Norwegian University of
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Modeling of the indoor environment of buildings heated using wood stoves

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Master of Energy Use and Energy Planning
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MASTER THESIS

for

Student
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Modelling of the indoor environment of buildings heated using wood stoves

Modellering av termisk inneklima for bygninger oppvarmet ved bruk av vedovn

Background and objective

Many of the building concepts for current and future energy-efficient buildings are based on highly-insulated building envelopes, such as passive houses. As these houses are highly-insulated, the space-heating power is limited (< 3kW) while the nominal power of existing stoves is significantly higher (typically 4-8 kW). There is thus a strong risk of overheating when integrating wood stoves in highly-insulated houses. At the same time, Norway is aiming at increasing its share of bioenergy use. The question of the integration of wood stoves within highly-insulated buildings is thus strategic.

A simplified wood stoves model has been previously developed that capture the all-year global thermal comfort at an acceptable computational cost. Nevertheless, this TRNSYS model suffers several limitations that prevent its application to a large set of buildings. Furthermore, the model is by essence unable to capture the *vertical temperature stratification* which appears to be significant with wood stoves. The company EQUA is currently developing a new zone model capturing stratification for their building simulation software, IDA-ICE. This new model requires a good modeling of the thermal plume generated by wood stoves. Therefore, these plumes will be investigated using measurement and the existing theory during the present Master thesis. When established, this plume model will be implemented in IDA-ICE by EQUA and the overall room model performance compared to existing measurements in the thesis. This project is part of the WoodCFD project leaded by SINTEF Energy Research.

The following tasks are to be considered:

1. Plan a measurement campaign in the lab using the experimental electric stove,
2. In parallel, review of the theory of plumes generated by heat sources,
3. Perform measurements of the plume in the lab, compare with theory,
4. As a function of the work progress, perform a plume measurement using a real stove in the lab and compare it to the generic stove. Discuss how the generic electric stove is able to emulate the plume of a real wood stove.
5. If EQUA manage to implement the plume model on time, compare the overall performance of the new room model with existing experiments (as a continuation of the specialization project).

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, 13. January 2016

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1. Abstract

English

This paper investigates the thermal plume caused by wood stoves, with the main goal of integrating wood stoves in highly insulated buildings, ensuring an acceptable thermal environment. The physical theory behind thermal plumes are reviewed as an introduction before an experiment where measurements of the physical properties of a plume are investigated, using an electric stove to simulate the effect of a real wood stove. The results show that the air speed and temperature distribution of a cross-section in a plume can be described with Gaussian functions, as expected. The goal is to figure out when the plume's air speed and temperature distribution becomes *self-similar,* which means that a new zonal model in the program EQUA, can be used properly, unlike the previous version where there was an error in the coding. The results from the experiment gives insight about when self-similarity is achieved in plumes.

Norsk

Denne rapporten undersøker den termiske luftsøylen som skapes av vedovner, med hovudfokus på å integrere vedovner i bygninger some er godt isolert, og som I tillegg skaper eit akseptabelt termiskt miljø. Den fysiske teorien som ligger i grunn for termiske luftsøyler er gjennomgått som en introduksjon før et eksperiment der målinger av de fysiske egenskapene til en luftsøyle er undersøkt, der en elektrisk ovn er tatt i bruk for å simulere effekten av en virkelig vedovn. Resultatene viser at lufthastighets- og temperaturfordelingen i et tverrsnitt i en luftsøyle kan beskrives ved å bruke Gaussiske funksjoner, som forventet. Målet er å finne ut når luftsøylens lufthastighets- og temperaturfordeling er *selvlik*, som betyr at en ny sone-model i programmet EQUA, kan brukes ordentlig, ulikt den tidligere sone-modellen der det var en feil i kodingen. Resultatet fra eksperimentet gir innsikt om når selvlikhet i luftsøyler oppnås.

2. Table of content

Innhold

3. Introduction

The world needs to decrease the pollution of greenhouse gases, in order to reduce the heating of the planet. From 1880 to 2012, the average global temperature increased by 0,85 degrees [1]. With the ongoing emission, the temperature increase of the planet will have devastating results for the planet and the people on it, with less food production and less habitable land and more dangerous floods, to name some of the issues we could face.

This is considered the biggest issue on the planet for most societies. The biggest news in human history, concerning global warming and climate change, happened during the United Nations Climate Change Conference (UNCCC) in Paris in December 2015 (COP21), where 195 countries agreed to a legally binding climate deal. Key elements of this deal is to prevent the global temperature to increase above 2 degrees to preindustrial levels, but aiming at not increasing the temperature above 1,5 degrees. Every country have delivered an energy-plan to the UN, with a detailed plan of how their country can contribute to the common goal. The plans will be followed up on every five years [2].

The EU have been one of the first major economies to submit its support to the reduction of greenhouse gases. EU's goals related to energy affects Norway as well, even though Norway is not part of the EU at this time (August 2016), because of the EØS agreement between EU and Norway.

EU have declared these goals by 2020:

- 20% reduction in greenhouse gas emissions from 1990 levels.
- 20% of EU energy from renewable sources.
- 20% improvement in energy efficiency from 1990 levels.

It is further planned to reduce the greenhouse gases to 40% of 1990 levels by the year of 2030, and a minimum renewable energy delivery of 27% of the total energy delivered.

Norway have goals concerning both increase of renewable energy and increase of energy efficiency. With regards of being more energy efficient, the government has declared that all new buildings must be built according to the determinative building regulation TEK10. Key points of TEK10 is that the building must be built airtight and have thick walls, decreasing the energy use. TEK10 also states that buildings with an area below 500 m^2 are required to have 40% of its energy supply for space heating (SH) and heating of domestic hot water (DHW) to origin from energy sources that does not include either direct electricity or fossil fuels. For buildings over 500 m^2 the demand is 60%. This demand does not count if it is practically impossible to get renewable energy at the buildings location, or if the energy need for heating is less than 15 000 kWh [3]. TEK15 will be the new building regulation, and it is still under development at this time. The Norwegian passive house standard NS3700 will most likely serve as a basis for the new regulation. The most important goal of NS3700 is to reduce the heat loss in buildings. This can be achieved in many ways, for example: Thick insulation and well insulated windows, balanced ventilation with heat exchanger and reduced air leaks. In addition, the percentage of energy supply for SH and heating of DHW from non-fossil or direct electricity sources are increased to 60% for buildings below 500 m^2. This means that future buildings will use less energy and the maximum power loads will decrease as well.

Some key specifics about the passive house standard are listed below.

Description	Value
U-value walls	0,16 W/m^2
U-value roof	0,06 W/m^2
U-value basement floor	0,10 W/m^2
U-value windows	0,78 W/m^2
Heat recovery efficiency in ventilation	88%
Leakage number	0,60 h^{-1}
Specific fan power (SPF)	1,40 kW/$\frac{m^3}{s}$

Table 1: Building specification, passive house

Norway used 14,5 TWh of biofuels in 2006, where 7 TWh came from logs used in wood stoves. The energy generated in wood stoves are used for SH and DHW. Biofuel is considered a CO2 neutral fuel, since its emissions is part of the photosynthesis cycle. It is therefore desirable to increase the use of biofuels in Norway. Norway has a plan to increase the use of biofuels by 14 TWh by the year 2020. 8 TWh are expected to be a part of the increase in spot heating in residential buildings and older buildings without waterborne heating systems. The remaining 6 TWh are expected to be a part of the development of district heating. However, the development of the increase seems not to go according to plan [4].

Average household energy consumption in 2012 in Norway was 20 230 kWh, where electricity accounted for 16 kWh, and fuel wood came in second place with 3200 kWh [5]. Below is a figure illustrating the development of different energy sources from 1993 – 2012 in households.

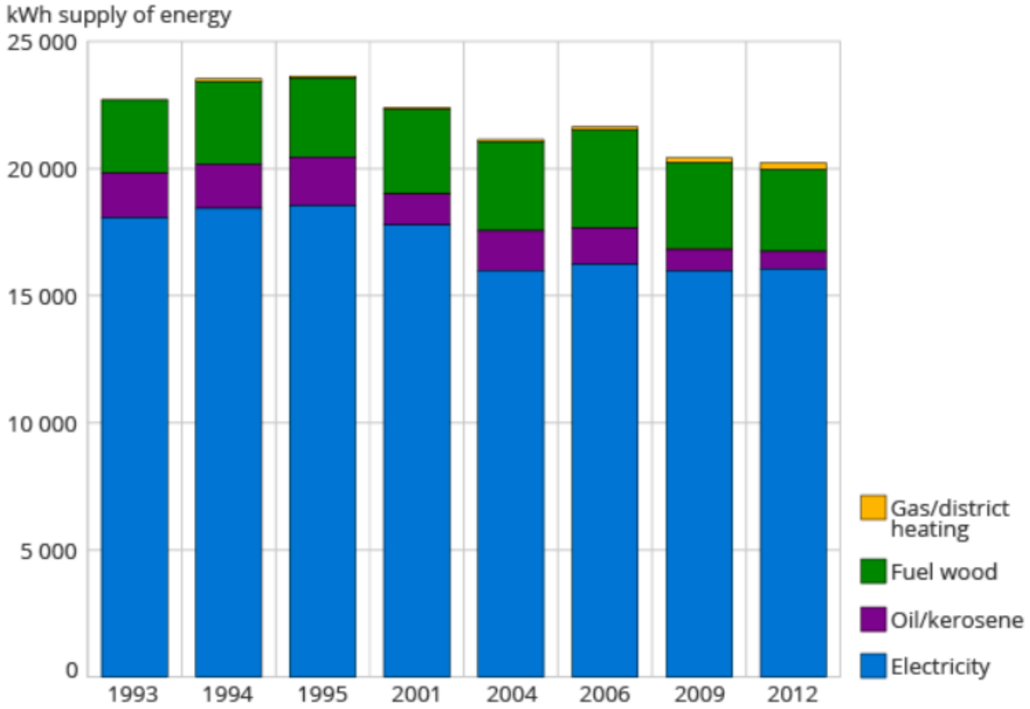

Figure 1: Energy supply in households from different sources [5]

To plan increase of biofuels over time is easier said than done. The use of biofuels in households has to keep up with laws and regulations of today, and how the laws are going to develop in the future. By looking at figure (1), the amount of energy delivery to households from wood logs have been stable from year 1993 to 2012. As discussed above, buildings will become more insulated and more airtight, and the presence of a relatively large point source in a room (wood stove) in a passive house, poses some challenges about the indoor environment. This could be the reason for the deviation in the plan about increasing the use of biofuels in Norway. It is also worth noticing the gradual decrease of energy use in buildings in figure (1).

Implementing wood stoves in passive houses have both positive and negative effects:

+ It is a good measure to decrease the electricity use for space heating, keeping the building in accordance with NS3700.

+ It does not increase the amount of CO_2 in the atmosphere.

+ It could have a positive effect on the economy. Unlike electricity and oil, wood logs and pellets have relative stable fuel price. For a building with a heating demand of 11.000 kWh, a wood stove covering 50% of the SH and a fuel price of wood being 45 øre/kWh cheaper than electricity, will save around 2500 kr/year [6].

- The smallest wood stoves nominal power output of 5-8 kWh [7] is high relative to the power demand of the building at dimensioning winter temperatures. This could cause very high temperatures in the room it is situated in, causing thermal discomfort among the occupants.

- Having a point load poses challenges regarding transport of energy through the whole building.

4. Goal and previous work

The project is part of the CFD-Wood project lead by SINTEF Energy Research. The overall goal with the CFD-Wood project is to investigate the effect of wood stoves in highly insulated houses, such as a passive house. Existing building simulation tools have been implemented with a “hot object”, which serves as the stove, to study the indoor environment when subjecting the building to different environments over time. Long periods of time with variations in weather must be studied to get a clear picture of the effects a wood stove has in a building, so that the critical operating hours can be determined. The time-step calculations are relatively small to the total time the program is designed to perform a simulation, which could be every minute or so. That means the program must calculate every value of interest in the building every minute for a period of what could comprise of a full year. The reason for the small time steps is that passive houses have a relatively high time constant, which means that it is highly reactive to sudden changes and could use a long period of time to return to its initial state. For example, a couple of minutes of sunlight could affect the thermal environment of great effect if the stove is up and running at the same time (there is no sudden off button on the stove). Small time steps are important to capture every fluctuation in temperature. It has therefore been desirable to use CFD-free building simulation tools, to avoid long computational times. Previously, a thermodynamic model were implemented in the building simulation tool TRNSYS, and a measurement campaign were completed where an electrical stove, which simulated a real wood stove, were put in a passive house in Granåsen, Trondheim, to verify the model implemented in TRNSYS. A new zonal model was developed by the company EQUA, which used the model in their program; IDA-ICE. It was favourable to use the new CFD-free IDA-ICE instead of TRNSYS, because it could give a better understanding of the thermal environment. The new zonal model was validated, although it failed to give a correct picture of the thermal stratification where the hot object is situated, which in turn affects the thermal environment in a room. The figure below shows the thermal stratification in the room the stove was situated:

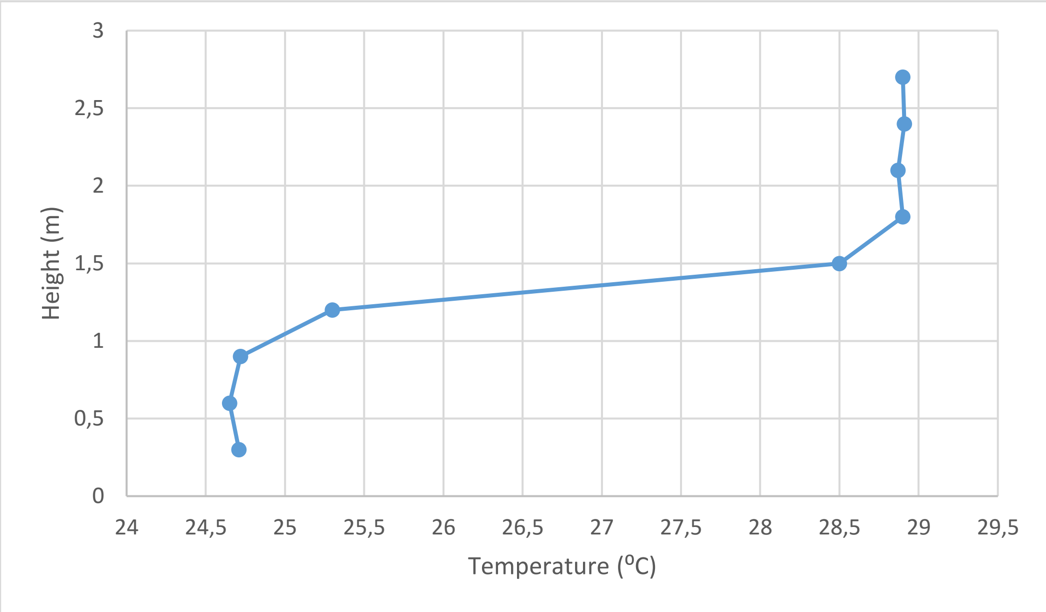

Figure 2: Thermal stratification

The data in figure (2) is provided by work done in the pre-project to this master thesis. The sudden change in temperature at height 1,2 m seems suspicious, since a linear temperature stratification were expected in the room. After discussing with Laurent Georges, researcher at NTNU, project participant in the CFD-Wood project and supervisor for this master thesis, he suspected that there was an error with EQUA's model, which will be discussed more thoroughly later. EQUA has been cooperative and created a new model. Measurements of a plume to verify the new model is desirable, and formed the basis of this master thesis.

This paper will investigate the plume created above a hot source in a room, in order to supply data so that the new thermodynamic model created by EQUA can be approved and implemented in IDA-ICE with confidence.

5. Report setup

First, some theory about plumes will be explained. Following, there will be an experimental setup, where the results from the experiment will be presented. Last, there is a discussion about the results and an conclusion.

6. Background theory

6.1 Thermal comfort

The basis for the thermal comfort assessment is taken from NS7730. The definition is as follows: “Thermal comfort is that condition of mind which expresses full satisfaction with the thermal environment.” There will usually be people dissatisfied with the thermal environment. Some people can also experience thermal neutrality, and be indifferent to the increase or decrease of the temperature of the air. However, one should strive to design the thermal comfort so that the percentage of dissatisfied (PD) people is as low as possible. Local thermal discomfort is described as when a body part is too hot or too cold compared to the rest of the body. The most common cause of local discomfort is draught. Another cause can be high vertical temperature difference between head and ankles. Looking at figure (2) one can see that the temperature difference between head and ankles are 28,9 - 24,65 = 4,25. The PD caused by this temperature difference can be calculate using this formula:

$$PD = \frac{100}{1+\exp(5{,}76-0{,}856*\Delta t_{a,v})} = 10{,}7 \qquad (1)$$

A PD of 10,7 is not good enough for a passive house/building.

6.2 Plumes

When an object is hotter than the surrounding air, it will transfer heat. The warmed up air, will become less dense than the surrounding air, causing it to rise upwards, due to less gravitational force to the heated volume. Cold air in the same area will replace this air, and the process continues. This is called the buoyancy effect, and is described as:

$$B = Qg' \qquad (2)$$

Where Q is the volumetric flow rate (m^3/s) and g’ (m/s^2) is the reduced gravity caused by a difference of density between the plume and the ambient air, described as:

$$g' = g\frac{\Delta\rho}{\rho_r} \qquad (3)$$

Where $\Delta\rho$ is the density difference and ρ_r is a reference density. Density difference of air can be caused by a temperature increase of an air volume, which is the source of buoyancy when using a wood stove.

The plume characteristics and flow patterns in a stable environment is dependent on the geometry of the heated area, and the temperature of the heated area. The plume will look different if its heat source is a vertical wall or a small heated ball in an open room. Regardless of the heat source, some similarities between plumes are found. If it is a case where a physical object of considerable size is the source of heat, which is the case with the electrical wood stove in this report, the plume gets affected in a certain way; when air starts to rise from the sides of the stove, and it reaches the top of the stove, it gets accelarated uppwards. To some degree it also gets “sucked” inwards to the centre of the stove before it rises. The reason for this is that the temperature gradient is steeper at the centre of the top of the stove, causing the air to become super buoyant in this area. When the air rises upwards from the centre it accelerates. Since the volume flow in this area is stable, it means that the cross sectional area at this height in the plume must become narrower. This zone is called the zone of establishement, and it is mainly characterized by chaos. The length of the zone of establishment is dependant of the power of the source and the geometry. The generalized formulas (17-19) cannot vouch for the behaviour of the air in this part of the plume. At a certain point when the zone of establishement has ended, the plume cross section temperature and air speed can be described with gaussian functions (bell shaped curve). It is at this point we consider the plume to be stable. After a certain height is reached, the plume will dissipate, because its temperature has become equal to the ambient fluid, resulting in losing its buoyancy force.

Plumes have been studied and researched for many years because of its relevance with the real world. For example, studying airflows over seas, predict pollution from stacks from factories, or in this case; prediction of plumes from heated stoves in airtight buildings to explore the possibilities of integration of wood stoves in passive houses. The literal term of the “rising air” is dependent on the context. Different papers describes it as thermals, thermal plumes, natural convection flows or plumes. In this paper, it will be referred to as plumes. Although, a plume could in many cases describe a rising fluid surrounded by a different fluid, for example a chimney exhausting smoke into the air.

The first publications regarding plumes are those from Zeldovich (1937) and Schmidt (1941) [8]. Formulas for centreline velocity, centreline excess temperature and airflow rate of plumes origining from point sources and line sources are derived from looking at the conservation of mass-, conservation of energy- and conservation of momentum formulas. The air velocity and temperature profiles are assumed Gaussian in the plume cross-sections, and the heat source is considered to be very small. The book “Building Ventilation, Theory and Measurement”, by David Etheridge and Mats Sandberg [9], describes the theoretical background of the equations used to find numerical values of key elements in a plume. These are the same formulas that are used in EQUA. Somewhere in the program, there has been a misunderstanding of the theory, and it has been programmed in a way that was not logical relative to the real world. The theory in the book by Etheridge and Sandberg is also the background to the equations below, (17-19), taken from the publication of Zeldovich and Schmidt, where Zeldovich and Schmidt uses more of an experimental approach.

In order to use the following equations (4-7), one must assume the velocity and temperature distribution to be self-similar. That means that the shape of the velocity and temperature distribution is not dependent on the distance z from the heat source.

The volumetric flow rate, specific momentum, energy and buoyancy force can be described as the following, respectively [10]:

$$Q(z) = A(z) * v_c(z) * I_1 \qquad (4)$$

$$m(z) = A(z) * v_c^2(z) * I_2 \qquad (5)$$

$$E_{P-a}(z) = \rho C_P A(z) * v(z) * \Delta T_c(z) * I_3 \qquad (6)$$

$$F_B(z) = g\beta A(z) * \Delta T_c(z) * I_4 \equiv g_c'(z) * A(z) * I_4 \quad (7)$$

Where the profile dependent coefficients are:

$$I_1 = \int_0^1 f(\eta) * d\left(\frac{\Delta A}{A}(\eta)\right) \quad (8)$$

$$I_2 = \int_0^1 f^2(\eta) * d\left(\frac{\Delta A}{A}(\eta)\right) \quad (9)$$

$$I_3 = \int_0^1 f(\eta) * f_T(\eta) * d\left(\frac{\Delta A}{A}(\eta)\right) \quad (10)$$

$$I_4 = \int_0^1 f_T(\eta) d\left(\frac{\Delta A}{A}(\eta)\right) \quad (11)$$

Where $\eta = \frac{b}{b(z)}$, The area $A = \pi b^2$ and the area differential $\Delta A = 2\pi x dx$ for axisymmetric round plume. “b” is the width from the z-axis to the plume boundary layer.

The values of the profile dependant coefficient integrals for three-dimensional plumes are

$$I_1(Volume\ flux) = 1 \quad (12)$$

$$I_2(Momentum\ flux) = \frac{1}{2} \quad (13)$$

$$I_3(Energy\ flux) = \frac{\lambda^2}{1+\lambda^2} \quad (14)$$

$$I_4(Buoyancy\ force) = \lambda^2 \quad (15)$$

Where $\lambda = \frac{b_T}{b_v}$, which is the width of the temperature field divided by the width of the velocity field. They do not always tend to be equal.

6.3 Gaussian curve

The general Gaussian curve can be written as:

$$f(x) = a * e^{-\frac{(x-b)^2}{2c^2}} \quad (16)$$

The function can describe many real world phenomena, often applied in statistics where it describes the normal distribution. In this case, it will describes the distribution of heat and air speed in a plume.

a, in function (16), is the expected value, which is the highest value on the y-axis. B, decides where the expected value are located on the x-axis. In the cases in this paper, b will be equal to 0, since the maximum values in the cross sections in the plume will be “bent over” to x = 0. C is the standard deviation, which decides how wide the curve is. The standard deviation also tells us when the area beneath the graph is 34,13% of the total area.

6.4 Plumes from point sources

The following formulas of the plume characteristics for point sources are derived based on what is written above about background theory about plumes.

$$v = C_1 * P_{ec}^{\frac{1}{3}} * Z^{-\frac{1}{3}} \quad (17)$$

$$\Delta T = C_2 * P_{ec}^{\frac{2}{3}} * Z^{-\frac{5}{3}} \quad (18)$$

$$Q = C_3 * P_{ec}^{\frac{1}{3}} * Z^{\frac{5}{3}} \quad (19)$$

Where v, ΔT and Q is the centreline velocity, centreline excess temperature and airflow rate respectively. Pec is the convective power of the source in wats, and Z is the height above the source in meters. C_1, C_2 and C_3 are dimensionless constants, and they differ slightly from different sources. The formulas in the table below correspond well with experiments conducted before, and they will be used further to compare with the measurement results in the experiment. In addition, characteristics from line sources are added in the table.

Parameter	Point source	Line source
Centreline velocity (m/s)	$v = 0{,}128 * W^{\frac{1}{3}} * Z^{-\frac{1}{3}}$	$v = 0{,}067 * W^{\frac{1}{3}}$
Centreline excess temperature (^{o}C)	$\Delta T = 0{,}329 * P_{ec}^{\frac{2}{3}} * Z^{-\frac{5}{3}}$	$\Delta T = 0{,}094 * P_{ec}^{\frac{2}{3}} * Z^{-1}$
Airflow rate (m3/s)	$Q = 0{,}005 * P_{ec}^{\frac{1}{3}} * Z^{\frac{5}{3}}$	$Q = 0{,}013 * P_{ec}^{\frac{1}{3}} * Z$

Table 2: Formulas of plume characteristics

Typically, a plume from a point source will look like the figure below.

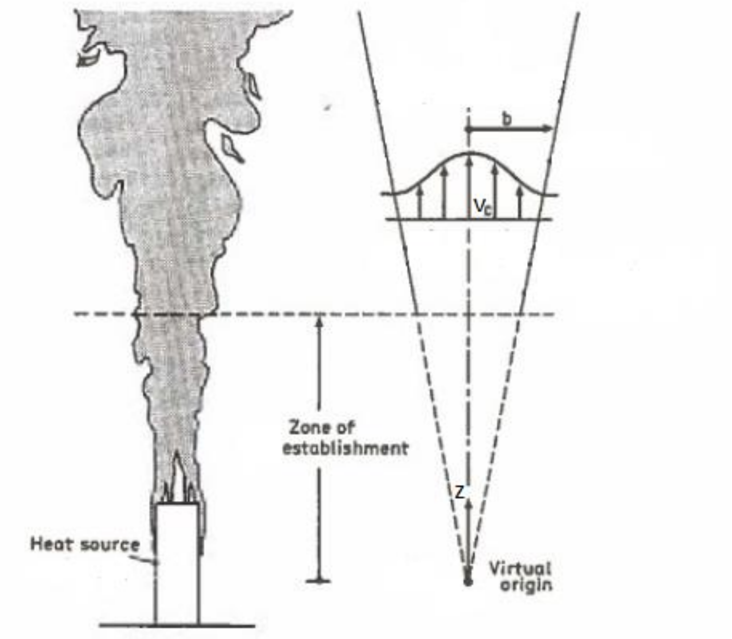

Figure 3: Plume visualization

6.5 Horizontal plate convection

Predicting the plume from a heated horizontal plate is complicated, and not as easily done as with point and line sources, or with vertical walls. Reasons for this is that the fluid leaves the surface at different locations at different times, and the location is very reactive to how the surroundings in the room behaves. Plumes from horizontal plate convection is treated the same way as for a point source, where the point source is located a certain distance below the top surface. We imagine that the cylinder is minimized into a point, with no definite size. The heat dispatch from this source remains the same, and we are able to calculate the characteristics of the plume imagining that it dissipates from the point source, as seen on the figure:

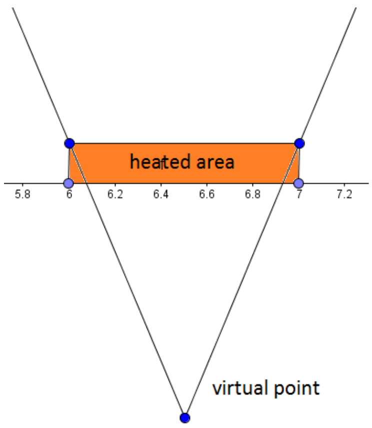

Figure 4: Point source

The difficult part of this method, is determining the length from the top of the cylinder to the virtual point.

Two theories of how to solve this problem for a heated cylindrical shape is described by the book “Industrial ventilation design guidebook” by Howard D. Goodfellow and Esko Tähti [10], as the maximum method, and the minimum method. The two methods will be described below. The geometry used in figure (5 and 6) is the electrical stove that is used in the experiment with the real dimensions.

6.5.1 Maximum case

The angle of the plume is set to: $\alpha = 25^{o}$. The two lines from the source point goes through the top edge of the stove, creating a wide plume diameter at the top of the stove. This method gives a distance from the source point to the top edge of the stove of: r = 1,35 m.

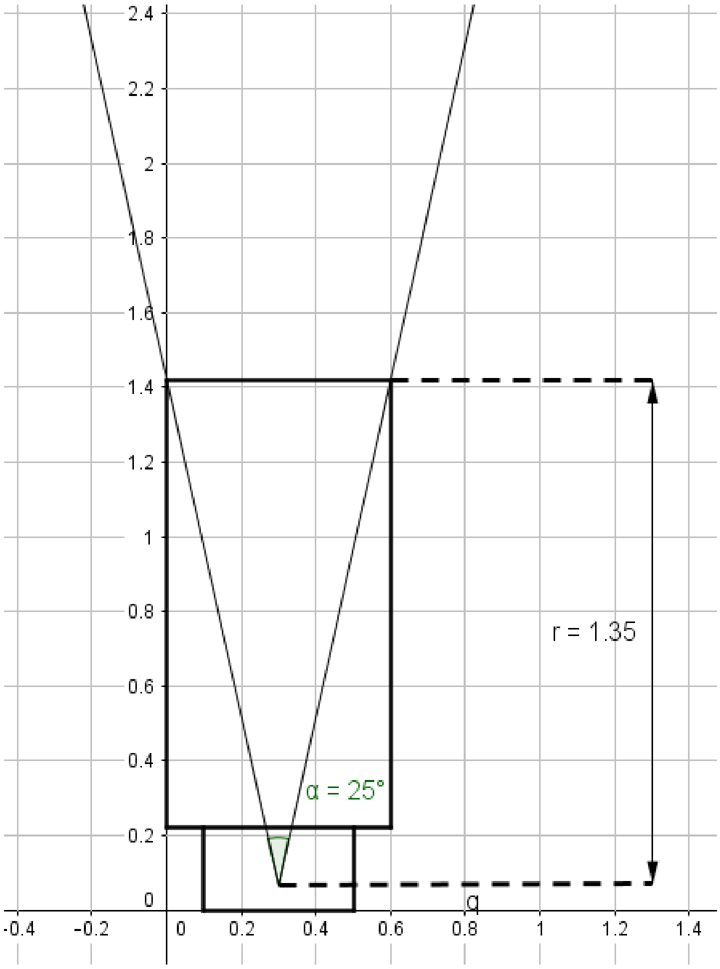

Figure 5: Maximum case

6.5.2 Minimum case

The angle of the plume is set to the same: α = 25°. The two lines from the source point will go through two points that makes the plume narrower. The points coordinates are defined such that the distance between them are 0,8 times the width of the stove, and 1/3 of the width above the stove. The picture below illustrates the minimum case. The distance r = 0,88, which is less than the r-value for the maximum case.

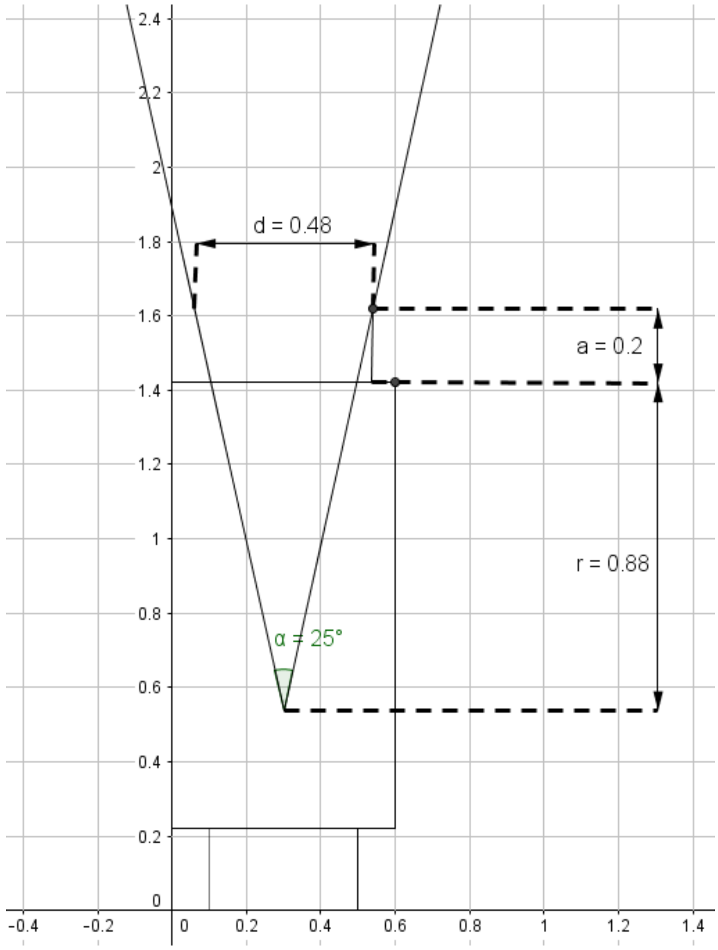

Figure 6: Minimum case

The reason for the different methodes to describe the length from the point source to the top of the stove, is that the behaviour of the air at the top edge of the stove is very dependant of which geometry and temperature the hot object consist of. There is no certain theory availible for every case of hot objects, but studying the minimum and maximum cases yield a calculated approach to how the plume will behave. The lines from the point source of both cases (figure 5 and 6) describing the movement of the plume are not valid until the plume is stable. The simplest way to figure out the distance of the zone of establishement is to do measurements.

6.6 Boundary layers

There are two main boundary layers that are of importance in this paper; the thermal boundary layer and the velocity boundary layer. The thermal boundary layer thickness is described as: $\delta_t = \frac{T_S - T}{T_S - T_\infty} = 0{,}99$, which is where the temperature in the plume (T) is closing the ambient temperature (T_∞). T_S is the centreline temperature. The same principal goes for the velocity boundary layer, where the velocity boundary layer thickness, δ_v, is equal to the distance between the centreline velocity in plume and v, where v fulfils the equation; $0{,}99v = v_\infty$, where v is the air speed in the plume and v_∞ is the ambient air speed. To get a physical picture of the topic; imagine a heated vertical plate immersed in a fluid. The figure below show the two boundary layers:

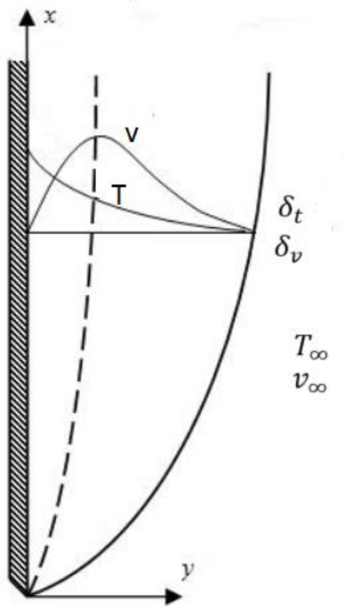

Figure 7: Velocity- and temperature boundary layer of vertical heated wall

The particles of the fluid that are in contact with the plate will not move upwards, they will slow down by the friction between the wall and the particles, and they will theoretically stand still. This means that the heat transfer is actually happening by conduction and not convection to the first layer of fluid. The rising fluid will be slowed down by friction of the wall on the left side and by friction of the still ambient fluid on the right side. That is why, as seen by figure (7), the maximum velocity of the air (shown by dotted line) is located somewhere between the wall and the velocity boundary layer. The temperature profile is naturally largest closest to the wall, and decreases, as the temperature boundary layer thickness gets thicker. The boundary layer thicknesses does not have to be equal as they show in figure (7).

7. Experimental layout

An overview of the measurement campaign is illustrate below.

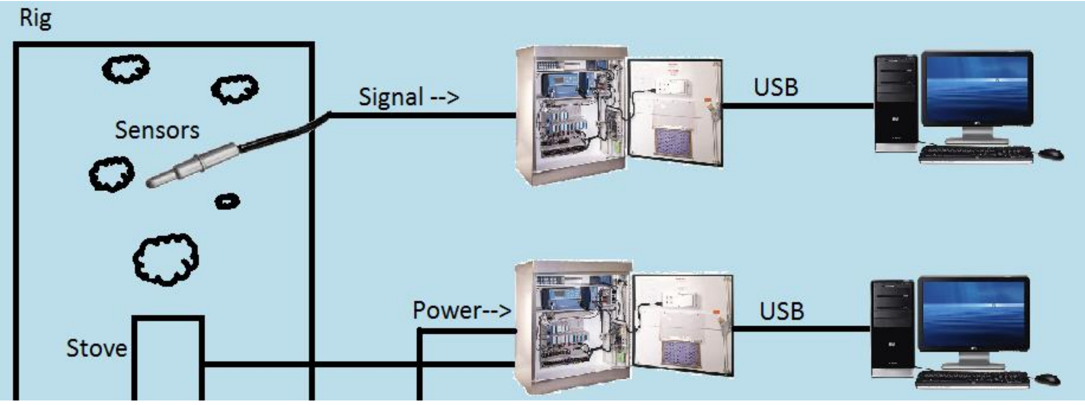

Figure 8: Overview measurements

A computer with LabView is connected to a cabinet, which controls the power and the control of the electrical stove. The stove heats up the air above, where sensors are located to measure air speed and air temperature. The measuring values is transferred to a cabinet and then to a computer equipped with LabView.

7.1 Electrical stove

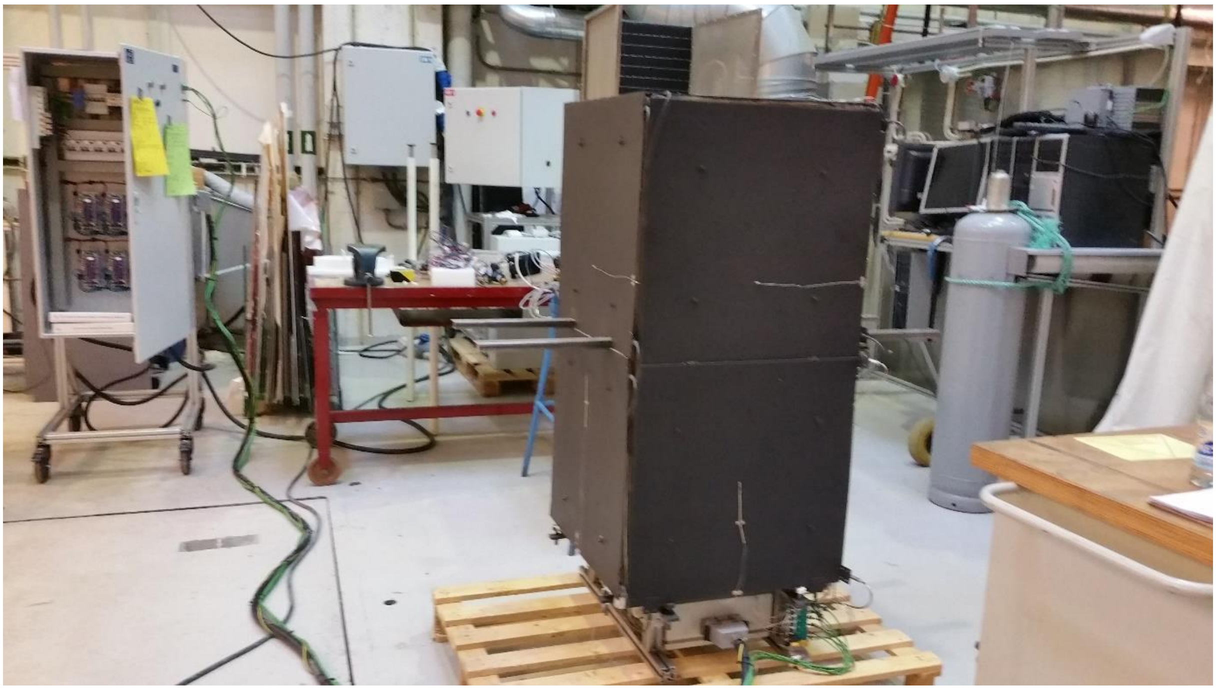

Figure 9: The electrical stove

The stove has dimensions 0,6m x 0,6m x 1,2m (L x W x H). It is heated by applying electrical power into electrical resistances. The electrical resistances are placed behind 9 aluminium plates, which makes up the exterior surface of the stove. Aluminium was a good choice of metal to ensure evenly distribution of heat to the plates, since aluminium has high thermal conductivity relative to other metals (k = 205 W/(m/K) , at 20 degrees Celsius). The stove were designed to have only 3 mm thick walls in order to have quick reaction time to changes in the power delivered to the plates. The inside of the stove is covered by 10 cm of mineral wool, ensuring that almost all the power delivered to the resistors are directed outwards through the plates. The electrical stove is designed to handle 15,55 kW of power. Although, during the experiment, when the power reached approximately 73 % of max capacity, the safety switch in the power cabinet activated and the power delivery stopped. This was not considered a real issue since it was not necessary to simulate wood stoves with a power dispatch of that level anyway.

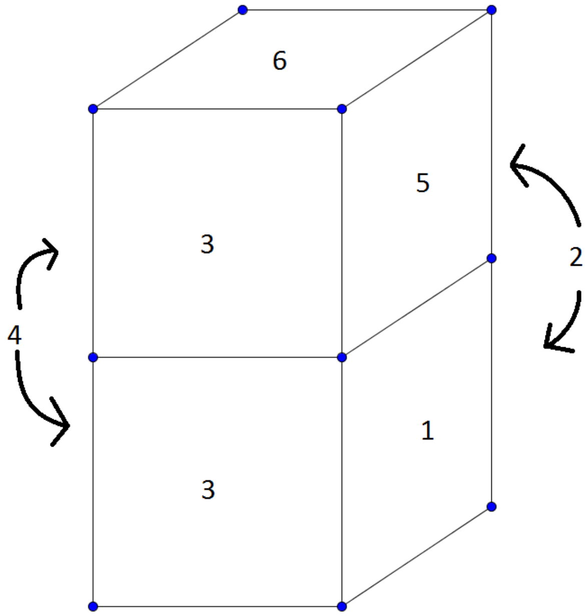

Figure 10: Overview of plates on the stove

Three surface temperatures are controlled independently, 1, 5 and 6. The rest, 3, 4 and 5 are controlled in pairs. This means the set point surface temperatures can be put to different values in order to simulate real wood stoves, because real wood stoves often have asymmetrical geometry, which leads to different heat transfer through the stove envelope, leading to different surface temperatures. In addition, the front of real wood stoves often has a "window" of variable size. This leads to a higher heat transfer in this particular area. Plate number 1 can be supplied with a higher power output (2750 W) than the other plates to simulate this effect.

Investigation of the plume created by the stove would of course be easier if the plume was symmetrical. The stove set point temperature was equal for all the plates during the experiment.

A detailed overview of the control and regulation system of the stove is illustrated below. The set point temperature is decided using a computer with LabVIEW. 6 thermocouples, which are attached to each plate number (figure (10)), measures the instant temperature. The instant temperature and the set point temperature are used in a PID regulator in LabVIEW. The PID regulator controls the output signal of 6 thyristors, which controls the power given to each plate. This control system makes sure the power delivery to the stove is large when the difference between the set point temperature and the real time temperature is large, and the power delivery will become less when the two inputs evens out.

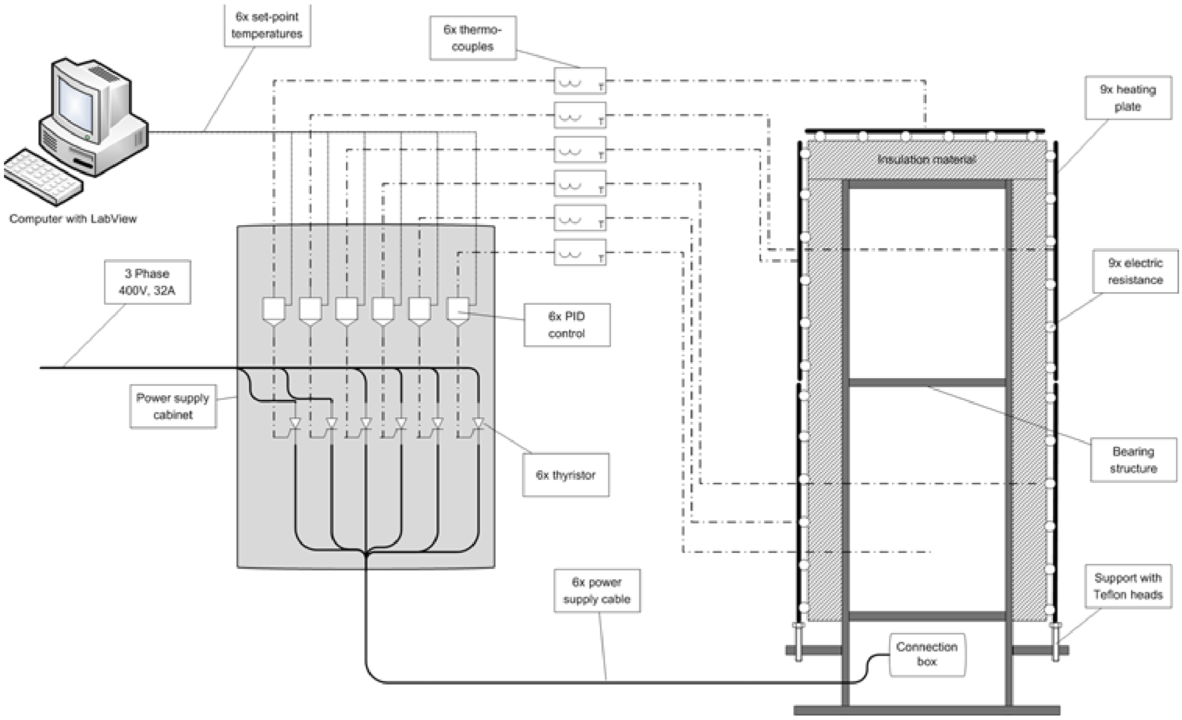

Figure 11: Overview of control-setup

Plate number	Power, W
1	2750
2	3200
3	3200
4	3200
5	1600
6	1600

Figure 12: Design power of each plate

Two methods were used to measure the power delivery (Pc) to the stove:

1) The formula (20) [11] gives a good result of the convective power, and is derived from looking at laminar and turbulent flows over an isothermal plate. Given characteristics about stove lengths and temperatures, gives the simplified formula for convective power:

$$P_{ec} = 1{,}22 * A * (T_{stove} - T_s)^{\frac{4}{3}} \qquad (20)$$

Where A = the stove area, Tstove = stove surface temperature and Ts = ambient room temperature.

During this experiment, the stove had a surface temperature of 170 degrees Celsius, which leads to a convective power dispatch of:

$$P_{ec} = 1{,}22 * (0{,}6 * 0{,}6 * 9) * (170 - 20)^{\frac{4}{3}} = 3150{,}35\ W \qquad (21)$$

2) LabVIEW did not give the value of delivered power to the stove, but it could log to the computer the percentage of maximum power each plate were using. The nature of the PID control makes the power delivery to each plate fluctuate. In order to get an accurate power reading of of each plate, the stove had to heat up for several minutes so that all the plates could reach the set point temperature. The thermocouples have a fault percentage equal to approximately 1 degree Celsius at a set point temperature of 170 degrees Celsius. When the plates reached this temperature, the PID percentages were logged to the computer for a couple of minutes, so that each temperature curve for the plates could have several fluctuations. The average PID for each plate were then multiplied with the maximum power each plate could use. The sum is the power given to the stove, Pc. It is estimated that 600 W is lost, and not dispatched as heat out through the plates. The remaining power, Pd, is released and divided as convective power, Pec, and radiated power, Per. Approximately 60 % of Pd is converted to Per, and 40 % to Pec. It is now easy to calculate Pec of the stove. Several surface temperatures were tested to figure out what powers they belonged to, and verified with method 1). The experiment uses a surface temperature of 170 degrees, which is equivalent to 8535 W delivered to the stove.

Calculation of method 2):

							Total power Pc, W
Plate number	1,0	2,0	3,0	4,0	5,0	6,0	
PID percentage, %	32,8	56,8	54,0	63,4	62,2	66,6	
Max power plate, W	2750,0	3200,0	3200,0	3200,0	1600,0	1600,0	15550,0
Power plate Pc**, W**	901,1	1816,2	1729,0	2028,2	994,9	1065,7	<u>8535,2</u>
Delivered powe Pd, W	7935,2						
Radiative part Per, W	<u>4761,12</u>						
Convective part Pec, W	<u>3174,1</u>						

Table 3: Calculation of method 2

Both methods seem to give an accurate answer for the convective power Pec, with only a few wats difference between them.

7.2 Rig

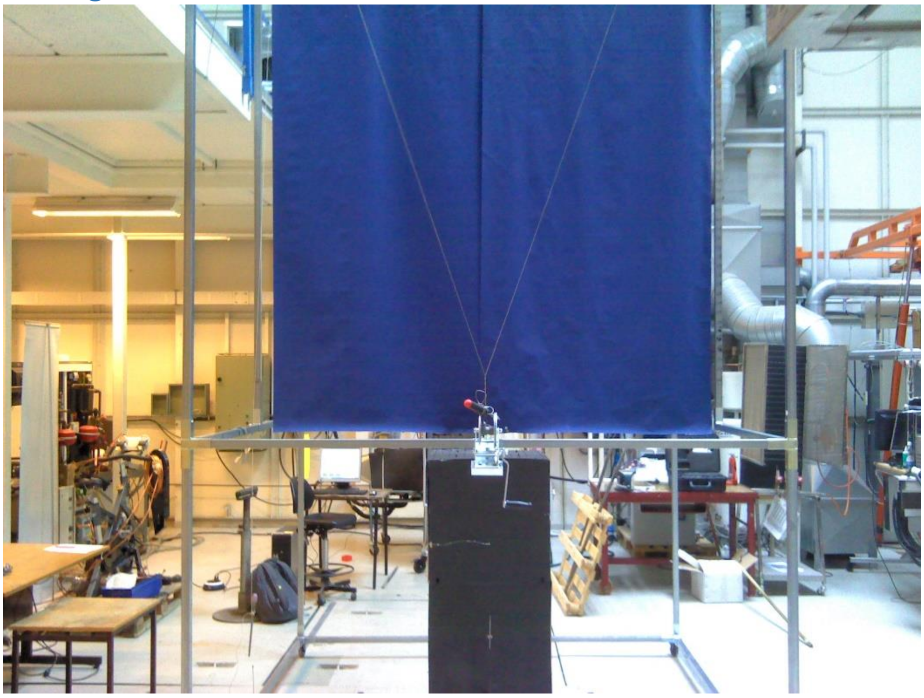

Figure 13: Rig

A rig was built in order to get accurate measurements of the characteristics of the plume. It was made of hollow steel profiles (0,035 m x 0,035 m) put together making the frame of a rectangular box. The height of the rig was 4,5 m with sides of 1,5 m. The stove were placed in the middle.

The temperature sensors and air speed sensors were attached to a steel profile that was mounted on the middle of two opposite sides, locating the sensors in the middle of the rig.

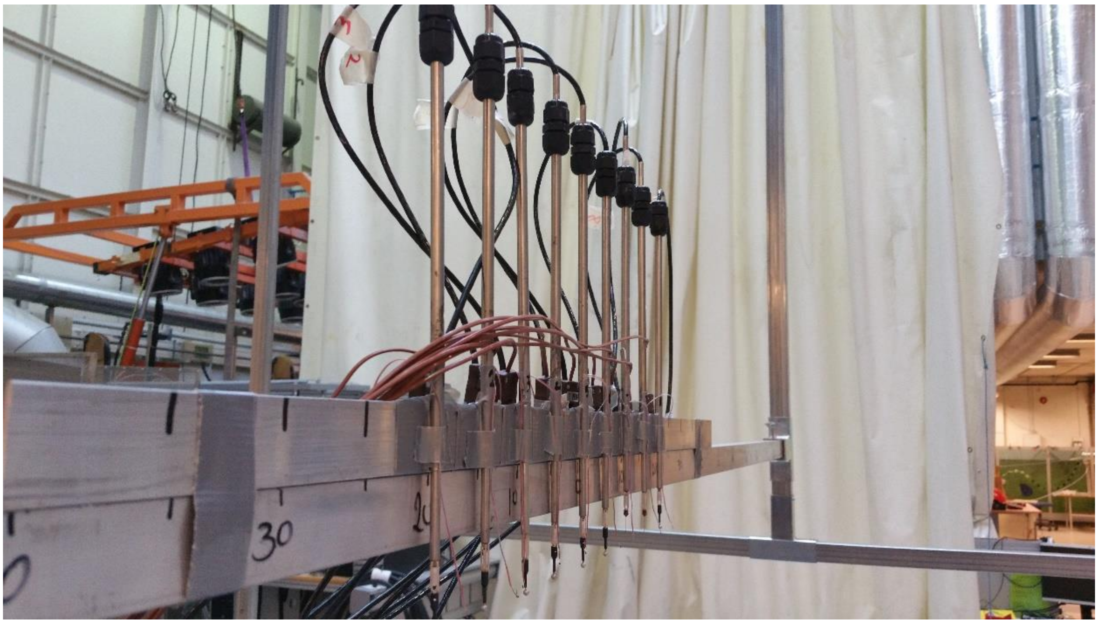

Figure 14: Velocity and temperature sensors

This profile were connected to a pulley system, which could be lowered and lifted using a crank attached to the rig. The rig were equipped with wheels, so it could move around in the room. A 3-D image of the air speed and the air temperature could be made by moving the sensors around in the room. A large coordinate system was drawn on the floor, were the top of the stove, in the middle, acted as the origin (x=0, y=0, z=0). Two key measuring point were fixed on the middle of two profiles adjacent each other. These measuring points pointed to the ground, indicating where in the two dimensional plane, x and y, the rig, and more importantly the sensors, were located relative to the stove. The z coordinate of the sensors were know simply by looking at the vertical bars where the height above the stove had been drawn.

Nine anemometers (no more were available) and nine thermocouples were ductaped in pairs on the steel profile in the middle of the rig.

Figure 15: Sensors. Ball shape is velocity and other is temperature

It was decided to have a spacing of five cm between each pair of sensors, making a line of 45 cm together. Less distance between each sensor pair will give a more concentrated picture. The initial plan was to make a five centimetre grid in the x and y direction, thus the five centimetre spacing of the sensors. This approach would lead to moving the rig 740 times, and would probably result in 40 hours of laboratory measuring work. Since the anemometers only were available for a finite period of time, It was decided to move the rig 10 centimetres in the y-direction for each measuring. This makes the results less concentrated, but halves the measuring campaign. Six levels in the z-direction were measured.

7.3 Sensors

Data of the anemometers are presented in table (4)

Air Velocity Transducer 8475	
Accuracy	+/- 3,0% of reading
	+/- 1,0% of scale
Velocity range	0,05 m/s -2,54 m/s

Temperature compensation range	0-60 Celsius
	Add 0,5% per degree Celsius outside 20-26 Celsius, within temperature compensation range
Response time	5,0 seconds

Table 4: Information about anemometers

The end of the sensors is a thin fragile globe. The globe measures the change in resistivity due to the temperature it has. The flow around the globe changes the convection coefficient, and change the temperature of the globe slightly. If the air does not have the default air temperature the program uses to calculate the air speed, it must of course be taken into account. As the table above states, 0,5 % per degree above 26 degrees must be added to the air speed.

7.3.1 Calibration due to offset values

Before the measuring campaign could start, the anemometers had to be calibrated, to see if the probes were giving accurate results. Nine anemometers were tested in an air speed drum, where the sensors where held at the same location, exposed to four different air speeds, three times each. The calibration air speed drum is used by changing the area the air could enter the drum (m), and the power of a motor sucking the air (rpm). The air speed is then read of a chart of a graph, dependent on the opening and the rpm. This is done manually, so there is chance that faults could happened. It is important to keep in mind the build in error when reading the values; +/- 3,0% of reading and +/- 1,0% of scale. The scale was put to 2,5 m/s during the test. The table below show the calibration of probe nr. 1.

Scale	**2,5 m/s**	
Error reading, +/-	3 %	
Error scale, +/-	1 %	0,025 m/s

Measuring number	Set value (m/s)	Measured value (m/s)	Error reading (m/s)	Error scale (m/s)	Min. value (m/s)	Max. Value (m/s)
1	0,3	0,344	0,01032	0,025	0,30868	0,37932
2	0,3	0,364	0,01092	0,025	0,32808	0,39992
3	0,3	0,363	0,01089	0,025	0,32711	0,39889
4	0,7	0,801	0,02403	0,025	0,75197	0,85003
5	0,7	0,806	0,02418	0,025	0,75682	0,85518
6	0,7	0,815	0,02445	0,025	0,76555	0,86445
7	1,1	1,214	0,03642	0,025	1,15258	1,27542
8	1,1	1,225	0,03675	0,025	1,16325	1,28675
9	1,1	1,241	0,03723	0,025	1,17877	1,30323
10	1,5	1,717	0,05151	0,025	1,64049	1,79351
11	1,5	1,778	0,05334	0,025	1,69966	1,85634
12	1,5	1,685	0,05055	0,025	1,60945	1,76055

Table 5: Calibration of probe nr. 1

It is clear that for probe nr. 1, after taking the errors into account, most of the minimum and maximum values are still outside the range of the set point value. This was surprisingly the case for all of the probes. A calibration factor must therefore be multiplied with all the values in order to get a correct result.

The correction of probe 1 is shown in the table below:

Set Point	**0,3**	**0,7**	**1,1**	**1,5**	**Avergage**
Measured 1	0,344	0,801	1,214	1,717	
Measured 2	0,364	0,806	1,225	1,778	
Measured 3	0,363	0,815	1,241	1,685	
Set point / measured 1	0,872	0,874	0,906	0,874	0,881
Set point / measured 2	0,824	0,868	0,898	0,844	0,859
Set point / measured 3	0,826	0,859	0,886	0,890	0,865
Average correction factor	**0,868**				

Table 6: Correction factor

This means all values from anemometer 1 must be multiplied with 0,868. The rest of the calibrations of all the probes are in attachment A. The anemometers give a signal to the control cabinet, which further sends a signal to the computer. A simple formula is used: $C = \frac{V_s}{I_a}$, where Vs is the air speed scale in m/s, Ia is the electrical current in mA and C is a constant. The constant C is set to 125, and the scale, Vs, is set to s 2,5 m/s. This yields; Ia = 0,02 mA. By reducing the constant to 50 in LabView, we get $V_s = 0{,}02\ mA * 50 = 1\ m/s$. The anemometers will only show results that are below 1 m/s. It is safe to assume the results will not give any air speeds in the plume above 1 m/s, after testing it manually with an air speed probe. By reducing the constant in the program, the scale error gets reduced from 0,025 m/s to 0,01 m/s.

7.4 Additional preparations of the experiment

An ideal experiment would require conditions of completely still air, were only the heat from the stove was affecting the air movement in the room. In addition, the room should be symmetric relative to the stove, without any obstacles, causing the air to move ideally as seen in figure below:

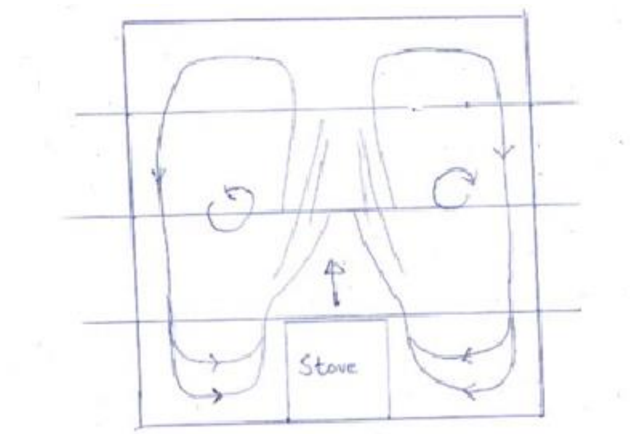

Figure 16: Air movement around stove, ideal room

The temperature in the room should not fluctuate, because of what time of the day it is and/or sunlight coming through the skylight. However, this was not the case, but efforts were made to simulate an ideal situation:

1) Air conditioning were turned off, lowering the airspeed in the room significantly.
2) Openings in the floor to the basement were ductaped and sealed shut. This was crucial for stable wind speed conditions since huge gust of wind came rushing through the openings just below the stove, when the basement doors opened.
3) Measurements happened mostly in the afternoon and night:
    a. Ensuring that the doors to the lab were closed shut and no people were walking by disturbing the air.
    b. Minimized temperature fluctuations in the lab caused by sudden solar gains through the skylight.

The anemometers operating temperature is 0-60 degrees Celsius. Measuring air velocity above 60 degrees Celsius risks destroying the sensors, which cost about 10 000 kr each. The highest temperature measured at a stove power of 8000 W was 46 degrees Celsius just above the stove surface. It was safe to attach the anemometers to the bar.

7.5 Risk analysis

A risk analysis had to be made before the measuring campaign could start. A risk analysis had already been conducted concerning the use of the electrical stove. The only additional remark to the report is the use of the rig.

The following safety hazards are:

- Electrical stove:
    - Could cause fire hazard if used improperly.
    - Hot surface could cause burn damage if treated carelessly.
- Power and control cabinet could cause electrical damage if treated improperly.
- Danger of blunt trauma from falling down leather when working with the tall rig.

The associated safety measures are:

- Fire hazard: Turn of power to the rig, extinguish the fire. If not able to extinguish the fire, activate nearest alarm and evacuate area.
- Electrical damage: Only lab technicians can work in the power and control cabinet.
- Blunt trauma: Follow regulations in "arbeidstilsynet". When working in height. If lab worker becomes subject of blunt trauma, use first aid kit and/or shout for help. Serious injury, call 113.

The full risk assessment report can be found in attachment C.

7.6 Treatment of data

7.6.1 Temperature stratification in building

The air temperature in a building varies according to the altitude in the room. The temperatures also changes throughout the day. To keep track of the ambient temperature in the room at all times, 6 thermocouples were placed on the rig at three different heights.

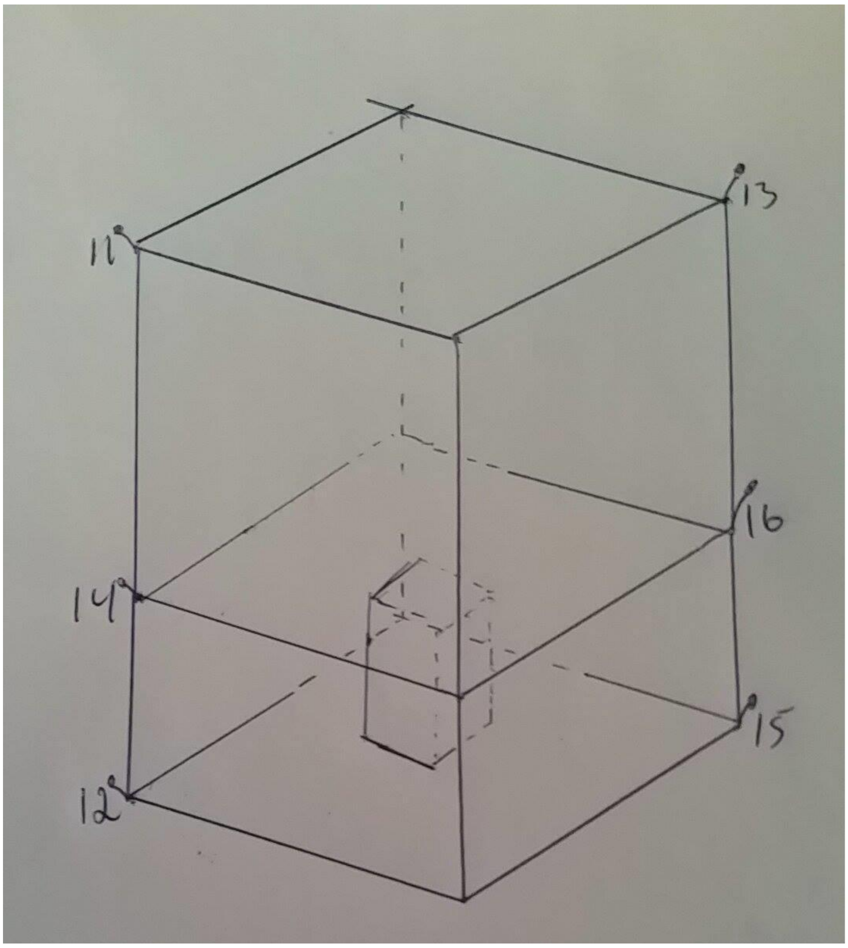

Figure 17: Sensor location of tempearture measurement of air

The ambient temperature is subtracted from the measured temperature in the plume in order to know by how much the stove is heating the air. The sensors are placed in a way so that the stove does not have any impact on them. If the plume is behaving so that it "moves" in the area of the sensors for some reason, the other set of sensors at the same height will then be used to measure the ambient temperature. One can argue that the ambient temperature should be measured at the associated height where the measurement of the plume is happening. The degree of which this is correct depends on “where” in the plume the measurements are happening. An illustrative figure (16) shows the air behaviour around the heated stove. The air close to the heated surface rises towards the edge of the stove because of the buoyancy force, creating a vertical boundary layer. “This” heated air mostly becomes a part of the volume of the plume that dominates the centre of the plume. Which means that the initial temperature of this air is in the range between what sensors 12 and 14 or 15 and 16 shows. The air at the edge of the plume is a mix of air that has been transported from the stove and ambient air that has been turbulently mixed with the rising plume at different heights. The initial temperature is therefore hard to determine at each height, and the time-cost value of taking into account “where” in the plume measurement is happening was not worth it. Simply because the temperature difference of the ambient air depending on height and air above the stove does not vary much. When using the measurement results, values from sensors 14 and 16 has been used as ambient temperature.

7.6.2 Air speed temperature compensation

When the measured temperatures are outside the range of 20-26 degrees, we must add 0,5% per degree Celsius above 26 degrees. All the temperature values greater than 26 degrees celisus were subtracted with 26 degrees Celsius. The remaining value was then multiplied with 0,5, which gave the percentage that the air speed, at that specific location, had to be increased.

Example:

Height 1,28 m above the stove. The maximum airspeed at this level is 0,5223 m/s. The corresponding temperature to this exact location is 33,82 degrees Celsius, which is 7,82 degrees celisus above 26. The actual air speed is then calculated to:

$$\left(\frac{7{,}82\ degrees\ celsius}{100\%}\frac{0{,}5\%}{per\ degree\ celsius} * 0{,}5223\,\frac{m}{s}\right) + 0{,}5223\,\frac{m}{s} = 0{,}543\,\frac{m}{s} \quad (22)$$

The airspeed increases by 0,021 m/s after the temperature compensation.

8. Results

The results will be presented in this chapter. The complementary analysis and discussion of the results will be presented in chapter (9).

The temperature and air speed results from the measurement of one arbitrary height will be will be presented first to show the characteristics of the plume. The results will be compared with the equations from chapter (7), where the height above the point source is taken from the theory of the minimum and maximum case. Further, cross sectional Gaussian temperature and air speed distribution will be shown for all heights.

8.1 Error of the results

The plume did not rise straight up with the stove at its centre, but it was “bending over” to one side. Therefore, the measured temperatures and air speeds directly above the stove (x = 0, y = 0), were not the maximum values. A simplification has been made were the plume has been “bent”, so that the plume looks like an ideal plume that is rising with the stove at its centre. The remaining report often uses maximum values from the measurements, and treats them as they were in the centre, exactly above the stove. The natural bending of the plume, which happened in the experiment, affects the results to some degree, and will be discussed further in chapter (9). The bending however will not ruin the main goal of the measurement campaign.

Temperature sensors 1 and 3 showed bad results. As soon as the temperature reached above 27 degrees, they measured less than the actual temperature. If their data is needed further in the report at their given location, for example to make Gaussian curves, their values are estimated from the values around these sensors. A clear deviation can be noticed in figure (18), where sensors 1 and 3 are located at x = -40 and x = -30 cm.

8.2 Temperature distribution

-90	-85	-80	-75	-70	-65	-60	-55	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15
-85	0,98662	0,15376	1,81733	2,5851	2,17671	1,68543	1,78333	2,08452	1,9559	0,79724	0,74785	1,59876	2,064	3,10933	0,67155	0,59755	1,13297	0,17894	2,1795	1,14586	1,73623
-80																					
-75	1,09288	0,48475	1,9085	1,65056	1,05475	0,73437	0,928	1,03038	0,77937	1,08361	2,21865	1,84151	3,14094	3,98461	2,22278	2,21708	2,1332	1,40459	2,32452	0,6689	1,66
-70																					
-65	1,14275	0,7275	2,02238	3,26869	2,43269	2,24144	2,51219	2,54931	2,193	1,19575	2,14156	1,849	3,20438	3,81144	2,06381	1,89494	1,78	0,96519	2,61862	2,37792	1,91177
-60																					
-55	1,26061	0,93078	2,08961	2,96	2,398	2,161	2,39539	2,82617	2,32467	1,74429	4,07247	2,327	4,90029	5,70918	4,81218	4,68182	4,43865	3,34418	2,76914	2,049	1,7832
-50																					
-45	1,29821	1,09707	2,13686	3,5325	3,20121	3,39879	4,26386	4,97757	5,04693	2,45846	6,23488	2,96865	6,89996	7,18658	6,60046	6,16185	5,88892	4,52458	3,14708	3,49615	2,02023
-40																					
-35	1,46619	2,00588	2,33931	5,03469	5,56337	6,484	7,08281	8,00563	7,47244	4,385	9,58505	4,0865	10,2988	10,6165	10,2436	9,53941	8,99018	6,78095	3,0394	4,2962	1,88067
-30																					
-25	1,57491	2,11983	2,21661	4,89422	5,70583	7,13165	8,61096	10,0807	10,6913	6,1264	12,635	5,14055	12,0119	10,8031	9,47685	8,41275	7,71835	6,07375	2,997	4,09669	1,71094
-20																					
-15	1,62014	2,22281	2,13938	4,75262	5,23852	6,45148	7,51433	8,71357	9,29386	6,81553	11,2245	5,76413	11,6427	11,2337	9,85513	8,46927	7,38853	5,10353	2,74216	3,93321	1,51953
-10																					
-5	1,57557	2,04862	1,92814	3,57229	3,17324	4,41771	5,59052	6,5731	7,36952	6,72769	8,34815	5,92723	8,44115	7,66038	6,22915	4,85946	4,36754	2,69938	2,16683	3,22344	1,2305
0																					
5	1,77453	2,84147	1,87993	4,6097	4,94757	5,1274	5,53153	6,0556	6,04313	6,29541	6,42009	5,91991	7,195	6,242	5,00182	4,30873	3,64414	2,07568	1,75975	2,17444	1,01906
10																					
15	1,69907	3,7685	1,712	4,71129	5,3805	4,65586	4,77571	5,0465	4,90964	5,85571	4,83041	5,61729	5,49794	4,52571	3,45871	2,76441	2,21724	0,75488	1,25711	0,04079	0,65284
20																					
25	1,26665	1,90848	1,39578	3,90122	4,08178	3,95722	3,96726	4,18065	3,663	5,42136	4,55164	5,30293	4,865	3,55464	2,37943	1,66471	1,22021	0,0105	1,1664	-0,0731	0,6956
30																					
35	1,19459	1,42582	1,22265	2,65	2,576	2,51953	2,67182	2,86676	2,23271	4,80489	2,38261	4,64711	2,42856	1,29222	0,36372	0,10678	0,17161	-0,4054	1,22562	-0,2342	0,71369
40																					
45	1,18907	1,29011	1,16711	2,116	2,00464	1,22582	1,103	1,08643	0,43421	4,16713	0,62053	4,07993	1,06967	0,35507	-0,029	-0,1055	0,08527	-0,4304	1,30025	-0,2143	0,75869
50																					
55	1,04127	0,3772	1,04593	1,29633	1,29927	0,44713	0,39367	0,2248	-0,275	3,5007	-0,1317	3,31141	0,60011	0,74205	-0,0844	-0,1338	0,03946	-0,4525	1,40461	-0,172	0,83122

Figure 18: Colorization of temperature values, x-y-plane

A simple colorization of the values has been done in excel, to show how the temperature field spreads in the x-y-plane. The figure shows results from height 1,28 m above the stove and 2,48 m above the ground. The ambient temperature is 22,6 degrees, whereas the maximum temperature at this height is 12,6 + 22,6 = 35,2, located at coordinate x = -0,35m and y = -0,25m. The dark area represents the centre in the two dimensional plane, meaning the plumes centre has bent over to the coordinate x = -0,35m and y = -0,25m.

8.3 Air speed distribution

-90	-85	-80	-75	-70	-65	-60	-55	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15
-85	0,1364	0,16364	0,10837	0,15521	0,18986	0,24212	0,31116	0,35332	0,33158	0,19141	0,19435	0,13417	0,18981	0,17798	0,183	0,20426	0,19478	0,17763	0,21272	0,1812	0,10456
-80																					
-75	0,13331	0,15376	0,12115	0,19342	0,20941	0,2316	0,2428	0,25906	0,24833	0,2469	0,25223	0,22085	0,25719	0,2243	0,24277	0,30491	0,28591	0,21296	0,14975	0,12409	0,03046
-70																					
-65	0,15739	0,18663	0,16212	0,2091	0,23105	0,28109	0,29601	0,33003	0,32061	0,25024	0,25436	0,22308	0,26071	0,23112	0,23842	0,281	0,24915	0,21107	0,27181	0,24145	0,15826
-60																					
-55	0,16073	0,18538	0,16314	0,22031	0,2292	0,27808	0,28074	0,29901	0,32972	0,35348	0,34118	0,34044	0,35133	0,29493	0,34687	0,37272	0,34984	0,30575	0,23628	0,20575	0,13334
-50																					
-45	0,15167	0,20409	0,19115	0,25176	0,2782	0,35461	0,37168	0,37575	0,42227	0,38682	0,3672	0,38119	0,36413	0,30661	0,37588	0,40101	0,39534	0,33996	0,35358	0,31956	0,20558
-40																					
-35	0,22117	0,26737	0,28273	0,34322	0,33562	0,44022	0,42585	0,45102	0,46437	0,47896	0,4246	0,45184	0,40276	0,31874	0,4241	0,40978	0,38523	0,37245	0,35266	0,30182	0,22292
-30																					
-25	0,25844	0,29414	0,29548	0,34627	0,3565	0,46574	0,46878	0,4823	0,51379	0,52078	0,42885	0,49589	0,42237	0,35842	0,45827	0,43054	0,40126	0,4013	0,35426	0,2827	0,1855
-20																					
-15	0,25202	0,27289	0,2716	0,32446	0,33052	0,43673	0,44	0,45868	0,49044	0,52274	0,45893	0,51273	0,42484	0,33953	0,44967	0,39724	0,37291	0,34284	0,34053	0,25913	0,15971
-10																					
-5	0,26871	0,29334	0,29107	0,30791	0,29555	0,37878	0,41818	0,45582	0,49221	0,49782	0,45312	0,47611	0,41317	0,36276	0,43762	0,3859	0,35558	0,32487	0,30603	0,25325	0,1545
0																					
5	0,30241	0,31506	0,32593	0,34245	0,30611	0,38925	0,38312	0,39405	0,39857	0,48957	0,45636	0,47465	0,41973	0,34622	0,35305	0,34897	0,31117	0,24314	0,24823	0,19806	0,09821
10																					
15	0,32714	0,33214	0,35196	0,37212	0,3085	0,38525	0,40528	0,40945	0,38894	0,43668	0,42333	0,42331	0,38611	0,33664	0,34818	0,34903	0,30207	0,22207	0,13322	0,12721	0,03671
20																					
25	0,19566	0,23364	0,24061	0,28235	0,26684	0,33015	0,33741	0,33963	0,3042	0,36811	0,35936	0,3225	0,29134	0,24278	0,23891	0,26159	0,21416	0,15257	0,1157	0,12024	0,03554
30																					
35	0,14895	0,18067	0,16225	0,21561	0,2044	0,22463	0,28681	0,28904	0,21117	0,24172	0,23872	0,1579	0,20838	0,19628	0,19281	0,20966	0,17437	0,13448	0,12149	0,1348	0,06252
40																					
45	0,15895	0,16506	0,12935	0,17229	0,16093	0,16964	0,20963	0,2158	0,15326	0,18969	0,2047	0,13529	0,20358	0,19809	0,19678	0,23539	0,20394	0,1524	0,10798	0,12115	0,04807
50																					
55	0,10315	0,12407	0,04673	0,12482	0,12906	0,12781	0,16166	0,15384	0,10659	0,15871	0,1751	0,10927	0,16298	0,17161	0,15919	0,19072	0,17976	0,13881	0,0943	0,10847	0,00233
60																					
65	0,10518	0,11878	0,04257	0,10921	0,11904	0,11298	0,13874	0,14446	0,10953	0,13241	0,15128	0,08781	0,13481	0,15144	0,13348	0,16923	0,16134	0,10838	0,10495	0,11574	0,02272
70																					
75	0,09726	0,10582	0,01296	0,1032	0,11281	0,10361	0,12911	0,12769	0,09546	0,12859	0,14572	0,07931	0,13276	0,14833	0,1392	0,18272	0,16158	0,11996	0,08656	0,10277	0,00893

Figure 19: Colorization of air speed, x-y-plane

The same has been done with the air speed at the same height as in chapter (something). The highest air speed at this height is 0,52 m/s and it is coordinates x = -40 and y = -15, which is in the same area as the maximum temperature.

8.4 Comparing with theory

Comparing results from measurement and theory will show large differences if not the height between the point source and the height in the plume is the same for both measurement and theory. This can be seen by looking at equations (17 and 18), where the temperature and air speed in plumes from heated horizontal surfaces are dependent on the height z from the point source. Since there is no exact answer to where the point source is located for the electrical stove used in the experiment, the existing theory of the minimum and maximum case are used.

8.4.1 Minimum case

As seen from chapter (6) the minimum case has its point source 0,88m below the top edge of the stove, hence minimum. The first measuring height is (0,88 + 0,28)m = 1,16m above the point source.

8.4.1.1 Temperature

Since the point source is relatively close to the first measurement height, the temperature from the theory is large at the first measuring point (1,16m).

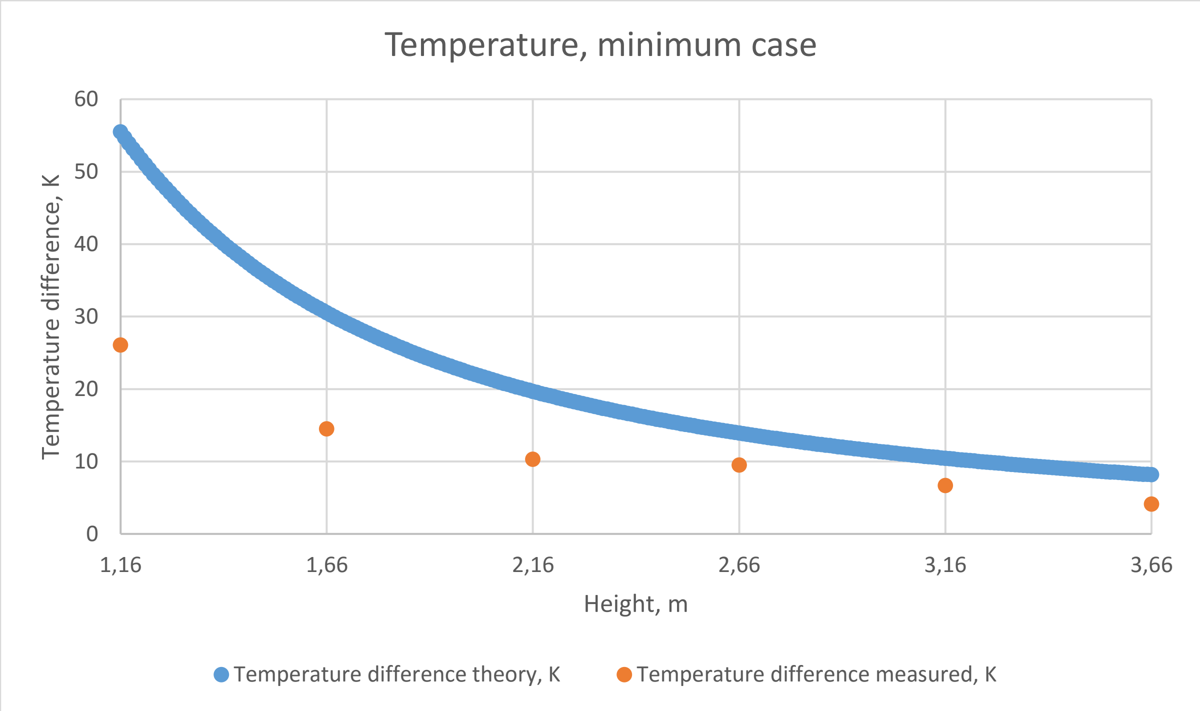

Figure 20: Temperature compared from measurement and theory, minimum case

Height above point source (m)	Temperature difference, theory, K	Temperature difference, measured, K
1,16	55,5	26,1
1,66	30,5	14,5
2,16	19,9	10,3
2,66	13,9	9,5
3,16	10,4	6,7
3,66	8,2	4,1

Table 7: Temperature from measurement and theory, minimum case

8.4.1.2 Air speed

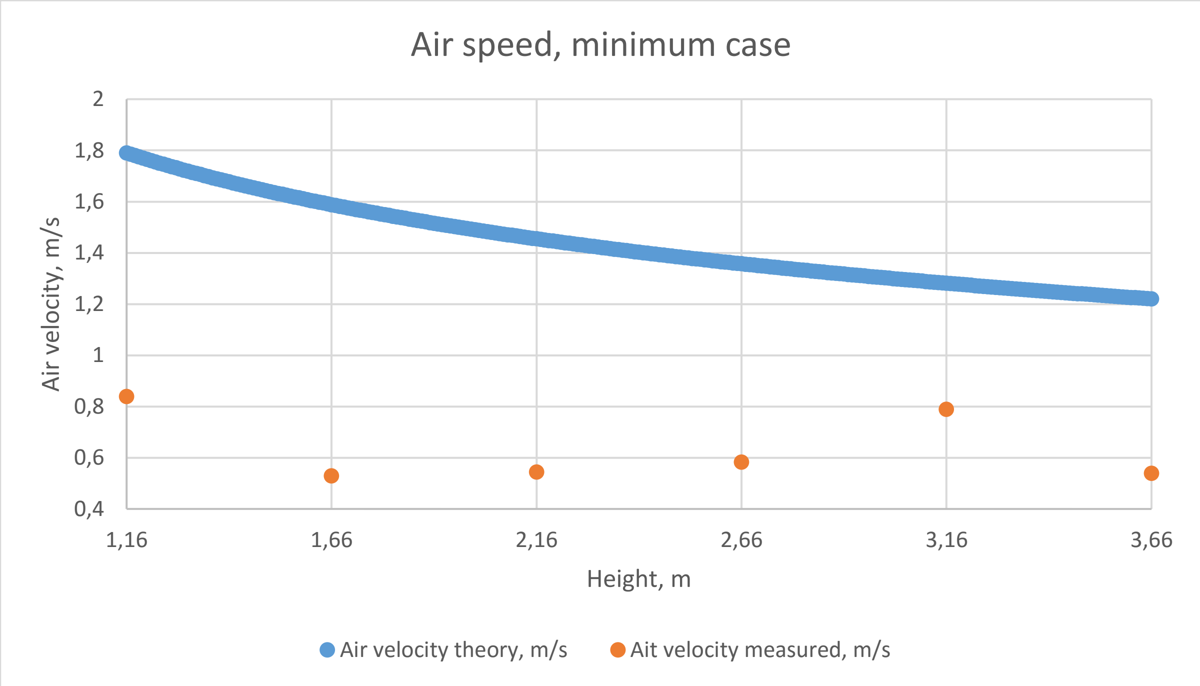

Figure 21: Air speed compared from measurement and theory, minimum case

Height above point source (m)	Air speed, theory, (m/s)	Air speed, measured, (m/s)
1,16	1,79	0,84
1,66	1,58	0,53
2,16	1,45	0,54
2,66	1,36	0,58
3,16	1,28	0,79
3,66	1,22	0,54

Table 8: Air speed from measurement and theory, minimum case

8.4.2 Maximum case

As seen from chapter (something) the maximum case has its point source 1,35m below the top edge of the stove, hence maximum. The first measuring height is (1,35 + 0,28)m = 1,63m above the point source.

8.4.2.1 Temperature

It is logical that the further the distance from the point source, the lower the temperature is measured.

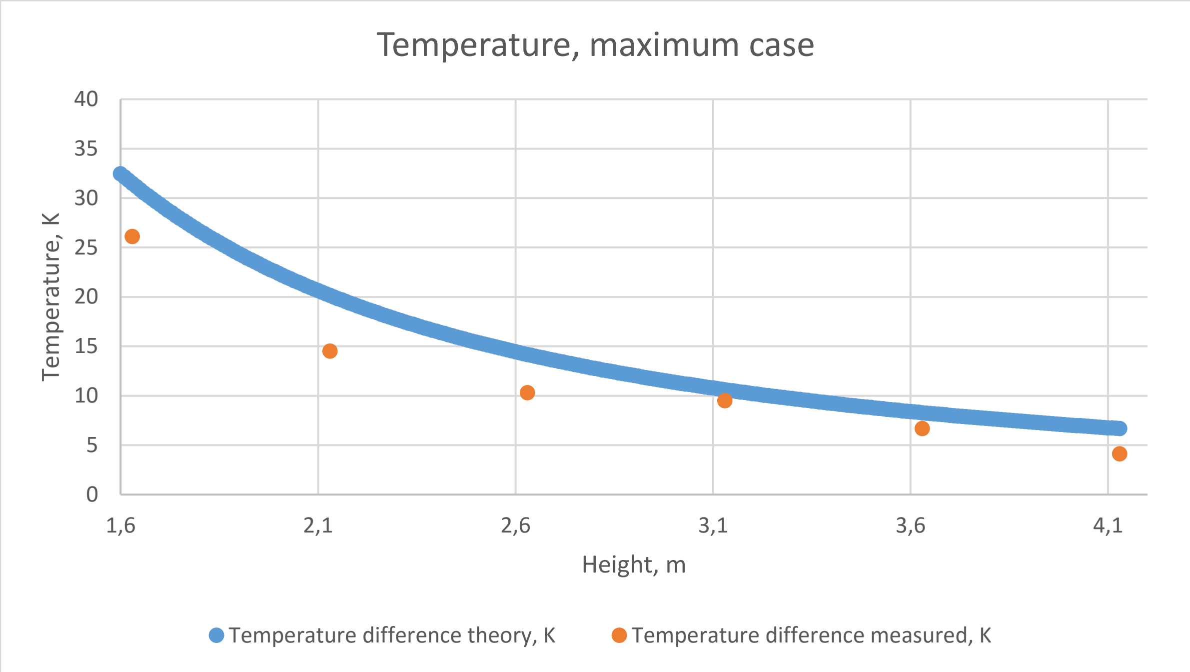

Figure 22: Temperature compared from measurement and theory, maximum case

Height above point source (m)	Temperature difference, theory, K	Temperature difference, measured, K
1,63	31,5	26,1
2,13	20,2	14,5
2,63	14,2	10,3
3,13	10,6	9,5
3,63	8,3	6,7
4,13	6,7	4,1

Table 9: Temperature from measurement and theory, maximum case

8.4.2.2 Air speed

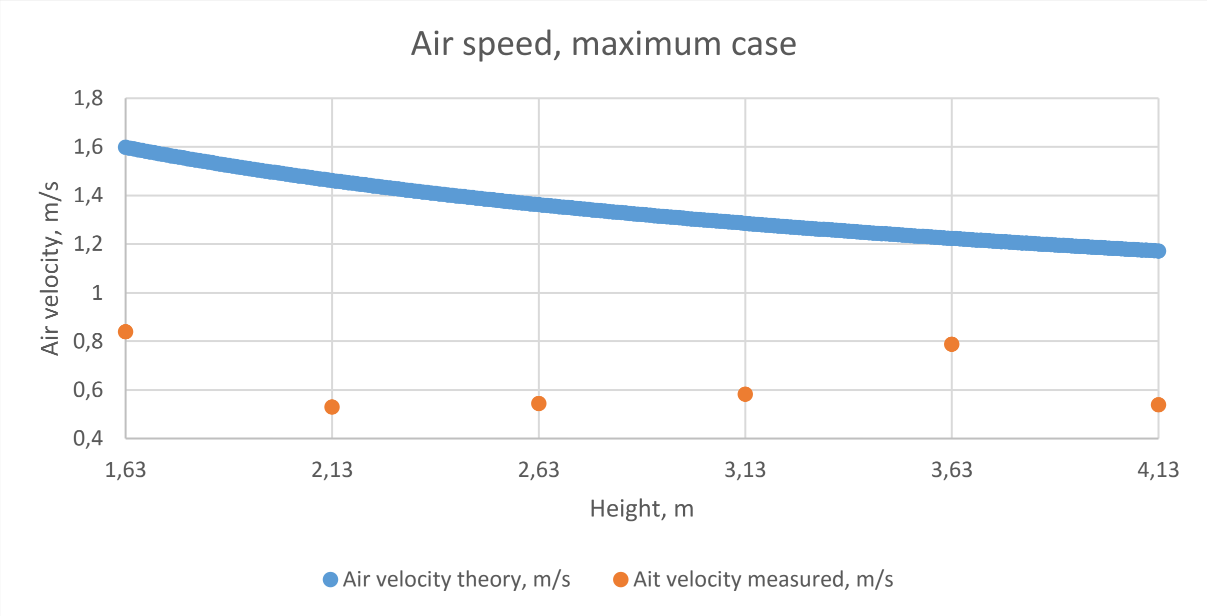

Figure 23: Air speed compared from measurement and theory, maximum case

Height above point source (m)	Air speed, theory, (m/s)	Air speed, measured, (m/s)
1,63	1,60	0,84
2,13	1,46	0,53
2,63	1,36	0,54
3,13	1,29	0,58
3,63	1,22	0,79
4,13	1,17	0,54

Table 10: Air speed from measurement and theory, maximum case

8.5 Gaussian approximations of temperature and air speed cross-sectional distribution

The figures below shows the measured temperature and air speeds in relevance to their location, for all heights. By inspecting the values plotted in the diagrams, one can see that they have similarities with a Gaussian curve, as expected. A Gaussian curve has been made to fit the points for all heights illustrated below. In some of the cases, the curve does not fit very well. For almost all heights the maximum value is at x =0. By looking at the values in context with the other values close by, the expected value (top of the curve) is not always at the same location as the maximum measured value, as seen in figure (24).

8.5.1 Temperature and air speeds at all heights

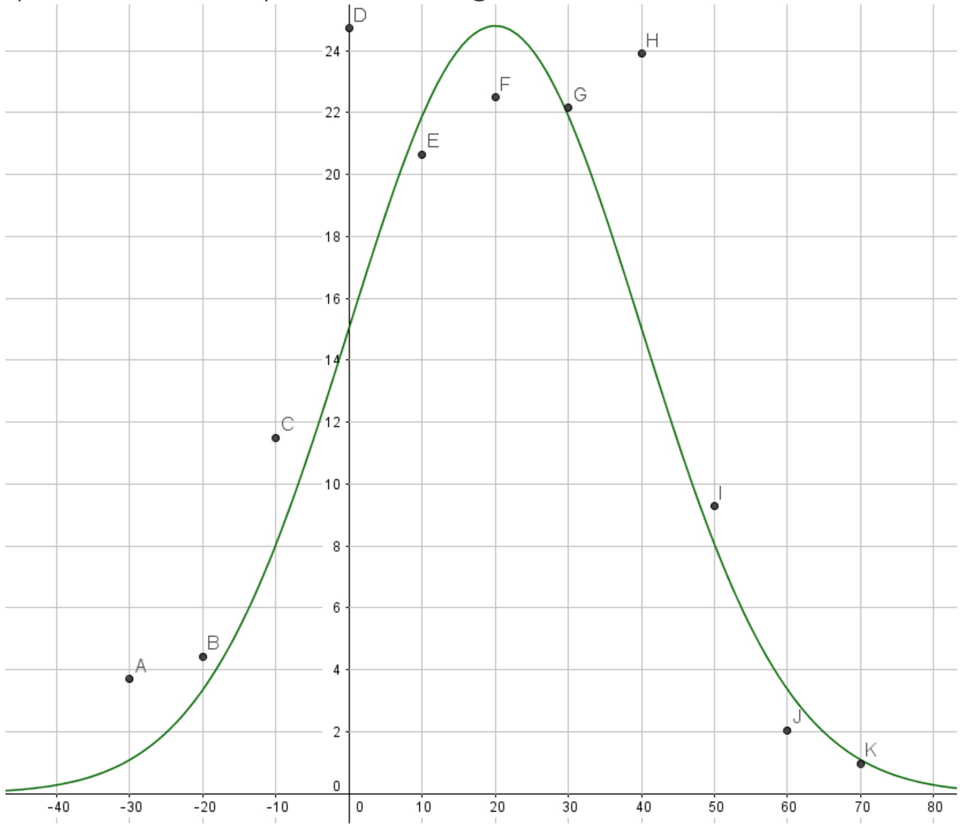

Figure 24: Measured temperature at 1,48 m above ground

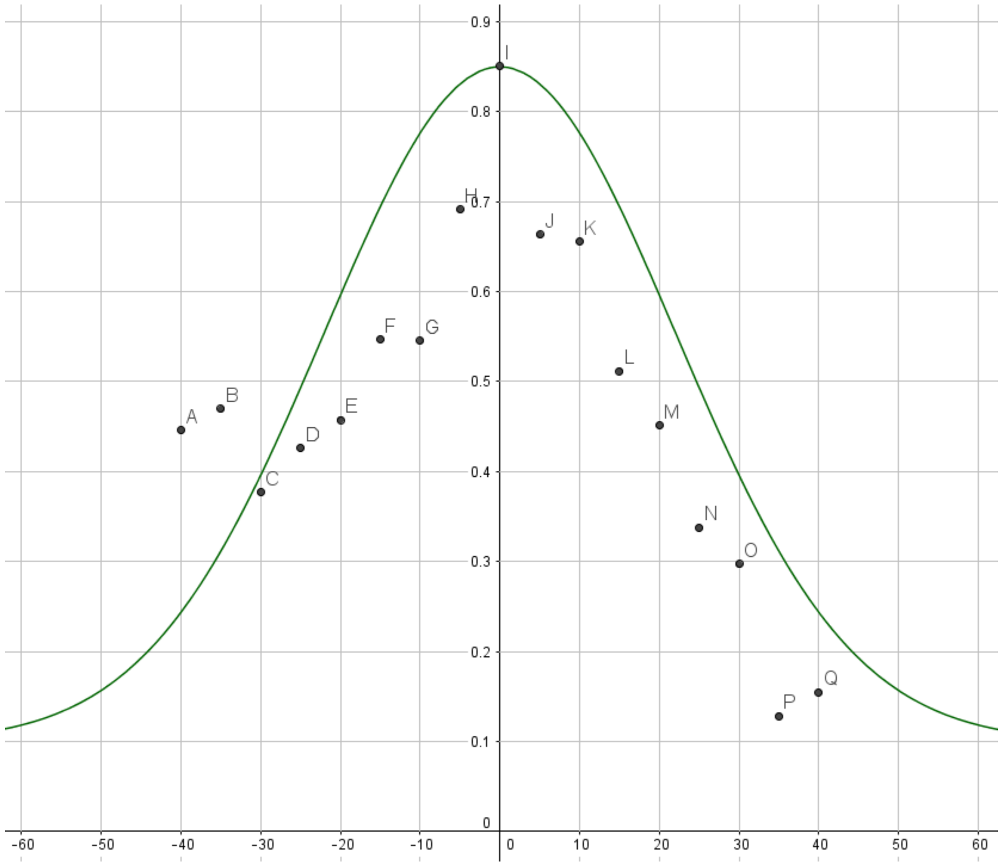

Figure 25: Measured air speed at 1,48m above ground

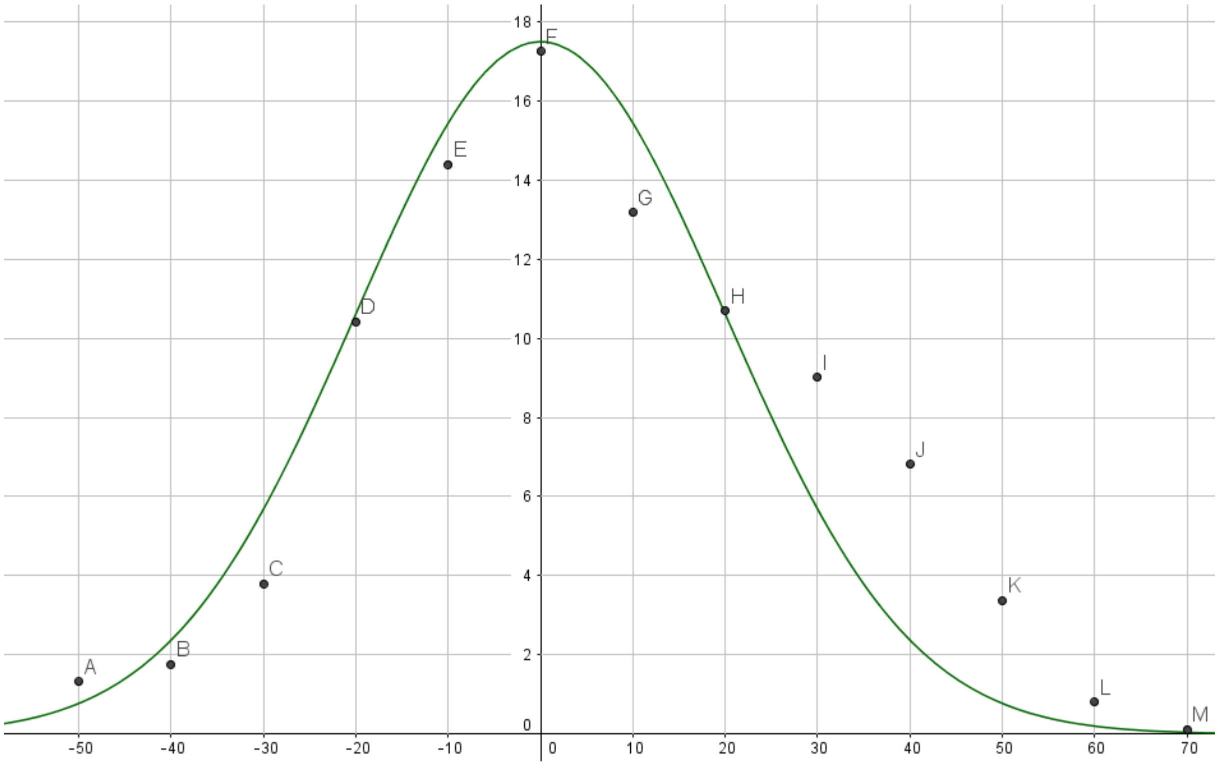

Figure 26: Measured temperature at 1,98m above ground

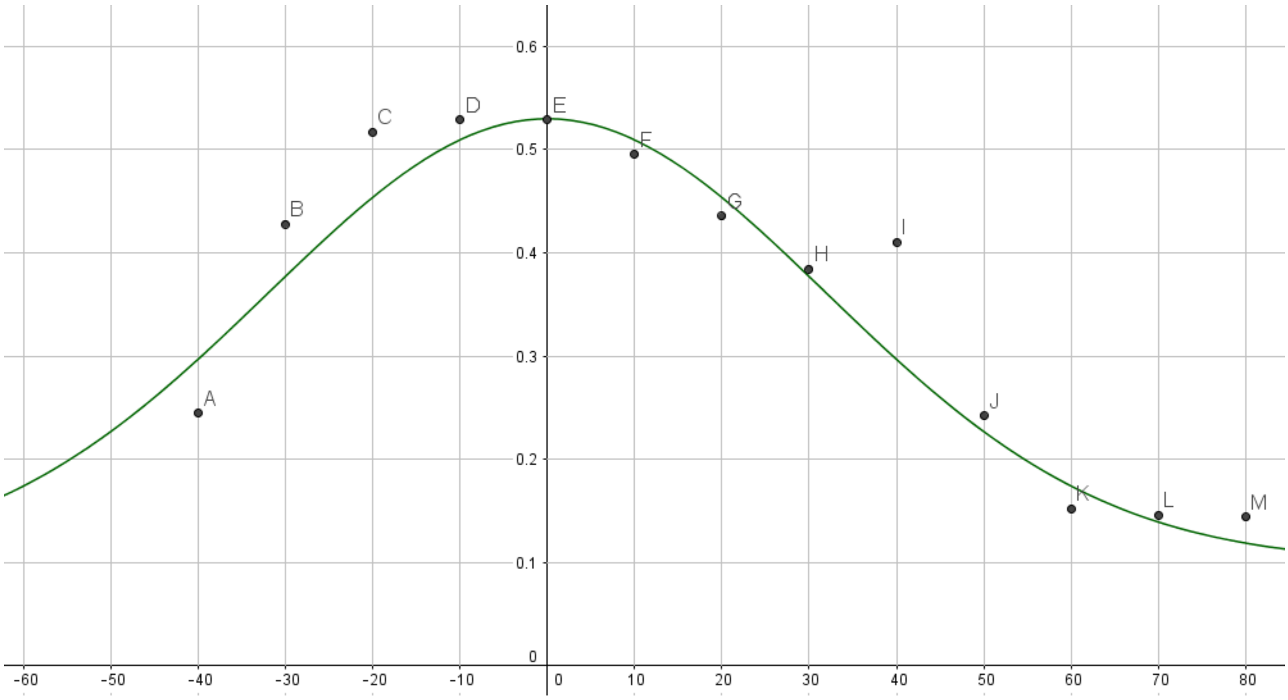

Figure 27: Measured air speed at 1,98m above ground

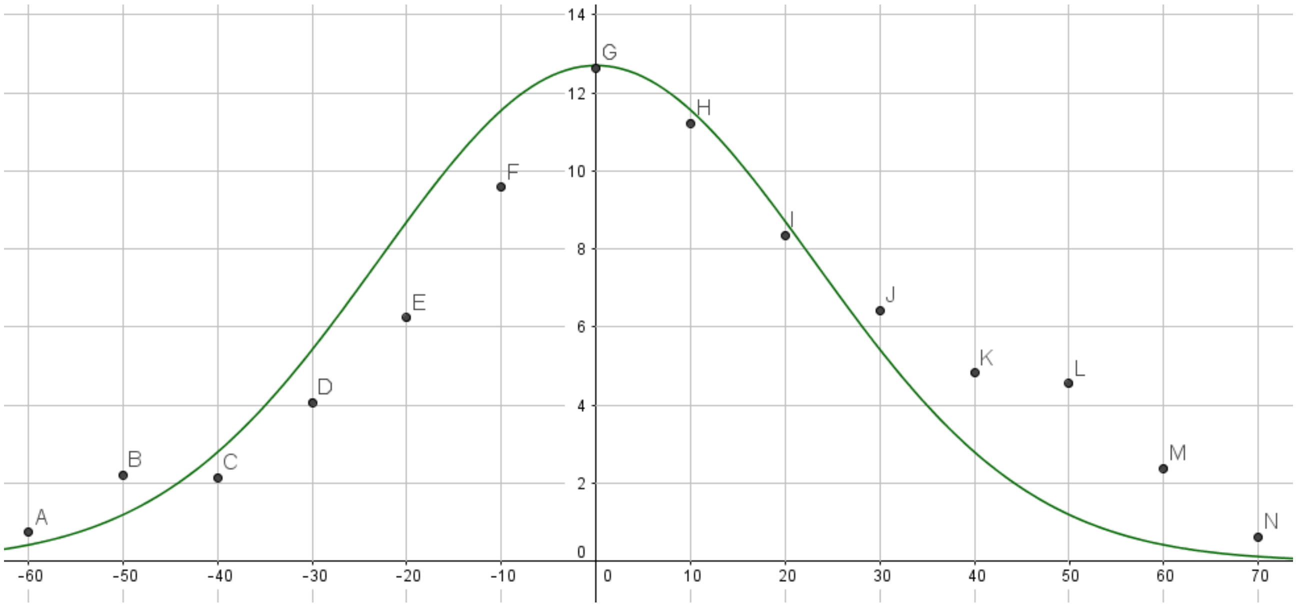

Figure 28: Measured temperature at 2,48 m above ground

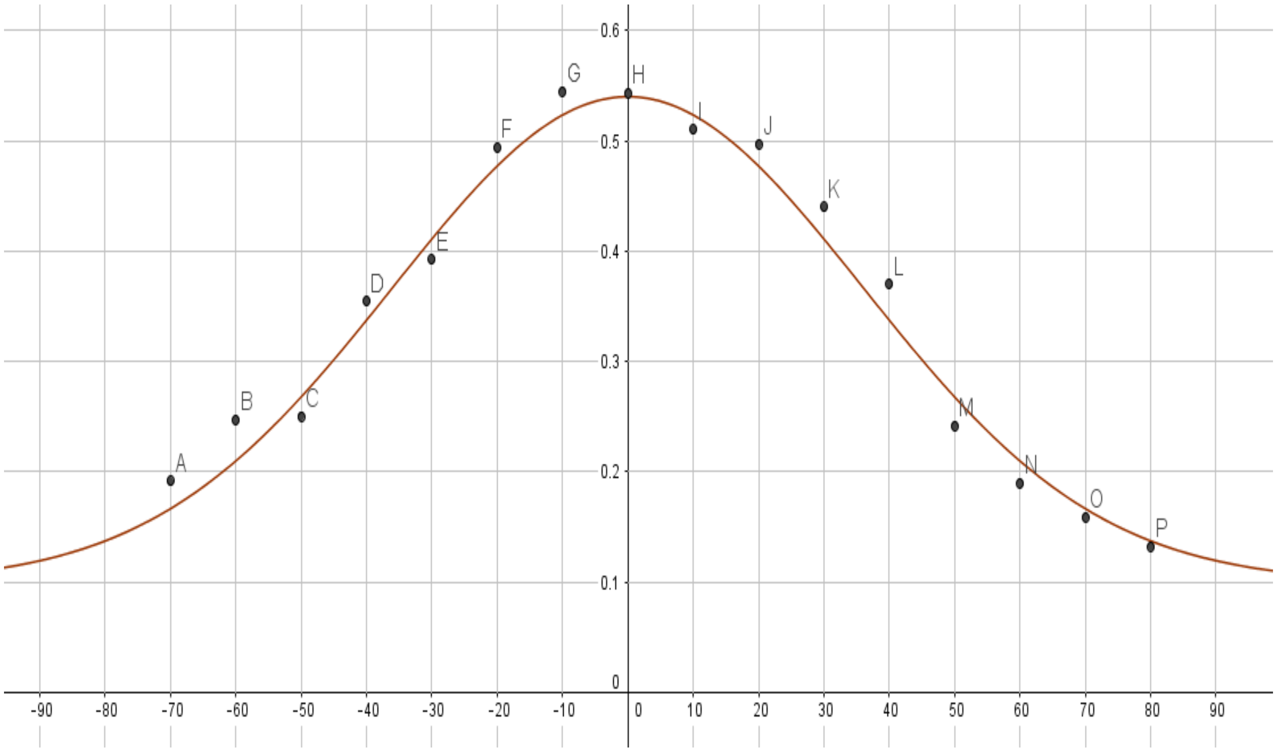

Figure 29: Measured ir speed at 2,48 m above ground

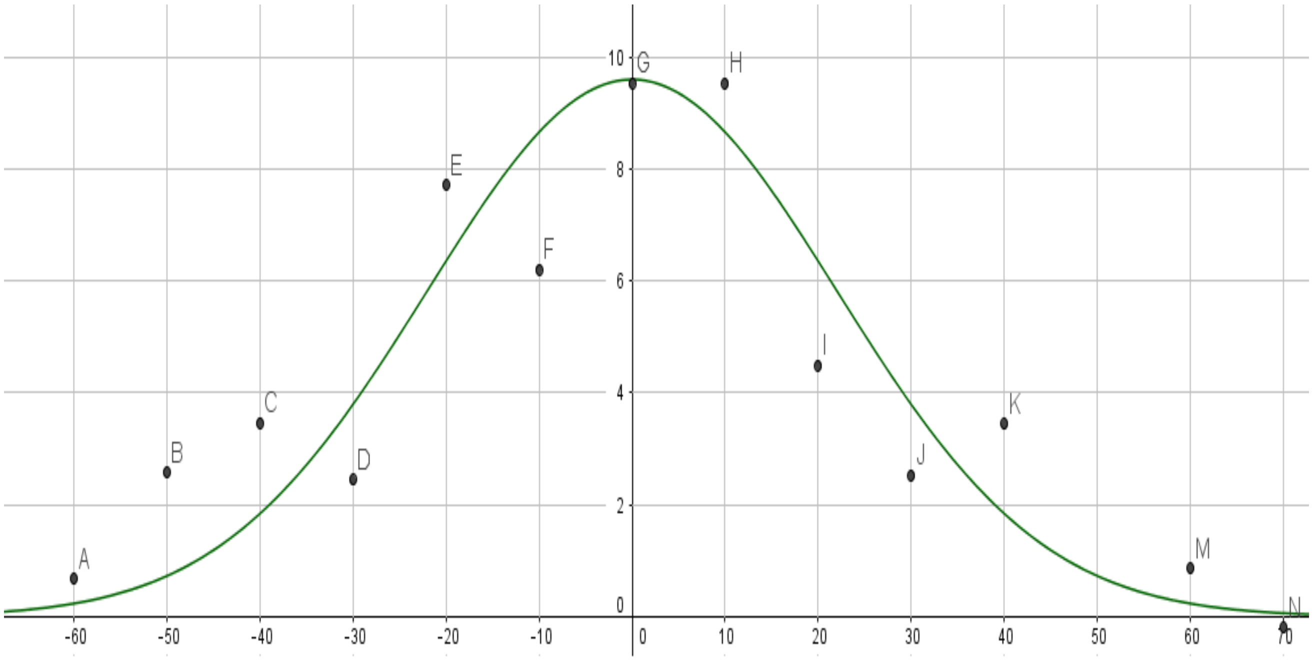

Figure 30: Measured temperature at 2,98m above ground

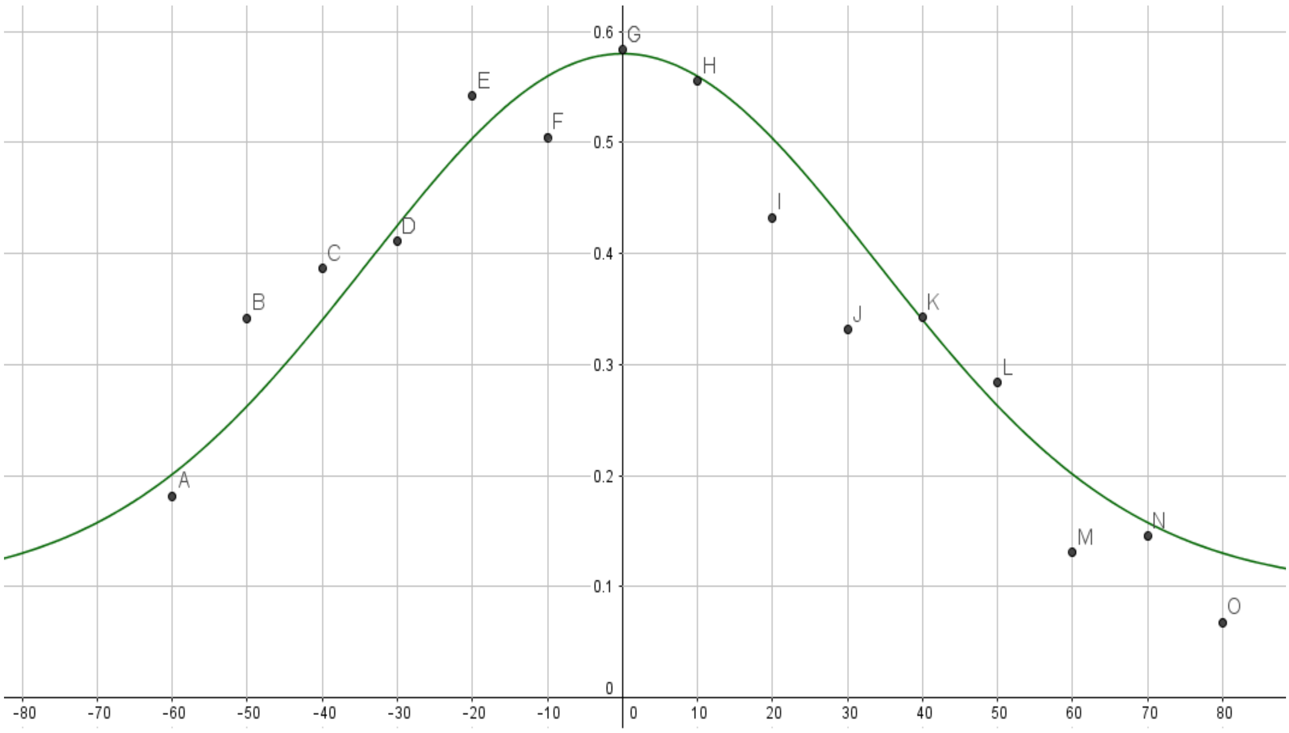

Figure 31: Measured air speed at 2,98 m above ground

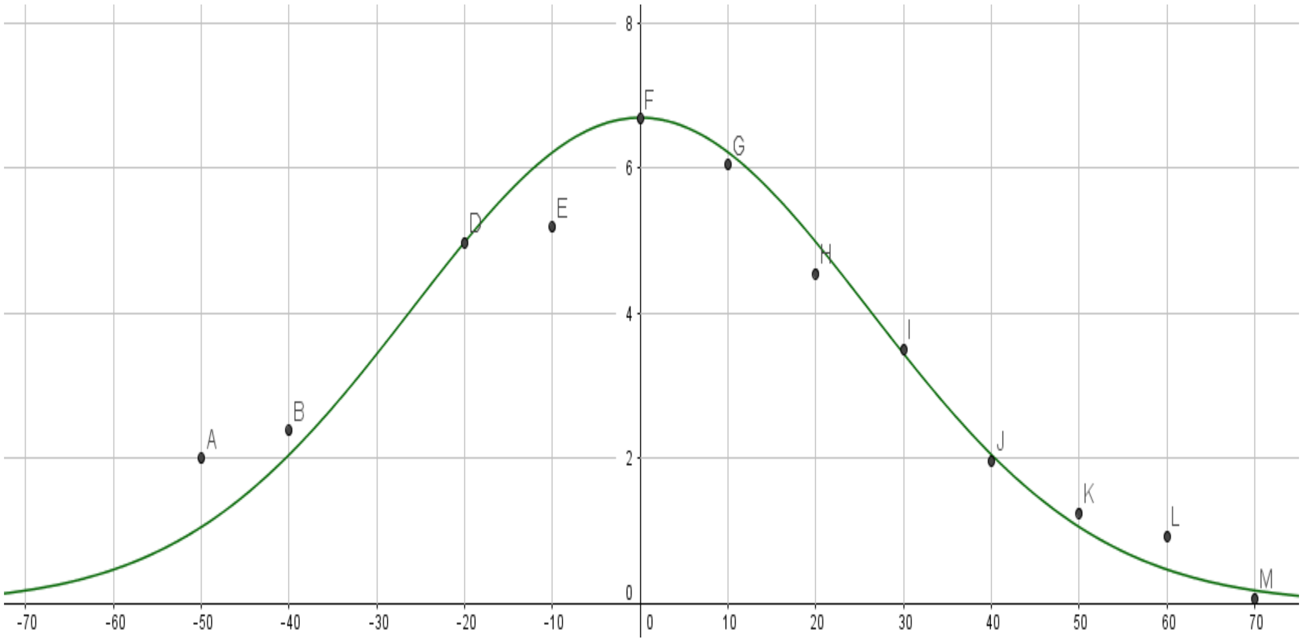

Figure 32: Measured temperature at 3,48 m above ground

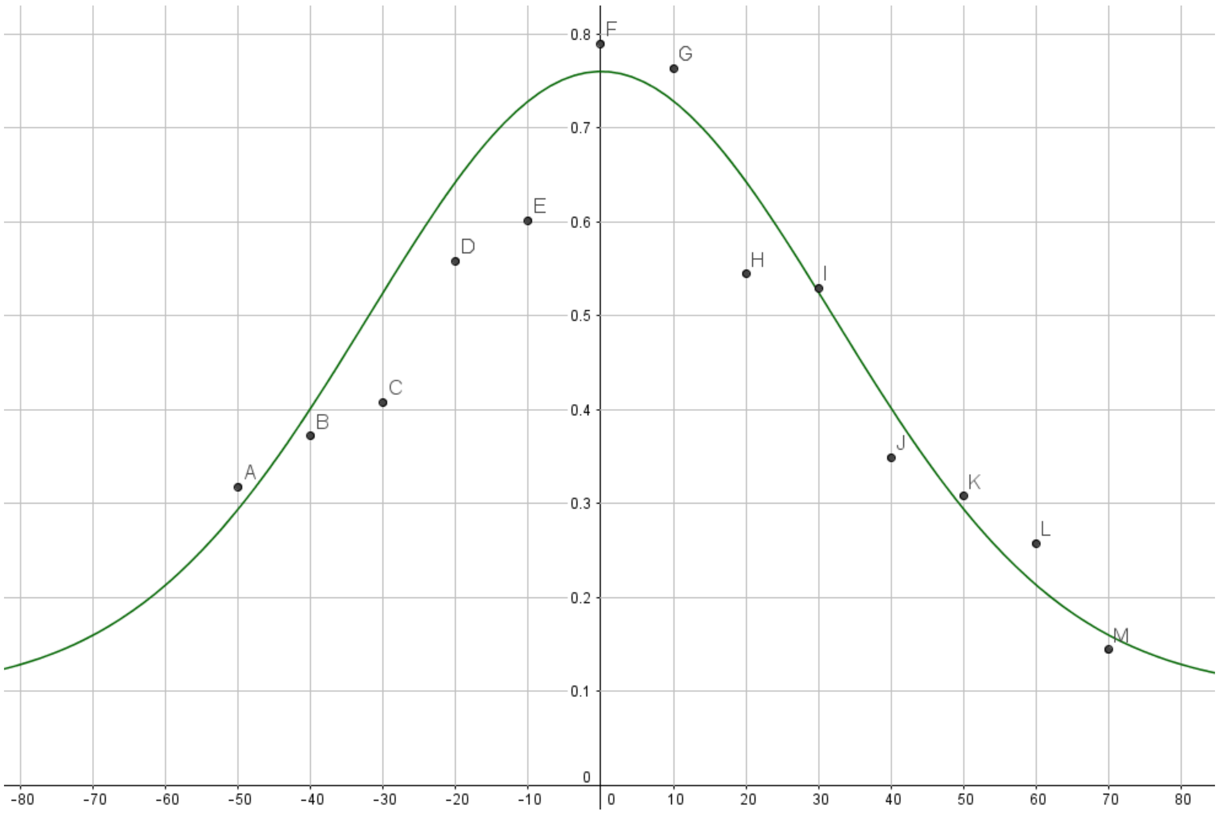

Figure 33: Measured air speed at 3,48 m above ground

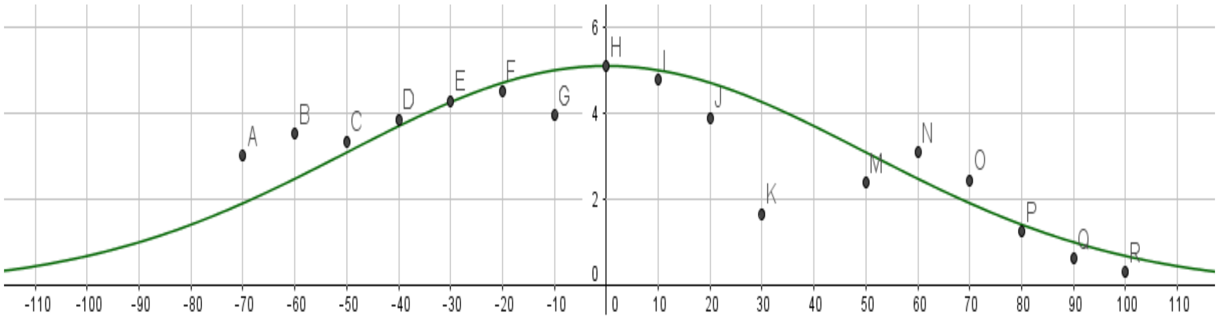

Figure 34: Measured temperature at 3,98 m above ground

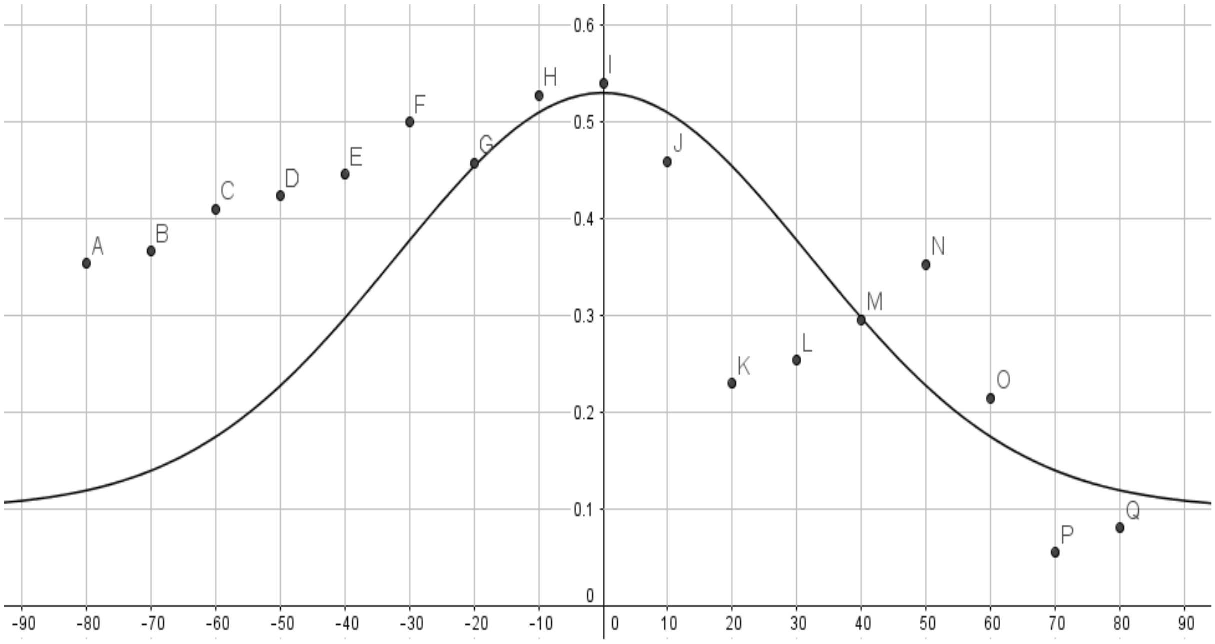

Figure 35: Measured air speed at 3,98 m above ground

The Gaussian curves have been put together for all heights to investigate the correlation between them in figure (36 and 37). The distances between key points in the x and y direction have the correct relation relative to each other, meaning; the width of the curves are in relation with the width of the stove. The height between the stove and the first measured values are in relation to the height between the measurements. The maximum value are labelled in the figures, as well as the measurement heights.

The cross sectional temperature and air speed distribution are plotted in GeoGebra, taking the maximum value at x = 0. The values on the x-axis is in cm for both figures (36 and 37). The y-axis is the temperature difference between the plume and the ambient air for figure (35), and it is the air speed for figure (36). In figure (36) the horizontal asymptote is leaning towards 0,1 m/s, and not 0. This is because the ambient air speed in the room is measured to be 0,1m/s. The temperature horizontal asymptote stretches towards 0 degrees.

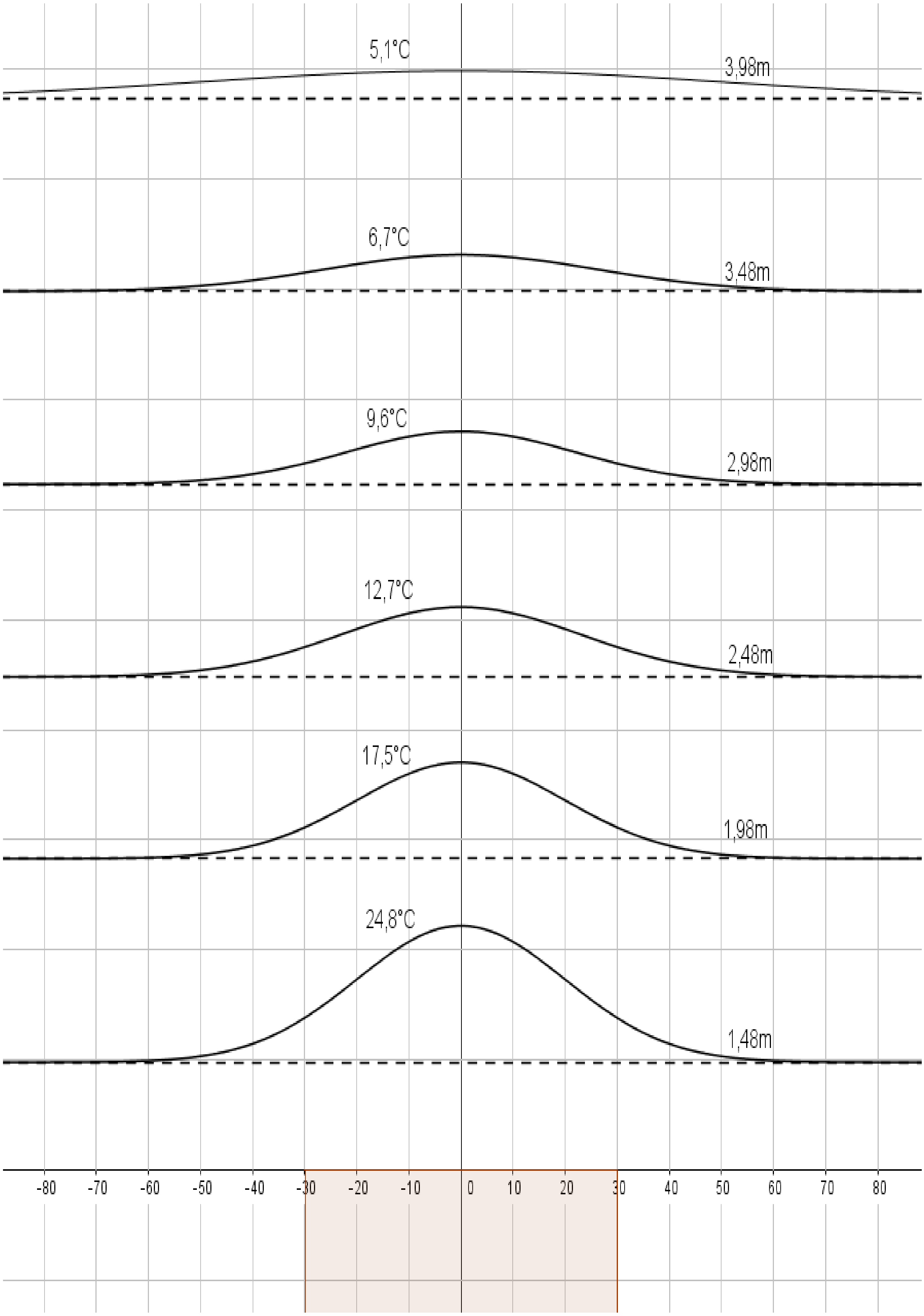

Figure 36: Gaussian curves showing temperature for all heights

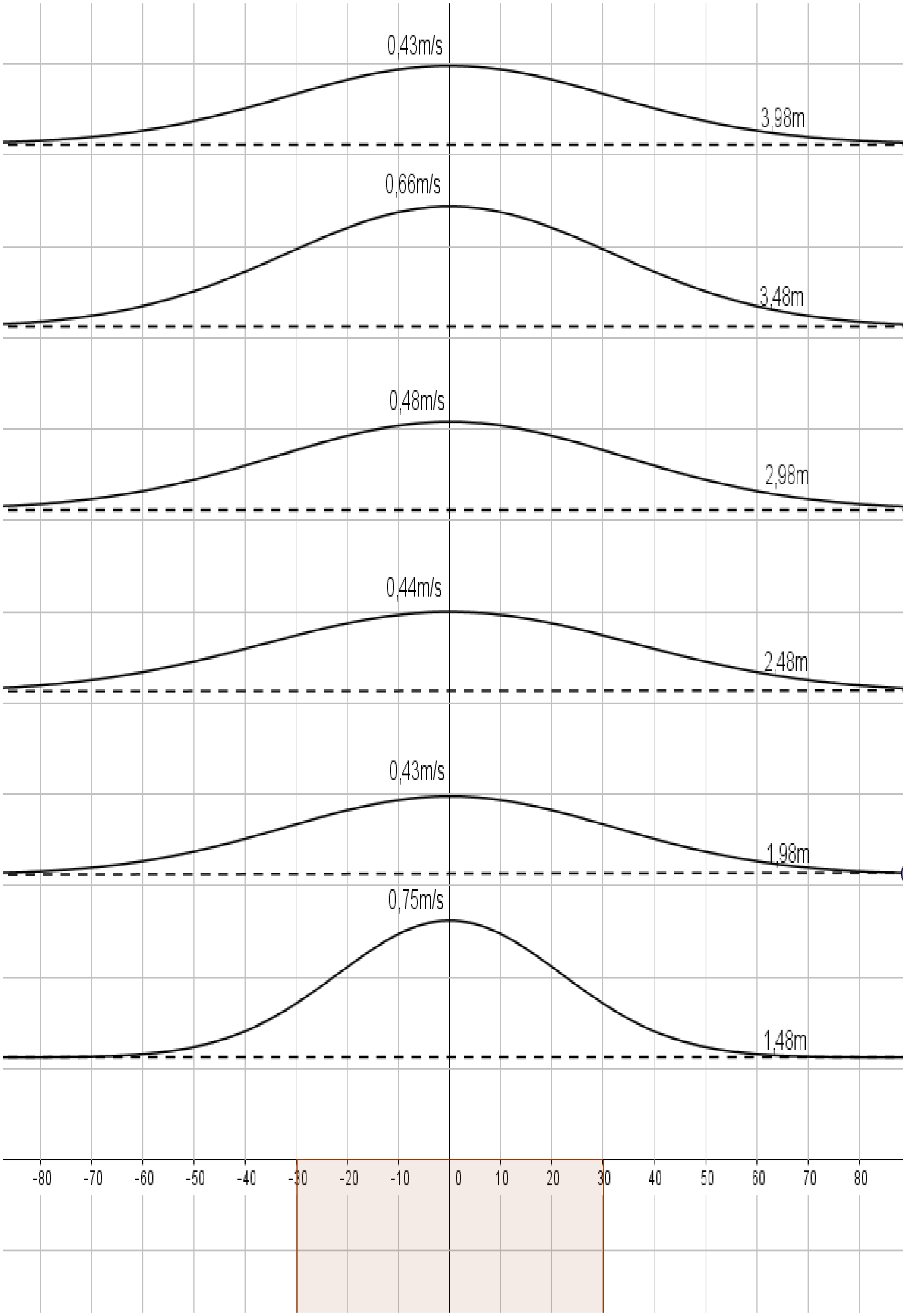

Figure 37: Gaussian curve for all measured air speed at all heights

The coefficients of the Gaussian function $f(x) = a * e^{-\frac{(x-b)^2}{2c^2}}$ for the Gaussian curves in figure (35 and 36) for temperature and air speed for all measured heights are listed in the tables below.

8.5.1 Temperature curves

Height above ground (m)	a	b	c
1,48	0,75	0	22
1,98	0,43	0	32
2,48	0,43	0	36
2,98	0,48	0	34
3,48	0,66	0	32
3,98	0,43	0	32

Tabell 11: Temperature coefficients

8.5.2 Air speed curves

Height above ground (m)	a	b	c
1,48	24,8	0	20
1,98	17,25	0	32
2,48	12,7	0	23
2,98	9,6	0	34
3,48	6,7	0	32
3,98	5,1	0	50

Tabell 12: Air speed coefficients

9. Discussion

9.1 Correction of the distance to the point source

The measured temperatures in the experiment are lower than what the theory suggest when using the distance from the virtual point to the measurement height as what the maximum and minimum cases suggests. Although, the curve of the values from the maximum case for temperature are very close to the theory. We notice that the curve of the theory and the measurement curves of figure (22) have similarities. In order to fit the curves together, the height used in the theory has to be changed. The equation of excess centreline temperature (18) is solved for z, the height, by putting it equal to 26,1 degrees, which is the value of the excess temperature at the first measuring height above the stove, which was 0,28m:

$$\Delta T = 0{,}329 * 3174^{\frac{2}{3}} * Z^{-\frac{5}{3}} = 26{,}1^{0}C$$

$$Z = 1{,}82m$$

The first measuring point is 1,82 m above the point source if we want the theory to match with what happened during the experiment. This means the point source is 1,82m – 0,28m = 1,54m below the stove top. That is beneath the ground floor. Since there is now a longer distance between the point source and the measuring heights (greater Z), the theory will give a lower temperature at the mentioned heights. With this change, comparison of the temperature curves yield:

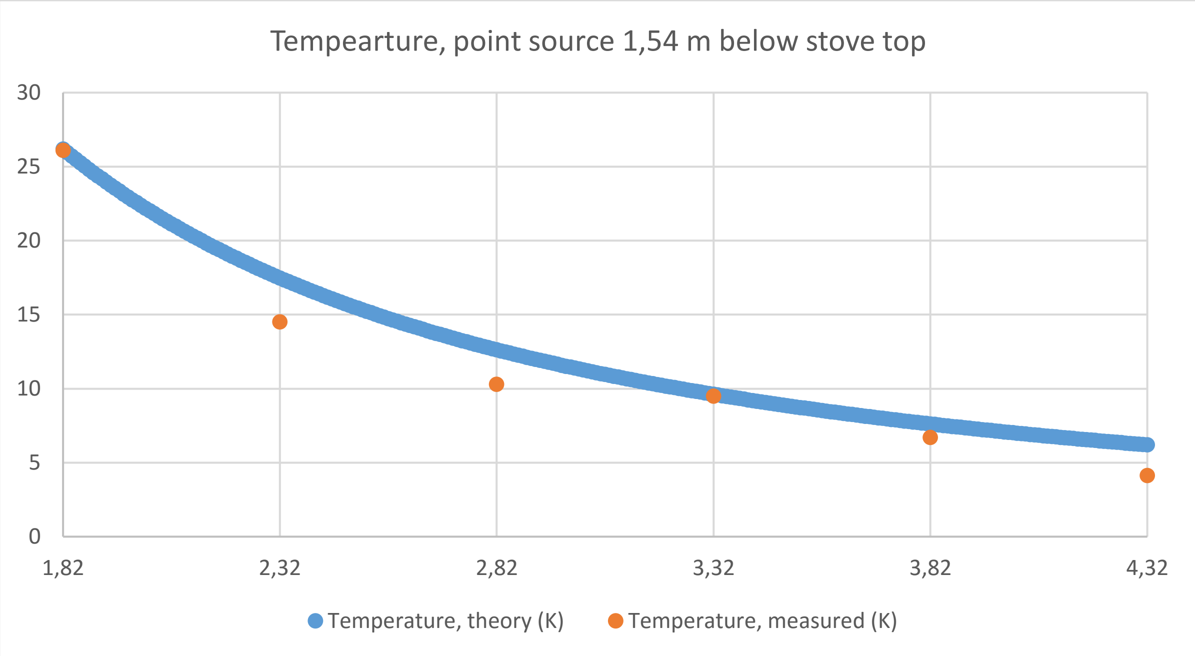

Figure 38: Comparison of theory when z is increased

The equation above (22) only considers the first measured value and makes the theory and the measurement the same. Although, the rest of the points matches the rest of the curve very nicely. This means that the centreline excess temperature equation explains the real physic of the temperature development in the plume. If only considering the temperature measurement, it could be safe to assume that the virtual point is in fact 1,54m below the stove top. But it is not that easy to make such a claim when the air speed is behaving as it is.

9.2 Bending of plume

As mentioned previously, the plume is not going straight up with the stove at its centre. Even though measurements happened at the best possible conditions at given circumstances, there was still crucial impacts on the plume from the environment in the lab. The main suspect of the "bending" of the plume is the main exhaust in the lab. It was located in a corner in the ceiling, which corner the plume was drawn to.

A thermo camera, FLIR E60, was used to look at how the plume was behaving. The material chosen in the FLIR E60 was paper, with emissivity ε = 0,8, which was a choice in the settings. The FLIR E60 has the following specifications:

Temperature range	-20 degrees to 650 degrees
Accuracy	+/- 2% of reading
Thermal sensitivity	<0,05 degrees
Video / resolution	Yes / 3,1 MP

Table 13: FLIR-60 spesifications

Since a thermo camera cannot visualize the temperature image of air, a large sheet of paper was placed in the middle of the steel frame so that the rising air would transfer heat with the paper, and the thermo camera could then create a temperature image of the flow by receiving the emissivity from the paper. The steel frame was then moved so that the stove and the paper was in the centre, cutting the stove in two rectangular parts when looking at it from above. The picture below shows how the setup is done. Thermal images were captured also when the steel frame and the paper was rotated 90 degrees, so that the plume could be studied from two angles.

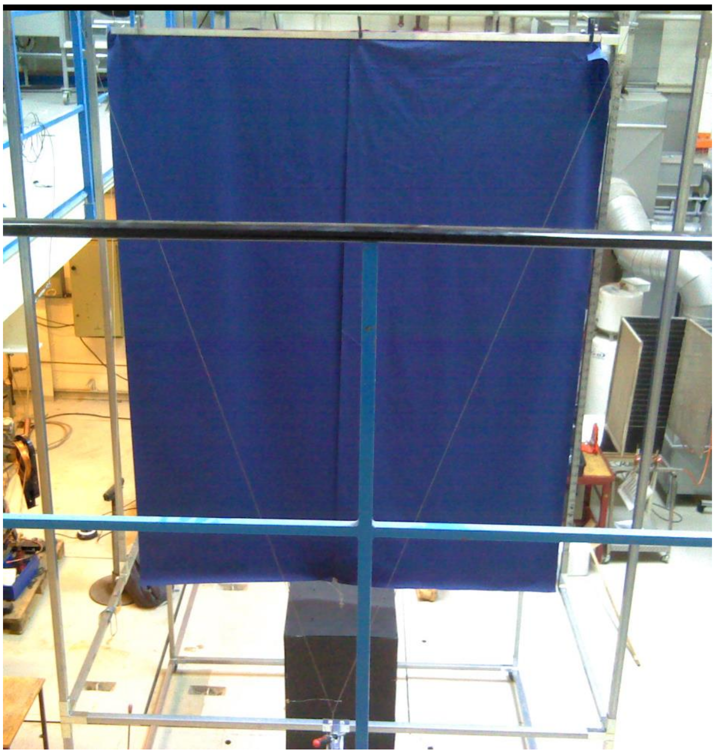

Figure 39: Setup of the rig with paper sheet

Images from the thermo camera:

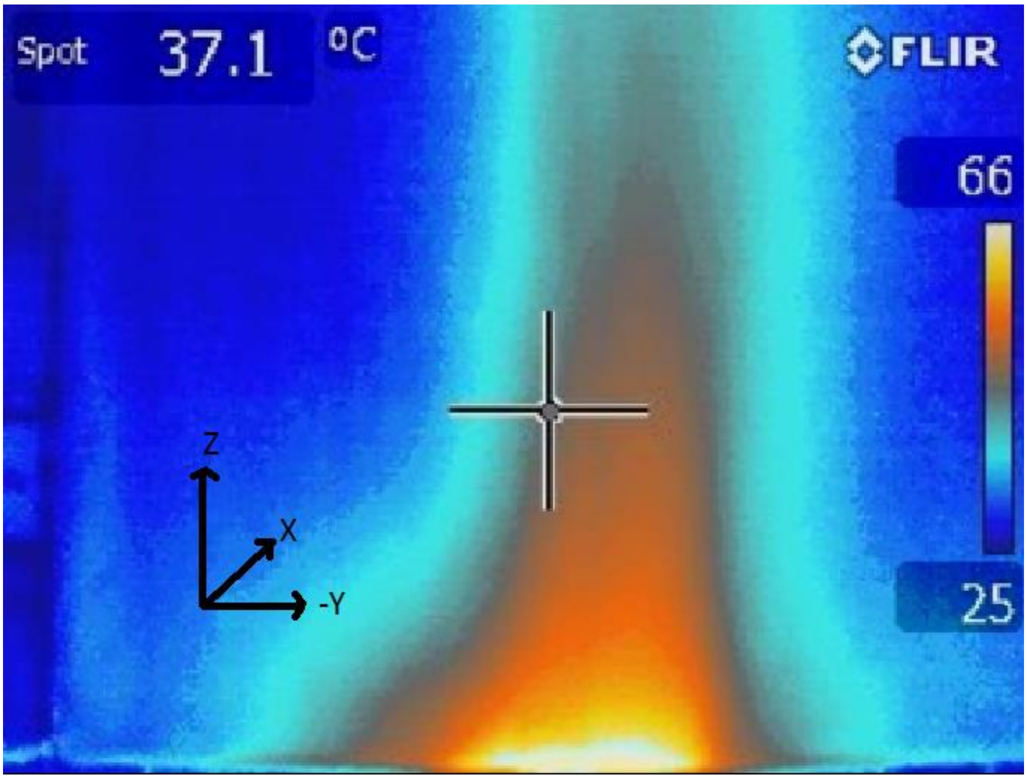

Figure 40: Thermo 1

The marker in figure (40) is pointed above the middle of the stove, y = 0 and x = 0.

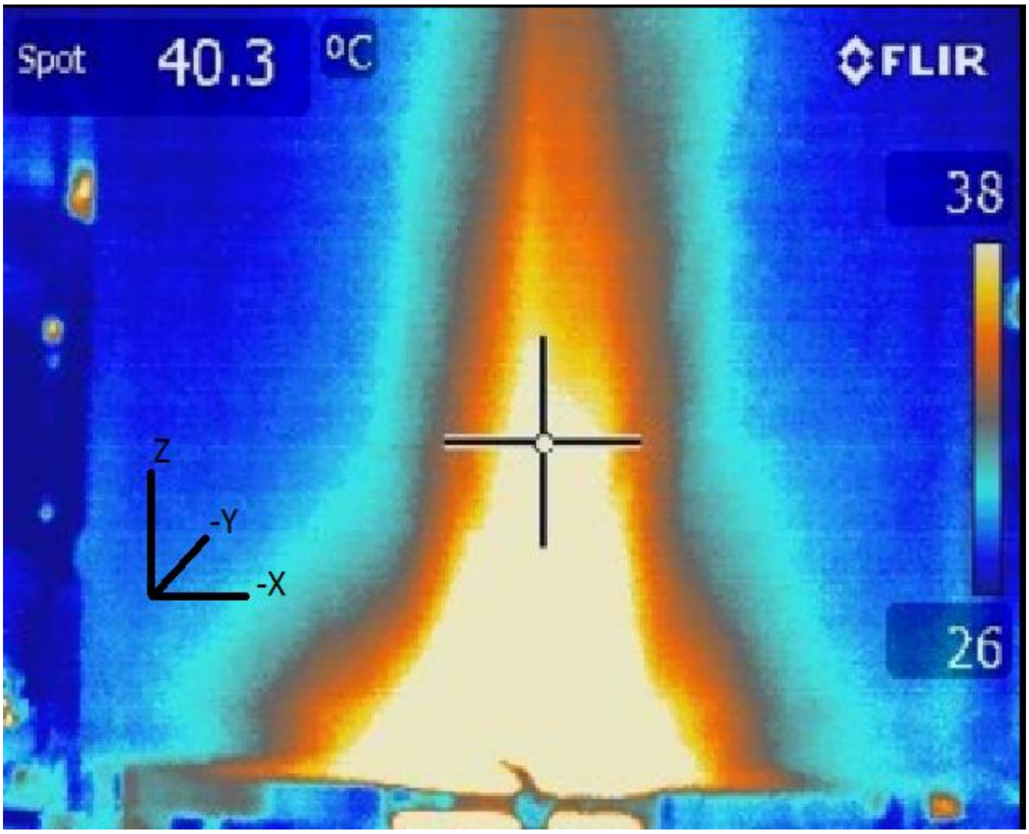

Figure 41: Thermo 2

The marker in figure (41) is pointed above the middle of the stove, y = 0 and x = 0 as well.

The coordinate systems in the pictures are oriented the same as the coordinate systems mentioned previously in the report. Figure (41) shows the plume moves to the right in the picture, along the negative y-axis. Figure (42) shows the plume move slightly to the right, along the negative x-axis. The marker in the two figures above (40 and 41) are located at z ≈ 2,0 m. The temperature measurements from that height are shown below:

-70	-65	-60	-55	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15
-65	2,35888	0,56029	1,70375	2,65142	2,59729	1,2195	1,3125	1,42808	1,00167	5,04462	1,36423	3,01938	2,10238	4,21138	0,79769	0,59046	0,17023
-60																	
-55	2,64116	0,96653	2,16237	2,88521	3,01547	1,74779	1,75579	1,927	1,50658	6,037	2,80027	4,44514	3,34832	4,86545	1,65318	1,28718	0,98868
-50																	
-45	3,0121	2,31329	3,68386	4,6931	5,463	4,05033	3,79348	3,7701	3,48	7,05588	6,25925	6,54525	6,74656	6,68675	5,38888	4,57312	3,35556
-40																	
-35	3,3237	3,26635	4,97261	8,0003	9,24465	10,0918	10,4163	10,0132	8,52	7,94137	8,11921	7,63147	9,27568	9,02321	7,37221	5,90411	5,04089
-30																	
-25	3,50868	6,16145	7,18655	11,173	13,2323	14,5262	14,3985	13,718	11,8534	8,721	12,8172	9,62146	11,795	10,2724	8,28504	6,04723	4,79412
-20																	
-15	3,22248	4,47543	5,90213	10,2977	13,2523	16,1482	17,2545	17,0007	16,3847	8,60508	14,0418	9,79138	12,0383	10,0245	7,02079	4,78896	2,99529
-10																	
-5	3,2755	3,02294	4,1575	8,12888	8,93825	11,5338	13,1795	13,959	14,0521	6,76426	13,2489	8,93995	11,0719	9,64142	6,99205	4,89984	3,52258
0																	
5	3,51141	3,49136	4,12277	6,73545	6,39836	8,56359	10,698	11,9586	12,0748	5,10821	7,07625	4,48296	4,76504	3,413	2,1485	1,54358	1,26429
10																	
15	3,65067	4,02883	4,45611	6,17583	6,22839	7,73606	9,01828	10,0022	9,91617	4,24554	6,60207	3,91449	4,4709	3,17034	1,78966	1,18256	0,85905
20																	
25	3,71479	5,50793	5,05786	6,73029	7,30514	7,03793	6,81129	6,38593	4,85229	3,00042	2,62008	1,85412	1,23388	0,68442	0,06588	-0,004	0,19196
30																	
35	3,46604	4,75913	4,42074	5,32396	5,16309	4,27048	3,36552	2,34604	1,08965	2,67382	1,30024	1,05929	0,62294	0,54794	0,01924	-0,0266	0,17529
40																	
45	3,181	2,35306	3,02078	3,57522	2,7685	1,26228	0,80094	0,30228	-0,1681	2,52391	0,28972	1,11475	0,72541	0,81541	0,07456	-0,0005	0,17094
50																	
	3,07081	1,01343	1,97114	1,48757	0,93281	0,30876	0,11524	0,1159	-0,1982	2,62539	-0,0545	1,14647	0,48121	0,49921	0,01245	-0,0107	0,15603

Figure 42: Temperature measurements from height 1,98 m

The blue marker indicates the point directly above the centre of the stove. The values in figure (42) corresponds well to what the thermal images show, which is that the hottest measurement are moving towards –x and –y. Although the values in figure (42) shows that the hottest area at y = 0 is somewhere between x = -15 or x = -35, which is longer away from the stove centre than what the thermo image in figure 41 shows its hottest temperature. A reason for that could be that the air in the building at the very moment the picture was taken behaved in such a way that the plume got “pushed” back towards x = 0, making it look like an almost perfect plume. The values shown in the excel are the average values during a measuring period of 1,5 minutes approximately, and should therefore be the determinative values when analysing the plume. Another reason for the deviation of the thermal image and the excel values could be that the sheet of paper acts like a large wall, that slows down/stops a possible air current that is heading towards the negative x-axis. The air are therefore not able to heat up the paper further out on the negative x-axis, as it should do according to the excel sheet. As one can see in figure (41), the marker is pointed a small distance on the negative x-axis, which makes the plume look like it is more symmetrical than it is.

As mentioned earlier, the bending of the plume should not make the pretended centreline values of temperature and air speed in the plume, which is used in this report, deviate much from what the values would have been if the plume were a perfect plume, moving straight up from the source. When natural air currents in the room pushes onto the plume, the two volumes of fluid will not mix homogeneously. Although, a certain thickness from the outer edge of the velocity boundary layer will be mixed with the transparent air in the room and cool it down. How this effect the fluid in the centre of the plume is that the air speed may rise a bit because the plume is given extra momentum due to the air currents in the room, in addition to the main force, which is the buoyancy force, and the air will move away from the artificial origin in the coordinate system. The temperature however should stay unaffected.

The maximum temperature and air speed in the plume, which is considered the centreline temperature and air speed, at a given height, may have a little lower value than the value of the maximum temperature and air speed would have had at the same height if the plume was a perfect plume moving straight up from the source. This is because when the plume bends, it must travel farther to reach the same height as a plume moving straight up. Farther distance from the source means lower temperature and air speed. Ideally, the height where the measurements were taken, should take into account the distance the centerline values have from the origin in the x-y plane, and add a certain amount to the height when bending the plume towards the origin, so that it makes a perfect plume. The drawing below illustrates the problem simply:

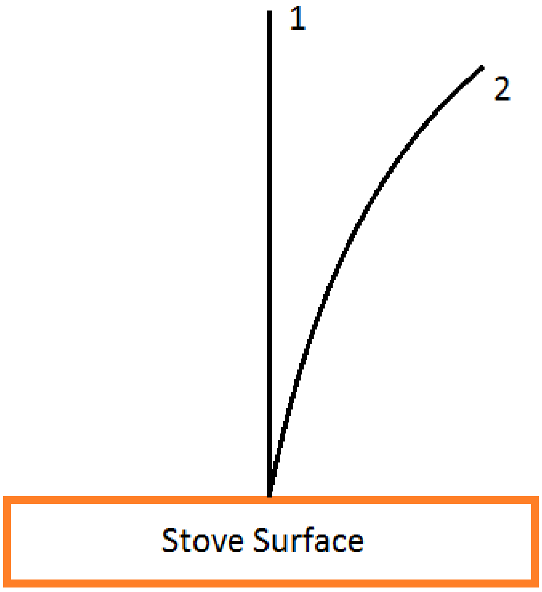

Figure 43: Plume trajectories

The numbers 1 and 2 both indicates plume centreline trajectories. Both has the same length, and the same temperature and air speed values at the end of the trajectories. In the experiment, the values are measured at a trajectory looking more like 2 than 1. Trajectory 2 has been pushed inwards to make an ideal plume. The values along trajectory 2 has been moved to the left without changing the height, which means that the values at the end of trajectory 2 are located a certain distance below the end of trajectory 1, even though the ends of both trajectories should have the same values. The result of this phenomena is that; values in the report and their associated height have a lower value than what an ideal plume would have had at the same height, because the temperature and air speed decreases with increasing distance from the heat source. A decision was made to not correct the measured values to take into account the decreased values caused by the bending, because it was complicated work to be done and quite time consuming. The correction however, would have been very small compared to other error sources in the experiment.

9.3 Plume analysis

9.3.1 Zone of establishment

The measurements from the first height, 1,48m above ground, shows that the temperature and air speed curves can resemble a bell shaped curve, if you know what you are looking for. It is not that clear for the temperature graph though (24), as it is for the air speed graph, figure (25). Below is a partial image of the Gaussian approximation of the temperature at height 1,48m above ground.

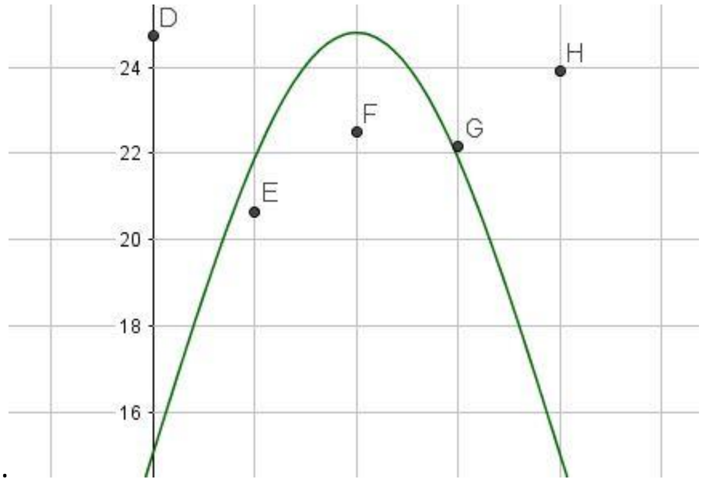

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Figure 44: Partial image of temperature at height 1,48m above ground

This shows that the temperature of the air at a distance of 20 cm above the stove top is mainly characterized by chaos. It is safe to conclude that the plume at this height is in the zone of establishment. The next measuring height at 1,98m above ground shows better results in term of aligning the measuring points with a fitting Gaussian curve for both the temperature and the air speed (26 and 27). Although, the temperature measurement shows a deviation away from the curve on the positive x-axis, which is displayed in the picture below;

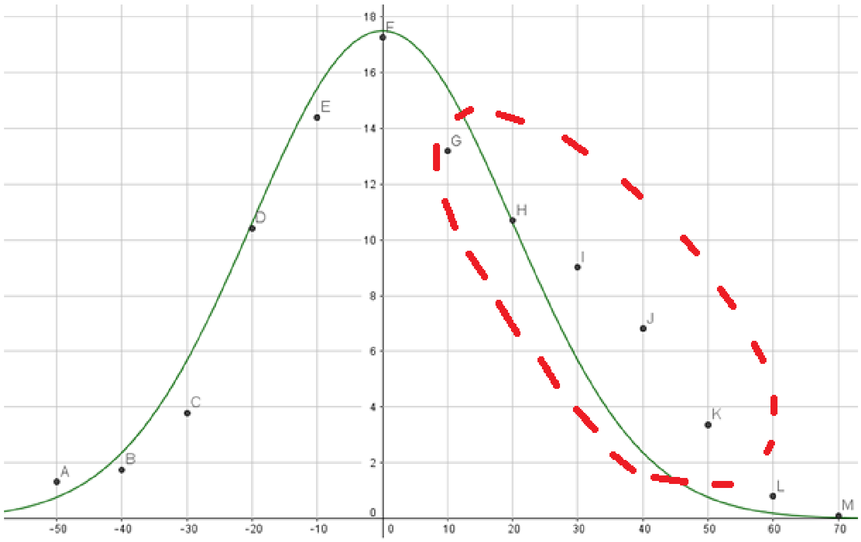

Figure 45: Temperature at height 1,98

This could be the result of an air current in the room, or as a result of how the air behaves when the plume is bended. The dotted area in the figure above is on the side where the plume is bending away from, which means that the measuring points from G to K is actually more centred (x=0, y=0) than point E, which is the extrema in figure (45). The bending of the plume is not static, and one could expect results to “jump off” its theoretically correct trajectory, because the plume could happened to move. A similar phenomena is captured from the temperature result from height 2,48m above ground:

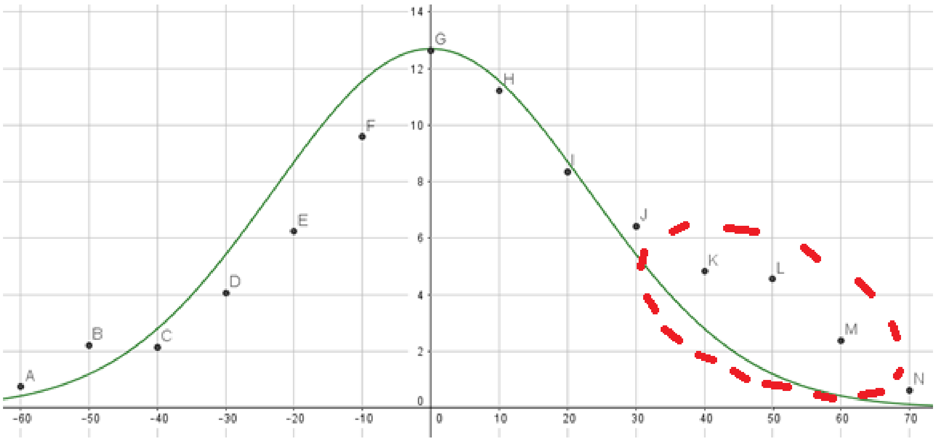

Figure 46: Temperature at height 2,48m

A viable conclusion is that the zone of establishment has ended at height 1,98m above ground, and that the temperature and air velocity can be described with Gaussian curves from this height. More measurement should have happened at the early stages of the plume, somewhere between 20 cm and 70 cm above the stove top in order to get a clearer picture of how far the zone of establishment stretches in this case. From the results, it is hard to claim anything other than that at 20 cm above the stove top we are in the zone of establishment, and at 70cm, it has ended.

9.3.2 Plume end

From the graphs (35) showing results from height 3,98m above ground, we see that the plume shows signs of dissipation. There is still considerable momentum of air in the centre of the plume, and the temperature is higher than the ambient air. An effort was made in the results to make a Gaussian curve to fit the measuring points, even though the curve did not follow the measured values well for the air speed. We can see clearly from figure (35) that the surrounding motion of the air becomes dominant at this height, and the air distribution shows no clear Gaussian profile. It is unfortunate that there is no higher level of measurements, since that could confirm if the chaotic distribution would be the trend from this point on and further.

9.4 Self-similarity

It is hard to determine accurately when the plume becomes self-similar. The temperature and air speed distribution in the cross-sections seems to develop differently. The centreline temperature is decaying, while the centreline air speed seems to be stable, which is interesting (with exception of the first measuring height where we are in the zone of establishment).

10. Conclusion

The measuring campaign provided useful information about the air speed distribution and the temperature distribution in the plumes cross sectional layers. When looking back on the project, it is clear that it would be favourable to do measurements at more heights, especially at the critical levels, which is at the plume start, where it transitions into a stable plume, and at the plume end. However, there was problems with both time and how big we could build the rig.

Plotting Gaussian curves for the air speed and temperature values at the cross-sections show that the Gaussian approximation is valid at heights 1,98m – 3,48m above ground. Maybe we could include the last measuring height 3,98m as well, but it is hard to determine if the impacts of the surroundings in the lab was the cause of the deviation from the Gaussian curve, or if the plume's nature made it behave off curve.

The question of self-similarity is a though question when working with the results. The centreline temperature seems to decay as expected, while the centreline air speed is quite stable. Bot distributions becomes wider as the height increases, and 25^o from the plume origin seems to be a good approximation. The data provided by the measurement campaign are also delivered with this thesis, which could help further work with this project of getting a clearer answer of the case of self-similarity, which again could help the company EQUA work of creating a solid and theoretically correct building zone-model.

The maximum and minimum cases regarding the distance from the stove top to the virtual point seems to not be accurate. When comparing the theoretical formula of centreline temperature with the measurements done in the lab, indicates the virtual point to be further away than what the maximum case suggest.

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12. Figure list

13. Table list

14. Nomenclature

SH = Space heating

DHW = Domestic hot water

PD = Percentage dissatisfied

B = Buoyancy effect $[\frac{m^4}{s^3}]$

Q = Volume flow $[m^3/s]$

g' = Reduced gravity $[m/s^2]$

g = Earth's gravity $[m/s^2]$

Z = Height from point source

B = Width of plume

V = Air speed

δ_t = Temperature boundary layer

δ_v = Velocity boundary layer

v_∞ = Ambient air speed

15. Attachements

A: Calibration

The calibration of the anemometers are divided in two parts. The first part is to determine the minimum values and the maximum values of the measurements. The second part is to calculate a correction factor of the probes relative to a reference air speed.

Calibrating part 1

Scale	2,5 m/s	
Error reading, +/-	3 %	
Error scale, +/-	1 %	0,025 m/s

Probe 1

Measuring number	Set value (m/s)	Measured value (m/s)	Error reading (m/s)	Error scale (m/s)	Min. value (m/s)	Max. Value (m/s)
1	0,3	0,344	0,01032	0,025	0,30868	0,37932
2	0,3	0,364	0,01092	0,025	0,32808	0,39992
3	0,3	0,363	0,01089	0,025	0,32711	0,39889
4	0,7	0,801	0,02403	0,025	0,75197	0,85003
5	0,7	0,806	0,02418	0,025	0,75682	0,85518
6	0,7	0,815	0,02445	0,025	0,76555	0,86445
7	1,1	1,214	0,03642	0,025	1,15258	1,27542
8	1,1	1,225	0,03675	0,025	1,16325	1,28675
9	1,1	1,241	0,03723	0,025	1,17877	1,30323
10	1,5	1,717	0,05151	0,025	1,64049	1,79351
11	1,5	1,778	0,05334	0,025	1,69966	1,85634
12	1,5	1,685	0,05055	0,025	1,60945	1,76055

Probe 2

Measuring number	Set value (m/s)	Measured value (m/s)	Error reading (m/s)	Error scale (m/s)	Min. value (m/s)	Max. Value (m/s)
1	0,3	0,306	0,00918	0,025	0,27182	0,34018
2	0,3	0,326	0,00978	0,025	0,29122	0,36078
3	0,3	0,313	0,00939	0,025	0,27861	0,34739
4	0,7	0,696	0,02088	0,025	0,65012	0,74188
5	0,7	0,719	0,02157	0,025	0,67243	0,76557
6	0,7	0,68	0,0204	0,025	0,6346	0,7254
7	1,1	1,025	0,03075	0,025	0,96925	1,08075
8	1,1	1,076	0,03228	0,025	1,01872	1,13328

9	1,1	1,04	0,0312	0,025	0,9838	1,0962
10	1,5	1,508	0,04524	0,025	1,43776	1,57824
11	1,5	1,423	0,04269	0,025	1,35531	1,49069
12	1,5	1,475	0,04425	0,025	1,40575	1,54425

Probe 3

Measuring number	Set value (m/s)	Measured value (m/s)	Error reading (m/s)	Error scale (m/s)	Min. value (m/s)	Max. Value (m/s)
1	0,3	0,173	0,00519	0,025	0,14281	0,20319
2	0,3	0,142	0,00426	0,025	0,11274	0,17126
3	0,3	0,156	0,00468	0,025	0,12632	0,18568
4	0,7	0,392	0,01176	0,025	0,35524	0,42876
5	0,7	0,404	0,01212	0,025	0,36688	0,44112
6	0,7	0,394	0,01182	0,025	0,35718	0,43082
7	1,1	0,642	0,01926	0,025	0,59774	0,68626
8	1,1	0,647	0,01941	0,025	0,60259	0,69141
9	1,1	0,647	0,01941	0,025	0,60259	0,69141
10	1,5	0,898	0,02694	0,025	0,84606	0,94994
11	1,5	0,915	0,02745	0,025	0,86255	0,96745
12	1,5	0,918	0,02754	0,025	0,86546	0,97054

Probe 4

Measuring number	Set value (m/s)	Measured value (m/s)	Error reading (m/s)	Error scale (m/s)	Min. value (m/s)	Max. Value (m/s)
1	0,3	0,317	0,00951	0,025	0,28249	0,35151
2	0,3	0,307	0,00921	0,025	0,27279	0,34121
3	0,3	0,3	0,009	0,025	0,266	0,334
4	0,7	0,704	0,02112	0,025	0,65788	0,75012
5	0,7	0,635	0,01905	0,025	0,59095	0,67905
6	0,7	0,676	0,02028	0,025	0,63072	0,72128
7	1,1	1,056	0,03168	0,025	0,99932	1,11268
8	1,1	1,027	0,03081	0,025	0,97119	1,08281
9	1,1	1,02	0,0306	0,025	0,9644	1,0756
10	1,5	1,426	0,04278	0,025	1,35822	1,49378
11	1,5	1,372	0,04116	0,025	1,30584	1,43816
12	1,5	1,411	0,04233	0,025	1,34367	1,47833

Probe 5

Measuring number	Set value (m/s)	Measured value (m/s)	Error reading (m/s)	Error scale (m/s)	Min. value (m/s)	Max. Value (m/s)

1	0,3	0,291	0,00873	0,025	0,25727	0,32473
2	0,3	0,3	0,009	0,025	0,266	0,334
3	0,3	0,277	0,00831	0,025	0,24369	0,31031
4	0,7	0,64	0,0192	0,025	0,5958	0,6842
5	0,7	0,635	0,01905	0,025	0,59095	0,67905
6	0,7	0,61	0,0183	0,025	0,5667	0,6533
7	1,1	0,963	0,02889	0,025	0,90911	1,01689
8	1,1	0,978	0,02934	0,025	0,92366	1,03234
9	1,1	0,955	0,02865	0,025	0,90135	1,00865
10	1,5	1,351	0,04053	0,025	1,28547	1,41653
11	1,5	1,36	0,0408	0,025	1,2942	1,4258
12	1,5	1,335	0,04005	0,025	1,26995	1,40005

Probe 6

Measuring number	Set value (m/s)	Measured value (m/s)	Error reading (m/s)	Error scale (m/s)	Min. value (m/s)	Max. Value (m/s)
1	0,3	0,313	0,00939	0,025	0,27861	0,34739
2	0,3	0,364	0,01092	0,025	0,32808	0,39992
3	0,3	0,327	0,00981	0,025	0,29219	0,36181
4	0,7	0,700	0,021	0,025	0,654	0,746
5	0,7	0,749	0,02247	0,025	0,70153	0,79647
6	0,7	0,711	0,02133	0,025	0,66467	0,75733
7	1,1	1,116	0,03348	0,025	1,05752	1,17448
8	1,1	1,12	0,0336	0,025	1,0614	1,1786
9	1,1	1,081	0,03243	0,025	1,02357	1,13843
10	1,5	1,509	0,04527	0,025	1,43873	1,57927
11	1,5	1,47	0,0441	0,025	1,4009	1,5391
12	1,5	1,488	0,04464	0,025	1,41836	1,55764

Probe 7

Measuring number	Set value (m/s)	Measured value (m/s)	Error reading (m/s)	Error scale (m/s)	Min. value (m/s)	Max. Value (m/s)
1	0,3	0,285	0,00855	0,025	0,25145	0,31855
2	0,3	0,275	0,00825	0,025	0,24175	0,30825
3	0,3	0,281	0,00843	0,025	0,24757	0,31443
4	0,7	0,64	0,0192	0,025	0,5958	0,6842
5	0,7	0,633	0,01899	0,025	0,58901	0,67699
6	0,7	0,64	0,0192	0,025	0,5958	0,6842
7	1,1	1,004	0,03012	0,025	0,94888	1,05912
8	1,1	1,006	0,03018	0,025	0,95082	1,06118
9	1,1	0,992	0,02976	0,025	0,93724	1,04676
10	1,5	1,352	0,04056	0,025	1,28644	1,41756

11	1,5	1,331	0,03993	0,025	1,26607	1,39593
12	1,5	1,335	0,04005	0,025	1,26995	1,40005

Probe 8

Measuring number	Set value (m/s)	Measured value (m/s)	Error reading (m/s)	Error scale (m/s)	Min. value (m/s)	Max. Value (m/s)
1	0,3	0,269	0,00807	0,025	0,23593	0,30207
2	0,3	0,267	0,00801	0,025	0,23399	0,30001
3	0,3	0,268	0,00804	0,025	0,23496	0,30104
4	0,7	0,576	0,01728	0,025	0,53372	0,61828
5	0,7	0,565	0,01695	0,025	0,52305	0,60695
6	0,7	0,566	0,01698	0,025	0,52402	0,60798
7	1,1	0,858	0,02574	0,025	0,80726	0,90874
8	1,1	0,867	0,02601	0,025	0,81599	0,91801
9	1,1	0,854	0,02562	0,025	0,80338	0,90462
10	1,5	1,17	0,0351	0,025	1,1099	1,2301
11	1,5	1,145	0,03435	0,025	1,08565	1,20435
12	1,5	1,145	0,03435	0,025	1,08565	1,20435

Probe 10

Measuring number	Set value (m/s)	Measured value (m/s)	Error reading (m/s)	Error scale (m/s)	Min. value (m/s)	Max. Value (m/s)
1	0,3	0,274	0,00822	0,025	0,24078	0,30722
2	0,3	0,232	0,00696	0,025	0,20004	0,26396
3	0,3	0,245	0,00735	0,025	0,21265	0,27735
4	0,7	0,567	0,01701	0,025	0,52499	0,60901
5	0,7	0,53	0,0159	0,025	0,4891	0,5709
6	0,7	0,528	0,01584	0,025	0,48716	0,56884
7	1,1	0,854	0,02562	0,025	0,80338	0,90462
8	1,1	0,8	0,024	0,025	0,751	0,849
9	1,1	0,827	0,02481	0,025	0,77719	0,87681
10	1,5	1,218	0,03654	0,025	1,15646	1,27954
11	1,5	1,087	0,03261	0,025	1,02939	1,14461
12	1,5	1,114	0,03342	0,025	1,05558	1,17242

1	Not ok
2	Not ok
3	Not ok
4	Not ok
5	Not ok
6	Not ok

7	Not ok
8	Not ok
10	Not ok

Calibrating part 2

Probe 1

Set Point	**0,3**	**0,7**	**1,1**	**1,5**	**Avergage**
Measured 1	0,344	0,801	1,214	1,717	
Measured 2	0,364	0,806	1,225	1,778	
Measured 3	0,363	0,815	1,241	1,685	
Set point / measured 1	0,872	0,874	0,906	0,874	0,881
Set point / measured 2	0,824	0,868	0,898	0,844	0,859
Set point / measured 3	0,826	0,859	0,886	0,890	0,865
Correction factor	**0,868**				

Probe 2

Set Point	**0,3**	**0,7**	**1,1**	**1,5**	**Avergage**
Measured 1	0,306	0,696	1,025	1,508	
Measured 2	0,326	0,719	1,076	1,423	
Measured 3	0,313	0,68	1,04	1,475	
Set point / measured 1	0,980	1,006	1,073	0,995	1,014
Set point / measured 2	0,920	0,974	1,022	1,054	0,993
Set point / measured 3	0,958	1,029	1,058	1,017	1,016
Correction factor	**1,007**				

Probe 3

Set Point	**0,3**	**0,7**	**1,1**	**1,5**	**Avergage**
Measured 1	0,173	0,392	0,642	0,898	
Measured 2	0,142	0,404	0,663	0,915	
Measured 3	0,156	0,394	0,647	0,918	

Set point / measured 1	1,734	1,786	1,713	1,670	1,726
Set point / measured 2	2,113	1,733	1,659	1,639	1,786
Set point / measured 3	1,923	1,777	1,700	1,634	1,758
Correction factor	**1,757**				

Probe 4

Set Point	**0,3**	**0,7**	**1,1**	**1,5**	**Avergage**
Measured 1	0,317	0,704	1,056	1,426	
Measured 2	0,307	0,695	1,027	1,372	
Measured 3	0,3	0,676	1,02	1,411	
Set point / measured 1	0,946	0,994	1,042	1,052	1,009
Set point / measured 2	0,977	1,007	1,071	1,093	1,037
Set point / measured 3	1,000	1,036	1,078	1,063	1,044
Correction factor	**1,030**				

Probe 5

Set Point	**0,3**	**0,7**	**1,1**	**1,5**	**Avergage**
Measured 1	0,291	0,64	0,963	1,351	
Measured 2	0,3	0,635	0,978	1,36	
Measured 3	0,277	0,61	0,955	1,335	
Set point / measured 1	1,031	1,094	1,142	1,110	1,094
Set point / measured 2	1,000	1,102	1,125	1,103	1,083
Set point / measured 3	1,083	1,148	1,152	1,124	1,127
Correction factor	**1,101**				

Probe 6

Set Point	**0,3**	**0,7**	**1,1**	**1,5**	**Avergage**
Measured 1	0,313	0,700	1,116	1,509	
Measured 2	0,328	0,749	1,12	1,47	
Measured 3	0,327	0,711	1,081	1,488	

Set point / measured 1	0,958	1,000	0,986	0,994	0,985
Set point / measured 2	0,915	0,935	0,982	1,020	0,963
Set point / measured 3	0,917	0,985	1,018	1,008	0,982
Correction factor	**0,976**				

Probe 7

Set Point	**0,3**	**0,7**	**1,1**	**1,5**	**Avergage**
Measured 1	0,285	0,64	1,004	1,352	
Measured 2	0,275	0,633	1,006	1,331	
Measured 3	0,281	0,64	0,992	1,335	
Set point / measured 1	1,053	1,094	1,096	1,109	1,088
Set point / measured 2	1,091	1,106	1,093	1,127	1,104
Set point / measured 3	1,068	1,094	1,109	1,124	1,098
Correction factor	**1,097**				

Probe 8

Set Point	**0,3**	**0,7**	**1,1**	**1,5**	**Avergage**
Measured 1	0,269	0,576	0,858	1,17	
Measured 2	0,267	0,565	0,867	1,145	
Measured 3	0,268	0,566	0,854	1,145	
Set point / measured 1	1,115	1,215	1,282	1,282	1,224
Set point / measured 2	1,124	1,239	1,269	1,310	1,235
Set point / measured 3	1,119	1,237	1,288	1,310	1,239
Correction factor	**1,233**				

Probe 10

Set Point	**0,3**	**0,7**	**1,1**	**1,5**	**Avergage**
Measured 1	0,274	0,567	0,854	1,218	
Measured 2	0,232	0,53	0,8	1,087	
Measured 3	0,245	0,528	0,827	1,114	

Set point / measured 1	1,095	1,235	1,288	1,232	1,212
Set point / measured 2	1,293	1,321	1,375	1,380	1,342
Set point / measured 3	1,224	1,326	1,330	1,346	1,307
Correction factor	**1,287**				

B: Data attachements

All the measurement data will be attached to this file, in case it could help the project's further work.

C: Risk Assessment Report

A risk assessment has been created regarding the use of the electric stove some time before this report was created, when the stove was part of a different project.

Movable electric stove

Prosjektnavn	Movable electric stove
Apparatur	Movable electric stove
Enhet	NTNU
Apparaturansvarlig	Laurent Georges
Prosjektleder	Laurent Georges
HMS-koordinator	Morten Grønli
HMS-ansvarlig (linjeleder)	Olav Bolland
Plassering	VATL- and private passive house
Romnummer	C163
Risikovurdering utført av	Laurent Georges

Approval:

Apparatur kort (UNIT CARD) valid for:	12 months
Forsøk pågår kort (EXPERIMENT IN PROGRESS) valid for:	12 months

Rolle	Navn	Dato	Signatur
Prosjektleder	Laurent Georges		
HMS koordinator	Morten Grønli		
HMS ansvarlig (linjeleder)	Olav Bolland		

TABLE OF CONTENTS

introduction

The movable electric stove aims at mimicking the influence of real wood stoves on the indoor thermal environment of buildings, especially passive houses. The surface temperature of the movable stove is imposed by electric resistances while the temperature profile is taken equivalent to real stoves.

Organisation

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

RISK MANAGEMENT in the PROJECT

Hovedaktiviteter risikostyring	Nødvendige tiltak, dokumentasjon	DATE
Prosjekt initiering	Prosjekt initiering mal	
Veiledningsmøte Guidance Meeting	Skjema for Veiledningsmøte med pre-risikovurdering	
Innledende risikovurdering Initial Assessment	Fareidentifikasjon – HAZID Skjema grovanalyse	
Vurdering av teknisk sikkerhet Evaluation of technical security	Prosess-HAZOP Tekniske dokumentasjoner	
Vurdering av operasjonell sikkerhet Evaluation of operational safety	Prosedyre-HAZOP Opplæringsplan for operatører	
Sluttvurdering, kvalitetssikring Final assessment, quality assurance	Uavhengig kontroll Utstedelse av apparaturkort Utstedelse av forsøk pågår kort	

DESCRIPTIONS OF EXPERIMENTAL SETUP

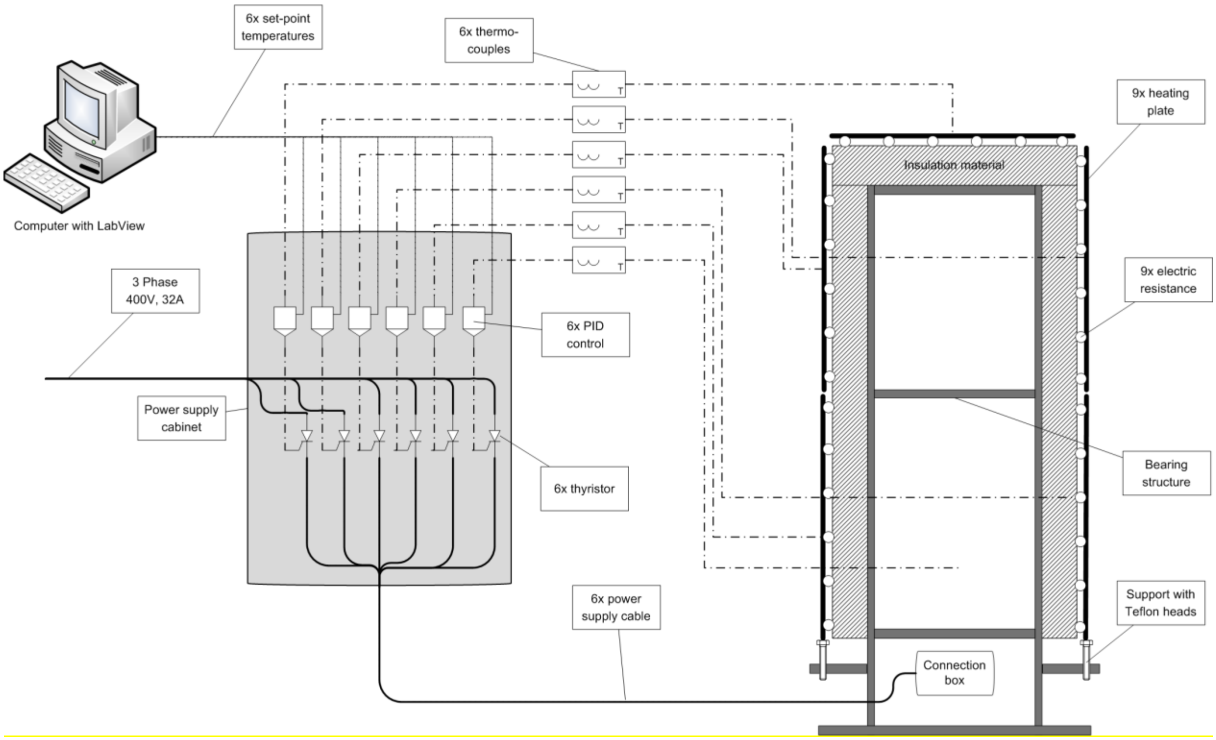

Figure 1. Schematic of the movable electric stove rig

The movable electric stove aims at mimicking the influence of real wood stove on the indoor thermal environment of buildings, especially passive houses. In practice, detached passive houses typically needs ~3kW for heating in the coldest days (using the Oslo climate) while the nominal power of existing wood stoves is well higher (i.e. above 6 kW). A main objective is to check the resulting overheating in the building and how the heat is distributed between rooms. The idea is to eventually place the movable electric stove in a real building.

In practice, the surface temperature of the movable stove is imposed by electric resistances while the temperature profile is taken equivalent to real stoves (i.e. measurements or results from other simulations). The electric stove heating elements have been designed to have a low thermal mass in order to follow quick variation of the set-point surface temperature. The behaviour of wood log stove can be simulated so that a unsteady set-point temperature can be imposed to surfaces. The maximum instantaneous power of the stove is 16kW which lead to nominal current of 32A. The movable stove is composed of 9 heated plates of 0.6m x 0.6m. All the plates are identical expect for one lower plate which has a higher nominal power in order to model the resulting radiation asymmetry of a stove combustion chamber. Nevertheless, 6 surface temperatures can be controlled. Therefore, 6 plates are controlled 2 by 2 (i.e. lateral vertical plates of the stove). In parallel, 3 plates are controlled independently. The electric resistances can stand 800°C while the insulating material (FireMaster 607) on the backside of the heating plates is non-combustible and sealed in pillows. One week point is the plate support below which is covered by Teflon is order to reduce the thermal bridge between the heated plates and the bearing structure. Teflon is expected to stand up to 300°C which is the close to the upper operating temperature of the movable stove.

Evacuation from the experimental area

Evacuate at signal from the alarm system or local gas alarms with its own local alert with sound and light outside the room in question, see 6.2

Evacuation from the rigging area takes place through the marked emergency exits to the assembly point, (corner of Old Chemistry Kjelhuset or parking 1a-b.)

Action on rig before evacuation:

Power off the electric supply (red button in front of the power supply box)

Warning

Before experiments

Send an e-mail with information about the planned experiment to:

iept-experiments@ivt.ntnu.no

The e-mail should contain the following items:

- Name of responsible person:
- Experimental setup/rig:
- Start Experiments: (date and time)
- Stop Experiments: (date and time)

You must get the approval back from the laboratory management before start up. All running experiments are notified in the activity calendar for the lab to be sure they are coordinated with other activity.

Non-conformance

FIRE

If you are NOT able to extinguish the fire, activate the nearest fire alarm and evacuate area. Be then available for fire brigade and building caretaker to detect fire place.
If possible, notify:

NTNU	SINTEF
Morten Grønli, Mob: 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

GAS ALARM

If a gas alarm occurs, close gas bottles immediately and ventilate the area. If the level of the gas concentration does not decrease within a reasonable time, activate the fire alarm and evacuate the lab. Designated personnel or fire department checks the leak to determine whether it is possible to seal the leak and ventilate the area in a responsible manner.

PERSONAL INJURY

- First aid kit in the fire / first aid stations
- Shout for help
- Start life-saving first aid•

CALL 113 if there is any doubt whether there is a serious injury

OTHER NON-CONFORMANCE (AVVIK)

NTNU:

You will find the reporting form for non-conformance on:

https://innsida.ntnu.no/wiki/-/wiki/Norsk/Melde+avvik

SINTEF:

Synergi

Assessment of technical safety

HAZOP

See Chapter 13 "Guide to the report template".

The experiment set up is divided into the following nodes:

Node 1	
Node 2	

Attachments: Form: Hazop_mal

Conclusion: (Safety taken care of)

Flammable, reactive and pressurized substances and gas

Are any flammable, reactive and pressurized substances and gases in use?

NO	x

Attachments:

Conclusion:

Pressurized equipment

Is any pressurized equipment in use?

NO	x

Attachments: (certificate for pressurized equipment)

Conclusion:

Effects on the environment (emissions, noise, temperature, vibration, smell)

Will the experiments generate emission of smoke, gas, odour or unusual waste?

Is there a need for a discharge permit, extraordinary measures?

NO	x

Attachments:

Conclusion:

Radiation

See Chapter 13 "Guide to the report template".

NO	x

Attachments:

Conclusion:

Chemicals

NO	x

Attachments: MSDS

Conclusion:

Electricity safety (deviations from the norms/standards)

NO	

Attachments:

Conclusion:

Assessment of operational safety

Ensure that the procedures cover all identified risk factors that must be taken care of. Ensure that the operators and technical performance have sufficient expertise.

Procedure HAZOP

The method is a procedure to identify causes and sources of danger to operational problems.

Attachments:: HAZOP_MAL_Prosedyre

Conclusion:

Operation and emergency shutdown procedure

The operating procedure is a checklist that must be filled out for each experiment.

Emergency procedure should attempt to set the experiment set up in a harmless state by unforeseen events.

Attachments: Procedure for running experiments

Emergency shutdown procedure: shut down the power supply

Training of operators

Attachments*:* Training program for operators

Technical modifications

Personal protective equipment

- It is mandatory use of eye protection in the rig zone
- Use gloves when there is opportunity for contact with hot/cold surfaces.

General Safety

- The experiment cannot run unattended, monitoring should be continuous

Conclusion: no flammable material should be located within 2m around the stove

Is Operator allowed to leave during the experiment? No more than 5min

Safety equipment

- Warning signs, see the Regulations on Safety signs and signaling in the workplace

Special predations

Quantifying of RISK - risk matrix

The risk matrix will provide visualization and an overview of activity risks so that management and users get the most complete picture of risk factors.

IDnr	Aktivitet-hendelse	Frekv-Sans	Kons	RV
1	*Contact with hot surfaces (between 150 and 250°C)*	1	C	C1

Conclusion :

CONSEQUENSES	**Svært alvorlig**	**E1**	**E2**	**E3**	**E4**	**E5**
	Alvorlig	**D1**	**D2**	**D3**	**D4**	**D5**
	Moderat	**C1**	**C2**	**C3**	**C4**	**C5**
	Liten	**B1**	**B2**	**B3**	**B4**	**B5**
	Svært liten	**A1**	**A2**	**A3**	**A4**	**A5**
		Svært liten	**Liten**	**Middels**	**Stor**	**Svært Stor**
		PROBABILITY				

The principle of the acceptance criterion. Explanation of the colors used in the matrix

Colour		**Description**
Red		Unacceptable risk Action has to be taken to reduce risk
Yellow		Assessment area. Actions has to be considered
Green		Acceptable risk. Action can be taken based on other criteria

Regulations and guidelines

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

DOCUMENTATION

- 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