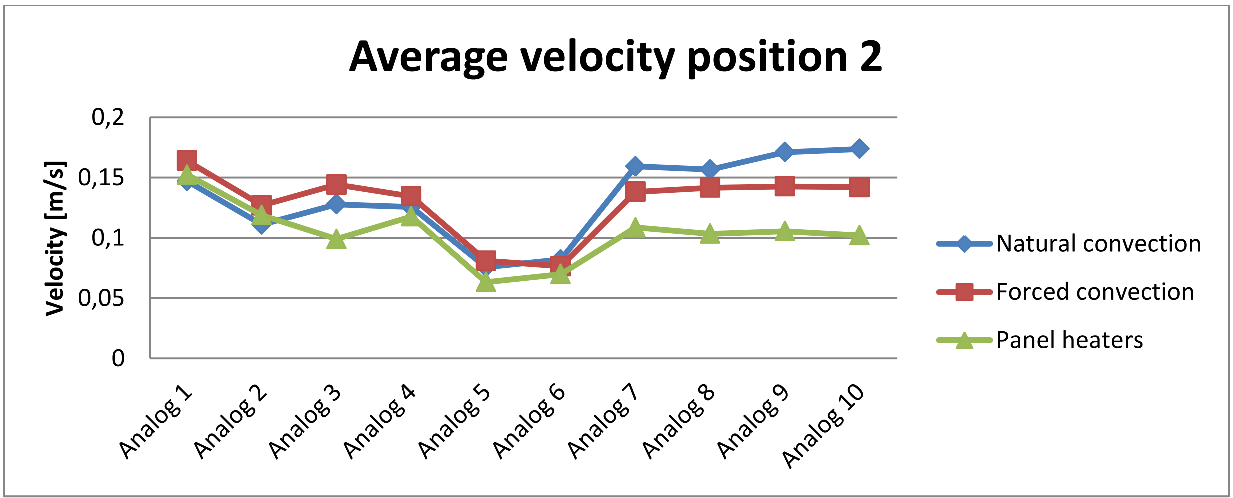

Figure 59: The average velocity for all heat sources in position 2.

The measured temperatures were divided into a warm and a less warm group with probe 5 in the middle for all cases. The gap between the groups and probe 5 differed between the cases. The average temperatures for the cases are shown in Figure 60. The graphs had similar shapes, but different values.

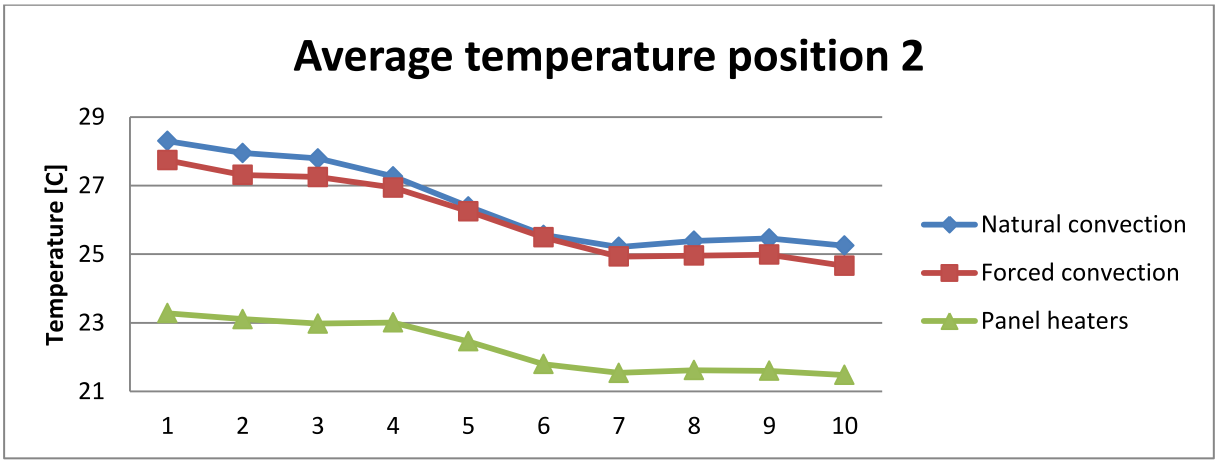

Figure 60: The average temperatures in the aperture for all heat sources in position 2.

The temperatures and stratification in the living room were stable in the initial PT-position for all three cases, the stratification was lowest for the case with the panel heaters and largest for the case with natural convection.

There were mostly small changes for the cases when the bar was moved, but there were more stable temperatures for the case with the panel heaters. The stratification turned negative when the bar was placed next to the oven with forced convection, but this negative stratification was changed back to being positive when the bar was moved further.

The surface temperatures behaved in similar ways for the three cases, but there were some differences due to the solar radiation affecting the temperatures when natural convection was applied.

The initial temperatures and stratification in the staircase were stable for the three cases, but the stratification were clearly lower when the panel heaters were used. The changes were the same, but with different magnitudes when the thread was moved; PT18 measured a temperature drop, PT19 and PT20 measured increased temperatures and the stratification declined. The temperature increases were significant lower for the case with the panel heaters.

7.7.3.3 Position 3

The order of the probes measuring the largest to the lowest velocities was similar for all cases, but there were gaps in different locations. The velocities were lower for the case with the panel heaters, this case also had more fluctuations. The three cases reacted differently when the bar was moved horizontally in the aperture.

Figure 61 shows the average velocity for all three cases; the graphs have similar shapes, but there are significant differences in magnitude. The velocities were larger for the lower probes for all cases, the difference between the upper and lower halves was smallest for the panel heaters. The velocity profiles have similar shapes for all three cases.

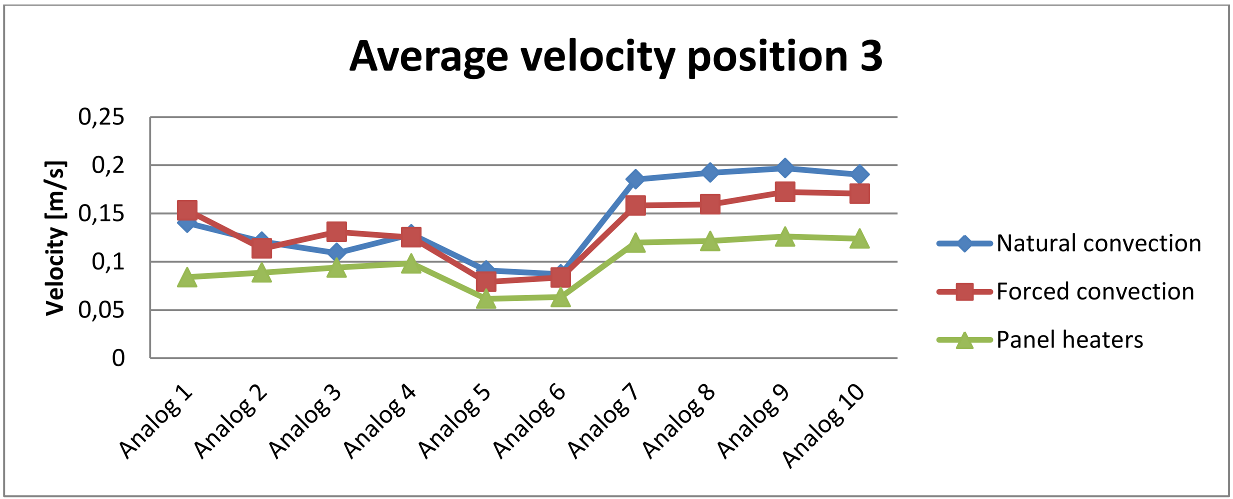

Figure 61: The average velocity in the aperture for all three heat sources in position 3.

The measured temperatures were divided into a warm and a less warm group for the cases with natural and forced convection, but the gap between the groupings differed. All the temperatures followed each other without any large gaps for the case with the panel heaters, there were also more fluctuations for the middle probes for this case. The temperature measured by probe 1 fluctuated more when forced convection was applied.

Figure 62 shows the average temperatures for all three cases; the graphs had similar shapes, but different values.

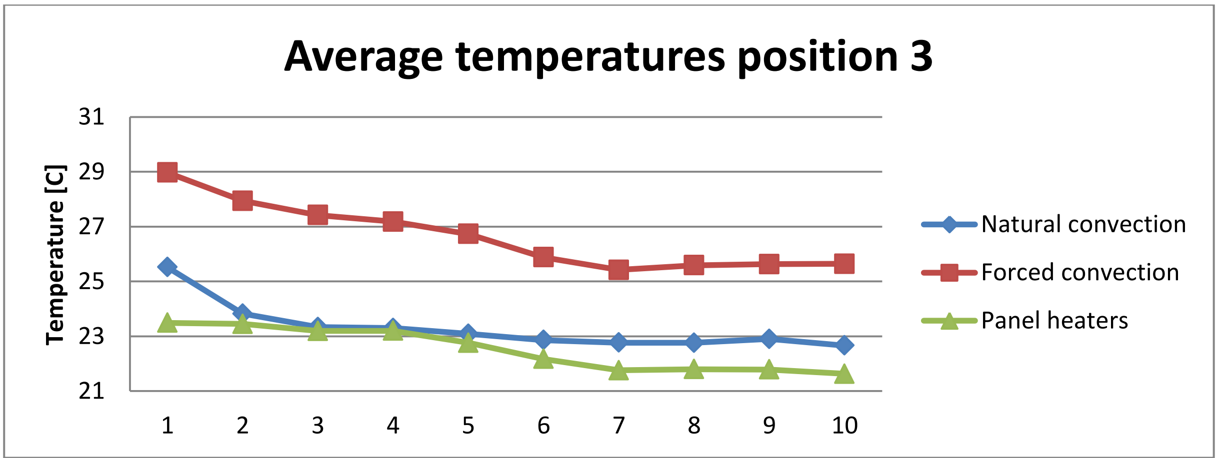

Figure 62: The average temperatures for all three heat sources in position 3.

The temperatures and the stratification in the living room were stable in the initial position for the cases with forced convection and the panel heaters, the temperatures increased and the stratification declined due to solar radiation for the case with natural convection. There was less stratification when the panel heaters were used.

In the following, the oven-positions are referred to as positions 1-4 and the positions for the bar with the PT-100 probes in the living room is referred to as PT-positions. There were mostly small changes for the cases when the bar was moved, but there were some temperature increases for the two cases with convection when the bar was in PT-position 5. These temperatures decreased again in PT-position 6, and the stratification also declined.

The surface temperatures behaved in similar ways for the three cases, but there were some differences due to the solar radiation affecting the surface temperatures differently.

The initial temperatures and stratification in the staircase were stable for the cases with forced convection and panel heaters, but the temperatures were increasing due to solar radiation when natural convection was applied. The initial stratification was clearly lower for the case with the panel heaters and largest for natural convection. The changes were the same, but with different magnitudes when the thread was moved; PT18 measured a temperature drop, PT19 and PT20 measured increased temperatures and the stratification declined. The temperature increases were significant lower when the panel heaters were used.

7.7.3.4 Position 4

The upper probes measured the largest velocity for both cases, but the upper probes had more similar velocities for the case with natural convection. There were a lot of fluctuations for both cases, especially for the lower probes. Probes 4 and 5 measured a lot of zero velocities and some negative velocities when natural convection was applied. The two cases reacted differently when the bar was moved horizontally in the doorway.

The average velocities for both cases are shown in Figure 63. The graphs have different shapes, but there were some similarities for the lower probes. The graph for the case with natural convection had the shape that was the most similar to the cases with the heat sources on the ground floor. The velocity profiles for the two cases have similar shapes.

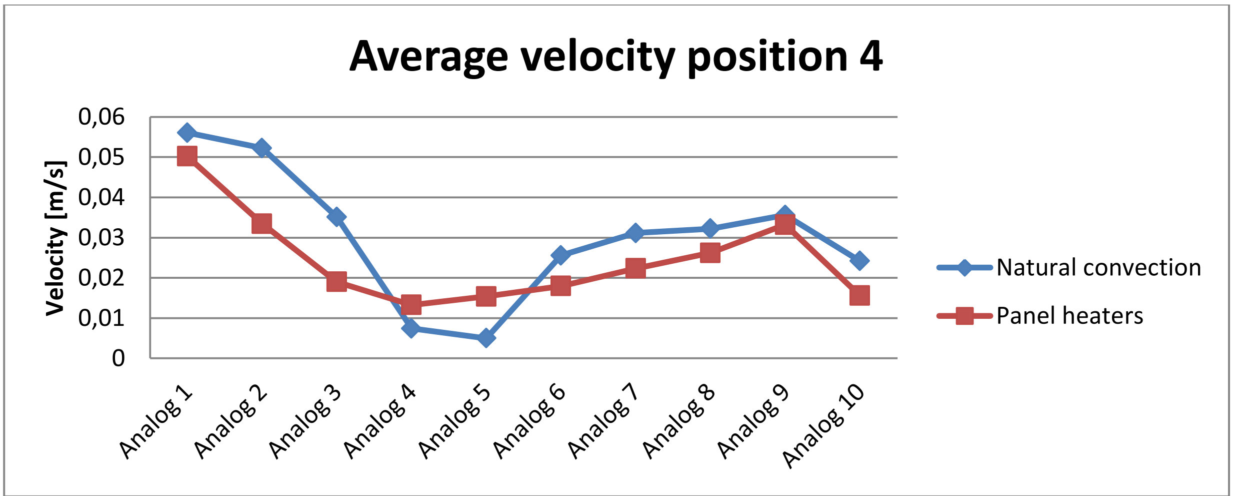

Figure 63: The average velocities for natural convection and the panel heaters in position 4.

The order for the probes measuring the warmest to the least warm temperature was the same for both cases. The temperatures were larger for probe 1 than for the other probes for both cases, but the temperature difference between probe 1 and the rest was larger when natural convection was applied. The average temperature for both cases is shown in Figure 64.

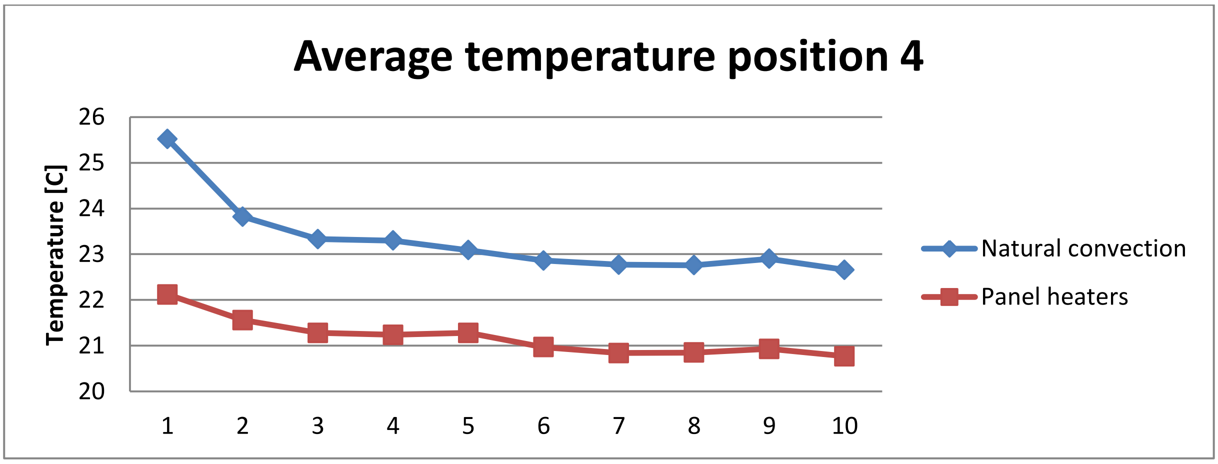

Figure 64: The average temperatures in the aperture with natural convection and the panel heaters in position 4.

The temperatures in the living room were stable when the bar was in the initial position for both cases and the initial stratification was approximately the same for both cases. There were only minor variations in the temperature in the living room.

The surface temperatures behaved in similar ways for both cases, but there were some differences due to the solar radiation affecting the temperatures when the panel heaters were applied.

For the staircase, both cases had stable temperatures for PT16 and PT17 during the whole measuring period, higher temperatures for PT 18, PT19 and PT20 in thread-position 2 and less stratification in thread-position 2.

7.8 Calculations

Calculations based on the measurement results will be conducted in this section. The results will be presented here, but they will be commented in the subsequent chapter.

7.8.1 Analytical calculations based on the measured temperatures

The obtained temperatures and temperature differences differ significantly from the values that were used in the analytical calculations in *Chapter 4.6 Analytical calculations*. Therefore, the MATLAB script was run again with the right values for the size of the aperture, the temperatures and the densities for all cases. The densities were found by interpolating in [19] and can be found in Table 21. The resulting velocities and volume flows can be found in *Attachment 8: Results for analytical calculations based on the measured average temperatures.*

The results show that the velocities and the volume flows are smaller than for the initial MATLAB calculations. However, the same trends still applies: The velocities are even and it is the same models that give the larger and smaller volume flows.

Table 21: The densities for the measured average temperatures in the living room and in the staircase.

Measurement	Density living room [kg/m³]	Density staircase [kg/m³]
Natural convection		
Position 1	1.180	1.190
Position 2	1.175	1.187
Position 3	1.169	1.184
Position 4	1.192	1.185
Forced convection		
Position 1	1.178	1.187
Position 2	1.176	1.187
Position 3	1.175	1.186
Panel heaters		
Position 1	1.194	1.199
Position 2	1.192	1.198
Position 3	1.191	1.198
Position 4	1.199	1.197

The velocities calculated by using the analytical models are larger than the average velocities based on the measured velocities and most of the measured velocities. The differences between the calculated and the maximum measured average velocity as a percentage of the measured value is also given in *Attachment 8: Results for analytical calculations based on the measured average temperatures*. This shows that the differences are larger than the margin of error of the equipment for all cases except the case with the panel heaters and position1. The deviations are also clearly larger when the heat sources are located on the first floor.

There are some probes that measured velocities at the level calculated in MATLAB for most of the cases:

- Natural convection, oven-position 1: The maximum velocities measured by probe 1 were at or above the level calculated in MATLAB.
- Natural convection, oven-position 2: Probes 9 and 10 measured some velocities that were larger than the analytical calculated values. Probes 3 and 7 also measured one or a few velocities at this level.
- Natural convection, oven-position 3: Probes 7-10 measured velocities at the same values as calculated with the theoretical models.
- Forced convection, oven-position 1: Probe 1 measured some velocities that were larger than the analytical calculated values and probe 2 measured a few velocities at this level.
- Forced convection, oven-position 2: Probes 1, 2 and 9 measured a couple of values at the same level as the calculated values, there were also some disturbances with even larger velocities.
- Forced convection, oven-position 3: Probes 7-10 measured velocities of same size as the calculated ones when the bar was moved from the initial position. Probe 1 also measured some velocities at the same level.

- Panel heaters, oven-position 1: There were a lot of fluctuations, so many of the probes measured values around the same level as velocities given by the analytical calculations.
- Panel heaters, oven-position 2: The average velocity calculated from the velocities measured by probe 1 was larger than the calculated velocities. Probe 7 measured a single value at the same level.
- Panel heaters, oven-position 3: The lower probes measured some velocities at the same level as the calculated velocities.

For the two cases with the oven located in the first floor the average velocities were significant lower than the calculated values, and only two of the probes for the case with panel heaters measured one or two single values close to these velocities.

7.8.2 Volume flows

The volume flows for the eleven cases presented in the above were calculated using the following equation:

$$q = u * A = \bar{u} * A \left[\frac{m^3}{s}\right] \tag{53}$$

The calculations were done using the MATLAB script in *Attachment 9: MATLAB script for calculating volume flows*. The velocities that were used for the calculations are the overall average velocities in the upper and lower halves of the aperture per case. For the two cases where the oven was located upstairs, the neutral plane was located further up; therefore, the velocities and the area is divided between probes 4 and 5. This gives the results displayed in Table 22.

These volume flows are mostly of the same magnitudes as the volume flows calculated by the analytical models, but there are some deviations: The lower halves have greater volume flows than the theory suggests, the volume flows for the two cases with the heat source located in the first floor are lower in Table 22 than in the calculations based on the analytical models and the two first cases with the panel heaters have slightly larger volume flows here than in *Attachment 8: Results for analytical calculations based on the measured average temperatures*.

Table 22: Calculated volume flows based on the measured velocities.

Measurement	Volume flow, upper half [m^3/s]	Volume flow, lower half [m^3/s]
Natural convection		
Position 1	0.1124	0.1209
Position 2	0.1242	0.1571
Position 3	0.1246	0.1801
Position 4	0.0319	0.0325
Forced convection		
Position 1	0.1272	0.1342
Position 2	0.1375	0.1355
Position 3	0.1274	0.1574
Panel heaters		
Position 1	0.1017	0.1122
Position 2	0.1166	0.1035
Position 3	0.0902	0.1173
Position 4	0.0245	0.0276

7.8.3 Heat transfer and convective heat transfer coefficients

The heat transfer with the air flows and the convective heat transfer coefficients were calculated using the following equations from Santamouris et al. [16]:

$$Q = \dot{m} * c_p * \Delta T = q * \rho * \dot{c_p} * \Delta T = h * A * \Delta T \;\; [kW] \tag{54}$$

$$h = \dot{m} * \frac{c_p}{A} \; [\frac{kW}{m^2}] \tag{55}$$

The calculations were done using the MATLAB script in *Attachment 10: MATLAB script for calculations of heat transfer*. The volume flows that were used are the ones that are calculated in the above calculations and the temperatures and the densities are still based on the measurements. The values for the specific heat capacity were taken from The engineering toolbox [37]. For the calculation of the convective heat transfer coefficient h the areas are used in the same way as described in the above. The results of the calculations are shown in Table 23.

The results show that the heat transfer is larger in the lower air stream for the majority of the models. For the cases with convection there is a larger heat transfer when the oven is in position 3, for the panel heaters the lower air flow is at its maximum when the heaters are in position 3, but the upper stream transfer more heat when the oven is in position 2. As follows from the sizes of the volume flows; the heat transfer is lower for the cases with the panel heaters and for both cases with the oven positioned on the first floor.

The magnitudes of the convective heat transfer coefficients follow that of the heat transfers, this is not surprising.

Table 23: Calculated heat transfer and convective heat transfer coefficients.

Measurement	Heat transfer [kW]	h [kW/m²]
Natural convection		
Position 1, upper air stream	0.3372	0.1260
Position 1, lower air stream	0.3658	0.1367
Position 2, upper air stream	0.4561	0.1387
Position 2, lower air stream	0.5828	0.1772
Position 3, upper air stream	0.5724	0.1384
Position 3, lower air stream	0.8379	0.2027
Position 4, upper air stream	0.0657	0.0452
Position 4, lower air stream	0.0666	0.0305
Forced convection		
Position 1, upper air stream	0.3825	0.1424
Position 1, lower air stream	0.4066	0.1514
Position 2, upper air stream	0.4631	0.1537
Position 2, lower air stream	0.4607	0.1529
Position 3, upper air stream	0.4243	0.1423
Position 3, lower air stream	0.5291	0.1774
Panel heaters		
Position 1, upper air stream	0.1489	0.1154
Position 1, lower air stream	0.1649	0.1278
Position 2, upper air stream	0.1997	0.1321
Position 2, lower air stream	0.1782	0.1178
Position 3, upper air stream	0.1803	0.1021
Position 3, lower air stream	0.2359	0.1335
Position 4, upper air stream	0.0151	0.0349
Position 4, lower air stream	0.0169	0.0262

7.8.4 Discharge coefficient

The discharge coefficients were found by running the MATLAB script with the different analytical models with a C_d value of 1, and then calculating the ratio between these theoretically ideal values and the measured velocities and the above calculated volume flows. The two-layer hydraulics model does not include C_d, so the result for this model is not affected by changing the value of C_d and should therefore not be commented in this case. The results can be found in *Attachment 11: Calculations of discharge coefficients* and the average values can be seen in Table 24. The average discharge coefficients were not calculated for the two-layer hydraulics model or for the model of Santamouris et al. as the equations from this model gave lower volume flows than the one based on the measured velocity for most cases. The equations giving the flow from the heated zone to the unheated zone were used with the equations that do not state which of the flows they give for the calculations for the upper half, and for the lower half the equations giving the volume flow from the unheated room were used with the general equations.

The discharge coefficients for velocity for the cases with convection, except position 4, are very similar. For the natural convection the coefficients for the volume flows in the upper half of the aperture are also similar, but the C_d values for the lower flows are slightly larger. For the cases with forced convection the C_d values are larger for the volume flows than for the velocities. The cases with the panel heaters have more varying discharge coefficients and the coefficients for the volume flows are larger than for the velocity. The two cases with the oven located in position 4 have very low discharge coefficients.

Following the correlations from TRNFLOW given in *Chapter 4.5 Discharge coefficient* the discharge coefficient should be 0.4821 as $H_{re}l$ is 0.9216 for the passive house. This value is larger than the majority of the calculated values.

Table 24: The average discharge coefficients for the upper and lower air flows for the eleven cases.

Average discharge coefficient			
Natural convection	**Velocity**	**Volume flow. upper half**	**Volume flow. lower half**
Position 1	0.35208	0.372201787	0.386737378
Position 2	0.357109	0.389117959	0.438971842
Position 3	0.361353	0.363342727	0.438261476
Position 4	0.152674	0.125953358	0.127264376
Forced convection			
Position 1	0.369376	0.422260533	0.434619174
Position 2	0.351968	0.420845704	0.418379003
Position 3	0.37103	0.416010859	0.463669833
Panel heaters			
Position 1	0.390217	0.485218277	0.51029328
Position 2	0.451467	0.486440428	0.458388462
Position 3	0.345771	0.43785925	0.411944428
Position 4	0.253935	0.182400266	0.193831294

8. Other measurements

Some additional measurements were concluded in addition to the main measurements, some. These are briefly presented in the following.

8.1 Measurements conducted with different ventilation flow rates

The ventilation system in the passive house has three flow rates; minimum, normal and maximum. The measurements from *Chapter 7* were all done for the normal flow rate. The following measurements were done with the convector in position 1 and with the minimum and maximum flow rates, the results are shown in the zip-file that is submitted with the thesis. Using the same settings and the normal ventilation flow rate gives the same conditions as for the measurements for natural convection and position 1 presented in *Chapter 7*, therefore, the results from this measurement are used. The average velocity and temperature are given in Figure 18 and Figure 20.

8.1.1 Velocity

The average velocities in the aperture for the minimum and maximum velocity are shown in Figure 65 and Figure 66. Comparing these and the average velocity for the normal flow rate one can see that the shapes of the graphs are similar, but with some differences; the velocity measured by probe 3 was higher for the cases with minimum and maximum velocity. The measurements for the maximum and minimum ventilation flow rates were done in the same day, thus, with the same temperatures and similar solar radiation. This can be the reason why these curves are more similar than the curve for the normal flow rate.

The maximum velocity was lower for the case with the minimum ventilation flow rate, besides this the differences are smaller and the velocities were both lower and larger than for the other cases. The average velocities for the lower probes were similar for the cases with minimum and maximum flow rate and lower than for the case with normal flow rate. The maximum average velocity was quite similar for the normal and maximum flow rate. Thus, there were more clear differences between the minimum flow rate and the normal flow rate than between the maximum and the normal flow rate.

The neutral plane was further form probe 6 when the minimum air flow was applied; the difference between the average velocities for probes 5 and 6 was 0.028 m/s. Corresponding numbers for the normal flow rate and the maximum ventilation flow rate are 0.01259 m/s and 0.01189 m/s, respectively. Thus, the neutral plane seems to be slightly closer to probe 6 for the case with the maximum flow rate. In general the neutral plane seems to be declining when the ventilation air flow is increased. To be sure that this is the case more simulations should be done as the small differences can be due to other factors affecting the air flow or due to the error margin of the equipment. One should also notice that the measurements for the minimum and maximum ventilation rates were done with only nine velocity probes as probe 4 was dysfunctional at the time.

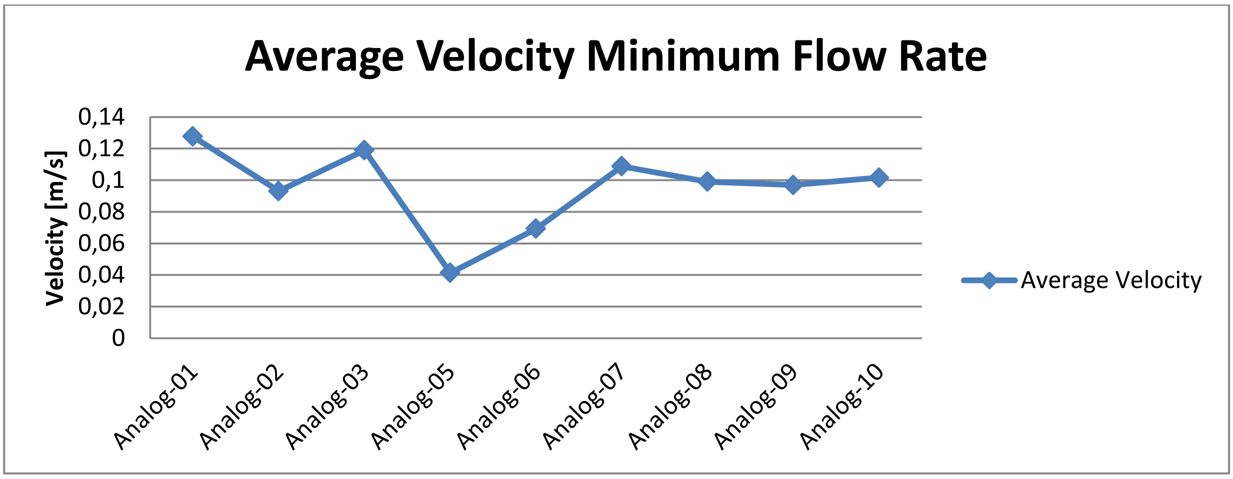

Figure 65: Average velocity per probe for the case with minimum ventilation flow rate.

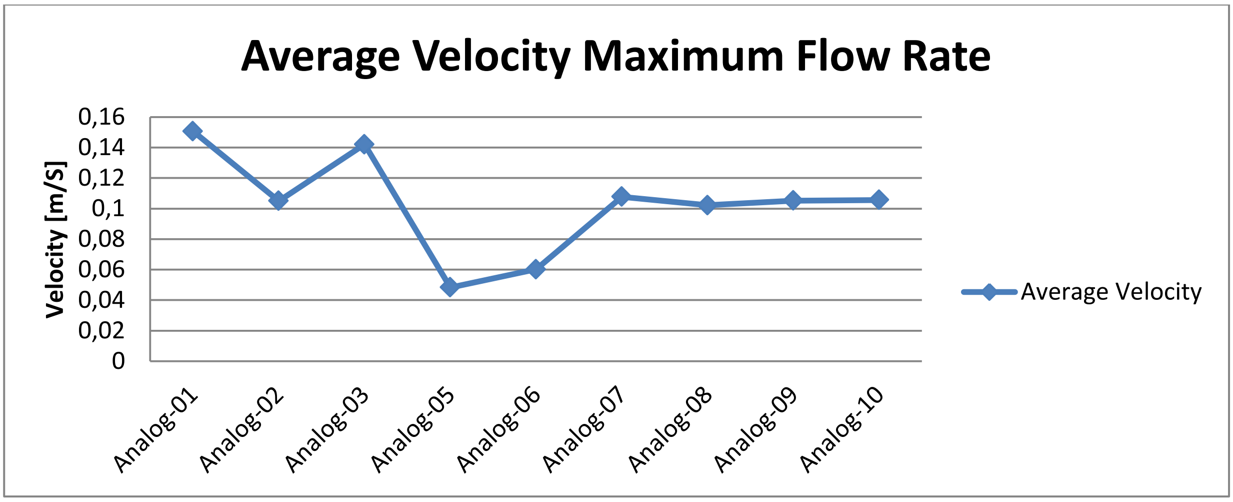

Figure 66: Average velocity per probe for the case with maximum ventilation flow rate.

8.1.2 Temperatures in the aperture

The average temperatures for the cases with minimum and maximum ventilation flow rate are given in Figure 67 and Figure 68. The temperatures are more difficult to compare due to different solar radiation and temperatures in the room when the test were started.

The curves are less straight for the cases with minimum and maximum ventilation flow rates, and the temperatures were lower. The measurement with the lower flow rate also had the lowest temperatures.

8.1.3 Temperatures in the two rooms

The temperatures behaved differently due to difference in solar radiation, besides this there were no significant changes between the three cases.

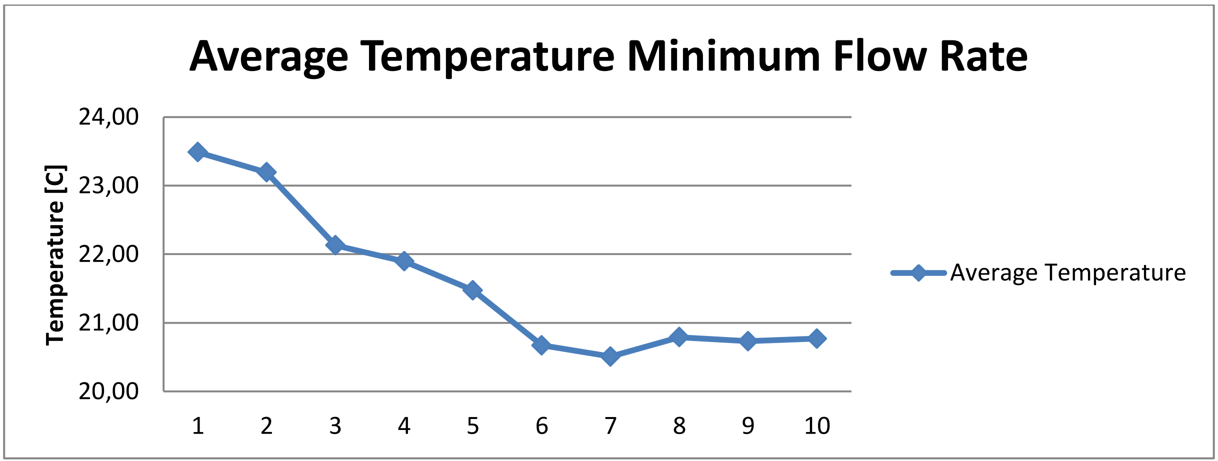

Figure 67: Average temperature per probe for the case with minimum ventilation flow rate.

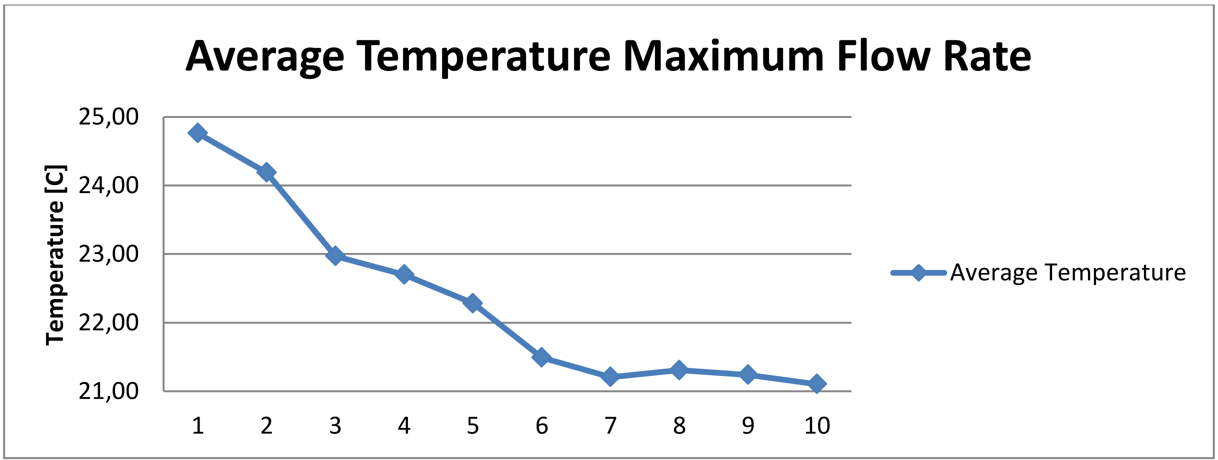

Figure 68: Average temperature per probe for the case with maximum ventilation flow rate.

8.2 Temperature measurements with closed internal doors

The internal doors on the first floor were closed with the convector located in the initial position with the fan off. This resulted in an immediate air temperature decrease, whilst the floor temperatures reacted slower; it took more time before the temperatures started to decrease and the decline was slower. The temperature measured by PT14 did not decrease, but increased due to solar radiation. A new steady state with constant surface and air temperatures was not reached, but the temperature declines slowed down with time. The measured temperatures by PT7 and PT13 can be seen in Figure 69. These results show that the thermal comfort is highly dependent on the internal doors being open.

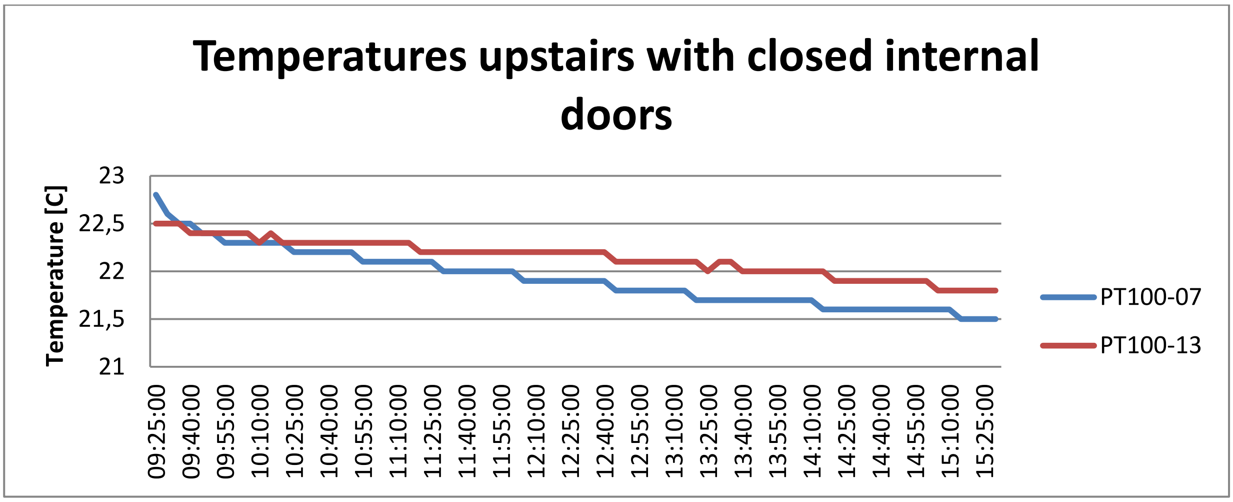

Figure 69: Measured temperatures upstairs with closed internal doors.

9. Analysis and discussion of passive house measurements

It is clear from the presentation of the measurement results in *Chapter 7.6 Measurement results* that the velocity profiles deviate some from the shape that is assumed in many of the analytical models. They follow the same shape as the theoretical velocity profile, but with many deviations which make the velocity profiles based on the measurements asymmetric. However, an assumption that seems to be satisfied is the assumption of only one neutral plane in the aperture, the neutral plane is also located close to the centre of the aperture for most cases. It is clear from the measurements and the smoke test that there is only one neutral plane in the doorway. The flow through the aperture do not resemble the flow pattern of the two-layer hydraulics model either; this model assumes that there are two uniform layers of heated and unheated air, but the measurements show that there are variations in temperature and velocity throughout the air flows. In this discussion the emphasis will be put on the orifice based models and the assumptions connected to these. A reason for the deviations from the theory will be sought by analysing and discussing assumptions the models use. In addition to this some site specific factors will be discussed. Then, a discussion of the differences and similarities between the different measurement results, thermal comfort and the calculations based on the measurements will be conducted.

9.1 Assumptions

As mentioned in *Chapter 4. Mathematical models* a clear majority of the theoretical models assume that the temperatures in the two thermal zones are uniform or it is assumed that there is no stratification. The temperature measurements conducted in the passive house show that none of these assumptions are directly satisfied as the temperature varies throughout the two rooms. The difference between the warmest and coldest temperatures which are measured during each measuring period can be found in Table 25; these values reveal that there are significant temperature differences. Thus, treating the rooms as uniform reservoirs might lead to errors, for instance the local variables being neglected. Even though the assumptions are not directly valid there are some other conditions that can determine if the assumptions are usable. Chen states that the assumption of uniform temperature can be acceptable for small rooms such as offices and bedrooms [8]. The measurements are done for large rooms; neither the living room which is connected to the kitchen and the entrance hall nor the staircase which is connected to the basement and the first floor qualifies as small rooms. According to Etheridge and Sandberg the assumption of uniform temperatures are valid when the vertical temperature difference is small compared to the temperature difference between the two rooms [13]. If the temperature differences in the living room and the staircase from Table 25 is one can see that the vertical temperature differences are of same size or larger than the horizontal temperature difference for the majority of the cases. Thus, according to the given criteria the assumption of uniform temperatures in the two rooms is not valid. This can lead to results that do not correspond to the models that use this assumption.

The assumption of uniform temperatures can be replaced with the assumption of the rooms as semi-infinite reservoirs with small and equal temperature gradients. Hensen et al. [11] states that this assumption is valid if the vertical temperature difference is small compared to the absolute temperature. The vertical temperature differences in the two rooms are smaller than the absolute temperatures, but not negligible as they count for 4.3-34.3 % of the absolute temperature. Again, the assumption is invalid.

In Annex 20 [14] it is stated that the assumption of a larger horizontal than vertical temperature difference does not allow for normal behaviour associated with large vertical openings. This is consistent with the above results.

Table 25: An overview over the maximum temperature differences in the heated and unheated zones per measurement, the horizontal temperature difference between the two rooms and the difference between the horizontal and vertical gradients.

	Maximum vertical temperature difference		**Maximum difference surface tempertaures**		**Horizontal tempe-rature difference**	**Difference horizontal and vertical gradient**	
Measurement	Living room	Staircase	Ground floor	First floor		Living room	Staircase
Natural convection							
Position 1	3.9	4	1	1.5	2.53	1.37	1.47
Position 2	3.9	5.2	2.3	2.3	3.11	0.79	2.09
Position 3	3.4	5.9	3.9	4.4	3.91	-0.51	1.99
Position 4	1	8.5	0.5	1	-1.72	-0.72	6.78
Forced convection							
Position 1	2.5	4.8	1.1	1.3	2.54	-0.40	2.26
Position 2	4.1	5	1.8	1.4	2.85	1.25	2.15
Position 3	2.3	5.4	0.8	1.6	2.82	-0.52	2.58
Panel heaters							
Position 1	1.2	1.3	1.1	0.9	1.22	-0.20	0.08
Position 2	2.1	1.9	1.4	0.8	1.43	0.67	0.47
Position 3	1	2.1	1.1	0.9	1,67	-0.67	0.43
Position 4	1.2	3.3	0.7	1.2	-0.51	0.69	2.79

The measurement results show that there is temperature stratification both in the living room and in the staircase, and that the vertical gradient is larger than the horizontal one for most of the cases. The temperature gradients for the different measurements with the panel heaters as heat source are calculated using equation 42 and can be found in Table 26. These cases are the only measurements with a known design temperature as the convector are set after temperature levels and not exact temperatures. The gradients are found as a scale as the temperature difference between the upper and lower sensors varied during the measurements. The design temperature is set as 23 °C for both the heated and unheated zones as this is the only known set temperature. The calculations show that the gradients varies a lot, and that the gradients are lower for the unheated zones, both when the panel heaters were in the living room and when they were upstairs.

Table 26: Temperature gradients for the four cases with the panel heaters as heat source.

Panel heater measurements	Design temperature [°C]	$\|T_t\text{-}T_b\|$ living room	$\|T_t\text{-}T_b\|$ staircase	Temperature gradient living room	Temperature gradient staircase
Position 1	23	0.7-1.0	0.6-1.3	0.03043-0.04348	0.02609-0.05652
Position 2	23	0.9-1.8	0.6-1.8	0.03913-0.07826	0.02609-0.07826
Position 3	23	0.7-1.0	0.8-2.1	0.03043-0.04348	0.03478-0.09130
Position 4	23	0.2-0.5	2.6-3.3	0.00870-0.2174	0.11304-0.14348

Temperature gradients shift the velocity profile from a symmetric parabolic shape to a non-symmetric and non-parabolic profile [13, 14], this seems to be the case for the passive house measurements. This can easily be seen from the graphs showing the average velocities, for instance Figure 18 and Figure 24. The shapes of the graphs are not symmetric about the middle of the aperture and are clearly non-parabolic.

There are many factors affecting the temperatures in the different part and heights of the two rooms, thus, the temperature profile are most likely not linear. Approximating a non-linear temperature profile as linear can lead to significant errors for the corresponding heat flow [14]. However, none of the theoretical models state that this has been done.

The orifice based models assume that there is no heat transfer between the two flows in or near the door, but this does not correspond with the measurement results. As the vertical temperature transition in the aperture happens gradually this might suggest that some heat energy is transmitted from the heated flow to the unheated flow. The temperatures are clearly lower under the neutral plane, but for all cases with the oven located on the ground floor probe 6 measured a temperature that was slightly warmer than that of probe 7. The same is the case for probe 5 when the heat sources were located on the first floor. This can imply that some heat energy from the heated air stream is transferred to the unheated air stream close to or in the aperture. Such mixing will, according to Annex 20 [14], affect the shape of the velocity profile close to the intersection between the flows.

All of the symmetric analytical models assume that there is no supplied ventilation air, since the passive house has a balanced cascade ventilation system this assumption is not suitable. All modern dwellings and other type of buildings have ventilation systems and as mentioned, this can results in an asymmetric velocity profile in the aperture or even in unidirectional flow. The measurements that were done suggest that the neutral plane declines when the ventilation rate is increased. Thus, the supplied ventilation air affects the flow through the aperture.

The models assume that the values are even in the horizontal plane; however, the measurements show that there are differences in the horizontal plane.

In addition to these assumptions that might affect the shape of the velocity profile there are some site specific factors that also are likely to affect the results. As mentioned earlier, the fact that the measurements are conducted in a staircase can result in incorrect results as the air flow is shaped after the stairway. This includes the air flow between the two zones in general and the air flow close to the bar with the probes due to the handrail being close, especially when the bar is placed in the left side of the aperture. The wall that was built around the staircase to imitate a doorway can also affect the air flow through the aperture. First, the wall deviates from the internal walls of the passive house and secondly the wall is not completely airtight and can therefore affect the flows in the room even though the smoke test showed that the air did not flow through the cracks around the wall. Besides this the solar radiation affecting the temperatures in the house will also indirectly affect the air flows.

Three asymmetric models are also presented in *Chapter 4*. The asymmetric model presented by Hensen et al. uses the same assumptions as the symmetrical model except for two differences; the neutral plane is no longer assumed to be in the middle of the opening, but outside the aperture and the two rooms are assumed to have different, but small temperature gradients. For the passive house measurements there is, as mentioned above, one neutral plane located in the aperture, and the gradients cannot be considered small. Thus, the assumptions for this model do not match the measurements results. The asymmetric model presented by Etheridge and Sandberg assumes that ventilation air is supplied in the warm zone and extracted in the cold zone. As there are air supply *and* outlets both in the living room and in the rooms connected to the staircase upstairs, this assumption is not applicable for the passive house. The equation for asymmetric flow presented by Santamouris et al. is given without stating any other assumptions than that the neutral plane is located in the opening, but not in the middle of the aperture and that there is no stratification in the applicable zone. The first assumption corresponds to the measurements results, but the second does not. Thus, none of the asymmetric models corresponds to the real case in the passive house.

The analytical models assume a stationary situation and give only one value for the velocity, but the measurements show that the velocities vary.

Summarizing the above one can say that the most commonly used assumptions amongst the analytical models are unfit for real cases, at least for these particular passive house measurements. The only assumption that is directly valid is the assumption of only one neutral plane in the aperture. As described in the above using these invalid assumptions can affect the results and the shape of the velocity profile, which is the case for these measurements.

9.2 Measurements

9.2.1 Velocity

The measured velocities varied some for all cases, thus, the probes alternated on measuring the largest velocity. This can be related to the temperature changes due to the solar radiation and the heat sources and to factors such as the staircase, the pole being moved and the ventilation system.

A result that recurred for all three heat sources was that the lower probes measured larger velocities than the upper ones when the heat source was in position 3, this deviates from the initial position. Having in mind that position 3 is close to the stairs this can be due to the temperature difference between the two sides of the aperture being larger for the lower half which results in larger velocity.

Much lower velocities and more fluctuations were measured when the heat sources were located upstairs. This is likely to be related as fluctuations and disturbances are more visible when the velocities are lower. The velocity measured by probe 1 was significant larger than the rest of the velocities for the case with natural convection, for the case with the panel heaters both probes 1 and 2 measured clearly larger velocities than the rest of the probes. This can also be due to the temperature differences between the two sides of the aperture being larger for the upper part of the door; a larger temperature difference gives larger velocity.

The velocities were in general lower and more alike for the cases with the panel heaters as heat source; this is linked to the lower and more even temperatures. The velocities fluctuated more for positions 2 and 3 than for the cases with convection even though the corresponding temperatures were not fluctuating significantly. This can be due to fluctuations being more visible for lower velocities in combination with measurement specific factors such as solar radiation and temperature.

As mentioned in *Chapter 7.7 Comparison for the measurement results* there was no clear pattern for how the velocities changed when the bar was moved horizontally in the opening, but there seemed to be more changes when the bar was moved to the left side of the aperture. This can be related to the fact that there is a handrail in the left side of the aperture. When the bar is moved to this side of the aperture the probes are close to the handrail and the air flow can be affected by this. Other factors, as the ones mentioned above can also influence this.

For a majority of the measurements the standard deviations increased with the velocity. This should be expected as the error connected to the equipment is given as a percentage of the measured velocity; a larger velocity will have a larger margin of error and therefore a larger standard deviation should be expected.

It is hard to give an exact location of the neutral plane, but it seems to be close to the middle of the aperture for all cases with the heat source on the ground floor, this corresponds with the theory. The measured velocities indicate that the neutral plane is located higher for the cases with the heat source upstairs. As the heat has to sink from the first floor to reach the aperture and flow into the living room it is reasonable that the flow from the heated zone to the living room is smaller than for the opposite way. As mentioned above, the location of the neutral plane also shifts when the supplied ventilation air flow is changed.

A possible source of error for the velocity measurements are the usage of two different kinds of velocity probes; all probes were of type 8475, but the probes had two different lengths.

9.2.2 Temperature

The measured temperatures were mostly warmer for the upper probe and then decreased with the height. This is expected as the warm air rises and the temperatures should therefore be warmer with increased height above the floor. The measurement results show that the temperatures were more similar in the lower half of the door. This can also be due to the fact that warm air has a lower density than colder air. The heated air mixes with the room air, thus, temperature variations are obtained. As the warm air rises there is less mixing in the lower zone of the room and therefore less temperature changes. The measured stratification in the room can also point in this direction.

There were cases where the temperatures were divided into a warm and a less warm group and cases where the temperatures were distributed without any large gaps. The case with natural convection and the oven in position 1 and the case with forced convection and the oven in position 3 both had temperatures that were distributed without any large gaps. The remainder of the cases all had temperatures that were divided into two groups. However, the size of the gaps between the groups and the composition of the groups differed some between the cases. As there is no pattern for this behaviour the differences are likely to come from factors that affect the measurements differently like solar radiation and the temperature in the rooms.

The cases with the oven in position 4 had a different heat distribution than the other cases; probe 1 measured a clearly warmer temperature than the other probes which measured similar temperatures. The measured temperatures were all lower than the temperatures measured for the initial position, and the temperature difference between probe 1 and the rest of the probes was larger for the case with natural convection. The temperatures are lower since the warm air must mix with unheated air before it can sink down to the aperture and the temperature difference is larger for the case with natural convection as the temperatures for the heated air were warmer for this case.

The temperatures were in general lower for the cases with the panel heaters; this is due to the temperatures being set on a lower temperature than for the cases with the convector.

There were small or no changes in the measured temperatures when the bar was moved horizontally in the opening, this might imply that the temperature is less dependent on the horizontal location than the velocity.

9.2.3 Temperatures in the two rooms

The temperatures in the living room were less warm and more stable for the panel heaters, thus, there were less stratification for the cases with the panel heaters. This is most likely related to the fact that the temperatures of the panel heaters could be controlled at 23 °C. Georges, Novakovic and Skreiberg states that increasing the percentage of heat emitted as radiation has a positive effect on overheating [2]. Thus, it is reasonable that there was less overheating in the living room when the panel heaters were used.

The temperature in the house increased throughout the day, this is related to the heat gains from the oven and solar radiation throughout the day. As the passive house is built with a tight building envelope the heat do not leak out and heat supplied early one day will remain for the measurements conducted later the same day.

There were small temperature changes in most of the PT-positions in the living room as long as the bar was not located right next to the oven. There were larger differences in position 4 and position 6; position 4 is in the heated air flow into the staircase and position 6 is next to the veranda door. The veranda door has a higher U-value than the walls and it can therefore be colder next to the door when it is cold outside, the window in the door also transmit solar radiation when it is sun outside which will give increased temperature in position 6.

The temperature in the living room was tangible less warm when the heat sources were located on the first floor. This should be expected as the heated air rises and will therefore not fall down to the ground floor before it has been mixed enough with the cold air to reach a density that allows it to descend.

The surface temperatures only had small changes unless they were affected by solar radiation, then the increases were significantly higher. The surfaces on the same floor had temperatures which were similar to each other and to the air temperatures in the room as long as there was no solar radiation. Thus, the surface temperatures seem to be more sensitive to direct solar radiation than to the heat sources.

The temperatures in the stair case were stable before the thread was moved; there was a close to steady state situation. The measured changes in temperatures when the thread was moved all make sense regarding the air flow pattern in the stair; the temperatures in the basement should be lower than that on the ground floor level and the temperatures should be colder in the air stream with unheated air than directly under or above this. There was one exception from this as the temperature measured by PT18 did not change when the thread was moved for the case with the panel heaters in position 1. As the temperature in the house increased throughout the day, the temperature difference when the thread was moved increased throughout the day as well (0.4 °C for position 2 and 0.7 °C for position 3). Thus, the missing temperature drop when the thread was moved can be due to the temperatures in the house being slightly colder for the first test of the day combined with the margin of error of the equipment.

The above mentioned changes only corresponds to the cases with the heat sources in the living room; the air flow pattern in the staircase was different when the heat was supplied on the first floor and there was therefore no stream of unheated air in the middle of the stair case.

The measured stratifications were mostly significantly larger than the values reported by Krajcik et al [18]as mentioned in section 4.4.1.

9.3 Thermal comfort

The average air temperature for the living room and the bedroom which is given in Table 20 reveals that the cases with the convector have temperatures that are too warm for thermal comfort. The convector was set on temperature level three for all the measurements, and the temperature can therefore be reduced. Reducing this temperature can lead to more comfortable temperatures both in the heated and unheated zones, as long as the effect of the oven is not reduced too much. The optimal temperature reduction varies between the cases and is in the range of 3-8 °C. For the cases with the largest temperature difference between the two rooms the required temperature reduction to avoid over heating in the living room can lead to too cold temperatures in the bedroom, see Table 27. Thus, sufficient thermal comfort might not be reachable for all cases using the convector.

For the cases with the panel heaters comfortable temperatures were reached in both thermal zones, a slight reduction of temperature of 1-2 °C can be necessary for some as we experience thermal comfort differently [38]. This shows that one can obtain thermal comfort in the whole passive house by using the panel heaters in a central room.

The passive house measurements were done during February and March which are some of the coldest months of the year. However, the outside temperatures were quite mild for this time of the year and the temperature coins measured an average outdoor temperature of 6.26 °C. It is possible that the results would have been different if these temperatures were colder. On the other hand passive houses react slowly to outdoor temperature changes and the temperature would have to be colder over a long period of time to affect the indoor temperatures significantly.

Table 27: Measured temperatures and temperatures after reduction in the living room and in the bedroom for the cases with convection.

	Measured temperature		Temperature reductions living room			Temperature reductions bedroom		
	Temperature living room [°C]	Temperature bedroom [°C]	-3 °C	-5 °C	-8 °C	-3 °C	-5 °C	-8 °C
Natural convection								
Position 1	26.06	23.63	23.06	21.1	18.06	20.6	18.6	15.63
Position 2	27.42	24.27	24.42	22.4	19.42	21.3	19.3	16.27
Position 3	29.02	25.34	26.02	24	21.02	22.3	20.3	17.34
Position 4	23.1	28.64	20.1	18.1	15.1	25.6	23.6	20.64
Forced convection								
Position 1	26.68	24.3	23.68	21.7	18.68	21.3	19.3	16.3
Position 2	27.13	24.33	24.13	22.1	19.13	21.3	19.3	16.33
Position 3	27.34	24.65	24.34	22.3	19.34	21.7	19.7	16.65

9.4 Calculations

Running the MATLAB script with the measured temperatures and the corresponding densities gave lower values than the initial analytical calculations. The velocities were larger than the calculated average velocity based on the measured values, the analytical values were also mainly larger than all measured velocities, but with some exceptions. This shows that the analytical models do not give similar results as the real case even though the variables that can corresponds to the measured values. The analytical calculations gave significant larger velocities for the cases with the heat source positioned on the first floor, the differences was so large that the values seemed unreasonable. This may suggest that the analytical models cannot be applied for situations where the heat source is located one floor above the aperture.

Calculating the volume flows based on the measured velocities gave volume flows of same magnitude as the analytical models, but the volume flows for the lower halves of the aperture were larger than for the analytical calculations. The volume flows for the two cases with the heat source located upstairs were calculated to be significant lower than the theoretical models suggest. Again, the analytical calculations and the calculations corresponding to the measurements gave different results. The models do not give exact values for the real case, but they can give a good indication of the size of the real volume flows.

The research presented in *Chapter 3. Investigation of thermal comfort using detailed dynamic simulations* uses TRNFLOW to find the volume flows, this model will therefore be looked further into in the following. Comparing the analytical results based on this model and the results based on the measurements gives the differences given in Table 28. The results are closer to the measurement based values for the heated flow, where the analytical values are larger than the measurement based ones. The measurement based values are larger for the unheated air flow and the deviations are negative. There is as good as zero difference for the two first cases, but since the deviations from the measurement based results are significantly larger for other cases one cannot say that the TRNFLOW model can be used to find exact values for volume flows. However, the TRNFLOW model seems to give reasonable indications for the majority of the cases. Again, the differences are much larger for the cases with the heat sources located on the first floor, thus, the TRNFLOW model cannot be used when the heat source is located above the aperture

Table 28: Difference between the analytical results based on the TRNFLOW model and the calculated volume flows based on the measured velocities. The differences are given as a percentage of the measurement based value.

Measurement	TRNFLOW 1→2	Measure-ment based 1→2	Difference 1→ 2	TRNFLOW 2→1	Measure-ment based 2→1	Difference 2→ 1
Natural convection						
Position 1	0.11267	0.1124	0.24 %	-0.11267	0.1209	-6.81 %
Position 2	0.1247	0.1242	0.40 %	-0.1247	0.1571	-20.62 %
Position 3	0.13954	0.1246	11.99 %	-0.13954	0.1801	-22.52 %
Position 4	0.093033	0.0319	191.64 %	-0.093033	0.0325	186.26 %
Forced convection						
Position 1	0.11278	0.1272	-11.34 %	-0.11278	0.1342	-15.96 %
Position 2	0.11941	0.1375	-13.16 %	-0.11941	0.1355	-11.87 %
Position 3	0.11873	0.1274	-6.81 %	-0.11873	0.1574	-24.57 %
Panel heaters						
Position 1	0.078636	0.1017	-22.68 %	-0.078636	0.1122	-29.91 %
Position 2	0.08508	0.1166	-27.03 %	-0.08508	0.1035	-17.80 %
Position 3	0.091918	0.0902	1.90 %	-0.091918	0.1173	-21.64 %
Position 4	0.050865	0.0245	107.61 %	-0.050865	0.0276	84.29 %

The heat transfers based on the measurements shows that the heat transfer is larger for the cases with the largest volume flows, most heat is transferred in the lower part of the aperture and the cases with the panel heaters and the heat source on the first floor give less heat transfer through the door. This simply follows from the equation and is therefore not surprising. The important thing to notice is that the heat transfer is proportional with the mass flow.

The calculations of the average discharge coefficients were done without using the model of Santamouris et al. as this model gave a significantly higher value due to the lower velocity and therefore a lower volume flow. The value differed a lot from the rest of the calculated discharge coefficients and seemed more unrealistic than the rest. However, not using this value in calculating the average discharge coefficients can be a source of error. The coefficients for velocity were similar for all the cases with the convector located on the ground floor. The cases with natural convection had a larger coefficient for mass flow in the lower half of the aperture than for the upper. The discharge coefficients for the cases with forced convection were larger for the volume flow than for the velocity. The cases with the panel heaters had more varying discharge coefficients and the coefficients for the volume flows were larger than for the velocity. The two cases with the oven located in position 4 had very low discharge coefficients; this can be related to the above stated statement of the models not being applicable for cases where the heat source is located above the aperture. As mentioned, C_d varied between the two halves of the aperture; this can be due to the staircase affecting the air stream differently in the two halves. The differences between the heat sources can be related to the different temperatures and velocities. The variations in C_d are small compared to the range used in some of the theory and does not change significantly between the cases with different heat sources and locations which is important information for design and simulations. The variations of the discharge coefficients between the heat sources and the oven-positions show that C_d is a very complex coefficient which is affected by many factors. Using a constant value for the discharge coefficients for all cases might be associated with error and different values or a range should be used.

9.5 Evaluation of the different mathematical models

The different models for the velocities are so similar that there is no real difference of the validity of the results between the models. However, there is one exception from this; the error from the measured value is 6% lower for the models from Etheridge and Sandberg and IEA for the case with forced convection and position 1, see *Attachment 8*. As there is no system for the variations this is most likely due to the already mentioned sources of error. The average difference between the measured and calculated values for all cases with the heat source on the ground floor is 7.5-8.7 % for all models. Thus, considering the error margin of the equipment there's no significant difference between the quality of the results of the different models.

There are more differences between the different models for the volume flows. The majority of the models give results of the same magnitudes, but the difference from the measurement based values still varies with up to 12 %. TRNFLOW, the two-layer hydraulics model and the model from Santamouris et al. give lower volume flows than the rest of the models. TRNFLOW has the results that are closest to the rest of the models and the difference from the measurement based values differs between the cases and is both lower and larger than the differences for the more similar models. The two-layer hydraulics model gave a bit lower values than TRNFLOW and has the second highest overall average difference from the measurement based values. The model from Santamouris et al. gives significant lower values than the other models and has the clearly largest overall average difference from the measurement based results. Thus, the similarities between the measurements based and the analytical calculated values differs between the models and the model from Santamouris et al. is found to be the less appropriate for this case.

10. Conclusion

When analysing the results one should always consider the sources of error as mentioned in the previous chapter. There are errors in coherence with the measuring equipment, due to the measurements being conducted in the staircase and due to the bars being moved and other disturbances. This has all been considered before the following conclusions have been drawn.

The measured velocity profiles deviates clearly from the two-layer hydraulics model as they are not divided into two uniform layers. The velocity profiles resemble the profile form the orifice based models more, but there are some clear differences. These differences make the profiles asymmetric and non-parabolic. This is due to the lack of the validity of many of the central assumptions. The assumptions of uniform temperatures, no stratification and of small and alike temperature gradients are not valid in the passive house. The presence of temperature gradients affects the velocity profile and shifts it from a symmetric and parabolic shape to a non-symmetric shape. The invalidity of the assumptions of no heat transfer in or near the doorway and of no supplied ventilation air also changes the air flow through the aperture away from the shape from the theoretical models.

The only assumption that is found to be valid is that of one neutral plane located in the middle of the aperture as both the measurements and the smoke test show that there is only one neutral plane in the opening. The exact location of the neutral plane is hard to determine, but it is located in or close to the middle of the door. However, this is only the case when the heat sources are positioned on the ground floor. For the two cases with the heat sources located on the first floor there was also only one neutral plane, but it was located above the middle of the opening. It was also found that the location of the neutral plane is affected some by the supplied ventilation flow rate.

The theoretical models are found to be inapplicable when the heat source is located above the aperture as the resulting flow through the door will have a completely different velocity profile than assumed by the models. This gives significant differences between the measured velocities and mass flows based on the measurements and the velocities and mass flows calculated by using the analytical models. The temperature distribution in the aperture was also different when the heat source was located on the first floor.

The calculations that were based on the measured velocities and temperatures gave different results than the calculations based on the analytical models even though the applied size of the door, the temperatures and the densities corresponded with the measurements. The differences were larger for the velocities than for the volume flows. Thus, the models do not give exact values neither for velocities nor for volume flows, but can be used to give an indication of the magnitude for the volume flows.

The discharge coefficients were also calculated for all cases; the results varied amongst the cases, it was also different for velocity and volume flow for the same case. This shows that one value for C_d cannot be used as a default value, but one should use a range of values.

Following the above the theoretical models are not directly applicable for the real situation in a passive house. There are too many assumptions that are not fulfilled and therefore the analytical models seem to be too simplified for real cases. Although this is the case the models can be used to investigate the order of magnitudes for the flow through the aperture as long as the heat source is not located above the vertical opening.

The outdoor temperature was very mild during the test period; this makes it difficult to conclude if thermal comfort can be obtained with this simplified heat system. However, there were no problems with the thermal comfort during the measurement period. There was overheating in the rooms where the heat sources were located, but this overheating was created artificially by imposing a temperature warm enough to give a measurable flow between the two floors. Thus, the settings of the heat sources are important for the thermal comfort; the settings of the heat source must be sat to fit the size and construction of the house, the outside weather conditions and the inhabitants' sensation of thermal comfort.

11. Future work

There are some shortcomings in the presented measurements and results which give possibilities for future work with similar measurements.

11.1 Measurements in an actual door

There are most likely errors in coherence with the measurements being conducted in a staircase, both due to the staircase itself and due to the frame being built around it to imitate a doorway. It could therefore be interesting to investigate if different results are obtained by measuring in an actual door.

11.2 Investigations of opening frequencies

The main measurements are done with open internal doors on the first floor and one test was done with closed doors. This test showed that the temperatures in the bedrooms are highly dependent on the doors being open. In practice it is not possible to have the internal doors open at all times as the residents would like to have some privacy. It is therefore of interest to investigate how the thermal comfort with the simplified heating system will be with different opening frequencies for the internal doors.

11.3 Measurements with colder outdoor temperatures

It has been difficult to conclude if thermal comfort can be achieved with the simplified heat system due to the mild winter. Measurements should be conducted with colder outdoor temperatures before such a conclusion can me drawn.

11.4 Measurements with a radiative heat source

The measurements showed differences between the convector and the panel heaters with a higher share of radiative heat; there were more even temperatures and less overheating when the panel heaters were used. It can therefore be of interest to investigate how the temperature distribution in a passive house will be with a pure radiative heat source.

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13. Figure and table lists

13.1 Figure list

13.2 Table list

Attachment 1: MATLAB Script for analytical calculations

```
%%//// MATHEMATICAL MODELS FOR FLOW THROUGH VERTICAL OPENINGS \\\\%%
%Defining constants
T_1 = 298.15; % [K] Temperature in the warm zone
T_2 = 293.15 ; % [K] Temperature in the cold zone
T_av = (T_1 + T_2)/2; % [K] Average temperature
rho_1 = 1.184; %[kg/m3] Density in the warm zone
rho_2 = 1.204; %[kg/m3] Density in the cold zone
rho_av = (rho_1 + rho_2)/2; % [kg/m3] Average density
H = 2.05 ; % [m] Height of the door
W = 0.84; % [m] Width of the door
Z_n = H/2; % [m] Neutral plane
C_d = 0.4; % Discharge coefficient
g = 9.81; %[m/s2]

%% // EQUATIONS FOR VELOCITY \\ %%
%%HENSEN ET AL
u_12_Hensen = C_d*sqrt(((2*g)/T_1)*(T_1-T_2)*(H-Z_n)); % [m/s]
u_21_Hensen = C_d*sqrt(((2*g)/T_2)*(T_1-T_2)*(Z_n-0)); % [m/s]
%%HEISELBERG
%Ventilation through vertical opening due to thermal buoyancy
u_max_Heiselberg =C_d*sqrt(((2*g*(T_1 - T_2))/T_av)*(H-Z_n));% [m/s]
%%ETHERIDGE AND SANDBERG
u_12_Etheridge = C_d*sqrt((2*g*(rho_2-rho_1)*(H-Z_n))/rho_1);% [m/s]
u_21_Etheridge = C_d*sqrt((2*g*(rho_2-rho_1)*(Z_n-0))/rho_2);% [m/s]
%%IEA ANNEX 20
u_12_IEA =C_d*sqrt((2/rho_1)*(g*(rho_1-rho_2)*(Z_n-H))); %[m/s]
u_21_IEA =C_d*sqrt(abs((2/rho_2)*(g*(rho_1-rho_2)*(Z_n-0)))); %[m/s]
%%Display results for velocity
V = ['The different models give the following velocities: '];
disp(V)
V_H_12 = ['Hensen et al, flow from zone 1 to zone 2: ',
num2str(u_12_Hensen), ' m/s.'];
disp (V_H_12)
V_H_21 = ['Hensen et al, flow from zone 2 to zone 1: ',
num2str(u_21_Hensen), ' m/s.'];
disp (V_H_21)
V_He = ['Heiselberg, maximum velocity: ', num2str(u_max_Heiselberg),
' m/s.'];
disp (V_He)
V_E_12 = ['Etheridge and Sandberg, flow from zone 1 to zone 2: ',
num2str(u_12_Etheridge), ' m/s.'];
disp (V_E_12)
V_E_21 = ['Etheridge and Sandberg, flow from zone 2 to zone 1: ',
num2str(u_21_Etheridge), ' m/s.'];
disp (V_E_21)
V_IEA_12 = ['IEA, flow from zone 1 to zone 2: ', num2str(u_12_IEA),
' m/s.'];
disp (V_IEA_12)
V_IEA_21 = ['IEA, flow from zone 2 to zone 1: ', num2str(u_21_IEA),
' m/s.'];
disp (V_IEA_21)
V_end = ['                         '];
disp(V_end)
```

```
%% // EQUATIONS FOR MASS FLOWS \\ %%
%%TRNFLOW MANUAL
%Flow is defined positive from the warm zone to the cold zone
m_12_TRNFLOW = sqrt(2*T_av*(((1/T_2)-(1/T_1))))*W*C_d*(2/3)*H^(3/2);
%[m3/s]
m_21_TRNFLOW = - sqrt(2*T_av*(((1/T_2)-
(1/T_1))))*W*C_d*(2/3)*H^(3/2); % [m3/s]
%%HENSEN
deltaP = -g*rho_av*T_av*((1/T_1)-(1/T_2))*Z_n;
K_1 = T_1 * rho_1;
K_2 = T_2 *rho_2;
C_a = (deltaP + g*K_1*H*((1/(T_1))-(1/(T_2)))); %
C_b = (deltaP);
C_t = C_a - C_b;
%Divide by rho to get m3/s
m_12_Hensen =
((2/3)*C_d*W*sqrt(2*rho_1)*(H/C_t)*(abs(C_a))^(3/2))/rho_1; % [m3/s]
m_21_Hensen = ((2/3)*C_d*W*sqrt(2*rho_2)*(H/C_t)*(-
C_b^(3/2)))/rho_2; % [m3/s]
%%HEISELBERG
%Mass flow per unit with
q_12_Heiselberg = C_d*sqrt(((2*g)/rho_1)*(rho_2 - rho_1))*(2/3)*(H -
Z_n); % [m3/s]
q_21_Heiselberg = C_d*sqrt(((2*g)/rho_2)*(rho_2 - rho_1))*(2/3)*(Z_n
- 0); % [m3/s]
q_tot_Heiselberg = (1/3)*W*H*C_d*sqrt((g*(T_1 - T_2)*(H-0))/T_1); %
[m3/s]
%% SANTAMOURIS ET AL.
% Same mass flow in both directions, given in [kg/s] - dividing by
rho_av
% gives [m3/s]
m_Santamouris = (2/3)*C_d*W*((Z_n)^1.5)*sqrt(g*((T_1-T_2)/T_av)); %
[m3/s]
%%IEA ANNEX 20
%given in [kg/s] - dividing by rho_av gives [m3/s]
m_IEA = (1/3)*C_d*W*(H^(3/2))*((T_1 - T_2)^(1/2))*sqrt(g/T_av); %
[m3/s]
%%ETHERIDGE AND SANDBERG
%Orifice model
deltarho_r = ((T_1 - T_2)/T_av)*rho_av ;
g_r = (g*deltarho_r)/rho_av ;
q_e_orifice = C_d*(1/3)*W*H*sqrt(g_r*H); %[m3/s]
%Two-layer hydraulics model
a_0 = (Z_n - (H/2))/H ; % =0 for symmetric flow
k = sqrt((((1/2) + a_0)^3)*((1/2) - a_0)^3)/(((((1/2) +
a_0)^3)+((1/2) - a_0)^3)));% = 1/4 for a_0 =0
q_e_twolayer = k*sqrt(g_r*H); % [m3/s]
%%Display results for mass flows
M = ['The different models give the following volume flows: '];
disp(M)
M_T_1= ['TRNFLOW, volume flow from zone 1 to zone 2: ',
num2str(m_12_TRNFLOW),' m3/s.'];
disp(M_T_1)
M_T_2= ['TRNFLOW, volume flow from zone 2 to zone 1: ',
num2str(m_21_TRNFLOW),' m3/s.'];
disp(M_T_2)
```

```
M_H_1= ['Hensen et al, volume flow from zone 1 to zone 2: ',
num2str(m_12_Hensen),' m3/s.'];
disp(M_H_1)
M_H_2= ['Hensen et al, volume flow from zone 2 to zone 1: ',
num2str(m_21_Hensen),' m3/s.'];
disp(M_H_2)
M_He_1= ['Heiselberg, volume flow from zone 1 to zone 2: ',
num2str(q_12_Heiselberg),' m3/s.'];
disp(M_He_1)
M_He_2= ['Heiselberg, volume flow from zone 2 to zone 1: ',
num2str(q_21_Heiselberg),' m3/s.'];
disp(M_He_2)
M_He_3= ['Heiselberg, total volume flow: ',
num2str(q_tot_Heiselberg),' m3/s.'];
disp(M_He_3)
M_S= ['Santamouris et al, volume flow: ', num2str(m_Santamouris),'
m3/s.'];
disp(M_S)
M_IEA= ['IEA, volume flow: ', num2str(m_IEA),' m3/s.'];
disp(M_IEA)
M_O= ['Etheridge and Sandberg, orifice model, volume flow: ',
num2str(q_e_orifice),' m3/s.'];
disp(M_O)
M_TL= ['Etheridge and Sandberg, two-layer hydraulic model, volume
flow: ', num2str(q_e_twolayer),' m3/s.'];
disp(M_TL)
```

Attachment 2: Risk analysis

A.2.1 Risk analysis report

Risikovurderingsrapport

Klimarom VVSLab - Varmekilde og måleprober

Prosjekttittel	Thermal comfort with simplified heat distribution systems in highly insulated buildings
Apparatur	Klimarom VVSLab - Varmekilde og måleprober
Enhet	NTNU
Apparaturansvarlig	Hans Martin Mathisen
Prosjektleder	Hans Martin Mathisen
HMS-koordinator	Morten Grønli
HMS-ansvarlig (linjeleder)	Olav Bolland
Plassering	Klimarom Mesanin VVSlab
Romnummer	C247C
Riggansvarlig	Laurent Georges
Risikovurdering utført av	Martine Blomvik Pettersen

Godkjenning:

	Navn	Dato	Sign
Prosjektleder	Hans Martin Mathisen		
HMS koordinator	Morten Grønli		
HMS-ansvarlig (linjeleder)	Olav Bolland		

INNHOLDSFORTEGNELSE

1. Innledning

Kandidaten skal måle og logge lufthastigheter og lufttemperaturer for luftstrømning gjennom en døråpning mellom et rom som er oppvarmet med en elektrisk varmekilde og et uoppvarmet rom. Den vertikale temperaturfordelingen og veggtemperaturene i begge rom skal også måles.

Målingene skal altså foregå i både det lille og det store rommet i klimarommet på VVSlaben, hvor det er det lille rommet som skal varmes opp.

2. Organisering

Rolle	**NTNU**
Prosjektleder	Hans Martin Mathisen
Apparaturansvarlig	Laurent Georges
Romansvarlig:	Martin Bustadmo
HMS-koordinator	Morten Grønli
HMS-ansvarlig (linjeleder)	Olav Bolland

3. Risikostyring av prosjektet

Hovedaktiviteter risikostyring	**Nødvendige tiltak, dokumentasjon**	**DTG**
Prosjekt initiering	Prosjekt initiering mal	
Veiledningsmøte	Skjema for Veiledningsmøte med pre-risikovurdering	

Innledende risikovurdering	Fareidentifikasjon – HAZID Skjema grovanalyse	15.01.2014
Vurdering av teknisk sikkerhet	Prosess-HAZOP Tekniske dokumentasjoner	15.01.2014
Vurdering av operasjonell sikkerhet	Prosedyre-HAZOP Opplæringsplan for operatører	15.01.2014
Sluttvurdering, kvalitetssikring	Uavhengig kontroll Utstedelse av apparaturkort Utstedelse av forsøk pågår kort	-

4. Tegninger, foto, beskrivelser av forsøksoppsett

Forsøkene utføres i klimarom VVSlab. Først må varmekilden slås på (effekt = 2 kW) og man må avvente til en temperaturforskjell mellom de to rommene på omtrent 5°C er oppnådd. Når dette er oppnådd vil målingen og loggingen av temperaturer og hastigheter starte.

Måleprobene festes på vertikale stolper; én i døråpningen med hastighets- og temperaturprober og en i hvert rom med temperaturprober. Måleprobene skal være koblet trådløst (WiFi) til en PC via en «base station».

Stolpen som måler i døråpningen må flyttes horisontalt i døråpningen i løpet av forsøket, og stolpene som måler temperaturfordelingen må flyttes rundt i rommet. Dette gjør at operatør oppholder seg inne i klimarommet under forsøkene.

Vedlegg:

- Komponentliste

5. Evakuering fra forsøksoppsetningen

Evakuering skjer på signal fra alarmklokker eller lokale gassalarmstasjon med egen lokal varsling med lyd og lys utenfor aktuelle rom, se 6.2

Evakuering fra rigg området foregår igjennom merkede nødutganger til møteplass, (hjørnet gamle kjemi/kjelhuset eller parkeringsplass 1a-b.)

Aksjon på rigg ved evakuering: Ved evakuering skal varmekilden skrus av og målingene stoppes.

6. Varsling

6.1 Før forsøkskjøring

Varsling per e-post, til iept-experiments@ivt.ntnu.no

I e-posten skal det stå:

- Navn på forsøksleder:
- Navn på forsøksrigg:
- Tid for start: (dato og klokkelslett)
- Tid for stop: (dato og klokkelslett)

All forsøkskjøringen skal planlegges og legges inn i aktivitetskalender for lab. Forsøksleder må få bekreftelse på at forsøkene er klarert med øvrig labdrift før forsøk kan iverksettes.

6.2 Ved uønskede hendelser

BRANN

Ved brann en ikke selv er i stand til å slukke med rimelige lokalt tilgjengelige slukkemidler, skal nærmeste brannalarm utløses og arealet evakueres raskest mulig. En skal så være tilgjengelig for brannvesen/bygningsvaktmester for å påvise brannsted.

Om mulig varsles så:

NTNU	SINTEF
Morten Grønli,Mmob: 918 97 515	Harald Mæhlum, Mob: 930 14 986
Olav Bolland: Mob: 918 97 209	Anne Karin T. Hemmingsen Mob: 930 19 669
NTNU – Sintef Beredskapstelefon	800 80 388

GASSALARM

Ved gassalarm skal gassflasker stenges umiddelbart og området ventileres. Klarer man ikke innen rimelig tid å få ned nivået på gasskonsentrasjonen så utløses brannalarm og laben evakueres. Dedikert personell og eller brannvesen sjekker så lekkasjested for å fastslå om det er mulig å tette lekkasje og lufte ut området på en forsvarlig måte.

Varslingsrekkefølge som i overstående punkt.

PERSONSKADE

- Førstehjelpsutstyr i Brann/førstehjelpsstasjoner,
- Rop på hjelp,
- Start livreddende førstehjelp
- **Ring 113** hvis det er eller det er tvil om det er alvorlig skade.

ANDRE UØNSKEDE HENDELSER (AVVIK)

NTNU:

Rapportering av uønskede hendelser, Innsida, avviksmeldinger
https://innsida.ntnu.no/lenkesamling_vis.php?katid=1398

SINTEF:

Synergi

7. Vurdering av teknisk sikkerhet

7.1 Fareidentifikasjon, HAZOP

Se kapittel 13 "Veiledning til rapport mal.

Forsøksoppsetningen deles inn i følgende noder:

Node 1	Rigg i testrommet

Vedlegg, skjema: A Hazop_mal

Vurdering: Sikkerhet er ivaretatt

Da det brukes en varmekilde og elektrisk utstyr kan det være brannfare, utstyret må derfor brukes riktig.

7.2 Brannfarlig, reaksjonsfarlig og trykksatt stoff og gass

Se kapittel 13 "Veiledning til rapport mal.

Inneholder forsøkene brannfarlig, reaksjonsfarlig og trykksatt stoff

NEI	

7.3 Trykkpåkjent utstyr

Inneholder forsøksoppsetningen trykkpåkjent utstyr:

NEI	

Trykkutsatt utstyr skal trykktestes med driftstrykk gange faktor 1.4,for utstyr som har usertifiserte sveiser er faktoren 1.8. Trykktesten skal dokumenteres skriftlig hvor fremgangsmåte framgår.

7.4 Påvirkning av ytre miljø (utslipp til luft/vann, støy, temperatur, rystelser, lukt)

Se kapittel 13 "Veiledning til rapport mal..

NEI	

7.5 Stråling

Se kapittel 13 "Veiledning til rapport mal.

NEI	

7.6 Bruk og behandling av kjemikalier

Se kapittel 13 "Veiledning til rapport mal.

NEI	

7.7 El sikkerhet (behov for å avvike fra gjeldende forskrifter og normer)

NEI	

Her forstås montasje og bruk i forhold til normer og forskrifter med tanke på berøringsfare

8. Vurdering av operasjonell sikkerhet

Sikrer at etablerte prosedyrer dekker alle identifiserte risikoforhold som må håndteres gjennom operasjonelle barrierer og at operatører og teknisk utførende har tilstrekkelig kompetanse.

8.1 Prosedyre HAZOP

Se kapittel 13 "Veiledning til rapport mal.

Metoden er en undersøkelse av operasjonsprosedyrer, og identifiserer årsaker og farekilder for operasjonelle problemer.

Vedlegg: HAZOP_MAL_Prosedyre
Vurdering: Enkel prosedyre. Misforståelser vil ikke føre til farlige situasjoner. Skjema er derfor ikke fylt ut.

8.2 Drifts og nødstopps prosedyre

Se kapittel 13 "Veiledning til rapport mal.

Driftsprosedyren er en sjekkliste som skal fylles ut for hvert forsøk.
Nødstopp prosedyren skal sette forsøksoppsetningen i en harmløs tilstand ved uforutsette hendelser.

Vedlegg "Procedure for running experiments
Nødstopp prosedyre: Nødstopp skjer ved brann, varmekilden skrus av.

8.3 Opplæring av operatører

Dokument som viser Opplæringsplan for operatører utarbeides for alle forøksoppsetninger.

- *Hvilke krav er det til opplæring av operatører.*
- *Hva skal til for å bli selvstendig operatør*
- *Arbeidsbeskrivelse for operatører*

Vedlegg: *H* Opplæringsplan for operatører

8.4 Tekniske modifikasjoner

- Tekniske modifikasjoner som kan gjøres av Operatør
  - Alle modifikasjoner utenom endringer på den elektriske koblingen av utstyr kan gjøres av operatør
- Tekniske modifikasjoner som må gjøres av *Teknisk personale:*
  - Endringer på den elektriske koblingen av utstyr må gjøres av Teknisk personale

8.5 Personlig verneutstyr

- *Da det er påbudt med vernebriller for studenter, skal vernebriller brukes.*

8.6 Generelt

- *Ventilasjonssystemet i testrommet skal ha normal operasjon for å sikre riktige resultater*

8.7 Sikkerhetsutrustning

- *Ikke nødvendig*

8.8 Spesielle tiltak

9. Tallfesting av RESTRISIKO – RISIKOMATRISE

Se kapittel 13 "Veiledning til rapport mal.

Risikomatrisen vil gi en visualisering og en samlet oversikt over aktivitetens risikoforhold slik at ledelse og brukere får et mest mulig komplett bilde av risikoforhold.

IDnr	Aktivitet-hendelse	Frekv-Sans	Kons	RV
1	*Fare for skade fra verktøy ved montering av utstyr*	2	B	B2
	Fare for å snuble i utstyr	2	B	B2

Vurdering restrisiko: *Deltakerne foretar en helhetsvurdering for å avgjøre om gjenværende risiko ved aktiviteten/prosessen er akseptabel. Avsperring og kjøring utenom arbeidstid*

10. Konklusjon

Riggen er bygget til god laboratorium praksis (GLP).

Apparaturkortet får en gyldighet på **6 måneder**

Forsøk pågår kort får en gyldighet på **6 måneder**

11. Lover Forskrifter og Pålegg som gjelder

Se http://www.arbeidstilsynet.no/regelverk/index.html

- Lov om tilsyn med elektriske anlegg og elektrisk utstyr (1929)
- Arbeidsmiljøloven
- Forskrift om systematisk helse-, miljø- og sikkerhetsarbeid (HMS Internkontrollforskrift)
- Forskrift om sikkerhet ved arbeid og drift av elektriske anlegg (FSE 2006)
- Forskrift om elektriske forsyningsanlegg (FEF 2006)
- Forskrift om utstyr og sikkerhetssystem til bruk i eksplosjonsfarlig område NEK 420
- Forskrift om håndtering av brannfarlig, reaksjonsfarlig og trykksatt stoff samt utstyr og anlegg som benyttes ved håndteringen
- Forskrift om Håndtering av eksplosjonsfarlig stoff
- Forskrift om bruk av arbeidsutstyr.
- Forskrift om Arbeidsplasser og arbeidslokaler
- Forskrift om Bruk av personlig verneutstyr på arbeidsplassen
- Forskrift om Helse og sikkerhet i eksplosjonsfarlige atmosfærer
- Forskrift om Høytrykksspyling
- Forskrift om Maskiner
- Forskrift om Sikkerhetsskilting og signalgivning på arbeidsplassen
- Forskrift om Stillaser, stiger og arbeid på tak m.m.
- Forskrift om Sveising, termisk skjæring, termisk sprøyting, kullbuemeisling, lodding og sliping (varmt arbeid)
- Forskrift om Tekniske innretninger
- Forskrift om Tungt og ensformig arbeid
- Forskrift om Vern mot eksponering for kjemikalier på arbeidsplassen (Kjemikalieforskriften)
- Forskrift om Vern mot kunstig optisk stråling på arbeidsplassen
- Forskrift om Vern mot mekaniske vibrasjoner
- Forskrift om Vern mot støy på arbeidsplassen

Veiledninger fra arbeidstilsynet

se: http://www.arbeidstilsynet.no/regelverk/veiledninger.html

12. DOKUMENTASJON

- Tegninger, foto, beskrivelser av forsøksoppsetningen
- Hazop_mal
- Sertifikat for trykkpåkjent utstyr
- Håndtering avfall i NTNU
- Sikker bruk av LASERE, retningslinje
- HAZOP_MAL_Prosedyre
- Forsøksprosedyre
- Opplæringsplan for operatører
- Skjema for sikker jobb analyse, (SJA)
- Apparaturkortet
- Forsøk pågår kort

A.2.2 Risk analysis attachments

Vedlegg til Risikovurderingsrapport

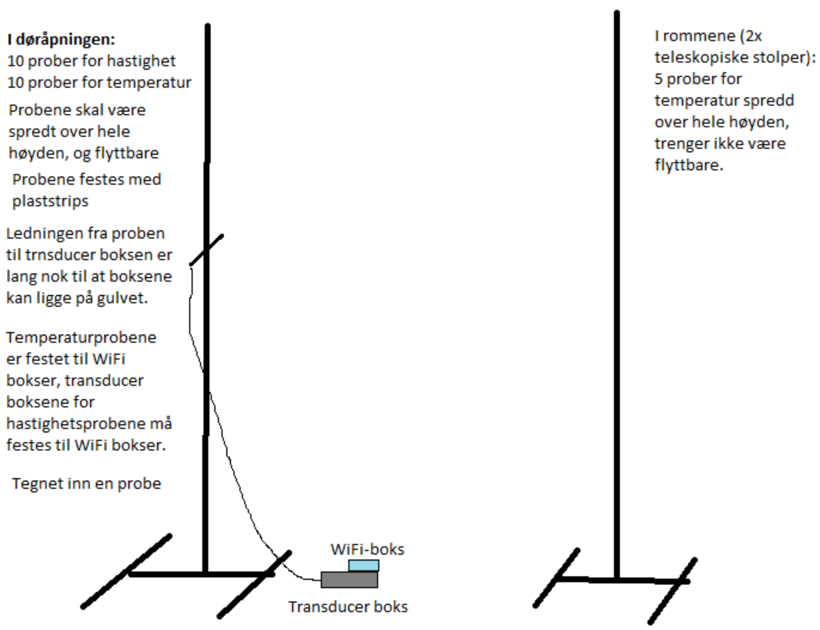
Klimarom VVSLab - Varmekilde og måleprober

Prosjekttittel	Thermal comfort with simplified heat distribution systems in highly insulated buildings
Apparatur	Klimarom VVSLab - Varmekilde og måleprober
Enhet	NTNU
Apparaturansvarlig	Hans Martin Mathisen
Prosjektleder	Hans Martin Mathisen
HMS-koordinator	Morten Grønli
HMS-ansvarlig (linjeleder)	Olav Bolland
Plassering	Klimarom Mesanin VVSLab
Romnummer	C247C
Risikovurdering utført av	Martine Blomvik Pettersen

INNHOLDSFORTEGNELSE

Vedlegg A: Prosess og instrumenteringsdiagram

- 10 TSI Omnidirectional sensor, 15 cm Probe
- 1 WiSensys Base station WS-BU with Ethernet output module
- 10 Wisensys Analog ext pr. Signal sens. 4-20 mA
- 20 WiSensys Temp For external PT-100 probe
- 20 Wisensys PT-100
- 10 WiSensys Temp for thermocouple probe, WS-DLTh
- Elektrisk varmekilde



Vedlegg B: HAZOP MAL

Project: Thermal comfort with simplified heat distribution systems in highly insulated buildings **Node: Rom C247, Klimarom VVSlab - Varmekilde**						**Page**	
Ref#	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	No flow	Ikke relevant					
	Reverse flow	Ikke relevant					
	More flow	Ikke relevant					
	Less flow	Ikke relevant					
	More level	Ikke relevant					
	Less level	Ikke relevant					
	More pressure	Ikke relevant					
	Less pressure	Ikke relevant					
1	More temperature	For høy effekt	For stor temperaturforskjell	Skru ned effekten på varmekilden			
2	Less temperature	For lav effekt	For liten temperaturforskjell	Skru opp effekten på varmekilden, bytt varmekilde hvis dette			

Project: Thermal comfort with simplified heat distribution systems in highly insulated buildings **Node: Rom C247, Klimarom VVSlab - Varmekilde**							**Page**
Ref#	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
				ikke er mulig			
	More viscosity	Ikke relevant					
	Less viscosity	Ikke relevant					
	Composition Change	Ikke relevant					
	Contamination	Ikke relevant					
	Relief	Ikke relevant					
	Instrumentation	Ikke relevant					
	Sampling	Ikke relevant					
	Corrosion/erosion	Ikke relevant					
	Service failure	Ikke relevant					
	Abnormal operation	Se ref 1-2					
	Maintenance	Ikke relevant					

Project: **Thermal comfort with simplified heat distribution systems in highly insulated buildings** **Node: Rom C247, Klimarom VVSlab - Varmekilde**						**Page**	
Ref#	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	Ignition	Ikke relevant					
	Spare equipment	Ikke relevant					
	Safety	Ikke relevant					

Project: Thermal comfort with simplified heat distribution systems in highly insulated buildings **Node: Rom C247, Klimarom VVSlab - Måleprober**						**Page**	
Ref#	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	No flow	Ikke relevant					
	Reverse flow	Ikke relevant					
	More flow	Ikke relevant					

Project: Thermal comfort with simplified heat distribution systems in highly insulated buildings **Node: Rom C247, Klimarom VVSlab - Måleprober**						**Page**	
Ref#	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	Less flow	Ikke relevant					
	More level	Ikke relevant					
	Less level	Ikke relevant					
	More pressure	Ikke relevant					
	Less pressure	Ikke relevant					
	More temperature	Ikke relevant					
	Less temperature	Ikke relevant					
	More viscosity	Ikke relevant					
	Less viscosity	Ikke relevant					
	Composition Change	Ikke relevant					
	Contamination	Ikke relevant					
	Relief	Ikke relevant					

Project: Thermal comfort with simplified heat distribution systems in highly insulated buildings **Node: Rom C247, Klimarom VVSlab - Måleprober**						**Page**	
Ref#	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	Instrumentation	Dårlig oppkobling	Feil resultater, elektriske feil	Skru av, koble opp på nytt, sjekk at det er riktige før målingene gjenopptas			
	Sampling	Ikke relevant					
	Corrosion/erosion	Ikke relevant					
	Service failure	Probene løsner	Feil resultater	Skru av, fest på nytt, gjenoppta målingene			
	Abnormal operation	Ikke relevant					
	Maintenance	Ikke relevant					
	Ignition	Ikke relevant					
	Spare equipment	Ikke relevant					
	Safety	Ikke relevant					

Vedlegg C: Prøvesertifikat for lokal trykktesting

Trykk testen skal utføres I følge NS-EN 13445 del 5 (Inspeksjon og prøving).
Se også prosedyre for trykktesting gjeldende for VATL lab

Trykkpåkjent utstyr:	
Benyttes i rigg:	
Design trykk for utstyr (bara):	
Maksimum tillatt trykk (bara): (i.e. burst pressure om kjent)	
Maksimum driftstrykk i denne rigg:	

Prøvetrykket skal fastlegges i følge standarden og med hensyn til maksimum tillatt trykk.

Prøvetrykk (bara):			
X maksimum driftstrykk: I følge standard			
Test medium:			
Temperatur (°C)			
Start tid:		Trykk (bara):	
Slutt tid:		Trykk (bara):	
Maksimum driftstrykk i denne rigg:			

Eventuelle repetisjoner fra atm. trykk til maksimum prøvetrykk:…………….

Test trykket, dato for testing og maksimum tillatt driftstrykk skal markers på (skilt eller innslått)

Sted og dato Signatur

Vedlegg D: HAZOP MAL Prosedyre

Project: **Node: 1**						**Page**	
Ref#	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	Uklar	Prosedyre er laget for ambisiøs eller preget av forvirring					
	Trinn på feil plass	Prosedyren vil lede til at handlinger blir gjennomført i feil mønster/rekkefølge					
	Feil handling	Prosedyrens handling er feil spesifisert					
	Uriktig informasjon	Informasjon som er gitt i forkant av handling er feil spesifisert					
	Trinn utelatt	Manglende trinn, eller trinn krever for mye av operatør					
	Trinn mislykket	Trinn har stor sannsynlighet for å mislykkes					
	Påvirkning og effekter fra andre	Prosedyrens prestasjoner vil trolig bli påvirket av andre kilder					

Vedlegg E: Forsøksprosedyre

Prosjekt Thermal comfort with simplified heat distribution systems in highly insulated buildings		
Apparatur Klimarom VVSlab - Varmekilde og måleprober	**Dato**	**Signatur**
Prosjektleder Hans Martin Mathisen		

	Conditions for the experiment:	**Completed**
	Experiments should be run in normal working hours, 08:00-16:00 during winter time and 08.00-15.00 during summer time. Experiments outside normal working hours shall be approved.	
	One person must always be present while running experiments, and should be approved as an experimental leader.	
	An early warning is given according to the lab rules, and accepted by authorized personnel.	
	Be sure that everyone taking part of the experiment is wearing the necessary protecting equipment and is aware of the shut down procedure and escape routes.	
	Preparations	**Carried out**
	Post the “Experiment in progress” sign.	
	Place the equipment in the right start positions and turn on the heat source.	
	During the experiment	
	Move the bars with the probes to all measuring points.	
	Monitor the results.	
	End of experiment	
	Turn off theheat source.	
	End the measurements.	

	Remove all obstructions/barriers/signs around the experiment.	
	Tidy up and return all tools and equipment.	
	Tidy and cleanup work areas.	
	Return equipment and systems back to their normal operation settings	
	To reflect on before the next experiment and experience useful for others	
	Was the experiment completed as planned and on scheduled in professional terms?	
	Was the competence which was needed for security and completion of the experiment available to you?	
	Do you have any information/ knowledge from the experiment that you should document and share with fellow colleagues?	

Operatører:

Navn	**Dato**	**Signatur**
Martine B. Pettersen		
Laurent Georges		

Vedlegg F: Opplæringsplan for opperatører

Prosjekt Thermal comfort with simplified heat distribution systems in highly insulated buildings		
Apparatur Klimarom VVSlab - Varmekilde og måleprober	**Dato**	**Signatur**
Prosjektleder Hans Martin Mathisen		

	Kjennskap til EPT LAB generelt	
	Lab - adgang - rutiner/regler - arbeidstid	
	Kjenner til evakueringsprosedyrer	
	Aktivitetskalender	
	Innmelding av forsøk til: iept-experiments@ivt.ntnu.no	
	Kjennskap til forsøkene	
	Prosedyrer for forsøkene	
	Nødstopp	
	Nærmeste brann/førstehjelpsstasjon	

Jeg erklærer herved at jeg har gjennomgått og forstått HMS-regelverket, har fått hensiktsmessig opplæring for å kjøre dette eksperimentet og er klar over mitt personlige ansvar ved å arbeide i EPT laboratorier.

Operatører

Navn	Dato	Signatur
Martine B. Pettersen		
Laurent Georges		

Vedlegg G: Skjema for sikker jobb analyse

SJA tittel:		
Dato:		Sted:
Kryss av for utfylt sjekkliste:		

Deltakere:		
SJA-ansvarlig:		

Arbeidsbeskrivelse: (Hva og hvordan?)
Risiko forbundet med arbeidet:
Beskyttelse/sikring: (tiltaksplan, se neste side)
Konklusjon/kommentar:

Anbefaling/godkjenning:	**Dato/Signatur:**	**Anbefaling/godkjenning:**	**Dato/Signatur:**

SJA-ansvarlig:		HMS koordinator	
Ansvarlig for utføring:		Annen (stilling):	

HMS aspekt	Ja	Nei	NA	Kommentar / tiltak	Ansv.
Dokumentasjon, erfaring, kompetanse					
Kjent arbeidsoperasjon?					
Kjennskap til erfaringer/uønskede hendelser fra tilsvarende operasjoner?					
Nødvendig personell?					
Kommunikasjon og koordinering					
Mulig konflikt med andre operasjoner?					
Håndtering av en evnt. hendelse (alarm, evakuering)?					
Behov for ekstra vakt?					
Arbeidsstedet					
Uvante arbeidsstillinger?					
Arbeid i tanker, kummer el.lignende?					
Arbeid i grøfter eller sjakter?					
Rent og ryddig?					
Verneutstyr ut over det personlige?					
Vær, vind, sikt, belysning, ventilasjon?					
Bruk av stillaser/lift/seler/stropper?					
Arbeid i høyden?					
Ioniserende stråling?					
Rømningsveier OK?					
Kjemiske farer					
Bruk av helseskadelige/giftige/etsende kjemikalier?					
Bruk av brannfarlige eller eksplosjonsfarlige kjemikalier?					

Er broken risikovurdert?					
Biologisk materiale?					
Støv/asbest/isolasjonsmateriale?					
Mekaniske farer					
Stabilitet/styrke/spenning?					
Klem/kutt/slag?					
Støy/trykk/temperatur?					
Behandling av avfall?					
Behov for spesialverktøy?					
Elektriske farer					
Strøm/spenning/over 1000V?					
Støt/krypstrøm?					
Tap av strømtilførsel?					
Området					
Behov for befaring?					
Merking/skilting/avsperring?					
Miljømessige konsekvenser?					
Sentrale fysiske sikkerhetssystemer					
Arbeid på sikkerhetssystemer?					
Frakobling av sikkerhetssystemer?					
Annet					

Apparaturkort / UnitCard

Dette kortet SKAL henges godt synlig på apparaturen!

This card MUST be posted on a visible place on the unit!

Apparatur (Unit) Klimarom VVSLab - Varmekilde og måleprober	**Dato Godkjent** (Date Approved)
Faglig Ansvarlig (Scientific Responsible) Hans Martin Mathisen	**Telefon mobil/privat** (Phone no. mobile/private)
Apparaturansvarlig (Unit Responsible) Hans Martin Mathisen	**Telefon mobil/privat** (Phone no. mobile/private)
Sikkerhetsrisikoer (Safety hazards) Varmekilde: Brannfare ved feil bruk Måleprober: Fare for elektriske feil ved feil elektrisk oppkobling	
Sikkerhetsregler (Safety rules) Vernebriller	
Nødstopp prosedyre (Emergency shutdown) Skru av varmekilden og stopp målingene	

Her finner du (Here you will find):

Prosedyrer (Procedures)	Ved PC
Bruksanvisning (Users manual)	Ved PC

Nærmeste (Nearest)

Brannslukningsapparat (fire extinguisher)	1. etasje VVSlab (syd)
Førstehjelpsskap (first aid cabinet)	1. etasje VVSlab (syd)

NTNU
Institutt for energi og prosessteknikk

Dato

____

Signert

____

FORSØK PÅGÅR /EXPERIMENT IN PROGRESS

Dette kortet SKAL henges opp før forsøk kan starte!

This card MUST be posted on the unit before the experiment startup!

<table>
<tr><td colspan="2">Apparatur (Unit)
Klimarom VVSLab - Varmekilde og måleprober</td><td>Dato Godkjent (Date Approved)</td></tr>
<tr><td colspan="2">Faglig Ansvarlig (Scientific Responsible)
Hans Martin Mathisen</td><td>Telefon mobil/privat (Phone no. mobile/private)</td></tr>
<tr><td colspan="2">Apparaturansvarlig (Unit Responsible)
Hans Martin Mathisen</td><td>Telefon mobil/privat (Phone no. mobile/private)</td></tr>
<tr><td colspan="3">Godkjente operatører (Approved Operators)
Martine Blomvik Pettersen
Laurent Georges</td></tr>
<tr><td>Prosjekt (Project)
Thermal comfort with simplified heat distribution systems in highly insulated buildings</td><td colspan="2">Prosjektleder (Project leader)
Hans Martin Mathisen</td></tr>
<tr><td colspan="3">Forsøkstid / Experimental time (start - stop)</td></tr>
<tr><td colspan="3">Kort beskrivelse av forsøket og relaterte farer (Short description of the experiment and related hazards)
Varmekilde:
En elektrisk varmekilde brukes for å få en temperaturdifferanse mellom de tom rommene. Denne må brukes riktige så det ikke oppstår brannfare.
Måleprober:
Prober for temperatur- og hastighetsmålinger skal kobles til en PC via WiFi, denne elektriske koblingen må gjøres riktig for å unngå elektriske feil. Probene skal måle temperatur og hastighet for luftstrøm gjennom døråpning samt temperturfordelingen i de to rommene.</td></tr>
</table>

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Dato

____

Signert

____

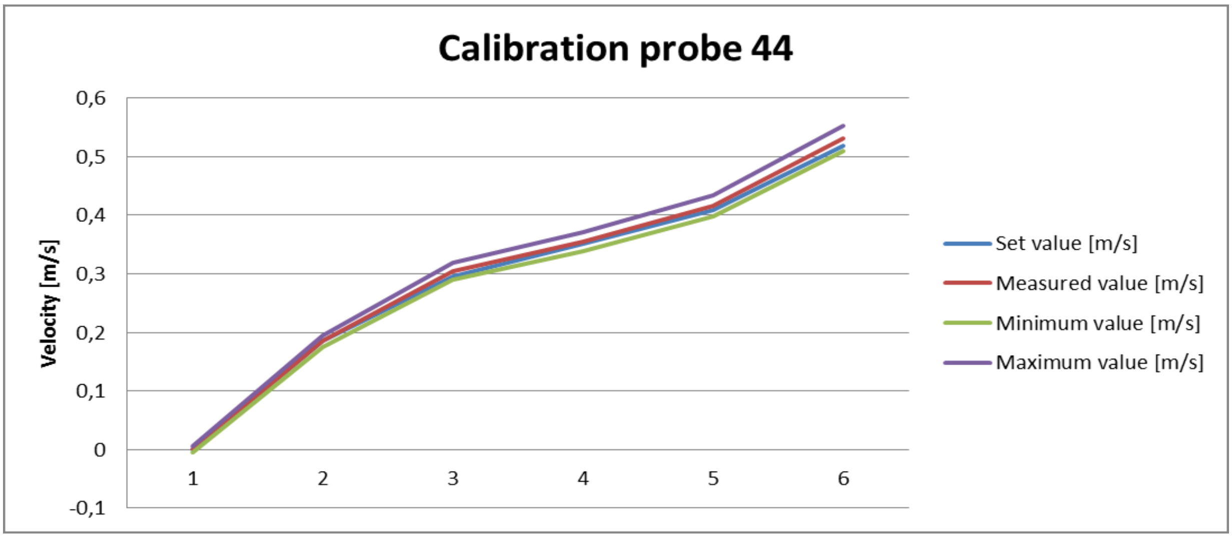
Attachment 3: Calibration of velocity probes

The following values apply to all probes:

Full scale	0-0.5 [m/s]	
Zero	0	
Span	1	
Error full scale	± 1 %	0.005 [m/s]
Error reading	± 3 %	

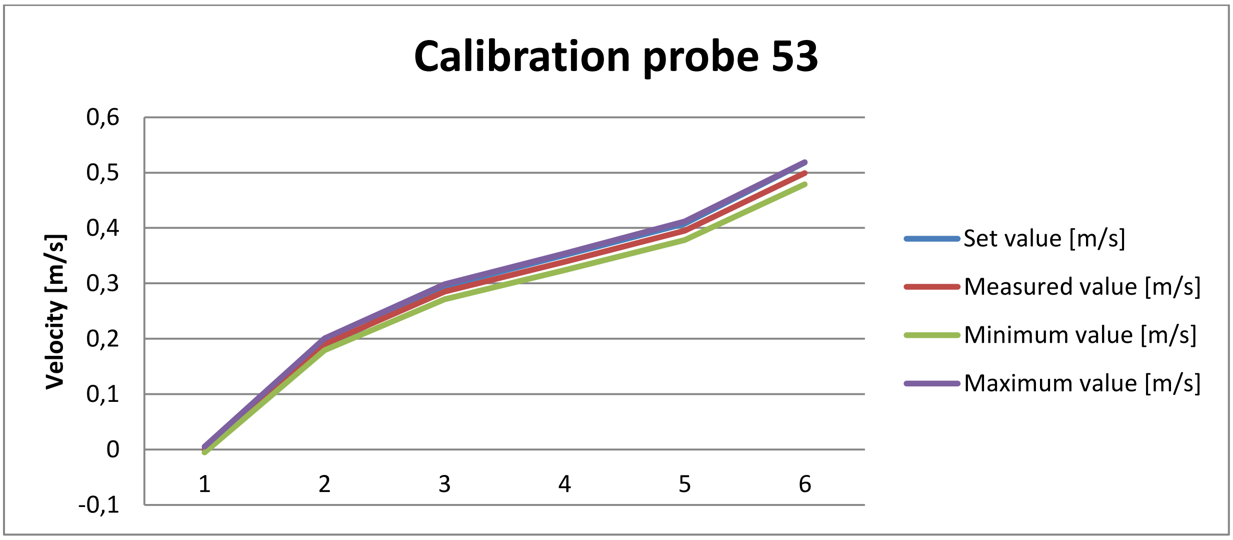
A3.1 Calibration of probe 44

Set value [m/s]	***Measured value [m/s]***	***Error reading [m/s]***	***Error total [m/s]***	***Minimum value [m/s]***	***Maximum value [m/s]***
0	0	0	0.005	-0.005	0.005
0.185	0.185	0.00555	0.01055	0.17445	0.19555
0.295	0.304	0.00912	0.01412	0.28988	0.31812
0.351	0.355	0.01065	0.01565	0.33935	0.37065
0.408	0.416	0.01248	0.01748	0.39852	0.43348
0.518	0.531	0.01593	0.02093	0.51007	0.55193



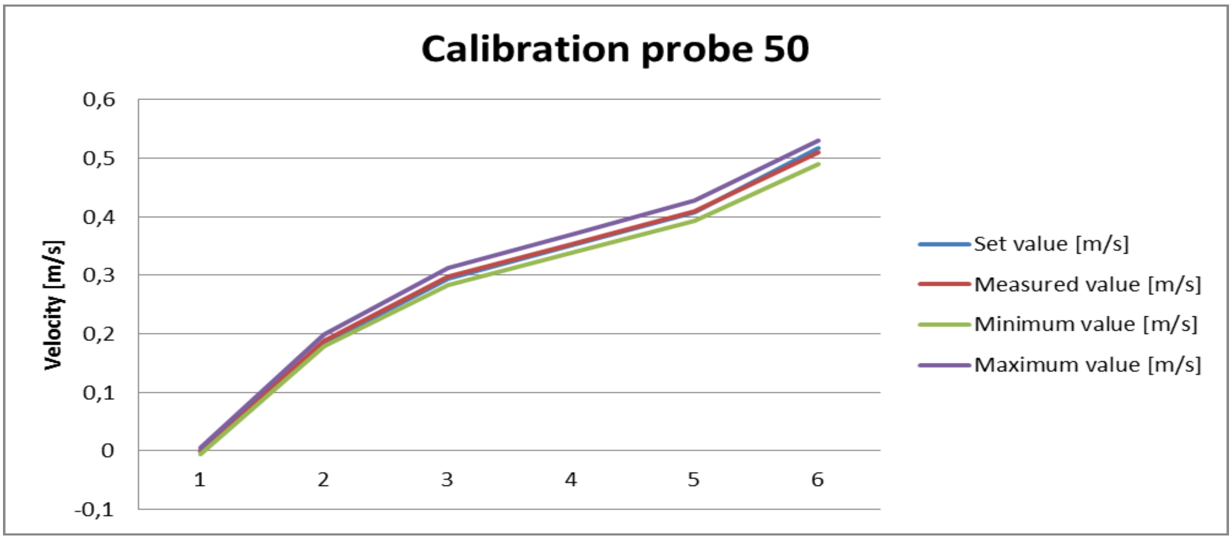
A3.2 Calibration of probe 53

Set value [m/s]	*Measured value [m/s]*	*Error reading [m/s]*	*Error total [m/s]*	*Minimum value [m/s]*	*Maximum value [m/s]*
0	0	0	0.005	-0.005	0.005
0.185	0.19	0.0057	0.0107	0.1793	0.2007
0.295	0.285	0.00855	0.01355	0.27145	0.29855
0.351	0.339	0.01017	0.01517	0.32383	0.35417
0.408	0.395	0.01185	0.01685	0.37815	0.41185
0.518	0.499	0.01497	0.01997	0.47903	0.51897



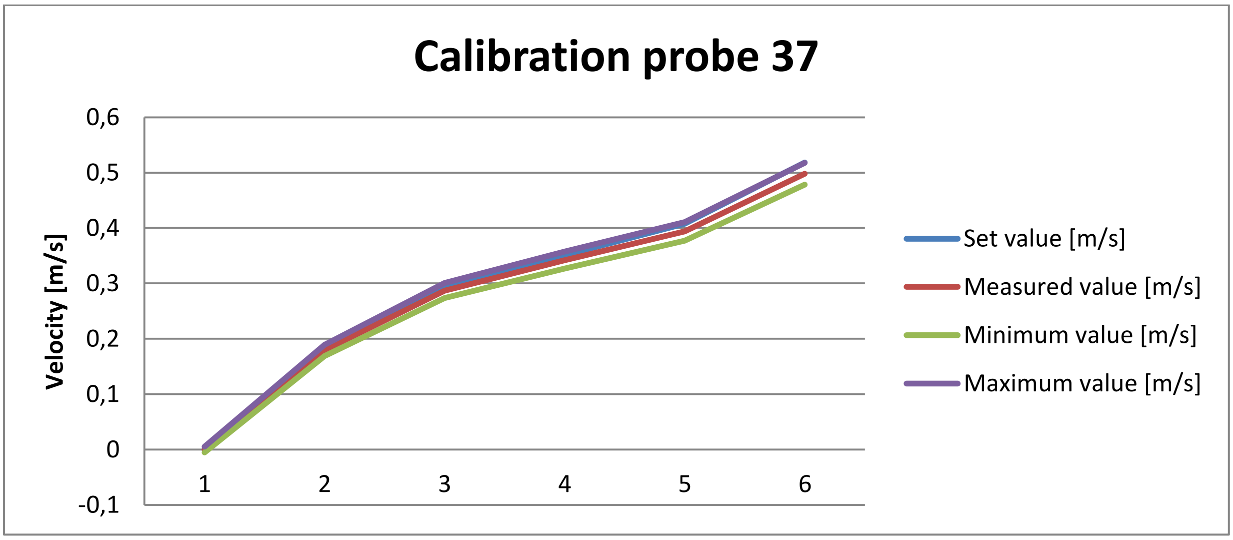
A3.3 Calibration of probe 50

Set value [m/s]	*Measured value [m/s]*	*Error reading [m/s]*	*Error total [m/s]*	*Minimum value [m/s]*	*Maximum value [m/s]*
0	0	0	0.005	-0.005	0.005
0.185	0.189	0.00567	0.01067	0.17833	0.19967
0.295	0.298	0.00894	0.01394	0.28406	0.31194
0.351	0.353	0.01059	0.01559	0.33741	0.36859
0.408	0.41	0.0123	0.0173	0.3927	0.4273
0.518	0.51	0.0153	0.0203	0.4897	0.5303



A3.4 Calibration of probe 37

Set value [m/s]	*Measured value [m/s]*	*Error reading [m/s]*	*Error total [m/s]*	*Minimum value [m/s]*	*Maximum value [m/s]*
0	0	0	0.005	-0.005	0.005
0.185	0.179	0.00537	0.01037	0.16863	0.18937
0.295	0.287	0.00861	0.01361	0.27339	0.30061
0.351	0.342	0.01026	0.01526	0.32674	0.35726
0.408	0.394	0.01182	0.01682	0.37718	0.41082
0.518	0.498	0.01494	0.01994	0.47806	0.51794



A3.5 Calibration of extra probe

Set value [m/s]	*Measured value [m/s]*
0	0
0.185	0.168
0.295	0.272

Attachment 4: Pictures

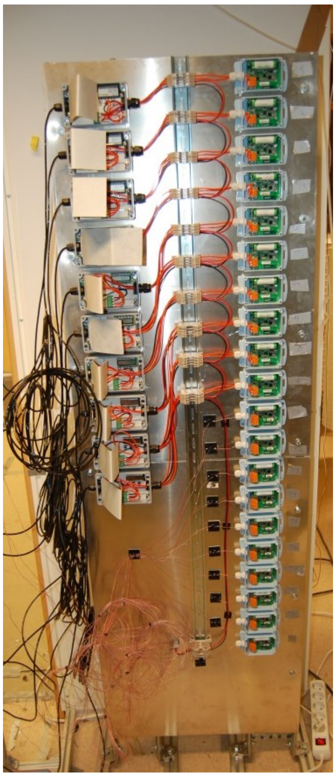


Figure 70: Thee setup for the transducers and the sensors for the velocities and temperatures in the aperture.

Figure 71: The convector.

Figure 72: The panel heaters.

Figure 73: The setup for the measurements in the staircase.

Figure 74: The probes measuring the surface temperatures were fastened with tack-it.

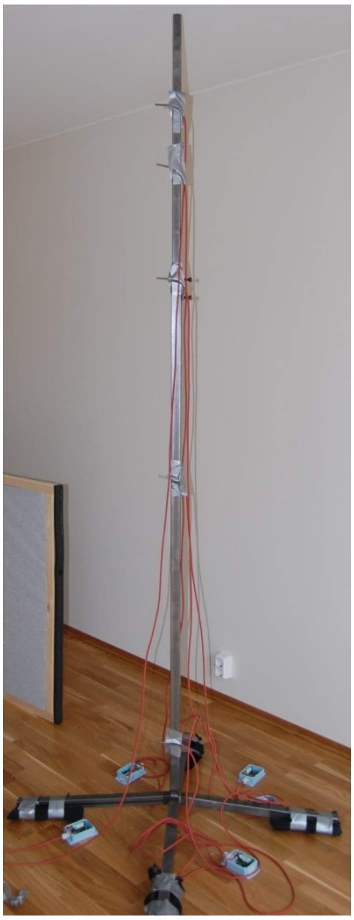


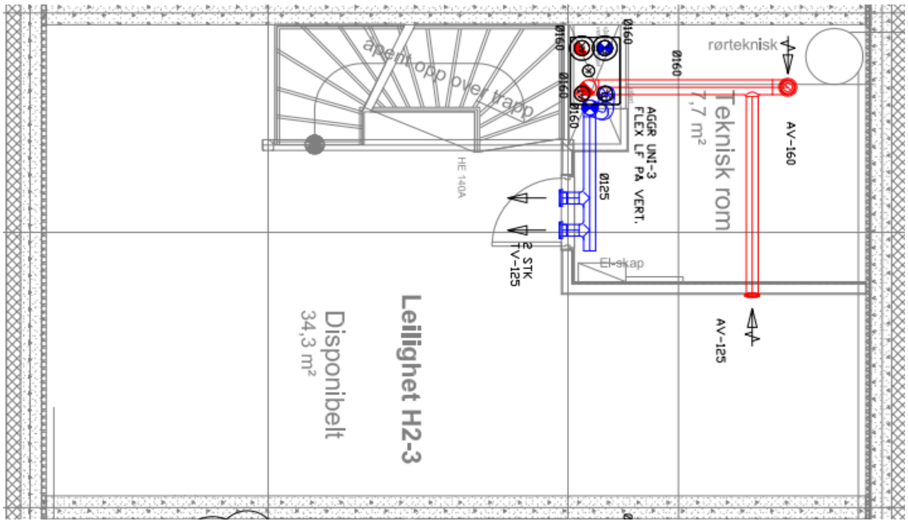
Figure 75: The bar with the PT-100 probes measuring the stratification in the living room.

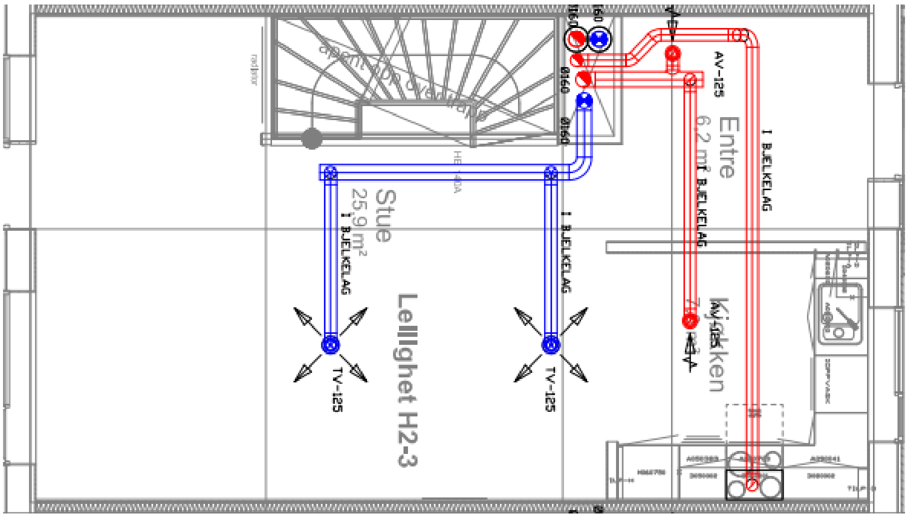
Figure 77: The upper part of the thread with PT-100 probes measuring the stratification in the staircase.

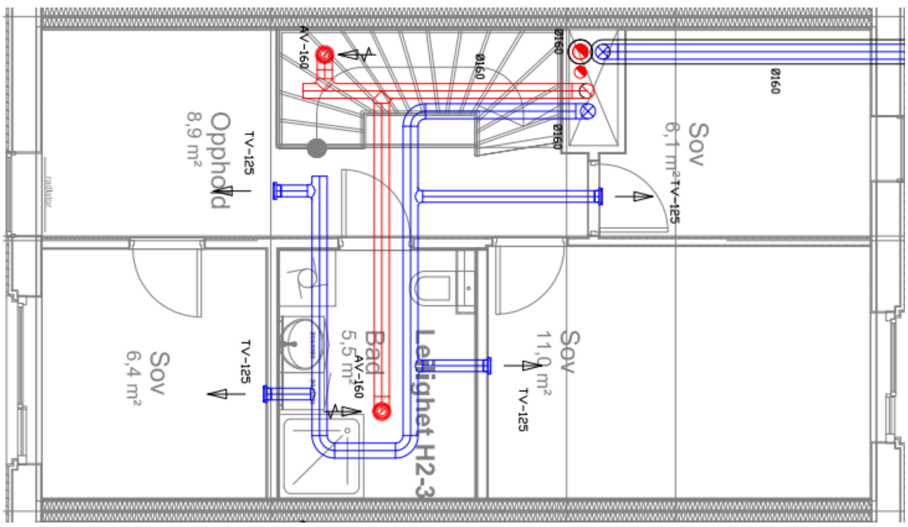
Figure 76: The wall that was built to close of the open staircase.

Attachment 5: Layout for ventilation system

The following pictures show the layout of the ventilation system in the house, one picture per floor.





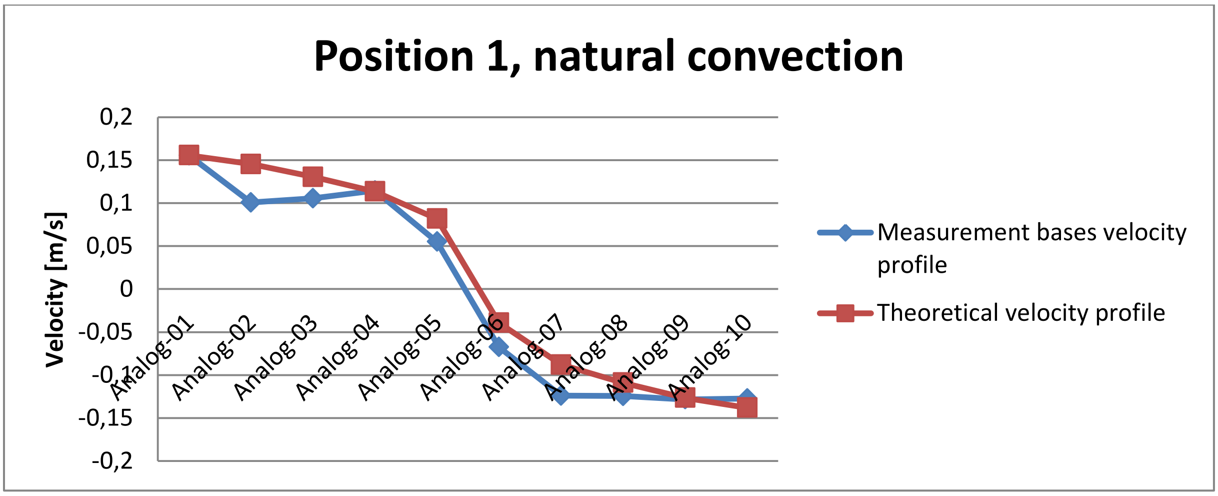


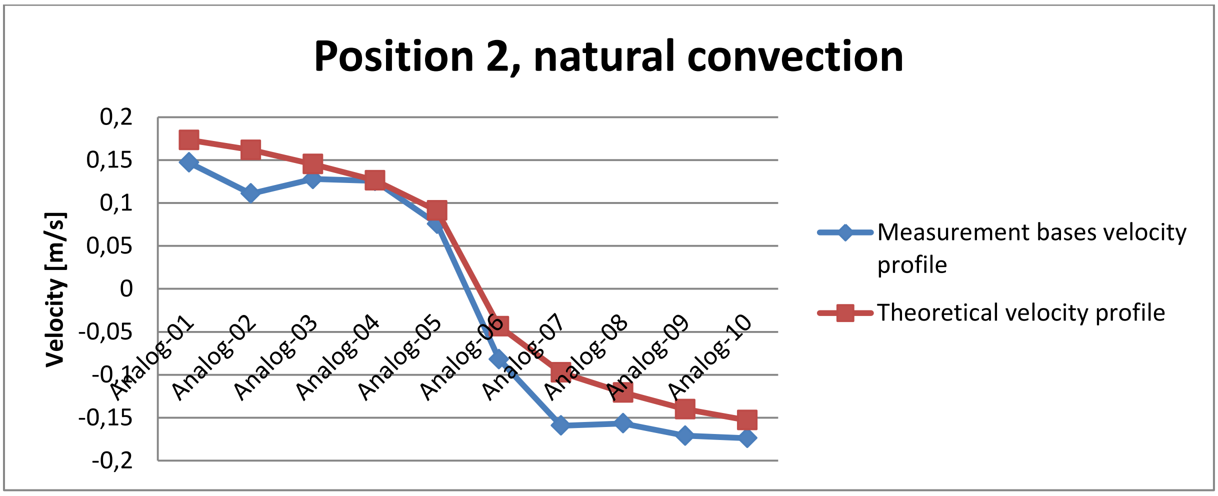
Attachment 6: Temperature coins

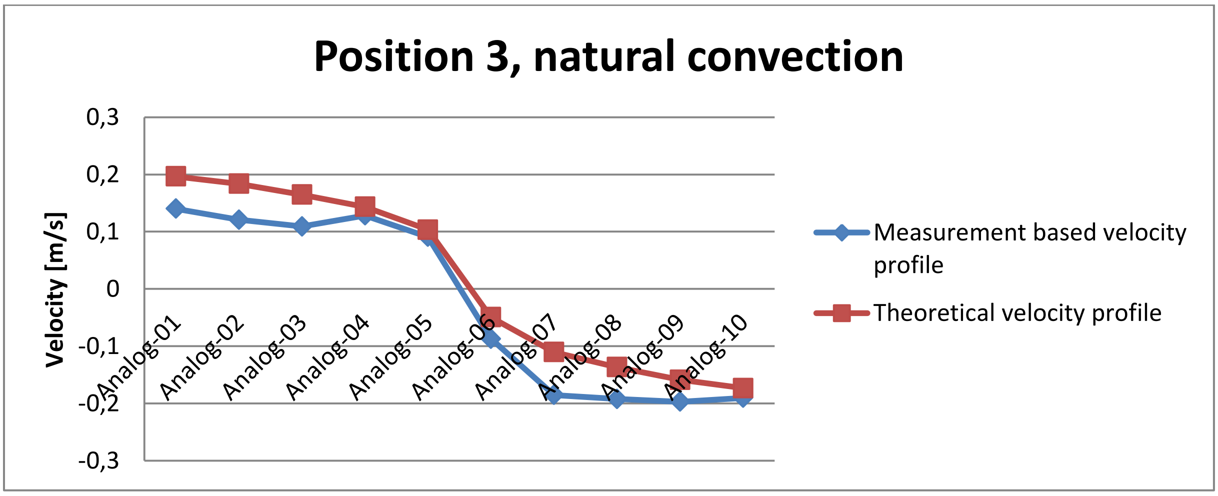
Number	Location	Average temperature [°C]	Standard deviation [°C]
1	Top of kitchen furniture	22.41	2.04
2	Wardrobe in the entrance hall	21.99	1.83
3	Living room, socket close to the floor	22.21	1.85
4	Outdoor, by the entrance	6.26	3.85
5	Handle in the staircase between the ground floor and the first floor	22.04	1.65
6	Basement	20.44	0.62
7	Ventilation unit, fresh after heat recovery	18.22	1.70
8	Ventilation unit, fresh preheated	20.26	0.76
9	Ventilation unit, fresh cold before heat recovery	8.80	5.68
10	Temperature in HVAC room	21.01	0.68
11	Staircase, top of handrail, first floor	22.38	2.03
12	Medium bedroom	22.28	2.28
13	Bathroom	22.03	1.28
14	Large bedroom	21.70	1.73
15	Small bedroom	21.60	1.80

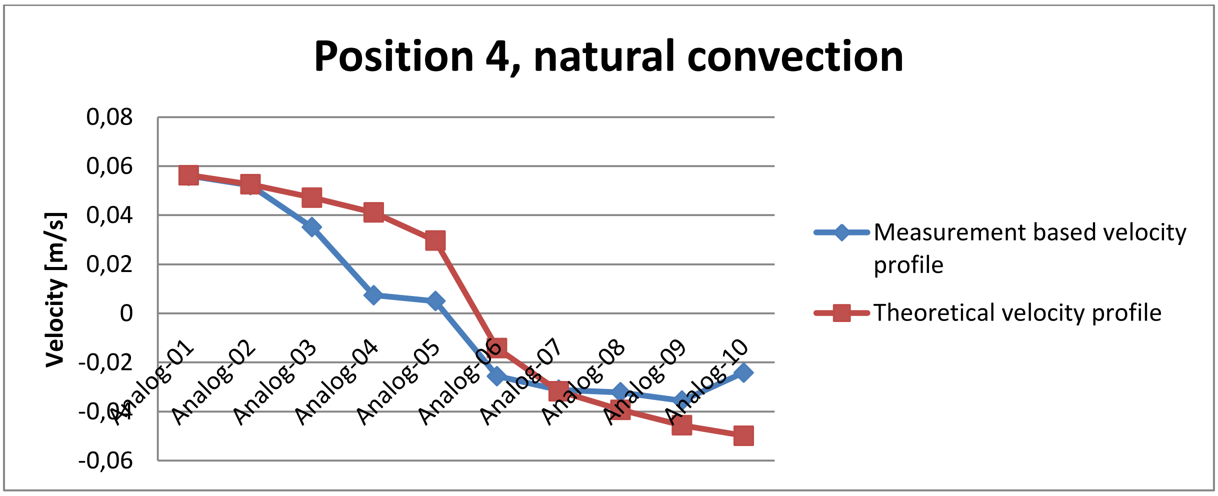
Attachment 7: Comparison of the measurements based and the theoretical velocity profiles

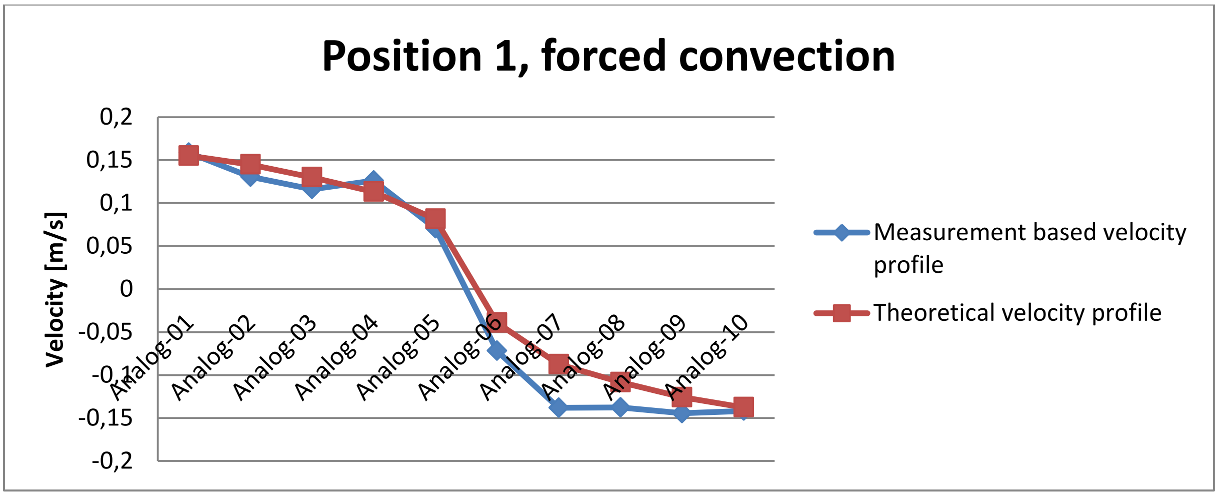
The velocity profiles based on the theory and on the measurement results are shown in the following figures.

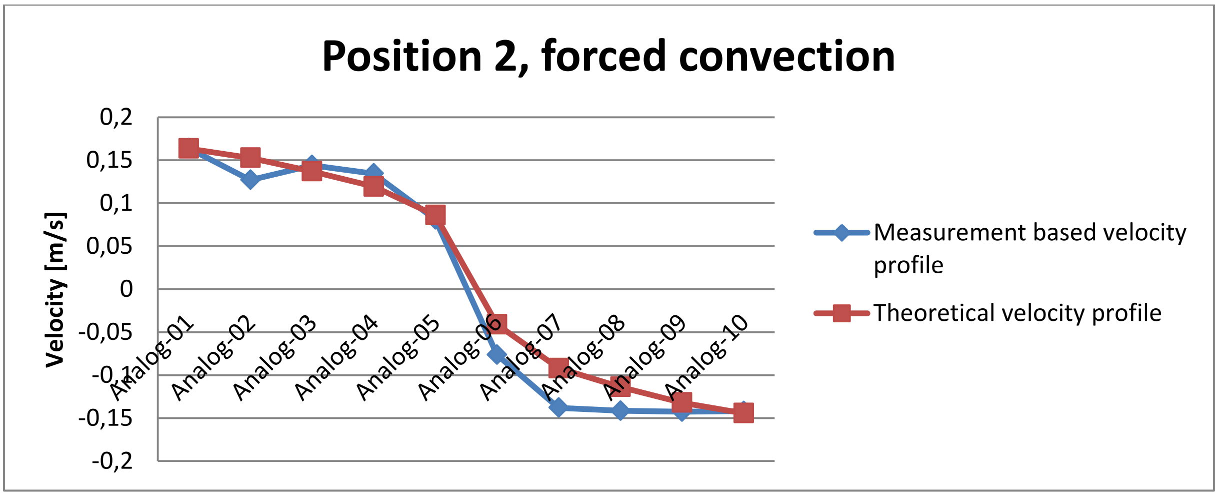


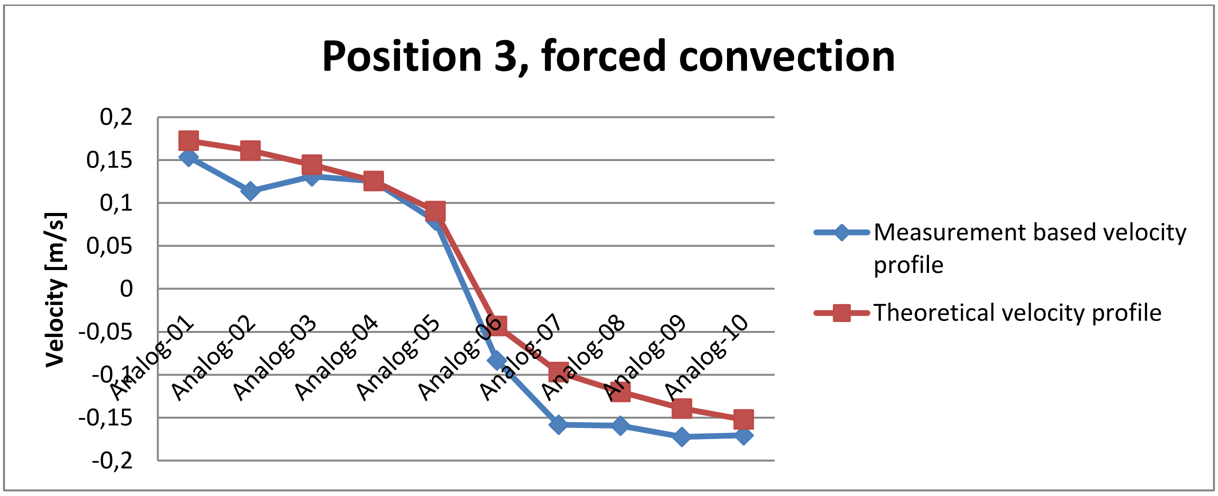


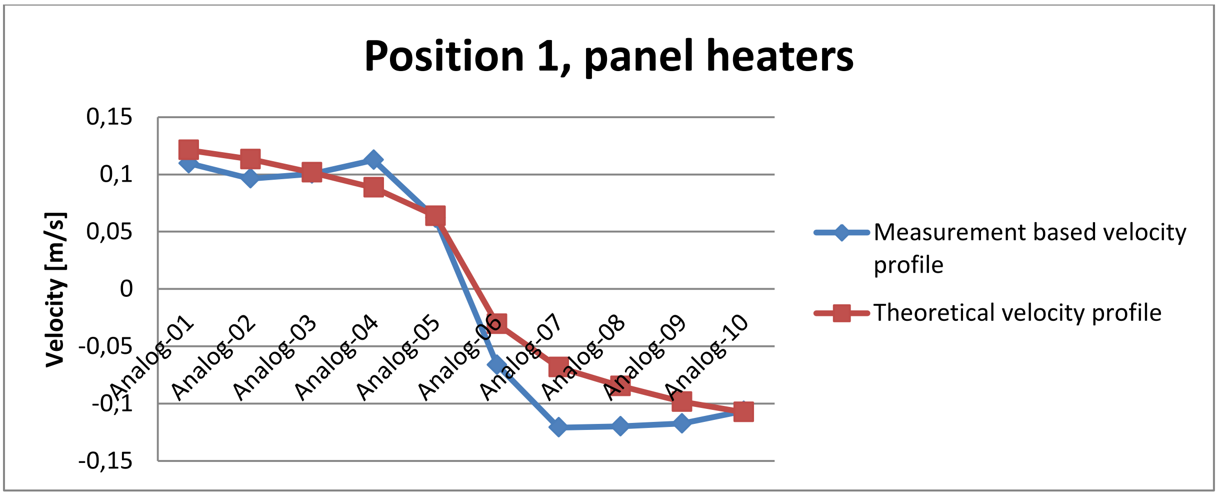


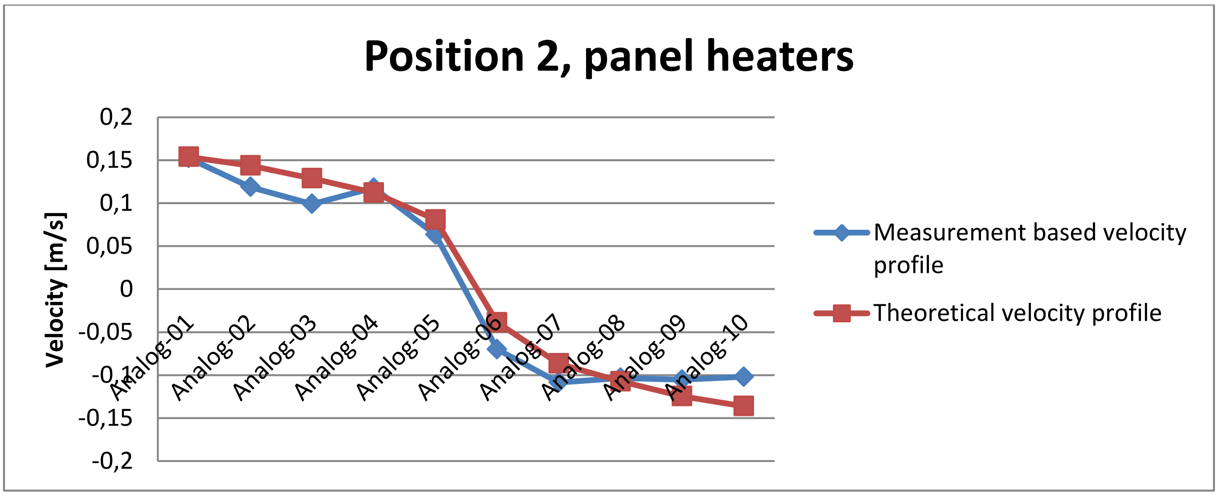

Position 4, natural convection
0,08
0,06
0,04
0,02
0
-0,02
-0,04
-0,06
Velocity [m/s]
Analog-01
Analog-02
Analog-03
Analog-04
Analog-05
Analog-06
Analog-07
Analog-08
Analog-09
Analog-10
Measurement based velocity profile
Theoretical velocity profile

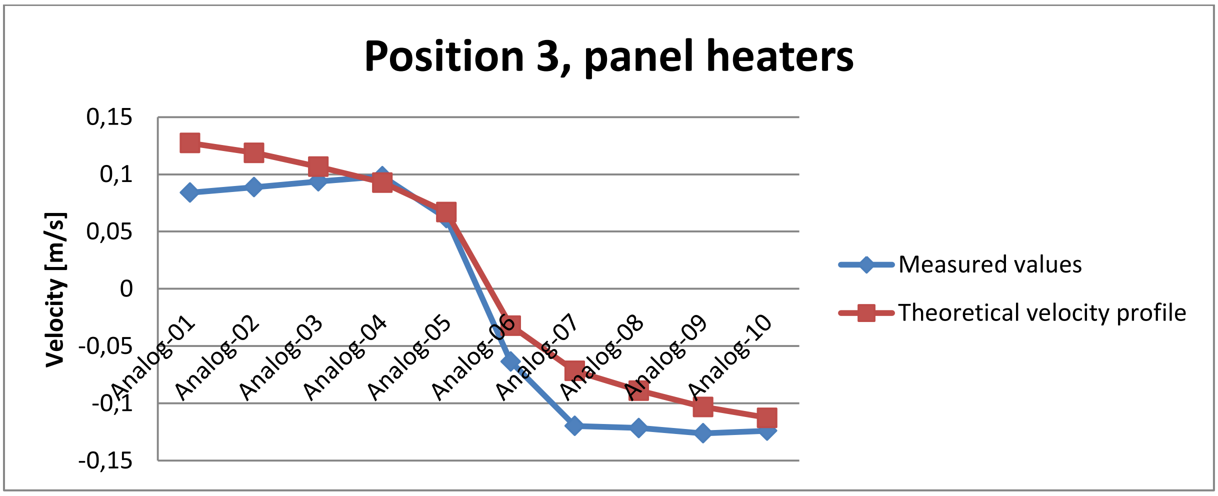

Position 1, forced convection
0,2
0,15
0,1
0,05
0
-0,05
-0,1
-0,15
-0,2
Velocity [m/s]
Analog-01
Analog-02
Analog-03
Analog-04
Analog-05
Analog-06
Analog-07
Analog-08
Analog-09
Analog-10
Measurement based velocity profile
Theoretical velocity profile

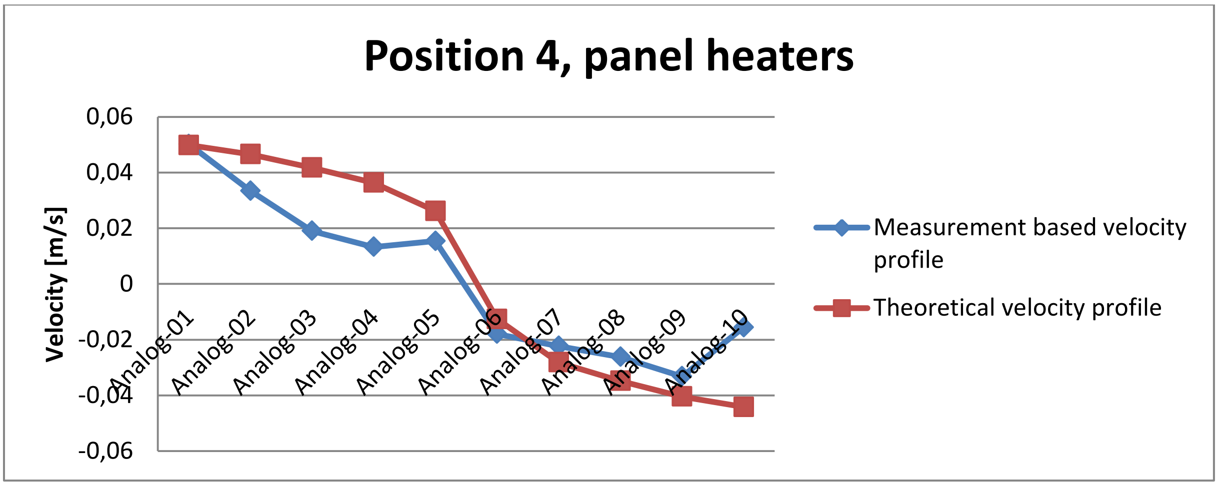

Position 2, forced convection
0,2
0,15
0,1
0,05
0
-0,05
-0,1
-0,15
-0,2
Velocity [m/s]
Analog-01
Analog-02
Analog-03
Analog-04
Analog-05
Analog-06
Analog-07
Analog-08
Analog-09
Analog-10
Measurement based velocity profile
Theoretical velocity profile


Position 3, forced convection
Velocity [m/s]
0,2
0,15
0,1
0,05
0
-0,05
-0,1
-0,15
-0,2
Analog-01
Analog-02
Analog-03
Analog-04
Analog-05
Analog-06
Analog-07
Analog-08
Analog-09
Analog-10
Measurement based velocity profile
Theoretical velocity profile


Position 1, panel heaters
Velocity [m/s]
0,15
0,1
0,05
0
-0,05
-0,1
-0,15
Analog-01
Analog-02
Analog-03
Analog-04
Analog-05
Analog-06
Analog-07
Analog-08
Analog-09
Analog-10
Measurement based velocity profile
Theoretical velocity profile


Position 2, panel heaters
Velocity [m/s]
0,2
0,15
0,1
0,05
0
-0,05
-0,1
-0,15
-0,2
Analog-01
Analog-02
Analog-03
Analog-04
Analog-05
Analog-06
Analog-07
Analog-08
Analog-09
Analog-10
Measurement based velocity profile
Theoretical velocity profile


Position 3, panel heaters
Velocity [m/s]
0,15
0,1
0,05
0
-0,05
-0,1
-0,15
Analog-01
Analog-02
Analog-03
Analog-04
Analog-05
Analog-06
Analog-07
Analog-08
Analog-09
Analog-10
Measured values
Theoretical velocity profile


Position 4, panel heaters
Velocity [m/s]
0,06
0,04
0,02
0
-0,02
-0,04
-0,06
Analog-01
Analog-02
Analog-03
Analog-04
Analog-05
Analog-06
Analog-07
Analog-08
Analog-09
Analog-10
Measurement based velocity profile
Theoretical velocity profile

Attachment 8: Results for analytical calculations based on the measured average temperatures

NC indicates natural convection, FC indicates forced convection, PH indicates panel heaters and 1-4 gives the oven-position. All velocities are in m/s, and all volume flows are in m^3/s. The numbers in parentheses are the deviations from the maximum average measured velocity as a percentage of the measured value for each measurement, the calculated general volume flows are compared with the average of the measurement based value of the upper and lower flow.

A8.1 Velocity

Model	NC-1	NC-2	NC-3	NC-4	FC-1	FC-2	FC-3	PH-1	PH-2	PH-3	PH-4
Hensen et al, flow from zone 1 to zone 2	0.1766 (14%)	0.19536 (12%)	0.21847 (11%)	0.14592 (160%)	0.17677 (12%)	0.18711 (14%)	0.18605 (8%)	0.12339 (2%)	0.13347 (-12%)	0.14417 (14%)	0.07986 (59%)
Hensen et al, flow from zone 2 to zone 1	0.17736 (14%)	0.19638 (13%)	0.2199 (12%)	0.14634 (161%)	0.17752 (12%)	0.188 (15%)	0.18693 (8%)	0.12364 (2%)	0.1338 (-12%)	0.14458 (15%)	0.07993 (59%)
Heiselberg, maximum velocity	0.17698 (14%)	0.19587 (13%)	0.21918 (11%)	0.14613 (161%)	0.17715 (12%)	0.18755 (14%)	0.18649 (8%)	0.12351 (2%)	0.13364 (-12%)	0.14438 (14%)	0.079895 (59%)
Etheridge and Sandberg, flow from zone 1 to zone 2	0.1768 (14%)	0.19409 (12%)	0.21755 (11%)	0.14761 (163%)	0.16787 (6%)	0.18575 (13%)	0.18583 (8%)	0.12428 (3%)	0.13626 (-11%)	0.14724 (17%)	0.078505 (56%)
Etheridge and Sandberg, flow from zone 2 to zone 1	0.17606 (13%)	0.19311 (11%)	0.21617 (10%)	0.14718 (163%)	0.16723 (6%)	0.18488 (13%)	0.18496 (7%)	0.12402 (3%)	0.13592 (-11%)	0.14681 (16%)	0.078439 (56%)
IEA, flow from zone 1 to zone 2	0.1768 (14%)	0.19409 (12%)	0.21755 (11%)	0.14761 (163%)	0.16787 (6%)	0.18575 (13%)	0.18583 (8%)	0.12428 (3%)	0.13626 (-11%)	0.14724 (17%)	0.078505 (56%)
IEA, flow from zone 2 to zone 1	0.17606 (13 %)	0.19311 (11%)	0.21617 (10%)	0.14718 (163%)	0.16723 (6%)	0.18488 (13%)	0.18496 (7%)	0.12402 (3%)	0.13592 (-11%)	0.14681 (16%)	0.078439 (56%)

A8.2 Volume flow

Model	NC-1	NC-2	NC-3	NC-4	FC-1	FC-2	FC-3	PH-1	PH-2	PH-3	PH-4
TRNFLOW, flow from zone 1 to zone 2	0.11267 (0.24 %)	0.1247 (0.40 %)	0.13954 (11.99%)	0.093033 (191.64%)	0.11278 (-11.34%)	0.11941 (-13.16 %)	0.11873 (-6.81 %)	0.078636 (-22.68 %)	0.08508 (-27.03 %)	0.091918 (1-90 %)	0.050865 (107.61%)
TRNFLOW, flow from zone 2 to zone 1	-0.11267 (-6.81 %)	-0.1247 (-20.62 %)	-0.13954 (-22.52%)	-0.093033 (186.26%)	-0.11278 (-15.96 %)	-0.11941 (-11.87 %)	-0.11873 (-24.57 %)	-0.078636 (-29.91 %)	-0.08508 (-17.80 %)	-0.09191 (-21.64 5)	-0.050865 (84.29%)
Hensen et al, flow from zone 1 to zone 2	-0.12504 (11.25 %)	-0.13847 (11.49 %)	-0.15505 (24.44 %)	-0.10316 (223.39%)	-0.12523 (-1.55 %)	-0.13256 (-3.59 %)	-0.13179 (3.45 %)	-0.087165 (-14.29 %)	-0.094314 (-19.11 %)	-0.10191 (12.98 %)	-0.056353 (130.01%)
Hensen et al, flow from zone 2 to zone 1	0.12451 (2.99 %)	0.13773 (-12.33 %)	0.15402 (-14.48%)	0.10288 (216.55%)	0.1246 (-7.15%)	0.13191 (-2.65 %)	0.13117 (-16.66 %)	0.08699 (-22.47 %)	0.094105 (-9.08 %)	0.10165 (-13.34 %)	0.056301 (103.99%)
Heiselberg, flow from zone 1 to zone 2	0.12777 (13.67 %)	0.14026 (12.93 %)	0.15722 (26.18%)	0.10667 (234.39%)	0.12131 (-4.63%)	0.13423 (-2.38 %)	0.13429 (5.41 %)	0.089813 (-11.69 %)	0.098468 (-15.55 %)	0.1064 (17.96 %)	0.056731 (131.56%)
Heiselberg, flow from zone 2 to zone 1	0.12723 (5.24 %)	0.13955 (-11.17 %)	0.15622 (-13.26%)	0.10636 (227.26%)	0.12085 (-9.95%)	0.13361 (-1.39%)	0.13366 (-15.08 %)	0.089625 (-20.12 %)	0.098221 (-5. 10 %)	0.10609 (-9.56 %)	0.056684 (105.38%)
Heiselberg, total volume flow	0.12451 (6.74 %)	0.13773 (-2.08 %)	0.15402 (1.10 %)	0.10287 (219.47%)	0.12462 (-4.65%)	0.13191 (-3.36 %)	0.13117 (-7.89 %)	0.086988 (-18.66 %)	0.0941 (-14.49 %)	0.10164 (-2.03 %)	0.056302 (116.13%)
Santamouris et al.	0.088226 (-24.37 %)	0.097642 (-30.58 %)	0.10926 (-28.28 %)	0.072846 (126.23%)	0.088309 (-32.43%)	0.093496 (-31.50%)	0.092968 (-34.71 %)	0.061573 (-42.43 %)	0.066619 (-39.46 %)	0.071973 (-30.63 %)	0.039828 (52.89 %)
Etheridge and Sandberg, orifice based model	0.12477 (6.96 %)	0.13809 (-1.82 %)	0.15452 (1.42 %)	0.10302 (219.94%)	0.12489 (-4.45%)	0.13222 (-3.14 %)	0.13148 (-7.67 %)	0.087078 (-18.58 %)	0.094214 (-14.39 %)	0.10179 (-1.89 %)	0.056326 (116.22%)
Etheridge and Sandberg, two-layer hydraulics model	0.11061 (-5.18 %)	0.12242 (-12.96 %)	0.13699 (-10.08 %)	0.09133 (183.63%)	0.11072 (-15.29%)	0.11722 (-14.12 %)	0.11656 (-18.15 %)	0.077197 (-27.82 %)	0.083523 (-24.10 %)	0.090235 (-13.03 %)	0.049934 (91.69%)
IEA	0.12477 (6.96 %)	0.13809 (-1.82 %)	0.15452 (1.42 %)	0.10302 (219.94%)	0.12489 (-4.45 %)	0.13222 (-3.14 %)	0.13148 (-7.67 %)	0.087078 (-18.58 %)	0.094214 (-14.39 %)	0.10179 (-1.89 %)	0.056326 (116.22%)

Attachment 9: MATLAB script for calculating volume flows

```
%Defining constants
H = 2.35; % Height of door [m
W = 0.90; % Width of door [m]
A = H*W;

%Average values per probe from Excel
v_NC1_upper = [0.155495833,0.100704167, 0.105504167, 0.114475,
0.05506251];
v_NC1_lower =[0.067645833, 0.123995833, 0.1243875, 0.128329167,
0.127445833];
v_NC2_upper = [0.147070833, 0.110991667, 0.1278125, 0.125604167,
0.075645833];
v_NC2_lower = [0.0820125, 0.159225, 0.1566125, 0.171054167,
0.1737375];
v_NC3_upper = [0.140225, 0.120783333, 0.109041667, 0.128420833,
0.090883333];
v_NC3_lower = [0.086979167, 0.1852875, 0.192258333, 0.1968375,
0.190225];
v_NC4_upper = [0.05605, 0.052229167, 0.035129167, 0.007429167];
v_NC4_lower = [0.004991667, 0.025583333, 0.031154167, 0.032195833,
0.035583333, 0.0241625];
v_FC1_upper = [0.158429167, 0.130508333, 0.116054167, 0.126033333,
0.070533333];
v_FC1_lower = [0.072066667, 0.138266667, 0.137858333, 0.1445875,
0.141675];
v_FC2_upper = [0.163904167, 0.126879167, 0.1441375, 0.134375,
0.080945833];
v_FC2_lower = [0.076441667, 0.138091667, 0.141616667, 0.1427125,
0.142];
v_FC3_upper = [0.153333333, 0.113679167, 0.130820833, 0.125208333,
0.0791875];
v_FC3_lower = [0.0836625, 0.158270833, 0.159391667, 0.1724,
0.170520833];
v_PH1_upper = [0.109633333, 0.096270833, 0.1004625, 0.112558333,
0.0619125];
v_PH1_lower = [0.066220833, 0.12085, 0.119820833, 0.117283333,
0.106379167];
v_PH2_upper = [0.152358333, 0.1188, 0.098991667, 0.117766667,
0.0633375];
v_PH2_lower = [0.069979167, 0.108516667, 0.103391667, 0.1054625,
0.1020875];
v_PH3_upper = [0.083954167, 0.0888, 0.0938625, 0.0983, 0.0616625];
v_PH3_lower = [0.063445833, 0.119725, 0.121466667, 0.126083333,
0.123904167];
v_PH4_upper = [0.0502, 0.0334375, 0.0190125, 0.013283333];
v_PH4_lower = [0.015375, 0.017966667, 0.022325, 0.026204167,
0.033191667, 0.015570833];

%Calculating the mean value in the whole aperture per measurement
v_av_NC1_upper = mean (v_NC1_upper);
v_av_NC1_lower = mean (v_NC1_lower);
v_av_NC2_upper = mean (v_NC2_upper);
v_av_NC2_lower = mean (v_NC2_lower);
```

```
v_av_NC3_upper = mean (v_NC3_upper);
v_av_NC3_lower = mean (v_NC3_lower);
v_av_NC4_upper = mean (v_NC4_upper);
v_av_NC4_lower = mean (v_NC4_lower);
v_av_FC1_upper = mean (v_FC1_upper);
v_av_FC1_lower = mean (v_FC1_lower);
v_av_FC2_upper = mean (v_FC2_upper);
v_av_FC2_lower = mean (v_FC2_lower);
v_av_FC3_upper = mean (v_FC3_upper);
v_av_FC3_lower = mean (v_FC3_lower);
v_av_PH1_upper = mean (v_PH1_upper);
v_av_PH1_lower = mean (v_PH1_lower);
v_av_PH2_upper = mean (v_PH2_upper);
v_av_PH2_lower = mean (v_PH2_lower);
v_av_PH3_upper = mean (v_PH3_upper);
v_av_PH3_lower = mean (v_PH3_lower);
v_av_PH4_upper = mean (v_PH4_upper);
v_av_PH4_lower = mean (v_PH4_lower);

q_NC1_upper = A/2 * v_av_NC1_upper
q_NC1_lower = A/2* v_av_NC1_lower
q_NC2_upper = A/2 * v_av_NC2_upper
q_NC2_lower = A/2 * v_av_NC2_lower
q_NC3_upper = A/2 * v_av_NC3_upper
q_NC3_lower = A/2 * v_av_NC3_lower
q_NC4_upper = A*0.4 * v_av_NC4_upper
q_NC4_lower = A*0.6 * v_av_NC4_lower
q_FC1_upper = A/2 * v_av_FC1_upper
q_FC1_lower = A/2 * v_av_FC1_lower
q_FC2_upper = A/2 * v_av_FC2_upper
q_FC2_lower = A/2 * v_av_FC2_lower
q_FC3_upper = A/2 * v_av_FC3_upper
q_FC3_lower = A/2 * v_av_FC3_lower
q_PH1_upper = A/2 * v_av_PH1_upper
q_PH1_lower = A/2 * v_av_PH1_lower
q_PH2_upper = A/2 * v_av_PH2_upper
q_PH2_lower = A/2 * v_av_PH2_lower
q_PH3_upper = A/2 * v_av_PH3_upper
q_PH3_lower = A/2 * v_av_PH3_lower
q_PH4_upper = A*0.4 * v_av_PH4_upper
q_PH4_lower = A*0.6 * v_av_PH4_lower
```

Attachment 10: MATLAB script for calculations of heat transfer

```
%Defining constants
c_p = 1.005; % kJ/kgK
A = 0.90 * 2.35; % Area of the whole aperture
deltaT_NC1 = 2.53; % The temperature difference between the measured
average in the two rooms
deltaT_NC2 = 3.11;
deltaT_NC3 = 3.91;
deltaT_NC4 = 1.72;
deltaT_FC1 = 2.54;
deltaT_FC2 = 2.85;
deltaT_FC3 = 2.82;
deltaT_PH1 = 1.22;
deltaT_PH2 = 1.43;
deltaT_PH3 = 1.67;
deltaT_PH4 = 0.51;

%Calculating mass flows, volume flows are calculated in own script:
m = rho*q
m_NC1_upper = 0.1124 * 1.180;
m_NC1_lower = 0.1209 * 1.190;
m_NC2_upper = 0.1242 * 1.175;
m_NC2_lower = 0.1571 * 1.187;
m_NC3_upper = 0.1246 * 1.169;
m_NC3_lower = 0.1801 * 1.184;
m_NC4_upper = 0.0319 * 1.192;
m_NC4_lower = 0.0325 * 1.185;
m_FC1_upper = 0.1272 * 1.178;
m_FC1_lower = 0.1342 * 1.187;
m_FC2_upper = 0.1375 * 1.176;
m_FC2_lower = 0.1355 * 1.187;
m_FC3_upper = 0.1274 * 1.175;
m_FC3_lower = 0.1574 * 1.186;
m_PH1_upper = 0.1017 * 1.194;
m_PH1_lower = 0.1122 * 1.199;
m_PH2_upper = 0.1166 * 1.192;
m_PH2_lower = 0.1035 * 1.198;
m_PH3_upper = 0.0902 * 1.191;
m_PH3_lower = 0.1173 * 1.198;
m_PH4_upper = 0.0245 * 1.199;
m_PH4_lower = 0.0276 * 1.197;

% Calculating heat transfer in with the different air flows
% Q = m*c_p*delta_T [kW]
Q_NC1_upper = m_NC1_upper * c_p * deltaT_NC1
Q_NC1_lower = m_NC1_lower * c_p * deltaT_NC1
Q_NC2_upper = m_NC2_upper * c_p * deltaT_NC2
Q_NC2_lower = m_NC2_lower * c_p * deltaT_NC2
Q_NC3_upper = m_NC3_upper * c_p * deltaT_NC3
Q_NC3_lower = m_NC3_lower * c_p * deltaT_NC3
Q_NC4_upper = m_NC4_upper * c_p * deltaT_NC4
Q_NC4_lower = m_NC4_lower * c_p * deltaT_NC4
Q_FC1_upper = m_FC1_upper * c_p * deltaT_FC1
Q_FC1_lower = m_FC1_lower * c_p * deltaT_FC1
Q_FC2_upper = m_FC2_upper * c_p * deltaT_FC2
```

```
Q_FC2_lower = m_FC2_lower * c_p * deltaT_FC2
Q_FC3_upper = m_FC3_upper * c_p * deltaT_FC3
Q_FC3_lower = m_FC3_lower * c_p * deltaT_FC3
Q_PH1_upper = m_PH1_upper * c_p * deltaT_PH1
Q_PH1_lower = m_PH1_lower * c_p * deltaT_PH1
Q_PH2_upper = m_PH2_upper * c_p * deltaT_PH2
Q_PH2_lower = m_PH2_lower * c_p * deltaT_PH2
Q_PH3_upper = m_PH3_upper * c_p * deltaT_PH3
Q_PH3_lower = m_PH3_lower * c_p * deltaT_PH3
Q_PH4_upper = m_PH4_upper * c_p * deltaT_PH4
Q_PH4_lower = m_PH4_lower * c_p * deltaT_PH4

%Calculating convection heat trnafer coefficients
% Q = h*A*delta_T [kW]
% h = m*c_p/A [W/m2]
h_NC1_upper = (m_NC1_upper * c_p)/(A/2)
h_NC1_lower = (m_NC1_lower * c_p)/(A/2)
h_NC2_upper = (m_NC2_upper * c_p)/(A/2)
h_NC2_lower = (m_NC2_lower * c_p)/(A/2)
h_NC3_upper = (m_NC3_upper * c_p)/(A/2)
h_NC3_lower = (m_NC3_lower * c_p)/(A/2)
h_NC4_upper = (m_NC4_upper * c_p)/(A*0.4)
h_NC4_lower = (m_NC4_lower * c_p)/(A*0.6)
h_FC1_upper = (m_FC1_upper * c_p)/(A/2)
h_FC1_lower = (m_FC1_lower * c_p)/(A/2)
h_FC2_upper = (m_FC2_upper * c_p)/(A/2)
h_FC2_lower = (m_FC2_lower * c_p)/(A/2)
h_FC3_upper = (m_FC3_upper * c_p)/(A/2)
h_FC3_lower = (m_FC3_lower * c_p)/(A/2)
h_PH1_upper = (m_PH1_upper * c_p)/(A/2)
h_PH1_lower = (m_PH1_lower * c_p)/(A/2)
h_PH2_upper = (m_PH2_upper * c_p)/(A/2)
h_PH2_lower = (m_PH2_lower * c_p)/(A/2)
h_PH3_upper = (m_PH3_upper * c_p)/(A/2)
h_PH3_lower = (m_PH3_lower * c_p)/(A/2)
h_PH4_upper = (m_PH4_upper * c_p)/(A*0.4)
h_PH4_lower = (m_PH4_lower * c_p)/(A*0.6)
```

Attachment 11: Calculations of discharge coefficients

A11.1 Natural convection

Velocity	Position 1		Position 2		Position 3		Position 4	
Model	*Velocity*	C_d	*Velocity*	C_d	*Velocity*	C_d	*Velocity*	C_d
Maximum measured average velocity	0.1555		0.1737		0.1968		0.05605	
Hensen et al, 1→2	0.44151	0.35220	0.4884	0.35565	0.54617	0.36033	0.36479	0.15365
Hensen et al, 2→1	0.44339	0.35071	0.49095	0.35380	0.54974	0.35799	0.36585	0.15320
Heiselberg, maximum velocity	0.44245	0.35145	0.48967	0.35473	0.54795	0.35916	0.36532	0.15343
Etheridge and Sandberg, 1→2	0.44201	0.35180	0.48522	0.35798	0.54388	0.36184	0.36903	0.15189
Etheridge and Sandberg, 2→1	0.44014	0.35330	0.48276	0.35981	0.54043	0.36415	0.36794	0.15233
IEA, 1→2	0.44201	0.35180	0.48522	0.35798	0.54388	0.36184	0.36903	0.15188
IEA, 2→1	0.44014	0.35329	0.48276	0.35981	0.54043	0.36415	0.36794	0.15233

Volume flow	Position 1		Position 2		Position 3		Position 4	
Model	*Volume flow*	C_d	*Volume flow*	C_d	*Volume flow*	C_d	*Volume flow*	C_d
Calculated, upper half	0.1124		0.1242		0.1246		0.0319	
Calculated, lower half	0.1209		0.1571		0.1801		0.0325	
TRNFLOW, 1→2	0.28169	0.39902	0.31175	0.39839	0.34886	0.35716	0.23258	0.13716
TRNFLOW, 2→1	-0.28169	0.42919	-0.31175	0.50393	-0.34886	0.51625	-0.23258	0.13974
Hensen et al, 1→2	-0.31259	0.35958	-0.34617	0.35878	-0.38762	0.32145	-0.2579	0.12369
Hensen et al, 2→1	0.31127	0.38841	0.34432	0.45626	0.38505	0.46773	0.25719	0.12637
Heiselberg, 1→2	0.31941	0.35189	0.35065	0.35419	0.39304	0.31702	0.26668	0.11962

Heiselberg, 2→1	0.31807	0.38011	0.34887	0.45031	0.39054	0.46116	0.26589	0.12223
Heiselberg, total q	0.31126	0.37477	0.34432	0.40848	0.38505	0.39566	0.25718	0.12520
Santamouris et al.	*0.22056*	*0.52888*	*0.2441*	0.57619	*0.27316*	0.55773	0.18212	0.17681
Etheridge and Sandberg, orifice based model	0.31192	0.37397	0.34522	0.40742	0.3863	0.39438	0.25755	0.12502
IEA	0.31192	0.37397	0.34522	0.40742	0.3863	0.39438	0.25755	0.12502
Etheridge and Sandberg, two-layer hydraulics model	*0.11061*	*1.05461*	0.12242	1.14891	*0.13699*	1.11212	0.09133	0.35257

A11.2 Forced convection

Velocity	**Position 1**		**Position 2**		**Position 3**	
Model	*Velocity*	*C_d*	*Velocity*	*C_d*	*Velocity*	*C_d*
Maximum measured average velocity	0.1584		0.1639		0.1724	
Hensen et al, 1→2	0.44192	0.35843	0.46776	0.35039	0.46513	0.37064
Hensen et al, 2→1	0.44381	0.35690	0.47	0.34872	0.46733	0.36890
Heiselberg, maximum velocity	0.44286	0.35767	0.46888	0.34955	0.46623	0.36977
Etheridge and Sandberg, 1→2	0.41968	0.37743	0.46437	0.35295	0.46456	0.37110
Etheridge and Sandberg, 2→1	0.41808	0.37887	0.46221	0.35460	0.4624	0.37283
IEA, 1→2	0.41968	0.37743	0.46437	0.35295	0.46456	0.37110
IEA, 2→1	0.41808	0.37887	0.46221	0.35460	0.4624	0.37283

Volume flow	**Position 1**		**Position 2**		**Position 3**	
Model	*Volume flow*	*C_d*	*Volume flow*	*C_d*	*Volume flow*	*C_d*
Calculated, upper half	0.1272		0.1375		0.1274	
Calculated, lower half	0.1342		0.1355		0.1574	

TRNFLOW, 1→2	0.28195	0.45114	0.29851	0.46062	0.29683	0.42920
TRNFLOW, 2→1	-0.28195	0.47597	-0.29851	0.45392	-0.29683	0.53026
Hensen et al, 1→2	-0.31309	0.40627	-0.3314	0.41490	-0.32949	0.38665
Hensen et al, 2→1	0.31149	0.43083	0.32977	0.41089	0.32792	0.47999
Heiselberg, 1→2	0.30328	0.41941	0.33557	0.40975	0.33572	0.37948
Heiselberg, 2→1	0.30213	0.44417	0.33402	0.40566	0.33416	0.47103
Heiselberg, total q	0.31156	0.41950	0.32977	0.41392	0.32792	0.43425
Santamouris et al.	*0.22077*	0.59201	*0.23374*	0.58398	*0.23242*	0.61268
Etheridge and Sandberg, orifice based model	0.31222	0.41861	0.33056	0.41293	0.32869	0.43323
IEA	0.31222	0.41861	0.33056	0.41293	0.32869	0.43323
Etheridge and Sandberg, two-layer hydraulics model	*0.11072*	1.18045	*0.11722*	1.16447	*0.11656*	1.22168

A11.3 Panel heaters

Velocity	**Position 1**		**Position 2**		**Position 3**		**Position 4**	
Model	*Velocity*	C_d	*Velocity*	C_d	*Velocity*	C_d	*Velocity*	C_d
Maximum measured average velocity	0.12085		0.1524		0.1261		0.0502	
Hensen et al, 1→2	0.30847	0.39177	0.33369	0.45671	0.36043	0.34986	0.19965	0.25144
Hensen et al, 2→1	0.30911	0.39096	0.3345	0.45560	0.36145	0.34887	0.19982	0.25122
Heiselberg, maximum velocity	0.30879	0.39136	0.33409	0.45616	0.36094	0.34936	0.19974	0.25132
Etheridge and Sandberg, 1→2	0.31071	0.38894	0.34065	0.44738	0.3681	0.34257	0.19626	0.25578
Etheridge and Sandberg, 2→1	0.31006	0.38976	0.33979	0.44851	0.36702	0.34357	0.1961	0.25599
IEA, 1→2	0.31071	0.38894	0.34065	0.44738	0.3681	0.34257	0.19626	0.25578
IEA, 2→1	0.31006	0.38976	0.33979	0.44851	0.36702	0.34357	0.1961	0.25599

Volume flow	Position 1		Position 2		Position 3		Position 4	
Model	*Volume flow*	C_d	*Volume flow*	C_d	*Volume flow*	C_d	*Volume flow*	C_d
Calculated, upper half	0.1017		0.1166		0.0902		0.0245	
Calculated, lower half	0.1122		0.1035		0.1173		0.0276	
TRNFLOW, 1→2	0.19659	0.51732	0.2127	0.54818	0.22979	0.50741	0.12716	0.19267
TRNFLOW, 2→1	-0.19659	0.57073	-0.2127	0.48660	-0.22979	0.45041	-0.12716	0.21704
Hensen et al, 1→2	-0.21791	0.46670	-0.23579	0.49450	-0.25478	0.45764	-0.14088	0.17390
Hensen et al, 2→1	0.21747	0.51593	0.23526	0.43993	0.25412	0.40728	0.14075	0.19609
Heiselberg, 1→2	0.22453	0.45294	0.24617	0.47365	0.266	0.43834	0.14183	0.17274
Heiselberg, 2→1	0.22406	0.50075	0.24555	0.42150	0.26523	0.39022	0.14171	0.19476
Heiselberg, total q	0.21747	0.49179	0.23525	0.46780	0.25411	0.40828	0.14075	0.18507
Santamouris et al.	*0.15393*	0.69479	*0.16655*	0.66076	*0.17993*	0.57661	*0.099571*	0.26162
Etheridge and Sandberg, orifice based model	0.2177	0.49127	0.23553	0.46724	0.25446	0.40772	0.14081	0.18500
IEA	0.2177	0.49127	0.23553	0.46724	0.25446	0.40772	0.14081	0.18500
Etheridge and Sandberg, two-layer hydraulics model	*0.077197*	1.38541	*0.083523*	1.31760	*0.090235*	1.14977	*0.049934*	0.52168