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Analysis of wood fuel moisture content on enclosure fire through small scale experiments

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Master Thesis in Fire Safety Engineering

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Analysis of wood fuel moisture content on enclosure fire through small scale experiments

Master thesis in Fire Safety Engineering

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Western Norway
University of
Applied Sciences

Preface

This thesis is the final work in the master's program in Fire Safety engineering at Western Norway University of Applied Sciences.

The idea behind this master thesis was suggested to me from Prof. Torgrim Log. I found the case very interesting and important issue to asses. An experimental study is always exiting to do as it gives the opportunity to challenge both theoretical and practical skills.

Acknowledgements

I would like to show my gratitude the people that have helped and supported me through my master thesis. I would like to thank Prof. Torgrim Log and my supervisor Sanjay Kumar Khattri and for good input and guidance. Thanks to Arjen Kraaijeveld for providing necessary equipment and material. Thanks to my fellow students Sara Louise Einarsdóttir and Asbjørn Jørgensen for assisting me at the lab.

Finally, I would like to thank my family for the support throughout my education. A special thanks to my fiancé, Line Erland Jacobsen for moral support and for motivating me when times have been tough.

Abstract

Norway is a country where there are many dense residential areas consisting of wooden houses. Many of these areas consist of old buildings with historical value and mapping shows that there are 167 areas of this type. Areas as these are quite vulnerable if a fire occurs as shown in Lærdalsøyri in 2014, where 40 buildings, including 4 historic building was lost. Wood is a hygroscopic material, meaning it will absorb or release moisture depending on the air relative humidity and temperature. Low humidity prior to the Lærdal-fire resulted in low wood fuel moisture content which caused a rapid fire development.

The purpose of this master thesis is to investigate how the fuel moisture content (FMC) in the compartment linings affects the different stages in an enclosure fire. This has been examined by doing experiments of rooms which were scale down to 1/8 and 1/16 scale of the ISO-room from ISO 9705-1. The reason for this is to assess the possibility of doing small-scale experiments and see if they give sensible results compared to more costly and time-consuming large-scale experiments. I addition, it was an interest to find a scale and method which makes it easy to demonstrate these experiments in educational purpose. Based on this, it was conducted 17 experiments to get a good understanding of the effect of FMC and doing small scale experiments.

Ten rooms in 1/8 scale and seven rooms in 1/16 scale were tested with FMC ranging from 6,5 % to 16 %. The start fire was placed in the left back corner and was scaled down from the start fire in ISO 9705-1 using the Froude-scaling technique to assure correct scaling. This resulted in the start fire having a heat release rate of 0,85 kW for the 1/8 scale and 0,2 kW for 1/16 scale. Mass loss rate, temperature and observation was collected during the experiments to evaluated the fire development and to determine time to flashover.

The results shows that the impact of the FMC is greater in the pre-flashover period but also influences the post-flashover fire. By increasing the FMC from 6,5 % to 11,6% the time to flashover increases from 4 min to 7 min. A further increase to 14,5 % FMC, the time to flashover increases to 9 minutes. Results shows that scaling down to 1/8th scale using Froude-scaling and ISO 9705-1 provides a good representation of the full-scale fire phenomenon. Scaling further down to 1/16 scale has shown to be difficult and doesn’t give any reasonable results.

Sammendrag

På grunn av byggeskikk og tilgang på materialer har Norge flere områder bestående av trebygg i tettbebyggende strøk. Mange av disse områdene består av gamle bygninger med historisk verdi og kartlegging viser at det er 167 områder av denne typen. Områder som disse er sårbare dersom det oppstår brann noe som var tilfelle i Lærdalsøyri i 2014. Denne brannen medførte i 40 bygninger, inkludert 4 historiske bygninger gikk tapt. Tre er et hygroskopisk materiale, noe som betyr at det vil absorbere eller frigjøre fuktighet avhengig av luftens relative fuktighet og temperatur. Lav luftfuktighet i perioden før Lærdal-brannen resulterte i lavt fuktighetsinnhold i treverket noe som førte en rask brannutvikling.

Hensikten med denne masteroppgaven er å undersøke hvordan fuktinnholdet i treverket påvirker de forskjellige fasene i en rombrann. Dette har blitt undersøkt ved å gjøre forsøk i rom som ble nedskalert til 1/8 og 1/16 skala av ISO-rommet fra ISO 9705-1. Årsaken til nedskalering er for å vurdere muligheten for å gjøre småskala forsøk og se om de gir fornuftige resultater sammenlignet med mer kostbare og tidkrevende fullskala forsøk. I tillegg var det en interesse å finne en skala og metode som gjør det enkelt å demonstrere disse forsøkene i undervisningsformål. Basert på dette ble det gjennomført 17 forsøk for å få god forståelse av effekten av fuktinnholdet i en rombrann og i tillegg for å vurdere bruken av småskala forsøk.

Ti rom i 1/8 skala og syv rom i 1/16 skala ble testet med fuktinnhold fra 6,5 vekt% til 16 vekt%. Startbrannen ble plassert i bakerste hjørne til venstre og ble nedskalert fra startbrannen i ISO 9705-1 ved bruk av Froude-skalering for å sikre riktig skalering. Dette resulterte i at startbrannen hadde en energiproduksjon på 0,85 kW for 1/8 skala og 0,2 kW for 1/16 skala. Massetapraten, temperatur og observasjon ble samlet i under forsøkene for å evaluere brannutviklingen og for å bestemme tiden til overtenning.

Resultatene viser at effekten av fuktinnholdet i treverket er større i perioden før overtenning, men også påvirker brannen i noe grad etter overtenning. Ved å øke fuktinnholdet i treverket fra 6,5 vekt% til 11,6 vekt% øker tiden til overtenning fra 4 min til 7 min. En ytterligere økning til 14,5 vekt% viser resultatene at tid til overtenning blir 9 minutter. Resultatene viser at skalering ned til 1/8 skala ved bruk av Froude-skalering og ISO 9705-1 gir en god tilnærming av fullskala forsøk. Å skalere videre ned til 1/16 skala har vist seg å være vanskelig og gir ingen rimelige resultater.

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Definitions

FMC	Fuel Moisture Content
EMC	Equilibrium Moisture Content
HRR	Heat Release Rate
TFF	Time to Flashover

$\dot{Q}$	Heat release rate [kW]
$\dot{Q}_{F0}$	Minimum heat release rate required for flashover [kW]
$\dot{Q}_{stoich}$	Stoichiometric heat release rate
$\dot{m}''$	Mass flux [g/m^{2}s]
$\dot{m}$	Mass loss rate [g/s]
χ	Combustion efficiency
ΔH_c	Heat of combustion [j/g]
A_0	Area of door opening [m^2]
H_0	Height of door opening [m]
ρ	Density [kg/m^3]

1 Introduction

1.1 Motivation

Norway is a country with many wooden buildings and homes in dense areas that is described as buildings with historical value. The Norwegian Directorate for Civil Protection (DSB) together with The Directorate for Cultural Heritage (RA), completed a survey of the areas in 2005 [1]. The survey covers 167 areas, which are spread across the country. In January 2014, a fire started in a private villa in Lærdalsøyri located in Western Norway. The fire resulted in 40 buildings, including 4 historic building to be lost. Very windy conditions at the time made the firefighting work difficult as the fire spread fast and over long distances. Low humidity prior to the fire resulted in low wood fuel moisture content (FMC) for outdoor wood and inside the buildings, respectively 7,6% and 4,5%. This resulted in rapid fire development and within an hour from the first emergency call, four of the villas had burned down. [2]

The motivation of this master-thesis is to learn more about the fire risk in wooden buildings, depending on the FMC in wood. This will be examined by doing experiments. Because of the complexity with full scale experiments, this thesis will focus on doing small scale experiments. The motivation for this is to investigate the possibilities of small-scale experiments and see if they give reasonable results.

1.2 Aim of the master thesis

The purpose of this master thesis is to investigate how the fuel moisture content (FMC) in the compartment linings affects the different stages in an enclosure fire. This will be examined by doing small-scale experiments. The reason for this is to assess the possibility of doing small-scale experiments and see if they give sensible results compared to more costly and time-consuming large-scale experiments. Based on the findings, it will be recommended a suitable set-up so that the experiments easily can be used in teaching in the fire department and other fire related educations.

The experiments will be a scaled-down iso-room which consists of hygroscopic material in this case, wood. Earlier experiments in ¼ scale iso-room conducted in [3], show a clear distinction in the fire development for rooms with high and low FMC. Based on this information, the experiments conducted in this thesis will be scale down to 1/8 and 1/16 scale of an iso-room accordingly to the ISO 9705-1.

2 Theory

2.1 Mass loss rate

The mass loss rate is the mass rate of a solid or liquid fuel vaporized and burned. It is expressed as mass flow per unit time in either kg/s or g/s or as mass flux which is the mass loss rate per unit area kg/m^2s. The mass loss rate may be expressed by: [4, 5]

$$\dot{m} = \left(\frac{\dot{Q}_F'' + \dot{Q}_E'' - \dot{Q}_L''}{L_v}\right) \cdot A_f \ [kg/s]$$ *Eq. 1*

Where:

- $\dot{Q}_F''$ is the heat flux supplied by the flame [W/m^2]
- $\dot{Q}_E''$ is the heat flux from external heat sources [W/m^2]
- $\dot{Q}_L''$ is the heat loss from the fuel surface to the surroundings [W/m^2]
- L_v is the latent heat of vaporization and pyrolysis [J/kg]
- A_f is the surface area of the fire [m^2]

The mass loss rate for a specific fire can also be estimated trough experiments where the mass loss is recorded over a certain time. [4]

2.2 Heat release rate

The heat release rate (HRR) is described as the single most important parameter in a fire scenario. It is the most essential characteristic that describes how big a fire is. The HRR is measured in kilowatts [kW] and is the rate at which the combustion reactions produce heat. [6] The heat release rate can be calculated using:

$$\dot{Q} = A_f \cdot \dot{m}'' \cdot \chi \cdot \Delta H_c \ [kW]$$ *Eq. 2*

where the A_f [m^2] is the surface area of the fuel and $\dot{m}''$[kg/m^2s] is the mass flux of the burning fuel. The combustion efficiency (χ) is the ratio between the effective heat of combustion and the complete heat of combustion. The complete heat of combustion (ΔH_c) is a measure of how much energy is released when a unit mass of material combusts. It`s termed complete heat of combustion since the combustion is complete leaving no residual fuel and releasing all of the chemical energy of the material. It is measured in a device called the bomb calorimeter where a sample is completely combusted under high pressure in pure oxygen, leaving almost no residue and releasing almost all of its potential energy. For real fires, it`s more appropriate to use the effective heat of combustion (ΔH_{eff}), where only 70 to 80% of the mass is converted to volatiles that is burnt almost completely leaving some char or residue. For fuels that produce sooty flames the combustion efficiency is often around 60 to 70%. The effective heat of combustion can be found experimentally where the HRR and mass loss rate are known. [4, 6]

2.3 Heat transfer mechanisms

Heat transfer is essential for a fire to evolve and spread across the compartment. During a fire, the heat produced will spread across the enclosure in different modes, causing surrounding materials to heat up. Fundamentally, there are only two physical modes of energy transfer which are conduction and radiation. Conduction is a molecular energy transport. The energy is transferred through a medium from a point with a higher temperature to a point of lower temperature. The amount of energy transferred through a material per unit time depends on the temperature and the thermal conductivity and thickness of the material. Thermal radiation is energy transmitted at the speed of light by electromagnetic waves. Being electromagnetic waves, it does not require a medium for transmitting. Convection heat transfer is conduction between a moving fluid and a sloid boundary. The convective heat transfer in a fire is traced to the hot smoke and the flames. The smoke flows over the compartment lining and heats the material. In addition, the hot smoke will radiate heat to the floor and walls, not in contact with the smoke. [7, 8, 9]

2.4 Enclosure fire

The fire development in enclosures may be divided into five stages and can be discussed in terms of the temperature development inside the compartment. The enclosure fire starts with ignition of the fuel followed by growth phase, flashover, fully developed fire, and decay phase. Figure 1 illustrates an idealized description of the temperature variation with time in an enclosure fire.

Figure 1 Fire development in enclosure in terms of temperature [10]

The ignition is the first stage in a fire and can occur either by a piloted ignition or spontaneous ignition. The ignition may be described as a process that produces an exothermic reaction characterized by an increase in temperature greatly above the ambient. After the ignition, the fire grows and produces an increasing amount of energy. In a case where the start fire is located at a significant distance from the compartment boundaries, the enclosure does not affect the fire, which then is fuel controlled. Fires in a corner of a room lined with a combustible material have been shown to cause more rapid flame spread and growth to flashover compared to cases with fires in other locations within the room. This is due to contact with the flame and the wall which accelerates the combustion process. Furthermore, back radiation from the wall to the fuel surface will increase the burning rate. Another factor influencing the growth phase is the type of combustion, type of fuel, and access to oxygen. [10, 11]

As the fire grows, hot gases in the flame are surrounded by cold gases causing buoyancy of the hot gases due to the density difference. The buoyant flow, including any flames, is referred to as a fire plume. As the plume rises, cold air is entrained into the plume. The plume will eventually rise to the height of the ceiling and cause a layer of hot gases to be formed. The greatest portion of the mass of the plume originates from the entrained air. As a result of this entrainment, the total mass flow in the plume increases causing the average temperature and concentration combustion product to decrease with height. As the plume reaches the ceiling the gases spread across it as a momentum-driven circular jet. The ceiling jet eventually reaches the wall of the enclosure and is therefore forced to move downward. Due to buoyancy force in the hot gases, the flow will still turn upward. This causes the room to be divided into two distinct layers, the hot upper layer, and the cold lower layer. The upper layer will continue to grow as more air is entrained into the plume. [10]

When the hot layer descends and increases in temperature, the heat transfer by radiation and convection becomes significant. The walls and ceiling in contact with the hot layer is heated up due to convection and radiation. Heat from the hot layer is also radiated to the floor and the lower walls, and some of the heat will be absorbed by the air in the lower layer causing the room temperature to increase. The burning rate of the fuel bed also increases due to radiation from the hot layer. [10]

As a result of radiation from the hot layer toward the combustible material in the enclosure, there may be a stage where all the material in the enclosure is ignited causing a very rapid increase in energy release rate. This very rapid transition from a growing fire to a fully developed fire is called a flashover and is illustrated in Figure 1. The criteria often used for determining flashover is that the temperature in the smoke layer has reached $500 - 600℃$. In addition, flashover is said to occur when radiation to the floor of the compartment is $15 - 20\ kW/m^2$, or that flames occur at the outside of the enclosure openings. [10] Flashover is also said to occur when the HRR in the compartment has reached a certain point. The minimum heat release rate for flashover to occur can be predicted using Eq. 3 [12].

$$\dot{Q}_{F0} = 750 \cdot A_0\sqrt{H_0}\ [kW] \qquad \text{Eq. 3}$$

Where:

A_0 = Area of opening [m^2]

H_0 = Height of opening [m]

Eq. 3 is based on the approximation that the air flow into the compartment is $\dot{m}_a = 0{,}5A_0\sqrt{H_0}$ and that the heat release rate per mass of consumed air is approximately equal to 3000 kJ/kg. The maximum amount of fuel that can be burned completely with the income air is known as the stoichiometric amount. The stoichiometric heat release rate ($\dot{Q}_{stoich}$) can therefore be calculated:

$$\dot{Q}_{stoich} = 3000 \cdot \dot{m}_a = 3000 \cdot (0{,}5A_0\sqrt{H_0})$$

$$\dot{Q}_{stoich} = 1500 \cdot A_0\sqrt{H_0} \qquad \text{Eq. 4}$$

From this derivation, it is shown that the minimum $\dot{Q}_{Fo}$ equals $0{,}4 \cdot \dot{Q}_{stoich}$. Results from fire test has shown that data fall within a range of $\dot{Q}_{Fo} = 0{,}3 \cdot \dot{Q}_{stoich}$ to $\dot{Q}_{Fo} = 0{,}7 \cdot \dot{Q}_{stoich}$. A best fit of data therefore suggests that $\dot{Q}_{Fo} = 0{,}5 \cdot \dot{Q}_{stoich}$ which substituting into Eq. 4 results in Eq. 3. [12]

The fire has now reached a stage where it is a fully developed fire where the energy release rate is at its greatest. The fire is now ventilation-controlled since it's limited by the available oxygen which enters through the enclosure openings. The effect of ventilation-controlled fire causes unburnt gasses to gather under the ceiling. As these hot combustible gasses leave the openings they will mix with air and ignite causing flames to appear at the outside of the opening. The average gas temperature in the enclosure during a fully developed fire is often very high and in the range of $700 - 1200$°C. [10]

The fully developed fire is illustrated in Figure 1 where the temperature curve is flattened out. This state remains until it reaches the decay phase. In the decay phase, the temperature starts to go down as the fire decrease in size either by lack of oxygen or lack of access to fuel. [10]

2.5 Scaling fire

Investigation of the outcome in a potential fire hazard is often examined by doing full scale experiments. Full scale experiments are often preferred method as this is more representative to the reality. The disadvantage with full scale is that it can be hard to implement, time consuming and expensive. Scaling down experiments can therefore be an alternative for examine a problem. One of the methods for scaling fire is called Froude-scaling.

The Froud scaling theory assumes that two fires are similar to each other if the Froude-number of both fires is equal and all geometrical features related to the fire are scaled with the same scale. Furthermore, the fires are occurring at well-ventilated conditions and the combustion efficiency is the same for both reduce scale and full scale. The last criteria are that the flow in the buoyant plume is turbulent. [13, 14]

Froude scaling do not preserve the Reynolds number, which is the ratio on inertia to viscous forces. When the Reynolds number becomes sufficiently high the viscous forces are not strong enough to damp the instabilities and turbulence occur. Since full scale flows are turbulent this must also be obtained when scaling down the model. To ensure turbulent flow, the size of the model must be big enough. The minimum height of the model for this to occur is generally about 0,3 meters. [15, 16, 17]

The Froude number is the ratio of inertial force to the Archimedes force and it is defined as:

$$Fr = \frac{\rho u^2}{\Delta \rho g l} \qquad \text{Eq. 5}$$

Or

$$Fr = \frac{u^2}{gl} \qquad \text{Eq. 6}$$

Where ρ (kg/m^3) is the density, u (m/s) is the velocity, g (m/s^2) is the gravity and l (m) is the length scale. The second expression is more used in the fire community although the first expression resembles the underlying physics more correctly than the second expression. However, the differences are no more than a numerical factor depending on the densities at hand. [16, 17] A review of scaling relationships that was based on preserving the Froude number was provided in [18] by Quintiere, and the scaling relations are:

Temperature [°C]:

$$T_m = T_f \qquad \text{Eq. 7}$$

Time [s]:

$$\frac{t_m}{t_f} = \left(\frac{l_m}{l_f}\right)^{\frac{1}{2}} \qquad \text{Eq. 8}$$

Heat release rate [kW]:

$$\frac{\dot{Q}_m}{\dot{Q}_f} = \left(\frac{l_m}{l_f}\right)^{\frac{5}{2}} \qquad \text{Eq. 9}$$

Energy [kJ]:

$$\frac{E_m}{E_f} = \left(\frac{l_m}{l_f}\right)^3$$ *Eq. 10*

Air velocity [m/s]:

$$\frac{V_m}{V_f} = \left(\frac{l_m}{l_f}\right)^{\frac{1}{2}}$$ *Eq. 11*

Mass flow [kg]:

$$\frac{m_m}{m_f} = \left(\frac{l_m}{l_f}\right)^3$$ *Eq. 12*

2.6 Wood

2.6.1 Structure

A tree trunk consists of several parts with different effects starting with the heartwood in the centre. On the outside of this comes the sapwood, cambium layer, phloem, and bark. The sapwood is the part of the tree that transports water nutrients upwards. As the tree grows and no longer needs fluid transport through the inner part of the tree the cells die and form heartwood. In types of wood like pine and oak the heartwood divide from the sapwood by having a darker colour. The heartwood in spruce divides from the sapwood only by having a lower moisture content and the difference is therefore not so great. [19]

Wood is made up of oblong cells where the material can be compared to a bundle of straws. Most part of the cells lays parallel with the longitudinal direction of the tree and form fibres called tracheid. Across these fibres, medullary ray and medullary ray cells are formed. The cells in the Nordic coniferous tree vary in length from 2-6 mm and have a diameter from 0,02-0,05 mm. Pores between the cells provide fluid transport between the cells. The pores have a membrane that makes it possible to both open and close for fluid transport. Wood holds water in two ways, known as bounded water and free water. The bounded water is found in the cellulose located in the cell wall. Free water is found in the cavity of the cell and is the first water to evaporate when the wood is dried. Pine and spruce have a moisture content of 30 % when roughly all of the free water is gone. This is called fibre saturation point. Further drying of the wood makes the bounded water evaporate. This will cause the cell walls to shrink which causes the wood to shrink. An absolute dry state is reached when both bounded and free water has evaporated. The absolute dry state is measured when the has been dried at 103 ℃. [19]

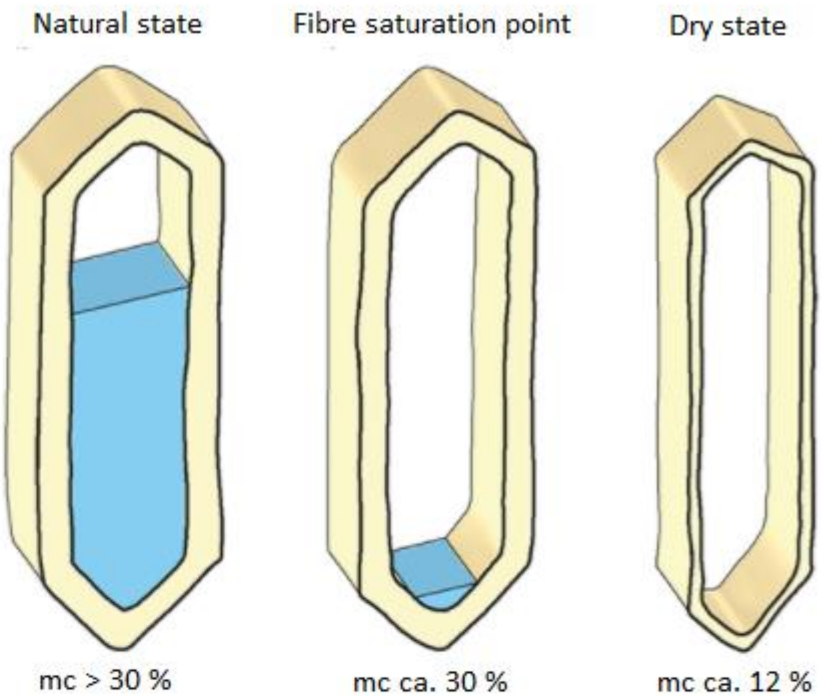


Figure 2 Illustration of moisture content (mc) in the cells [19]

2.6.2 Fuel Moisture Content

The moisture content in wood is a measure of the amount of water in the material and is expressed as a percent of the absolute dry state of the material. When used in fire-related work this is often expressed as the fuel moisture content (FMC). [19]

The fuel moisture content can be determined by using the oven dry method described in NS-EN 13183-1 [20]. The method uses the relationship between the mass of the material when containing moisture and the mass when the material has reached an absolute dry state. The procedure for this method is [20]:

1. Weigh the material and note the mass m_1.
2. Dry the material at 103°C $\pm$ 2°C until the difference in mass between weighing's separated by an interval of two hours is less then 0,1%. Note the mass m_0
3. Calculate the FMC using equation Eq. 13

$$\omega = \frac{m_1 - m_0}{m_0} \cdot 100 \qquad \text{Eq. 13}$$

Where:

m_1= is the mass of the material before drying

m_0= is the mass of the material after drying

2.6.3 Equilibrium moisture content

Wood is a hygroscopic material, meaning it will absorb or release moisture depending on the air relative humidity and temperature. When placed in an environment with steady relative humidity and temperature for a long time, the wood will reach a state where it no longer absorbs or release moisture. This is called the equilibrium moisture content (EMC). When dried at room temperature the EMC will be slightly higher than if the wood is moisture at the same temperature. Drying at higher temperatures makes this difference disappear. [21]

The equilibrium moisture content can be calculated using the work of Simpson [22].

$$EMC = \frac{1800}{W}\left(\frac{Kh}{1-Kh}+\frac{K_1Kh+2K_1K_2K^2h^2}{1+K_1Kh+K_1K_2K^2h^2}\right)(\%) \qquad \text{Eq. 14}$$

Where:

$W = 349 + 1{,}29T + 0{,}0135T_c^2$

$K = 0{,}805 + 0{,}000736T_c - 0{,}0000273T_c^2$

$K_1 = 6{,}27 - 0{,}00938T_c - 0{,}000303T_c^2$

$K_2 = 1{,}91 + 0{,}0407T_c - 0{,}000293T_c^2$

The T is temperature, h is relative humidity (%/100), EMC is moisture content (%) and W, K, K_1 and K_2 are coefficients of an adsorption model. [23]

2.6.4 Thermal decomposition of wood

Thermal decomposition is a process where the chemical composition of a material change, due to heat exposure or increased temperature in the material. [24] Before the thermal decomposition of wood can begin, the moisture content in the must be reduced. During heating of the material, the moisture in the wood will be driven out and the temperature will not increase further before most of the moisture is gone. The temperature in this phase is normally around 100°C. The time consumption for this phase depends on the amount of moisture in the material. [25]

At around 100 to 230°C, the thermal decomposition of wood starts. At this temperature, the pyrolysis process starts which is a chemical decomposition of the material. This results in flammable gases emitting from the material. As the temperature increases the process accelerates and a change to darker colour can be observed to the material. [25, 26]

The flash point is reached when the temperature reaches 230 to 260°C. This the lowest temperature where the emitted gasses mixed with air can be ignited by an ignition source. At this point the temperature and the pyrolysis is not sufficient to continue the combustion. Shortly after when the temperature reaches 260 to 290°C the fire point occurs. This is the lowest temperature where the gasses will ignite and produce sufficient gasses to continue the combustion without any external heat source. At around 350 to 400°C, gasses emitted from the wood and mixed with air will self-ignite without any contact of an ignition source such as a flame. This is also called auto-ignition. [25, 26]

2.6.5 Heat of combustion, wood

Wood is not a material with a single path of thermal decomposition and the actual response of wood heating is quite complicated. Experiments have shown that the effective heat of combustion varies as the thermal decomposition of wood continues. In the start, during the flaming combustion period the effective heat of combustion was measured to 12-15 Mj/kg. Further into the process when it is in the glowing combustion period the value increased to 30 Mj/kg. The effective heat of combustion is also influenced by moisture content in the material. [6, 27]

Experiments conducted by (Aniszewska & Gendek) [28] shows that the average effective heat of combustion in the flaming period for Norwegian spruce in dry state is 19,96 Mj/kg. To determine the heat of combustion for humid wood one can use Eq. 15. [28]

$$\Delta h_{c(humid)} = \Delta h_{c(dry)} \cdot \left(\frac{100}{100 + FMC}\right) \qquad \textit{Eq. 15}$$

FMC = fuel moisture content [%]

2.7 Acceptance criteria

Time to flashover (TFF) will in this thesis be determined based on the information give in previous chapters. The acceptance criteria for determining TTF is:

- Smoke-layer ha reached at temperature at 500-600°C
- Flames occurring at the outside of the enclosure vent
- The necessary HRR ($\dot{Q}_{Fo}$) for flashover is reached. This is calculated using Eq. 3.
    - $\dot{Q}_{Fo}$ for 1/8 scale iso-room: 8 kW
    - $\dot{Q}_{Fo}$ for 1/16 scale iso-room: 1,65 kW

3 Methods

The main purpose of this thesis is to gather more information about moisture in wood and the impact it has on a room fire. This will be done by doing experiments. Given that experiments are often time-consuming and expensive, this thesis will investigate how this can be limited but still give good results. The experiments followed trough in this thesis will therefore be scaled down 1/8 and 1/16 of an iso-room from ISO 9705-1 [29].

The experiments took place at the fire lab at Western Norway University of Applied Sciences in Haugesund. This chapter contains procedures and elements to conduct the experiments carried out for the master thesis.

3.1 Pre-experiment

Prior to the experiments it was conducted testing of what kind of material that was going to be used in the final experiments. Further on it was done simple experiments to have some idea of what size of the burner that would be reasonable to go further with.

3.1.1 Choosing material

There are several aspects of the choice of material in the experiment. The decision is based on:

- The range of fuel moisture content for the material. Is it able to obtain high and low moisture content?
- How homogeneous the material is?
    - The amount of resin, bark, knots and resin pockets
    - How similar the growth rings are throughout the slice?
    - How similar is the product between different manufactures and in different years?
- How easy it is to put together in a box of the chosen dimension
- Is the material representative for older houses

With this in mind, six different types of materials were tested for their ability to high and low moisture content. When the tests were conducted one material type was chosen based on the results and the criteria mention above. It was decided to move on with material type “spruce panel bord” shown in Figure 3. The conclusion for choosing this material can be read in Appendix 9.1.

Figure 3 Spruce panel board

3.1.2 Burner

3.1.2.1 Burner for 1/8 scale iso-room

The decision of the size of the burner is important in this thesis as this has an impact on the heat release rate which will further influence the fire growth in the rooms. The task of the burner is to ignite the rooms and release enough energy to maintain combustion in the wood so the rooms eventually reach flashover. If the start fire is too large the differences between dry and humid rooms will be less noticeable so an in-between solution was needed to be found.

Based on previous experiment, standards, Froud-scaling and initial experiment in this thesis, the size of the burner was determined. In the earlier bachelor thesis [30] conducted in 2016 a pan with dimensions $9\ cm \cdot 9\ cm$ giving a HRR of 2 kW was used in a room of ¼ scale of an iso-room. The thesis did not have any argumentation of how this pan size was chosen and is therefore only used as an indication for choosing pan size in this thesis.

To determine the size and the HRR of the burner the standard “ISO 9705-1 Test method for small room configuration” was used. The standard was not followed to the letter but only as a starting point to the final solution. The standard specifies a test method to evaluate the reaction of wall and ceiling products to fire when installed in an iso-room and exposed directly to a specified ignition source. The standard specifies using propane as an ignition source where the net heat output shall be 100 kW during the first 10 minutes and then increased to 300 kW for further 10 minutes. This thesis uses methanol as a fuel and is therefore not possible to control the heat output after ignition. Methanol is used due to its combustion efficiency which gives a clear blue flame. This makes it easier to observe when the walls and ceiling ignites.

Table 1 Fuel properties methanol [5, 31]

Combustion efficiency, χ	Heat of combustion, ΔH_c	Density,ρ
0,993	19,83 kJ/g	$719 \cdot 10^3\ g/m^3$

To have a connection between the standard and the 1/8 scale room used in this thesis the maximum net heat output of 300 kW described in the standard was evaluated. Using Froud-scaling (Eq. 9) gives that the maximum HRR in the 1/8 room should be 1,65 kW. This was assessed to be too high for the small room since it was used a 2-kW fire in ¼ scale room. The standard also gives an alternative ignition source where the maximum net heat output is set to be 162 kW. Using Froud-scaling (Eq. 9) gives that the maximum HRR in the 1/8 room becomes 0,9 kW.

Based on this information it was conducted simple free burn experiments in order to determine the size of the burner. The mass loss rate was measured and the HRR calculated using Eq. 2 and fuel properties from Table 1.The different burners that where tested had the dimension $48\ mm \cdot 48\ mm$ and $72\ mm \cdot 72\ mm$. The results from the free burning test are presented in Table 2.

Table 2 Results burner test 1

Burner size [mm]	Mass loss rate [g/s]	HRR [kW]
$48 \cdot 48$	0,038	0,76
$72 \cdot 72$	0,078	1,5

The $48\ \mathrm{mm} \cdot 48\ \mathrm{mm}$ pan was assessed to be the suitable burner size since this gave the closest result for HRR according to the scale down fire from the standard. The burner was then tested in humid room equal to those used in the final experiments. The burner was filled with 31 grams of methanol and the room had a fuel moisture content of 15,2 %. This test experiment did not end up with flashover and another solution was therefore necessary.

A new burner was built in steel having the dimensions of $55\ \mathrm{mm} \cdot 55\ \mathrm{mm}$. A room with same inner dimension as the 1/8 scale iso-room used in the experiments was built using a fire-resistant board, see Figure 4. This made it possible to measure the mass loss rate to the burner when placed in the left back corner inside the room. It was then conducted three runs with this set-up and the results is presented in Table 3. The HRR in Table 3 was calculated using Eq. 2 and fuel properties from Table 1.

Figure 4 Test room, non-combustible material

Table 3 Results burner test 2

Burner size [mm]	Methanol [g]	Time [min:sec]	Mass loss rate [g/s] ($\dot{m}$)	HRR [kW]($\dot{Q}$)
$55 \cdot 55$	26,7	10:07	0,043	0,85
$55 \cdot 55$	29	11:32	0,042	0,83
$55 \cdot 55$	33	12:44	0,043	0,85

Based on this result it was determined to go further with this burner size of $55\ \text{mm} \cdot 55\ \text{mm}$ and was the one used in the final experiments for the 1/8 scale iso-room.

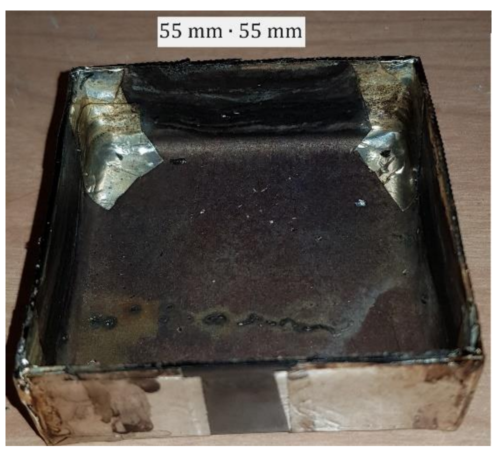


Figure 5 Burner in 1/8 scale iso-room

3.1.2.2 Burner for 1/16 scale iso-room

For the 1/16 scale experiments it was interesting to see if Froude-scaling technique could be applied to find the burner size. The HRR from 1/8 scale iso-room was used as a starting point to find the appropriate burner size for the 1/16 scale iso-room experiments. 1/16 scale is half the scale of 1/8 scale and is important to have in mind when doing the Froude-scaling calculations.

Eq. 9 was used to find the scale down HRR:

$$\frac{\dot{Q}_m}{\dot{Q}_f} = \left(\frac{l_m}{l_f}\right)^{\frac{5}{2}}$$

Where $\dot{Q}_f$ is the HRR for full scale, in this case from 1/8 scale from Table 3.

$$\dot{Q}_m = \left(\frac{l_m}{l_f}\right)^{\frac{5}{2}} \cdot \dot{Q}_f$$

$$\dot{Q}_m = \left(\frac{1}{2}\right)^{\frac{5}{2}} \cdot 0{,}85\ kW = 0{,}15\ kW$$

To find the necessary area of the burner Eq. 2 was used by isolating the A_f.

$$A_f = \frac{\dot{Q}_c}{\dot{m}'' \cdot \chi \cdot \Delta H_c}$$

The mass flux ($\dot{m}''$) was found by dividing the mass loss rate ($\dot{m}$) to the area of the burner from Table 3. This gives a mass flux at 14 g/m^{2}s. Combustion efficiency (χ) and heat of combustion (ΔH_c) for methanol from Table 1.

$$A_f = \frac{0{,}15\ kW}{14\frac{g}{m^2 s} \cdot 0{,}993 \cdot 19{,}83\ kJ/g} = 0{,}00054\ m^2$$

The dimensions for the burner were found by taking the square root of the area which gives $0{,}023\ m \cdot 0.023\ m$.

The amount of fuel to put in the burner depends on the preferred burning time. The burning time was scale down using Eq. 8. The burning time for the burner in the 1/8 scale experiments was around 11 min and 30 sec or 690 s. For small scale this becomes:

$$t_m = \left(\frac{l_m}{l_f}\right)^{\frac{1}{2}} \cdot t_f$$

$$t_m = \left(\frac{1}{2}\right)^{\frac{1}{2}} \cdot 690\ s = 488\ s\ or\ 8\min and\ 13\ s$$

The mass flux of 14 g/m^{2}s was multiplied with the scale down time and area of burner which gives 3,6 grams of methanol, rounded up 4 grams. 4 grams divided with the density of methanol from Table 1 gives the volume of $5{,}056 \cdot 10^{-6}\ m^3$. The height of the burner:

$$height = \frac{Volume}{length \cdot width} = \frac{5{,}056 \cdot 10^{-6}\ m^3}{0{,}023\ m \cdot 0{,}023\ m} = 0{,}095\ m\ or\ 9{,}5\ mm$$

By using the method of Froude-scaling combined with results from the 1/8 scale experiments the dimension of the burner in 1/16 scale becomes $23\ mm \cdot 23\ mm \cdot 9{,}5\ mm$. This dimension is not possible to buy and therefore had to be made by the author. A few millimetres were added to the height to avoid spilling and the burner made had the dimension $24\ mm \cdot 24\ mm \cdot 14\ mm$. To determine the exact HRR for this burner size the burner was filled with 4 grams of methanol and burnt in a free burning condition. This test burned for 4 min and 45 sec giving a mass loss rate $(\dot{m})$ of 0,014 g/s. Using Eq. 2 for calculating the HRR and fuel properties from Table 1 gave a HRR of 0,275 kW. This HRR was above the scale down HRR of 0,15 kW and a new burner with a smaller dimension had to be built.

Table 4 Results burner test 3

Burner size [mm]	Methanol [g]	Time [min:sec]	Mass loss rate [g/s] $(\dot{m})$	HRR [kW]$(\dot{Q})$
$19 \cdot 19 \cdot 19$	4,6	09:30	0,008	0,157
$19 \cdot 19 \cdot 19$	4,59	09:20	0,0082	0,16
$19 \cdot 19 \cdot 19$	4,6	09:33	0,0082	0,16

Table 4 gives the result for the new burner dimension that was built. The tests were conducted inside the room in Figure 4. Both the burning time and the HRR was acceptable from the scale down calculations and was therefore decided to use this burner size when starting the 1/16 scale experiments. This was not the final solutions of the burner size and the reason for this will be presented in chapter 4.2 and discussed in chapter 5.

3.2 Room size

The rooms were built in spruce panel board and hold together using screws and patent band. It was scaled down 1/8 of an iso-room and therefor had the inner dimension $450\ mm \cdot 300\ mm \cdot 300\ mm$. At the front wall, it was cut out a door opening where the height was 250 mm and the width was 100 mm. An illustration of the room is shown in Figure 6. The production of the room is closer described in Appendix 2, Production of rooms. The 1/16 scale of iso-room was built in the same way but had the inner dimension $225\ mm \cdot 150\ mm \cdot 150\ mm$ and a door opening of $125\ mm \cdot 50\ mm$.

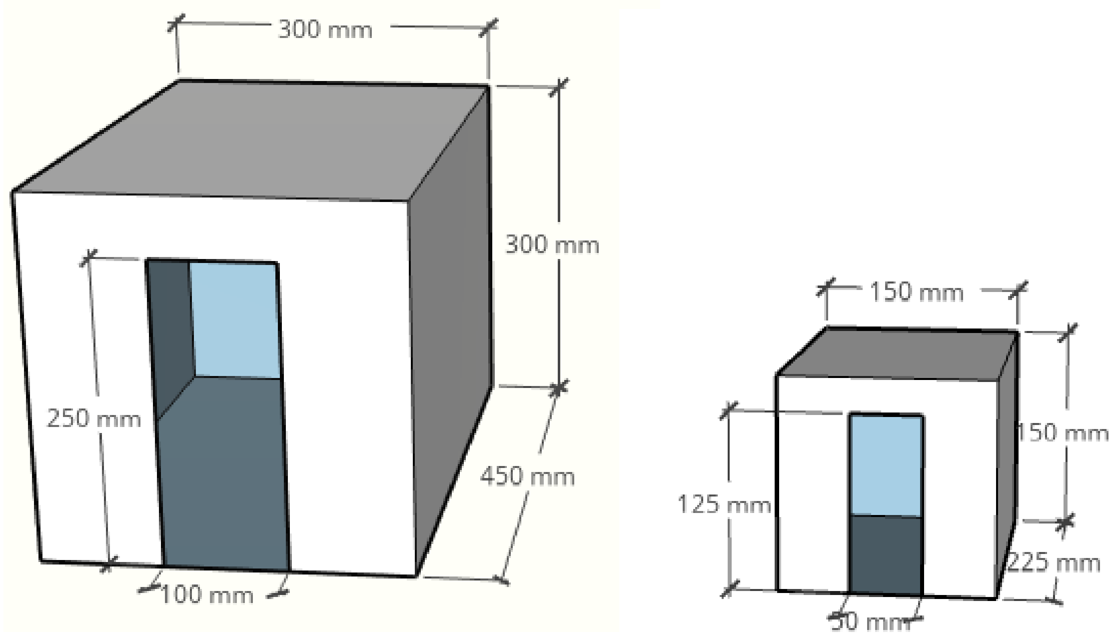


Figure 6 Room dimension: Left:1/8 scale, Right: 1/16 scale

3.3 Preparation of the rooms

The outside corners were taped with aluminium tape to prevent smoke leaking from other places than the door. All the rooms were marked with a number and the door that was cut out got the same number as the room it came from. The rooms and the belonging door were placed in the same climates for four days before used in the experiment. The doors were used as a reference to the room to determine the FMC in the rooms. The procedure for setting the preferred climate is described below.

3.3.1 Humid room

To set a humid environment it was built a tent in plastic, similar to a greenhouse. The tent had the dimension $1500\ mm \cdot 700\ mm \cdot 900\ mm$. Inside the tent it was placed a humidifier that was set to 80% relative humidity. In addition, it was placed a simple fan to get circulation in the air. The temperature was measured on regular basis and had a steady temperature at 20°C +-1°C. Three rooms with their belonging doors were put in the tent at the same time. The rooms laid on their side with small pieces of wood underneath to avoid contact with the concrete floor.

Figure 7 Climate tent

The climate tent in Figure 7 was easily built using a table, plastic (damp-proof membrane) and some tape to hold it together. The table plate was removed and the plastic was wrapped around the remaining construction.

3.3.2 Medium dry room

The medium dry rooms were put in the same tent as used for the humid rooms. The climate was controlled by using a dehumidifier that was set to 50 % relative humidity. The relative humidity outside the tent was around 40 % which made the humidity in the tent going down. To stabilize the relative humidity at 50 % a pan with water was placed inside the tent to add humidity. The pan of water had a surface area of $0{,}3\ m^2$. Three rooms were placed in the same way as the humid rooms.

3.3.3 Dry rooms

To get a dry climate, it was used an environmental chamber type Termaks kb 8400 f [32]. The settings on the chamber were set to 20 % relative humidity and 40 °C. This high temperature was set to avoid unnecessary stress to the dehumidifier and to reduce the time for climatizing the rooms.

3.4 Determine FMC

To determine the fuel moisture content in the rooms it was used the method described in chapter 2.6.2. Since the rooms were going to be burned it was not able to use this method directly to the rooms. However, the door related to each room was placed in the same environment as the rooms and could therefore be used as a reference to the connected room.

When the rooms were taken out of the preferred environment the doors were taken out as well and weighted immediately and the mass (m_1) was noted. Further on, the doors were put in an oven and dried at a temperature at $103℃ \mp 2$ until the difference in mass between two successive weighing's separated by an interval of 2 hours was less than 0,1%. The FMC was then calculated using Eq. 13.

The oven used for drying the door was a normal oven found in every home kitchen. The door of the oven stayed slightly open to release the moisture. Inside in the centre of the oven, it was mounted a single thermocouple to monitor the temperature to assure that it was stable at $103℃$.

Figure 8 Oven used to dry the doors

3.5 Experimental Set-up

The set-up was placed under a ventilation hood to vent the smoke out. The room was placed on top of a weight. Between the weight and the room, it was placed a 50 mm thick fire resistance plate to protect the weight from the heat. The burner was placed in the left back corner of the room. It was placed ten thermocouples inside the room and four in the door opening. An illustration of the experimental setup is showed in Figure 9.

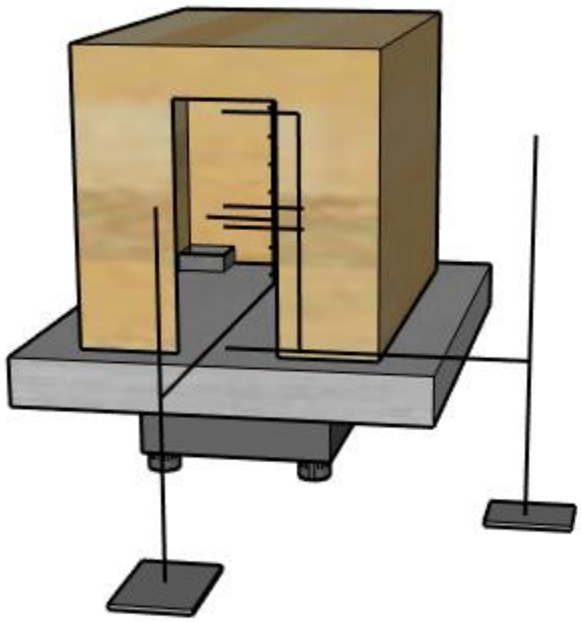


Figure 9 Experimental set-up

3.5.1 Equipment

Thermocouples:

During the experiments it was used thermocouples of the type K 1 mm [33], to measure the temperature. The response time for 1 mm thermocouples was found to be 5 seconds. See chapter 9.5 for determination of response time.

In order to get a good understanding of the temperature in the room, it was used a total of 14 thermocouples. Thermocouples 1-9 was placed in centre room at different heights, 10-13 was in the door opening and number 14 was placed above the burner. To be able to get the number of thermocouples and to not block the door opening too much, it was necessary to make a custom-made stand. This was also necessary to avoid that the thermocouples made contact with the construction and the weight. The exact placement of the thermocouples is shown in the Table 5. The small dimension in 1/16 scale made it difficult to mount the same number of thermocouples as in 1/8 scale. It was therefore determined to use only three thermocouples in the 1/16 scale. These was placed in the centre of the room with the distance 0,5 cm, 5 cm and 13 cm from the ceiling.

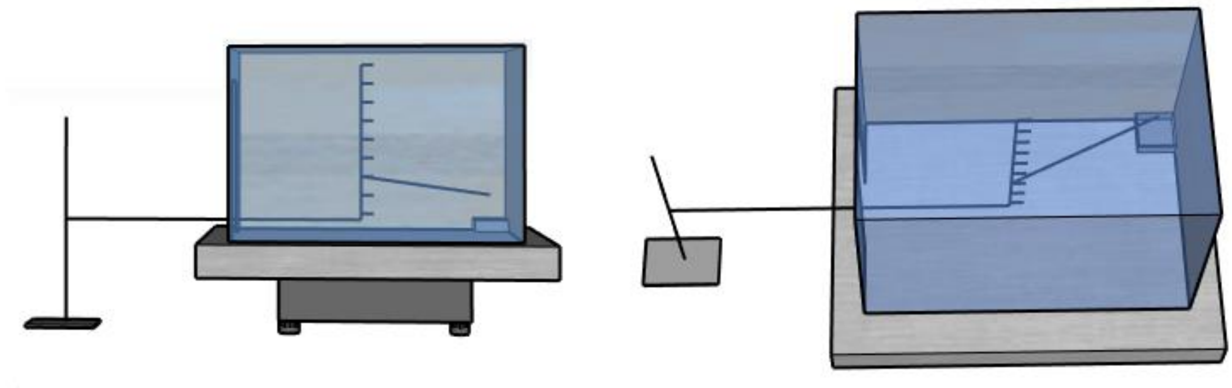


Figure 10 Illustration of thermocouples inside the room

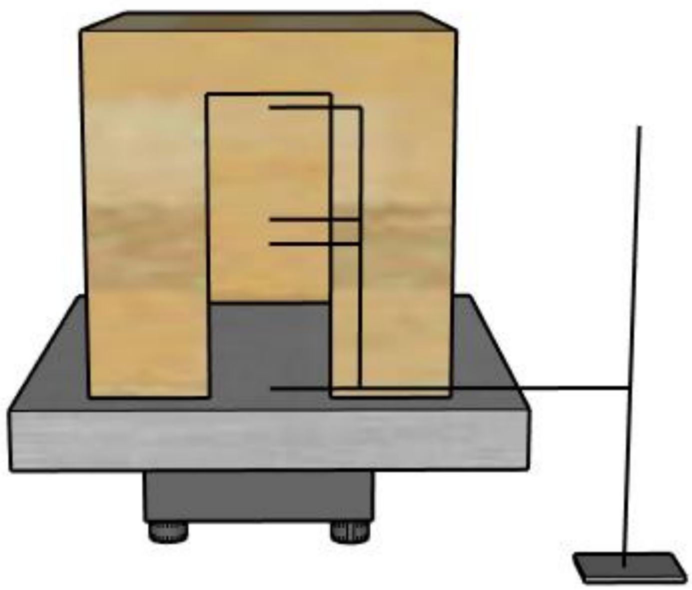


Figure 11 Illustration of thermocouples at the door opening

Table 5 Location of thermocouples in 1/8 scale experiments

Placement of thermocouples	
Centre room	
Thermocouple	Height from roof (cm)
1	25
2	22
3	19

4	16
5	13
6	10
7	7
8	4
9	1
Door opening	
Thermocouple	Height from floor (cm)
10	1
11	13
12	15
13	24
Over burner	
1 cm from the corner and 6 cm from the floor	

Weight: During the experiment the mass was measure in order to calculate the mass loss rate. The weight was type KERN DS 30K0.1L with weighing capacity of 30 kg [34]. The weight was connected to a computer and the data was registered at an interval of five seconds.

Data logger: During the experiments it was used the Keysight 34970A Data Acquisition. The data logger switch register and convert the measurements from the thermocouples. The frequency of the measurement was set to every five second. The datalogger was connected to a computer where the measurements were registered in the data program BrannDatalog6 v6.3 and presented in an Excel-file. [35]

Burner: See chapter 3.1.2.

Igniter: To ignite the methanol, it was used a one meters long stick with isolation dipped in methanol at the tip. The igniter was light up and carefully inserted into the room and ignite the methanol.

Humidity and temperature measurement: Before the experiments started the ambient temperature and humidity was measured using Extech Instruments RH390. [36]

Safety equipment: On the day that the experiments were completed the smoke ventilation system was on. During the experiments the effect of the fan was increased. The participants wore fire resistance gear and used face mask for smoke protection. A fire hose was rolled out and ready for use if needed.

3.6 Procedure

For each experiments a procedure plan was followed in order to maintain control and make the experiments as similar as possible. The procedure plan used is showed in the table under (Table 6). Information and observations of each experiments was noted before and during the experiments in a note-sheet, see Table 7. The time from taking the rooms out of the humidity chamber to starting the experiments took about five minutes for each experiment.

Table 6 Procedure plan

Procedure		
Nr.	**Task**	**Status**
1	Turn of the fire alarm system	
2	Turn on the fan	
3	Get the extinguish water ready	
4	Check every thermocouple	
5	Prepare the igniter	
6	Note the RH and temperature in the fire lab	
7	Place the burner and tare the weight	
8	Fill the burner with methanol and note the weight	
9	Start the logger	
10	Weigh the door and place the room on the weight	
11	Push the burner into the corner	
12	Start the camera	
13	Ignite the burner	
14	When the room has reached flashover, end the experiment	

Table 7 Information & Observation

File name:	Date:	Time ignition [HH:MM:SS]:

Fire lab RH %: Temperature:	

	Nr.	Mass [g]	From climate		Time taken out [HH:MM:SS]
			RH%	Temp [°C]	
Room					
Door					
	Type	Methanol [g]	Mass door after drying at 100+-3°C:		
Burner					

Observation	**Time [min:sec]**
Ignition walls	
Smoke out door	
Ignition roof	
Ignition roof second time	
Smoke layer reaches 600 °C TC 7, TC 8, TC 9	
Flame out door	
Continuous flame out door	
Flashover	
Other observations:	

3.6.1 Overview experiments

There were conducted 17 experiments where 10 of them was in 1/8 scale iso-room and 7 was 1/16 scale iso-room. An overview of the experiments is presented in Table 8. in addition, five initial experiments of 1/8 scale iso-room was conducted to determine the size of the burner.

Table 8 Overview experiments

Exp	Scale	Burner size [mm]	Methanol [g]	From climate		FMC [%]	Fire lab	
				RH%	Temp [°C]		RH [%]	Temp [°C]
1	1/8	55 · 55 · 19	33	20	40	6,4	44,3	15,5
2	1/8	55 · 55 · 19	33,3	20	40	6,5	43	16
3	1/8	55 · 55 · 19	32,5	20	40	6,7	28	15,4
4	1/8	55 · 55 · 19	33,7	56,6	20,7	11,4	27,8	15,9
5	1/8	55 · 55 · 19	33,2	54	20	11,9	28	15,5
6	1/8	55 · 55 · 19	33	54	20,6	11,3	26,8	16,1
7	1/8	55 · 55 · 19	33,8	80	20	16	43,6	15,7
8	1/8	60 · 60 · 16	33,2	75	17,8	14,3	52,8	15,2
9	1/8	55 · 55 · 19	33	76	18	14,4	53,2	15,6
10	1/8	55 · 55 · 19	32,7	75	18	14,6	43,6	16,4
11	1/16	19 · 19 · 19	4,6	75	20	16,3	32,2	17,3
12	1/16	21 · 21 · 19	5,53	75	20	15,3	31,2	17,4
13	1/16	24 · 24 · 19	8	75	20	15,9	31,1	17,4
14	1/16	24 · 24 · 29	11,55	75	20	15,8	28	17,8
15	1/16	24 · 24 · 29	11,49	20	40	6,1	23,9	18,5
16	1/16	24 · 24 · 29	11,54	20	40	6,1	28,8	15,6
17	1/16	24 · 24 · 29	11,49	20	40	6,1	28,3	15,9

4 Results

4.1 1/8 scale iso-room

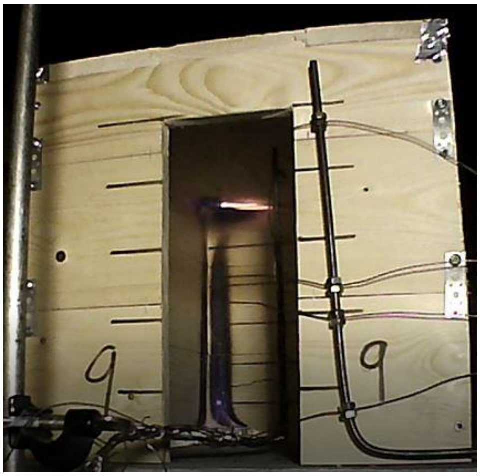
4.1.1 Observations

Table 9 Observations 1/8 scale

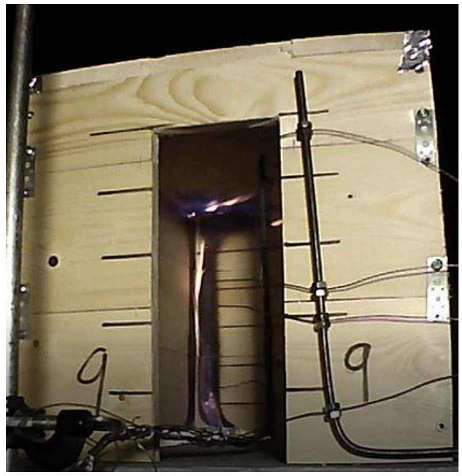
Exp ->	1	2	3	4	5	6	7	8*	9	10
FMC %	6,4	6,5	6,7	11,4	11,9	11,3	16	14,3	14,4	14,6
Ignition walls	00:51	00:59	00:57	01:22	01:04	01:06	01:25	02:00	01:56	02:49
Ignition roof	01:50	01:45	01:50	02:55-03:15	02:05-03:00	03:20	02:55-03:20	02:38	03:50-04:35	03:43-05:45
Ignition roof 2nd time	x	x	x	03:35-05:50 10:20	04:25	x	04:15-05:45		06:35	07:20
Flame out door	04:50	04:30	04:40	12:12	07:17	07:20	x	06:00	09:55	09:10
Continuous flame out door	05:00	04:53	05:03	12:35	07:40	07:38	x	06:25	10:13	09:40
Burner stops	11:26	11:30	10:47	12:10	11:20	11:21	13:10		11:33	11:31

Exp 10, 04:10 min, Resin dripping from roof and ignites at the floor, filling the room with smoke. The dripping resin burns in 1 min and 23 sec. Exp 8 deviates from the other experiments, having a bigger burner size ($60\ mm * 60\ mm * 16\ mm$) than the others. In exp 4 the second ignition of the roof retreated after 05:50 min. This resulted in a third ignition of the roof after 10:20 min which then went to flashover.

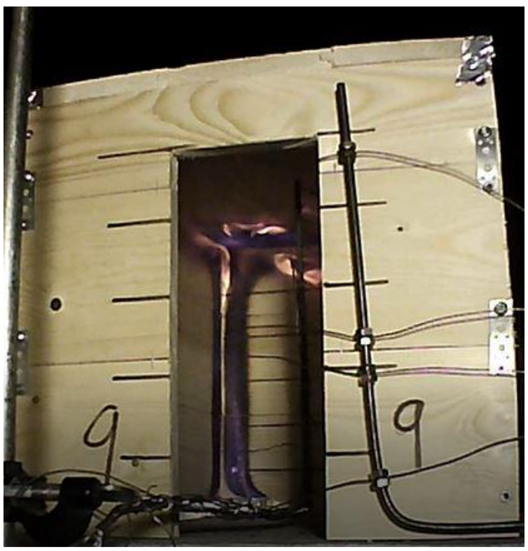
3 min 50 sec



4 min 5 sec



4 min 20 sec



4 min 35 sec

Figure 12 Observations during experiment 9 (FMC 14,4 %)

4.1.2 Temperature

Figure 13 shows the temperature development as a function of the time. Each graph represent a experiment with their FMC. The temperature in Figure 13 is measured in the center of the room, one centimeter from the ceiling.

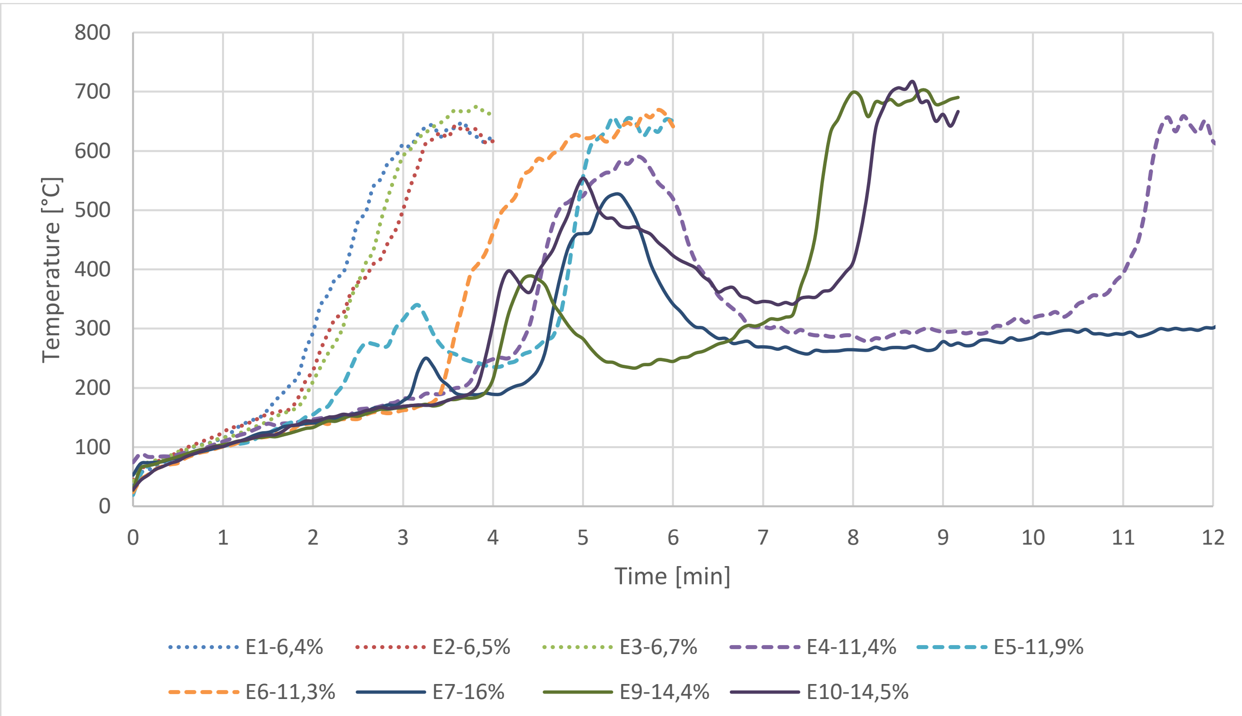


Figure 13 Temperature development I (E1-6,4% = Experiment 1-FMC)

Figure 14 shows temperature development as function of time with different FMC, ranging from 6,4 to 16 %. The figure gives the temperature development in the centre of the room at different heights. Each graph represents the distance from the thermocouple to the ceiling.

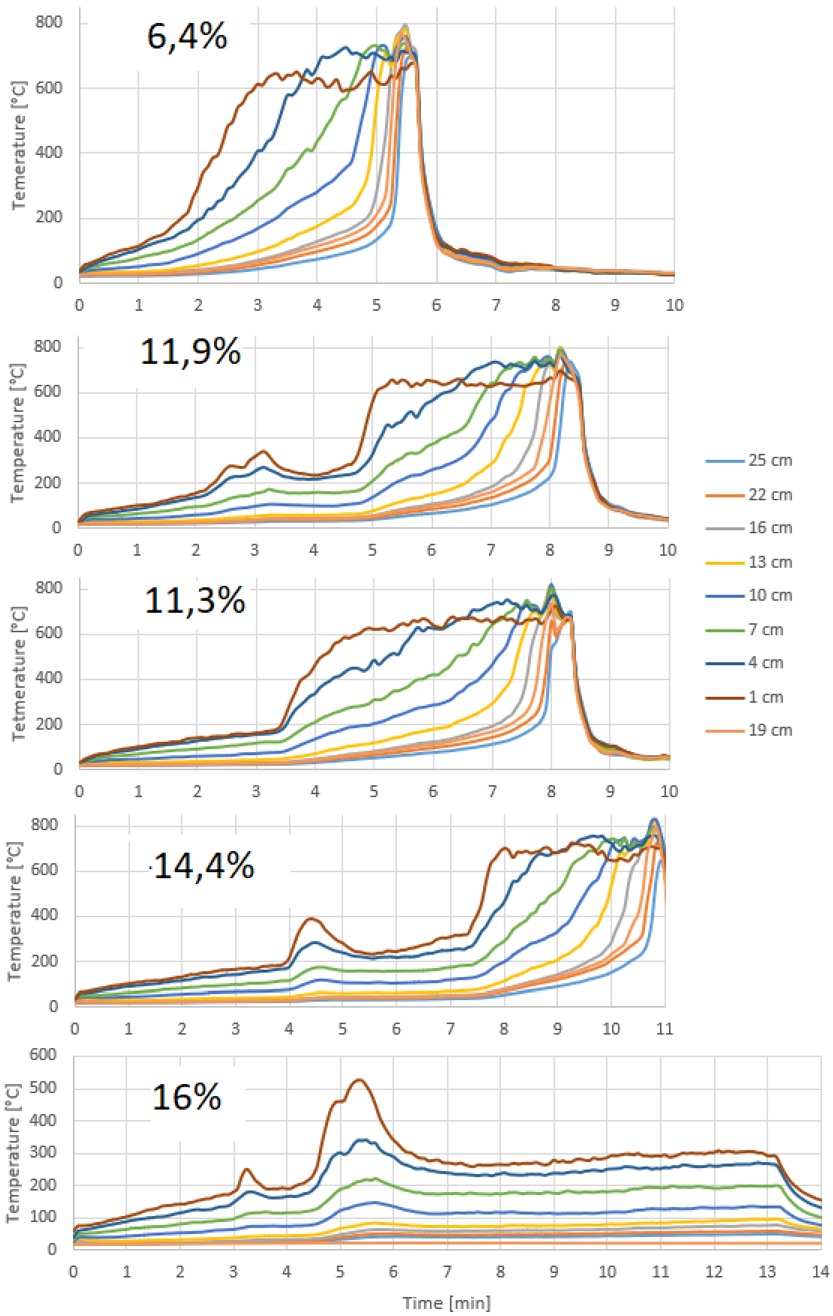


Figure 14 Temperature development II

Figure 15 shows the measured temperature in the smoke-layer and gives an indication to when flashover occurs, i.e., when the temperature has reached 600°C. The graphs represent the experiments conducted with different FMC.

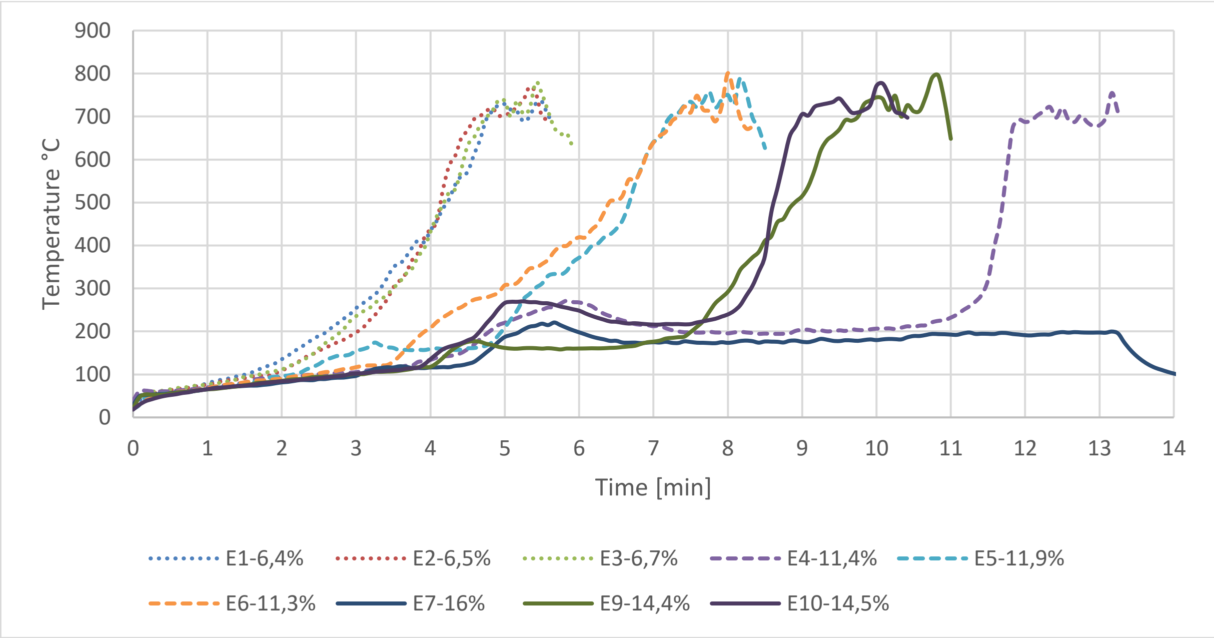


Figure 15 Temperature in smoke layer

Figure 16 gives the temperature in the flame from the start fire as a function of time. The measurement is done 1 cm from the corner and 6 cm above the floor.

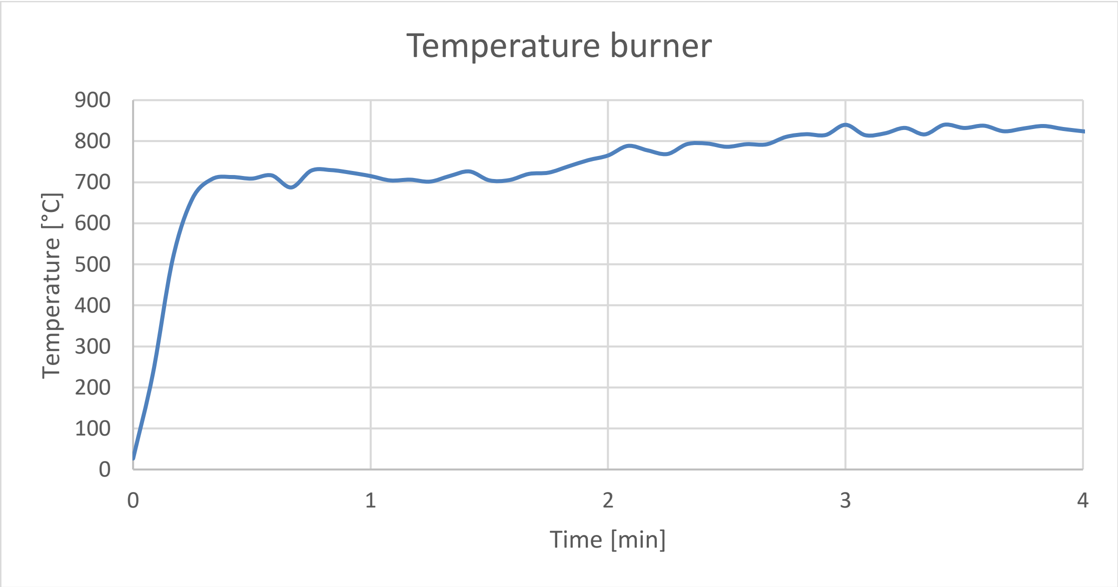


Figure 16 Temperature start fire

4.1.3 Heat release rate

Figure 17 represent the heat release rate ($\dot{Q}$) as a function of time. The graphs represent the experiments conducted with different FMC. The HRR is calculated using Eq. 2 where the combustion efficiency (χ) assumed to be 0,7. The mass loss rate ($\dot{m}$) was measured during the experiments. The heat of combustion for wood ($\Delta h_{c(humid)}$) was calculated for each experiment using Eq. 15. The dotted line in the diagram represents the predicted HRR ($\dot{Q}_{Fo}$) to obtain flashover and was calculated using Eq. 3.

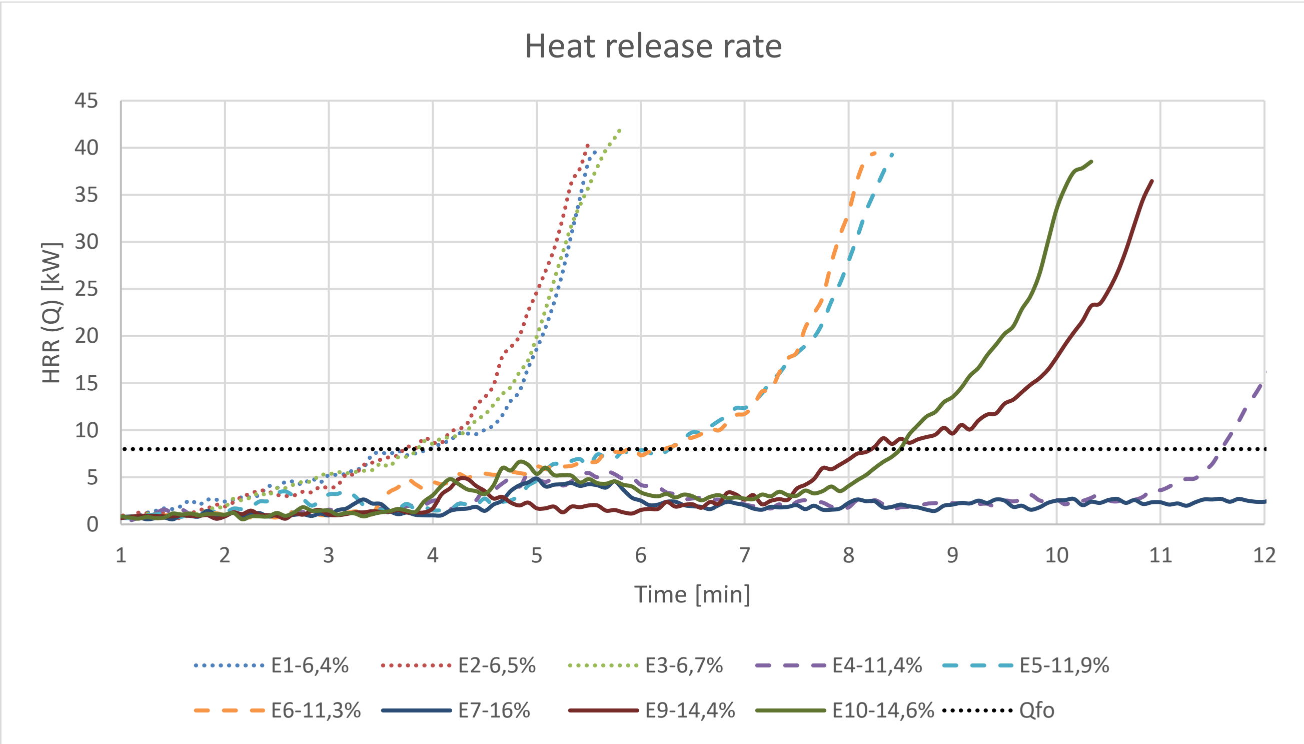


Figure 17 Heat release rate

Figure 18 represent the heat release rate ($\dot{Q}$) as a function of time. The contiguous graphs represent the experiments conducted with different FMC. The dotted lines are the adjusted polynomial function for each of the experiment. The figure shows the derived of the functions at a short time after flashover has occurred which illustrates that the slope numbers decrease as the FMC increases.

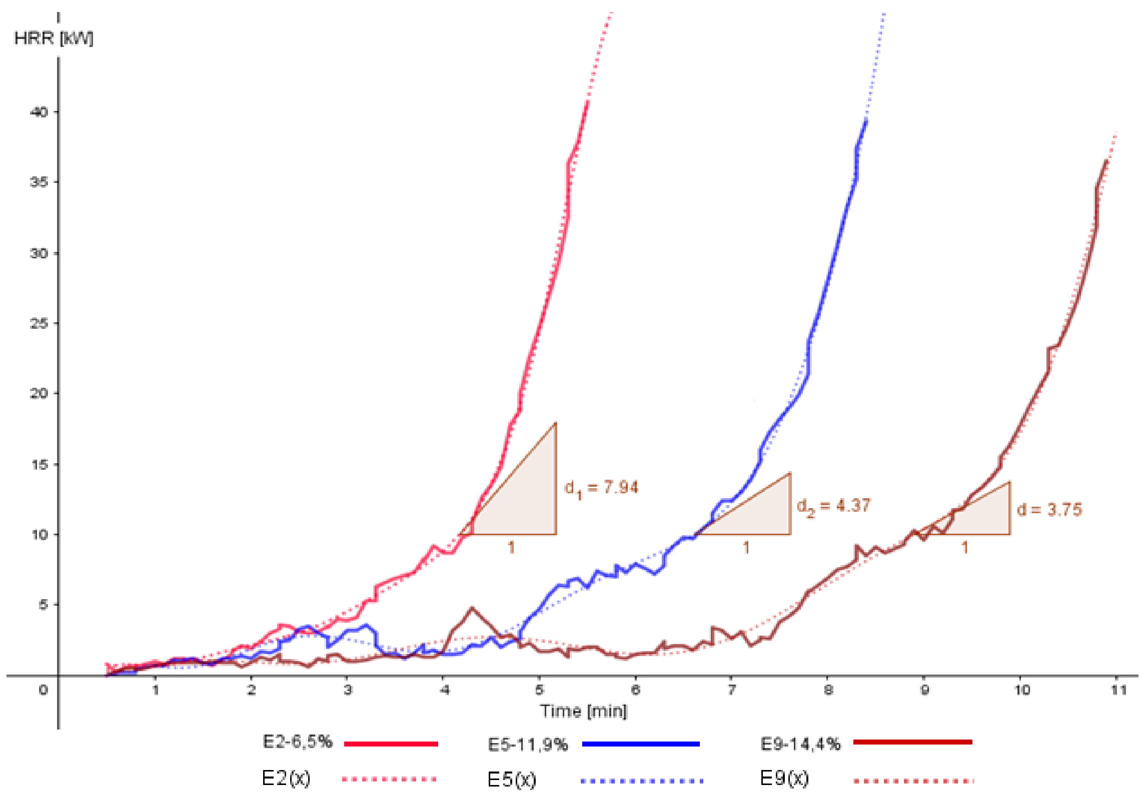


Figure 18 Heat release rate & slope numbers

4.1.4 Flashover

Figure 19 gives the time to flashover as a function of the fuel moisture content. The figure gives a summary of the obtained results and the TFF is evaluated based on the acceptance criteria's given in chapter 2.7.

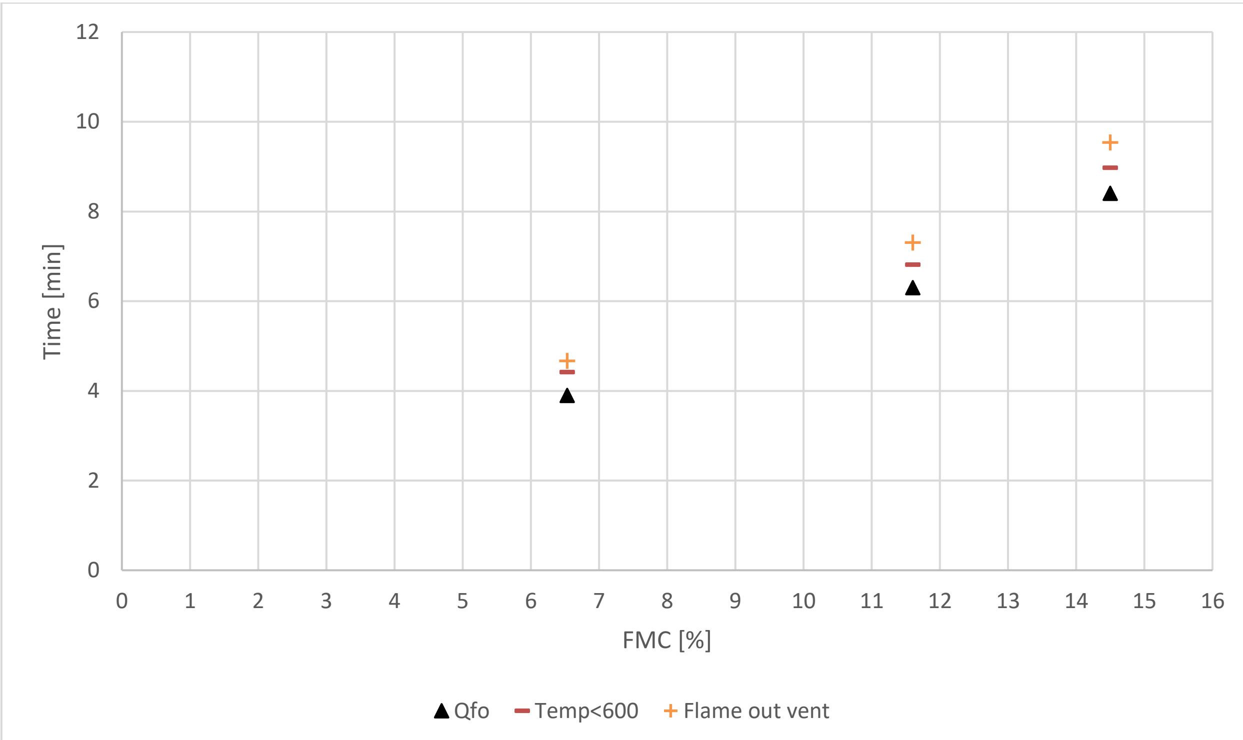


Figure 19 TFF as function of FMC

Figure 20 shows the fire development after the first flame was observed at the outside of the door opening for experiment 1 and 9 having an FMC respectively of 6,4 % and 14,4 %.

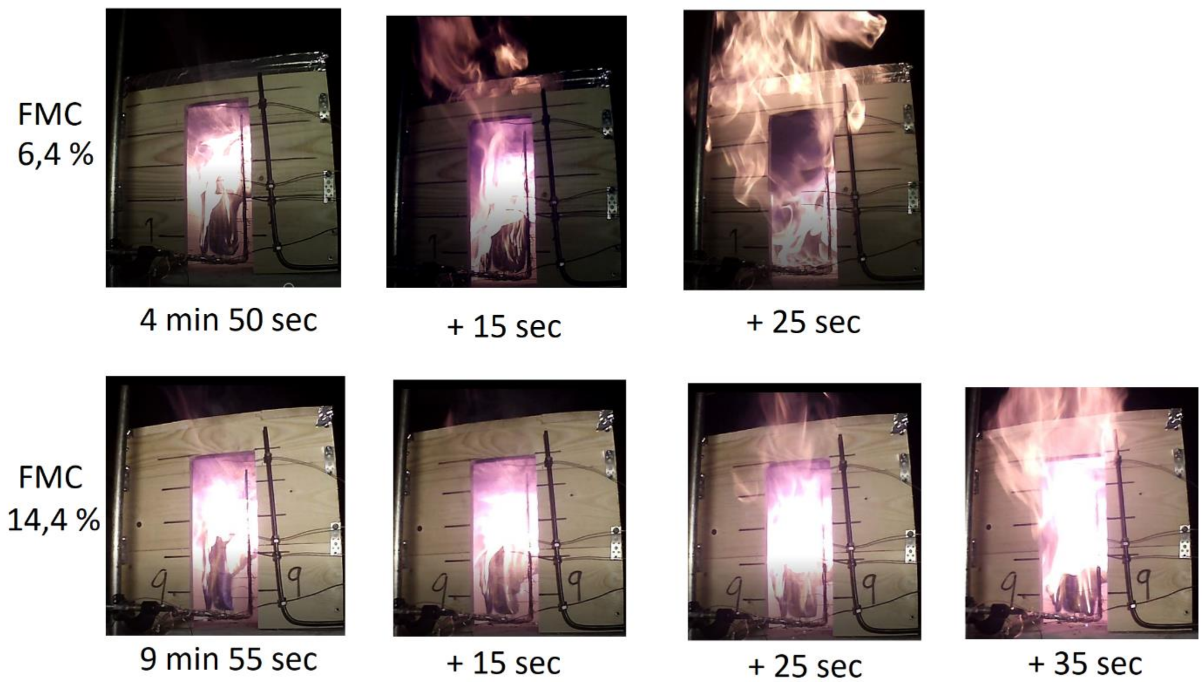


Figure 20 Post Flashover fire for Exp 1 and Exp 9

4.2 1/16 scale iso-room

The burner size found in chapter 3.1.2.2 was used when starting the experiment for 1/16 scale iso-room. Experiment 11, which was the first experiment in 1/16 scale had this burner size and did not go to flashover. A new burner was made to increase the HRR and had the dimensions $21\ \mathrm{mm} \cdot 21\ \mathrm{mm} \cdot 19\ \mathrm{mm}$ which gave a HRR of 0,17 kW. This was then used in experiment 12 but neither this resulted in flashover. This led to a new burner size with dimension $24\ \mathrm{mm} \cdot 24\ \mathrm{mm} \cdot 19\ \mathrm{mm}$ and HRR of 0,2 kW and was used in experiment 13. The burner stopped before the room reached flashover. It was added more methanol to the burner and 40 seconds after the burner stopped it was reignited and shortly after the room reached flashover. It was decided to increase the height of the previous burner to increase the burning time. The last burner made, and the one used in experiment 14-17 had the dimension $24\ \mathrm{mm} \cdot 24\ \mathrm{mm} \cdot 19\ \mathrm{mm}$ with a HRR of 0,2. (See Ch.9.4 for testing of the different burner size)

4.2.1 Observations

Table 10 Observations 1/16 scale

Exp ->	11	12	13	14	15	16	17
HRR of Burner [kW)	0,16	0,17	0,2	0,2	0,2	0,2	0,2
FMC %	16,3	15,3	15,9	15,8	6,1	6,1	6,1
Ignition walls					00:57	01:03	
Ignition roof	03:54-04:26	03:10-03:45	02:00-03:00	05:13-06:56	01:13-02:42	01:03-01:48	01:00-02:04
Ignition roof 2nd time			04:06-05:30	09:30-14:36	04:01	02:44	03:01
Flame out door			16:48		06:52	06:10	06:11
Continuous flame out door			17:28		07:40	06:54	06:52
Burner stops	10:33	10:15	12:05	16:55	14:10	15:00	14:57

Figure 21 Exp 11 (left) & Exp 12 (right) after first ignition of ceiling

4.2.2 Temperature

Figure 22 shows the temperature development in the smoke-layer as a function of the time. Each graph represent a experiment with their FMC.

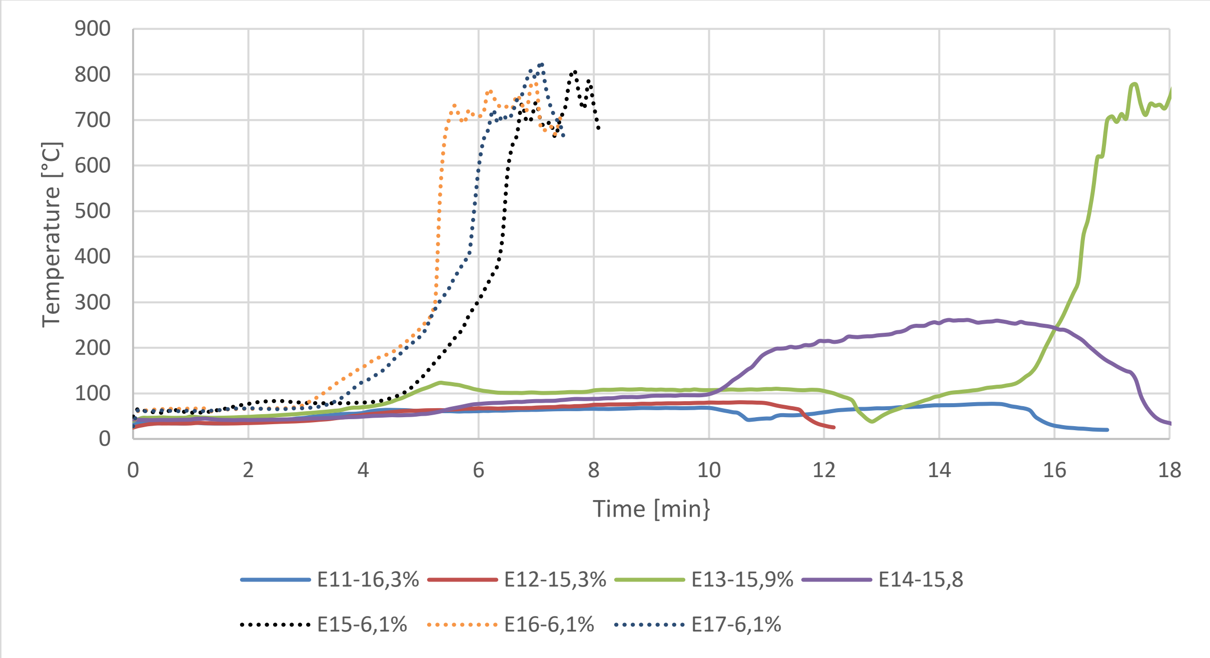


Figure 22 Temperature in smoke layer

4.2.3 Heat release rate

Figure 23 represent the heat release rate ($\dot{Q}_c$) as a function of time. The graphs represent the experiments conducted with different FMC. The HRR is calculated using Eq. 2 where the combustion efficiency (χ) assumed to be 0,7. The mass loss rate ($\dot{m}$) was measured during the experiments. The heat of combustion for wood ($\Delta h_{c(humid)}$) was calculated for each experiment using Eq. 15. The dotted line in the diagram represents the predicted HRR ($\dot{Q}_{Fo}$) to obtain flashover and was calculated using Eq. 3.

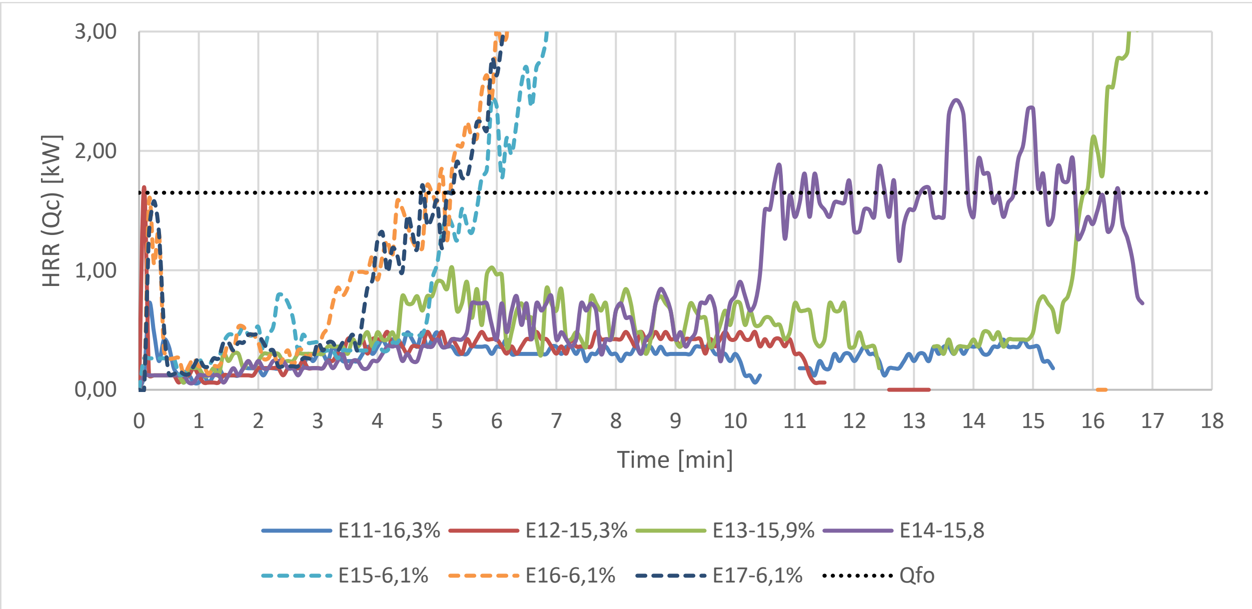


Figure 23 Heat release rate

4.2.4 Flashover

Figure 24 gives the time to flashover as a function of the fuel moisture content. The figure gives a summary of the obtained results and the TFF is evaluated based on the acceptance criteria's given in chapter 2.7. The figure only gives the result from the dries rooms since this was the only experiments that got flashover.

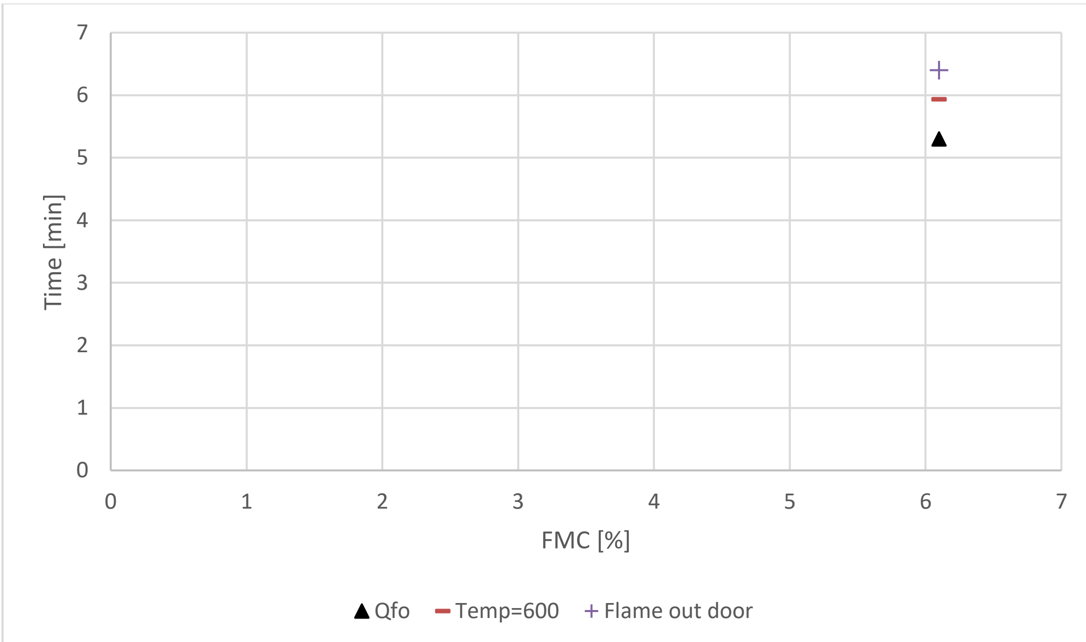


Figure 24 TTF as function of FMC

4.3 Results, earlier work

In this chapter it is presented results from previous bachelor thesis conducted in 2016 [30]. The bachelor thesis investigated how FMC influences fire development and time to flashover in wooden compartments of about ¼ scale of iso-room from ISO 9705-1. The results presented will be used to compare the result from this thesis to evaluate similarities and differences.

The room used in the bachelor thesis was built using 18 mm pine glulam boards and had the inner dimension of $900\ mm \cdot 600\ mm \cdot 600\ mm$ with a door opening in the front having the dimension $200\ mm \cdot 400\ mm$. Correctly scaling would give a door height of 500 mm instead of 400 mm. The burner that was used had the dimension $90\ mm \cdot 90\ mm$ and was filled with 200 grams methanol which had a HRR of 2 kW. The thesis did not use Froude-scaling technique to determine the HRR of the scale down burner. If Froude-scaling had been applied the burner should had a HRR of 5 kW when scaling from the alternative ignition source from ISO 0705-1 [29].

Figure 25 gives the temperature development as a function of time from the ¼ scale experiment in the bachelor thesis.

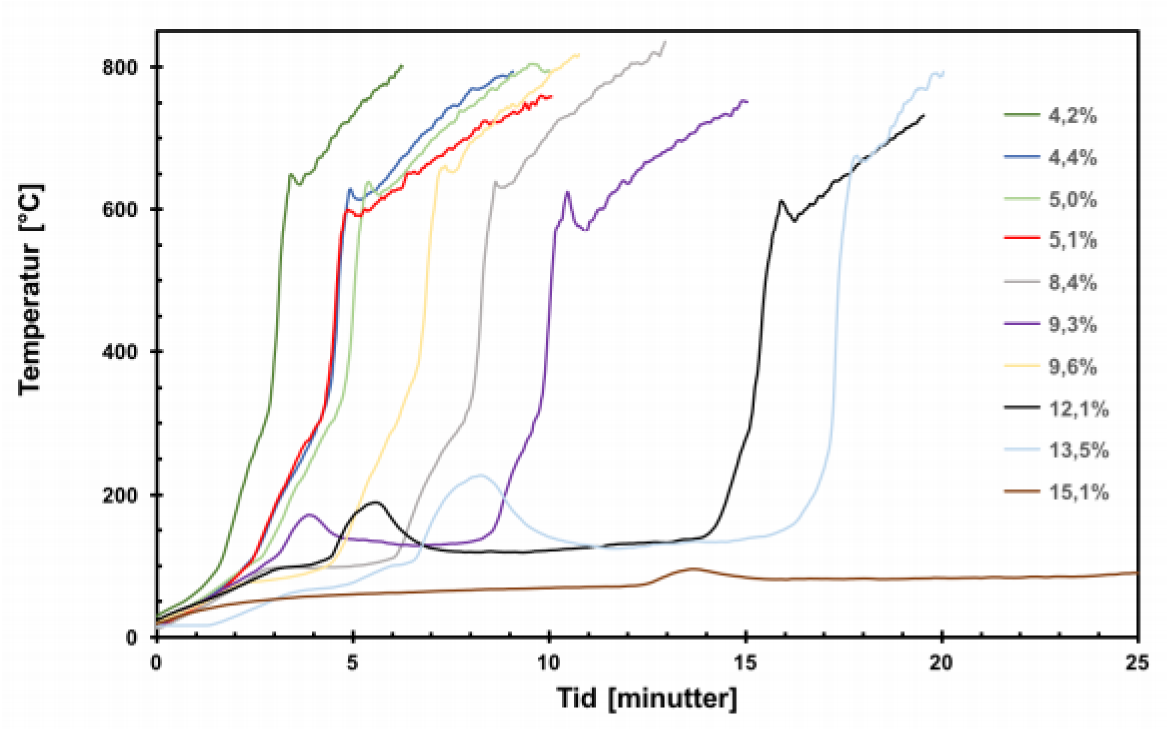


Figure 25 Temperature development [30]

Figure 26 gives the time to flashover as a function of the fuel moisture content in the wood. Each graph represents the scale of the compartment and is the trend line of the obtained results. “1/4 scale” is the trend line from the bachelor thesis and “1/8 scale” is the trend line from this thesis.

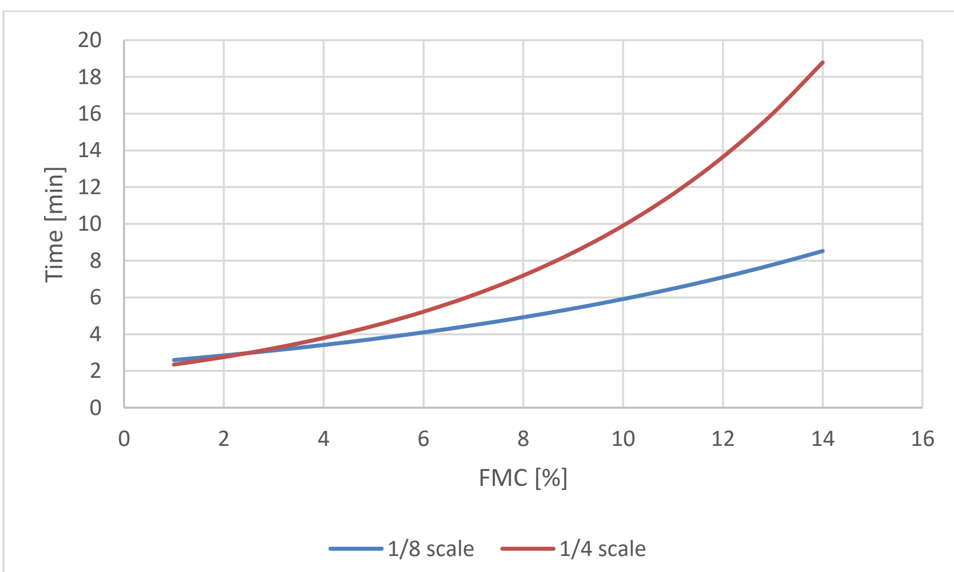


Figure 26 Compared results of TFF

5 Discussion

5.1 Fire development

The fire development in the experiments gives a good reflection of what one can expect from theory and full-scale configuration. After ignition the fire grows and the temperature increases gradually. After some time, a rapid increase in the temperature occurs, indicating the transition from growth phase to fully develop fire, known as flashover. After flashover the temperature stabilizes at around 700-800°C. The different stages take both longer time and occurs later on in the fire as the FMC increases, showing that the FMC influences the fire development, as illustrated in Figure 13 and Figure 14. Results shows that by increasing the FMC from 6,5 % to 11,6% the time to flashover increases from 4 min to 7 min. A further increase of 3 % in FMC i.e., 14,5 % FMC, the TFF increase to 9 minutes.

Figure 17 represent the heat release rate ($\dot{Q}$) as a function of time where each graph represents the FMC in the wood. The figure shows clearly that by increasing the FMC, the growth rate at pre flashover will be less. The reason for this is that the fire uses more energy to evaporate the water and the combustion process will therefore be slowed down. At post flashover the growth rates are more similar for the different FMC but still smaller for the most humid rooms. Figure 18 shows that after a short time after flashover has occurred, the slope numbers decrease as the FMC increases. This indicates that not all of the water has evaporated and the FMC still influence the fire for a short time even after flashover has occurred. Observations presented in Figure 20 shows that at post flashover the fire develops at a slower for rate in the humid room compared to the dry room. Furthermore, its observed larger flames outside the door opening for the driest room.

During the experiments, it was observed that for the most humid rooms and some of the medium humid rooms, that after ignition of the ceiling it looked like the fire was growing and heading for flashover. Instead, the flames retreated and stopped entirely 30-60 seconds later. At this time, the fire still dependent on the start fire to continue the combustion process and a second ignition in the room takes some time depending on the FMC. These observations can be related to the bumps in the growth phase, seen in Figure 13 and Figure 14. The collage in Figure 12 also shows this interesting observation. When the first ignition of the ceiling above the burner occurs, the temperature close to the ceiling increases. This increased temperature causes large amount of moisture in the wood to evaporate which results in a greater heat loss to the fire. As a result, the energy needed to continue the combustion process is too low and the fire does not spread further. During this period a charred layer in the walls and ceiling above the burner has established. This charred layer protects the underlying unburnt wood, which slows down the combustion process. Figure 21 shows how the state of the rooms is after first ignition of the ceiling has ended. A clear charred layer can be observed in the ceiling where the burner was located. A faint brown colour in the ceiling has occurred where the hot flames has been before retreating.

This event does not depend solely on the FMC but also on the HRR of the start fire. In experiment 8 the FMC was high (14,3%) but after the first ignition of the roof, the fire continued to grow. The reason for this is that this experiment had a bigger burner size which resulted in a higher HRR of the star fire. In the dry rooms at 1/16 scale, this event did occur due to the small burner size, although having a very low HRR.

Experiment 4 differs from the other experiments with the same FMC. This experiment takes a longer time to flashover, compared to the experiments having the same FMC and also for the experiment having higher FMC. The reason for this may lie in the first ignition of the ceiling. The first ignition of the roof occurred after 02:55 but retreated after 20 seconds due to the FMC and charring. The second ignition of the room was at 03:35 min, which is 20 seconds after the first ignition had stopped. During this time frame more of the surface area close to the fire had heated up. When the second ignition occurred, a greater surface area was therefore included in the combustion process, causing a larger surface of charred wood to establish. This explanation is strengthened by the high temperature measured during the second ignition (see Figure 13 graph E4-11,4%). The third ignition then takes a considerably longer time due to the greater surface of the charred layer combined with the FMC, which protects the underlying wood.

Observation during the experiments shows that the time to ignition in walls and ceiling increases as the FMC increases. The time to ignition at the wall is not that noticeable between the dry rooms and medium dry rooms. This is first noticeable when the FMC reaches 14,5 % where the time to ignition takes 1-2 minutes longer than the driest room. The most noticeable difference between the various FMC is the time to the ceiling ignites. It follows a clear trend where the time increases as the FMC increases. After ignition of the burner, the flame quickly reaches 700°C (see Figure 16). Because of the high temperature, the moisture in the wood near the external flame evaporates quickly. As a result, the properties of the wood near the flame become relatively similar for the various experiments shortly after ignition. This explains why the time difference to ignition of the wall does not vary as much despite having different FMC in the beginning. The ceiling being further away from the external flame results in reduced heat flux to the surface. As a result, the moisture in the wood takes longer time to evaporate, and the time to ignition in the ceiling increases as the FMC increases.

5.2 Time to flashover

The three criteria's set for predicting flashover seems to coincide within the same time frame for both dry, medium humid and humid rooms (see Figure 19). The criteria "Q_{Fo}" gives the shortest time to flashover as this is the minimum HRR required for flashover. The criteria "Flame out vent" has the longest time to flashover. This criterion is based on observation and human error may occur. Overall, the three criteria's gives a good approximation of when flashover occurs.

The heat release rate in 1/16 scale for experiment 14 shows that the HRR is above Q_{Fo} despite that flashover occurred in this experiment. Unstable reading of the mass during this experiment may be the explanation for this.

5.3 Comparing ¼ scale and 1/8 scale

Comparing the result from this thesis and the previous work conducted in the bachelor thesis show that it's a clear pattern between these two configurations. By comparing the temperature development from Figure 13 and Figure 25 it seen that the fire development follows the same pattern for both of the thesis. Both theses experienced an increased temperature followed by a decrease early in the growth phase for the most humid rooms. This early increase-decrease illustrates the ceiling igniting where flames spreads but then retreats shortly after. The reason for this is discussed in chapter 5.1.

Comparing the time to flashover in Figure 26 it is seen that the TFF for ¼ scale overall takes longer time than the 1/8 scale experiments. The biggest difference is seen at the highest FMC where the time TFF is almost twice as high for the ¼ scale. According to Froude-scaling the start fire in ¼ scale is smaller than the start fire in 1/8 scale relative to the compartment size. As mention in 4.3 the start fire in ¼ would have been 5 kW if Froude-scaling had been applied. If this start fire had been used the TFF would be less and the results would probably been more similar to the ones conducted in this thesis. The time difference of TFF between ¼ and 1/8 scale is less at the lower FMC. When the FMC is this low the time to evaporate the moisture take shorter time and the heat loss from the start fire is reduced. After the moisture has evaporated both start fires produces sufficient energy to ignite the wood. The door height relatively to the compartment size is lower in the bachelor thesis than this thesis. A lower door height causes more hot gases to gather in the ceiling before they are vented out. This causes a faster increase of the temperature in the smoke-layer which results in a shorter TFF.

5.4 Small scale experiments

The results from the 1/16 scale experiments shows that the rooms with highest FMC the fire doesn't evolve and go to flashover. In addition, the driest rooms take longer time to flashover compared to the driest rooms in the 1/8 scale. This indicates that the start fire has a HRR which is not sufficient enough to evaporate the moisture and igniting the wood before the fuel is used. The heat loss due evaporation of the moisture and the total energy to ignite the wood does not change when the same type of wood is used. This is because the conductivity of the wood does not scale. More fuel would have resulted in a longer burning time but then an increased height of the burner would been necessary. The burner in use, already had a height which was 1/5 of the room height and an increased height would have resulted in a start fire not representable for full scale experiments. A higher HRR of the start fire would also be a solution to achieve flashover but then it would deviate from the Froude-scaling.

The experiments carried out in 1/8 scale have proven to be an appropriate size with few problems throughout the process. Due to its low dimension, it makes it easier to assemble and set up. However, when scaling further down to 1/16 scale some challenges do appear and working with these small dimensions most of process becomes a struggle. The small door opening made it hard to make a stand that holds the thermocouples and at the same time didn't take too much space. This also made it difficult to have all the thermocouples as wished and the number therefore had to be reduced. The small burner was difficult to make due to the very small dimension and for the same reason, made it hard to fill the burner without spilling any methanol.

The 1/8 was a relatively easy scale to work with and made the preparation process effective. Due the low dimension the work becomes a one-man job in contrast to large scale where an extra hand is needed. The material used in this thesis had a dimension which made the assembling process a bit time consuming. When doing these experiments for educational purpose only, a different type of material can be used in order to make the assembling more effective. A recommended set-up for educational purpose can be seen in 9.3.

5.5 Uncertainty/ limitations

The experiments are limited to only one type of material and that only walls and ceiling can be ignited. The experiments still provide a good approach of how the FMC will affect the fire development.

The humid chamber which was used to moisture the material didn’t had the feature to control the temperature inside the chamber. It therefore relied on being placed in a room with steady temperature which is a slightly disadvantage but not a big problem.

The weight measured both the mass loss of the methanol and the burning wood and the HRR is therefore a combine effect of these two.

6 Conclusion

The experiments conducted in this thesis shows that the fuel moisture content influences the fire development and time to flashover. Results shows that by increasing the FMC from 6,5 % to 11,6% the time to flashover increases from 4 min to 7 min. A further increase to 14,5 % FMC, the TFF increase to 9 minutes. The effect of the FMC is greater in the pre-flashover period, but results shows that it also influences the post flashover fire. It is therefore a basis for assuming that the FMC will affect further fire spread.

The moisture content causes an increase heat loss of the start fire due to evaporation of the moisture. This delays the pyrolysis process which delays the time to ignition. During the flaming combustion a charred layer is established which slows down the combustion and protects the underlying wood. For the most humid rooms it was observed that after ignition of the ceiling the flames retreated and stopped entirely 30-60 seconds later due to the FMC.

The Froude-scaling technique proves to be a good method for scaling the fire. Results shows that scaling down to 1/8th scale via Froude-scaling and ISO 9705-1 provides a good representation of the full-scale fire phenomenon. When scaling further down to 1/16 scale it is difficult to get a connection between the small scale and the full scale. The main reason being that the HRR of the start fire is too low to evaporate the moisture and ignite the wood. In addition, the 1/16 scale has such low dimension which make all the elements in the experiment difficult to implement.

The 1/8 scale has shown to be a good scale to conduct these experiments in and is the lowest recommended scale for these experiments. Scaling down the experiments has shown to be an effective and economical way to do experimental study.

7 Further work

For further work it would be interesting to do the experiments in ½ scale and full scale. In larger scale its worth considering using propane in the start-fire to make it easier to control the HRR and to make it more similar to ISO 9705-1.

The material used in this thesis is untreated wood and for most cases when using wood as surface linings, the material is treated with either oil, wood stain or paint. It would therefore be interesting to see the effect of the FMC when the wood it treated with some common surface products.

Another case to could be to examine the fire spread to exterior facade with different FMC.

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9 Appendix

9.1 Appendix 1, Choosing materials

It was tested six different materials to determine what kind of material to use in the experiments. The test-slices were put in different environments to see how able they were to get low and high fuel moisture content. The method used to moisture the test slice and determine the FMC was equal to the one described in chapter 3.3 and 3.4.

The different type of material that was teste is shown in the table below.

Front	Cross section
Spruce Panel Board	
	
Spruce Sawn Timberboard	

Pine Panel Board, with knots

Pine Panel board

Pine glulam board, with knots

Fibreboard

Table 11 Test slice results with high RH

Fuel moisture content when RH 77% and 21,5 °C						
Test slice	Material	m1 [g]	m0 [g]	FMC %	Average	Standard deviation
1	Spruce Panel Board	209,85	183,52	14,35		
2	Spruce Panel Board	214	187,57	14,09		
3	Spruce Panel Board	210,71	185,13	13,82	14,09	0,2
4	Spruce Sawn Timber Board	415,43	363,54	14,27		
5	Spruce Sawn Timber Board	426,32	375,65	13,49		
6	Spruce Sawn Timber Board	423	367,38	15,14	14,30	0,7
7	Pine Panel Board, with knots	263,89	234,48	12,54		
8	Pine Panel Board, with knots	240,6	215,23	11,79		
9	Pine Panel Board, with knots	269,05	240,74	11,76	12,03	0,4
10	Pine Panel Board	265,33	233,76	13,51		
11	Pine Panel Board	267,72	235,94	13,47		
12	Pine Panel Board	267,6	232,53	15,08	14,02	0,8
13	Pine Glulam Boards, with knots	558,45	502,13	11,22		
14	Pine Glulam Boards, with knots	548,8	492,9	11,34		
15	Pine Glulam Boards, with knots	543,16	491,54	10,50	11,02	0,4
16	Fibreboard, Forestia	579,87	531,03	9,20		
17	Fibreboard, Forestia	584,81	530,8	10,18		
18	Fibreboard, Forestia	578,37	529,01	9,33	9,57	0,4

Table 12 Test slice results medium RH

Fuel moisture content when RH 40% and 21,5 °C						
Test slice		m0 [g]	m1 [g]	FMC %	Average	Standard deviation
1	Spruce Panel Board	183,95	201	9,3		
2	Spruce Panel Board	182,36	200,6	10,0		
3	Spruce Panel Board	184,28	201,8	9,5	9,6	0,3
4	Pine Panel Board	232,51	251,6	8,2		
5	Pine Panel Board	239,51	260,1	8,6		
6	Pine Panel Board	234,97	256,7	9,2	8,7	0,5
7	Fibreboard	529,54	566,2	6,9		
8	Fibreboard	534,8	571,2	6,8		
9	Fibreboard	522,17	563,7	8,0	7,2	0,5
10	Pine Glulam Board, with knots	494,35	535,1	8,2		

11	Spruce Sawn Timberboard	365,28	398,1	9,0		
12	Spruce Sawn Timberboard	369,26	405,8	9,9		
13	Spruce Sawn Timberboard	372,94	406,3	8,9	9,3	0,4

Table 13 Test slice results low RH

Fuel moisture content when RH 20% and 40 °C						
Test slice		m0 [g]	m1 [g]	FMC %	Average	Standard deviation
1	Spruce Panel Board	183,95	194,4	5,7		
2	Spruce Panel Board	182,36	193,7	6,2		
3	Spruce Panel Board	184,28	194,9	5,8	5,9	0,2
4	Pine Panel Board	232,51	244	4,9		
5	Pine Panel Board	239,51	252,5	5,4		
6	Pine Panel Board	234,97	248,4	5,7	5,3	0,3
7	Fibreboard	529,54	556,3	5,0		
8	Fibreboard	534,8	561,3	4,9		
9	Fibreboard	522,17	554,5	6,2	5,4	0,6
10	Pine Glulam Board, with knots	494,35	521,4	5,5		
11	Spruce Sawn Timberboard	365,28	386,4	5,8		
12	Spruce Sawn Timberboard	369,26	394,3	6,8		
13	Spruce Sawn Timberboard	372,94	395	5,9	6,2	0,4

Discussion

Fuel moisture content when RH 77% and 21,5 °C:
Results shows that "Spruce Sawn Timber Board" has the highest fuel moisture content with an average of 14,3 %. Test slice "Spruce panel board" is just behind with an average of 14,09 % FMC. The spruce panel board is also the material with lowest standard deviation. The pine panel board also contain a high FMC but with greater variety. This may due to that pine has heartwood which differs from spruce that is quite equal trough the cross section.

Fuel moisture content when RH 20% and 40 °C:
In this condition the test slices obtain quite similar results were pine panel board and fibreboard manage to have the lowest FMC. The Spruce Panel Board isn't far behind and also has the lowest deviation.

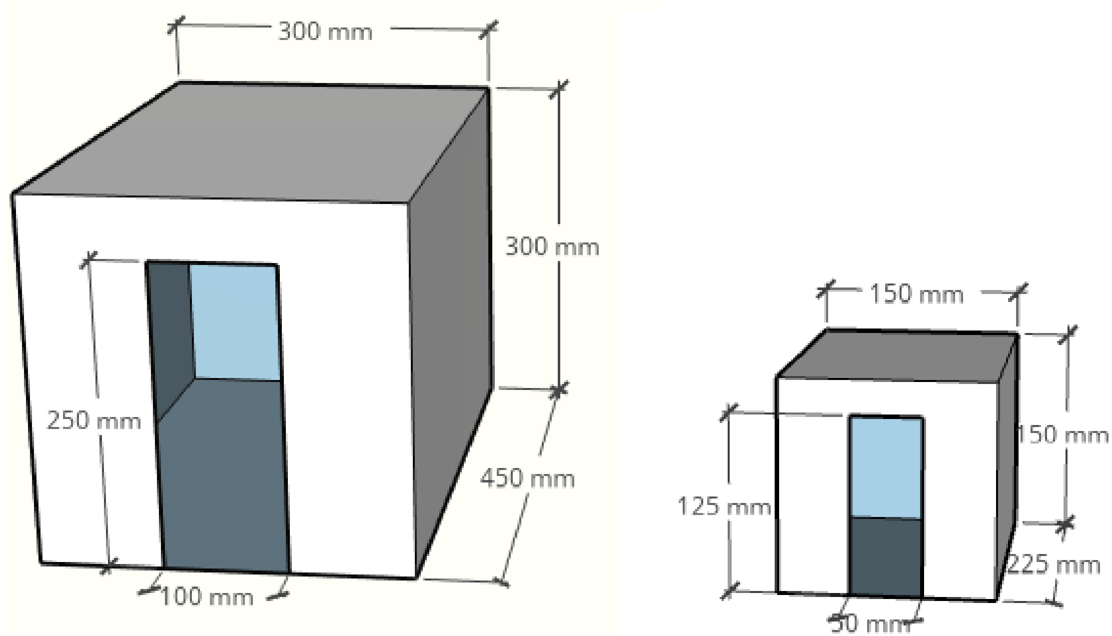
Conclusion

Based on these results it seems like it would be reasonable to use spruce panel board in the final experiments. This material has the highest and most stabile FMC at 77% RH and the lowest deviation at 20% RH. It needs shorter time in the humidity chamber which will save some time.

It’s easy to cut the material such that there at little to none grains in the material which makes it more homogenous. Further on the material has no heartwood which supports this assumption. It’s easy to put together and is quite representative to the material used in indoor walls of older building.

9.2 Appendix 2, Production of rooms

The rooms have the dimension of 1/8 scale 1/16 scale of an iso-room. For the 1/8 scale the inner dimension is $450\ mm \cdot 300\ mm \cdot 300\ mm$ with a door opening of $100mm \cdot 250\ mm$. For the 1/16 scale the inner dimension is $225\ mm \cdot 150\ mm \cdot 150\ mm$ with a door opening of $50mm \cdot 125\ mm$. The door opening is located at the centre of the front wall. An illustration of the rooms is given in the picture below.



Tools and material for building the rooms:

- Spruce panel board
- Screwdriver
- Screws (30 mm)
- Patent bond
- Saw

Production:

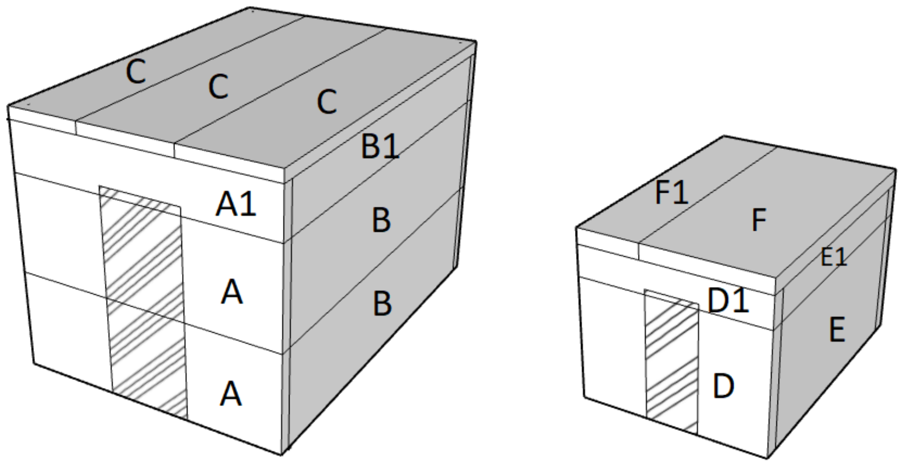


Figure 27 Assembling instruction

Element	Length [mm]	Width [mm]	Amount
	1/8 scale		
A	330	120	4
A1	330	60	2
B	450	120	4
B1	450	60	2
C	480	120	3
	1/16 scale		
D	180	120	2
D1	180	30	2
E	225	120	2
E1	225	30	2
F	255	120	1
F1	255	60	1

Let the material acclimatize for at least five days before the assembling. Start by cutting all the pieces. Screw the pieces together like illustrated in Figure 27. Cut out the door and tape all the joints using aluminium tape to avoid smoke leakage

9.3 Appendix 3, Alternative experiment for teaching purpose

In this section it is presented three alternative set-up which can be used as a demonstration for educational purpose. The set-ups are a simplified version of the 1/8 scale experiment conducted in this thesis. The simplified version is almost in 1/8 scale but have a slight change in dimension because it is used a different material type. This is done to simplify and shorten the assembling process. The material used is pine glulam board which is 18 mm thick. This comes in different width and lengths and can be bought at most stores that sells material. The door dimension is $100\ mm \cdot 250\ mm$. To obtain hight FMC, use the method in 3.3.1 and to get low FMC use either the method in 3.3.3 or the one used in [30].

It is recommended to use a burner with the dimension $55\ mm \cdot 55\ mm \cdot 22\ mm$ and fill it with 40 grams of methanol or 50 ml. The burner can be made out of 1 mm thick steel plate. Cut the hatched fields as shown in Figure 28 and bend the walls. Tape the inner and outside corners with aluminium tape to avoid leakage.

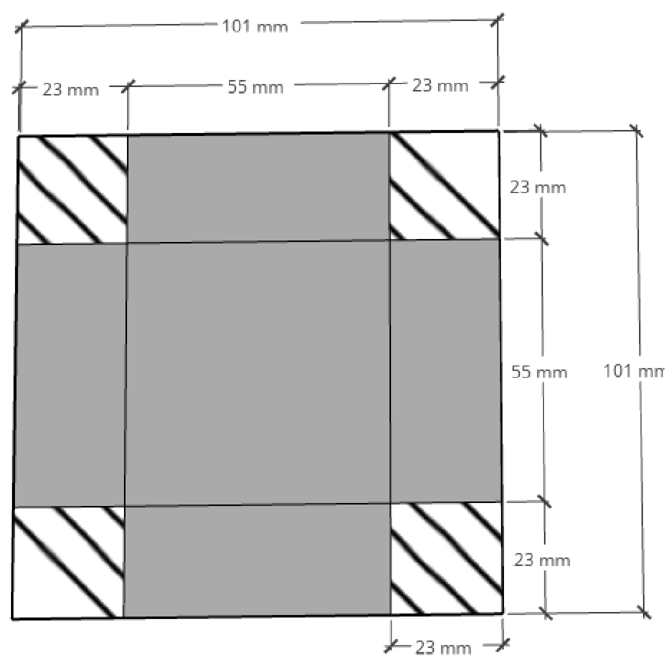


Figure 28 Alternative Burner

9.3.1 Alternative 1

Alternative 1 involves using only one length of pine glulam board having the dimension $300\ mm \cdot 2400\ mm$. Inner dimension then becomes $450\ mm \cdot 264\ mm \cdot 300\ mm$. This alternative is 36 mm shorter in width than a correct 1/8 scale room. Cost for building one room is about 270 kr.

The room is assembled as Figure 29 illustrates and the different elements is cut as Figure 30 shows.

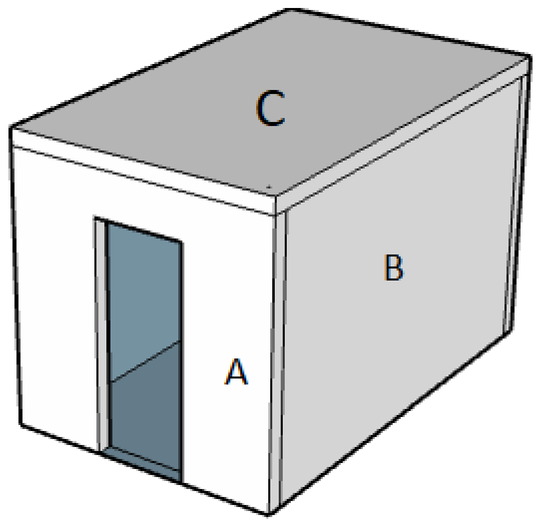


Figure 29 Alternative 1

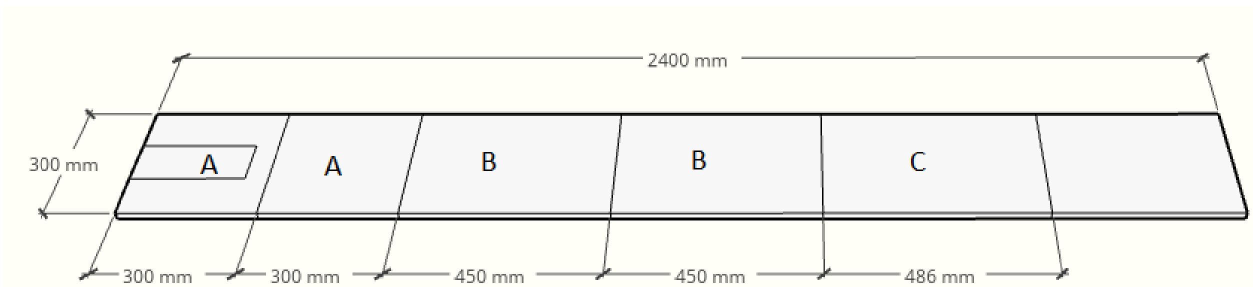


Figure 30 Dimensions of the elements

9.3.2 Alternative 2

Alternative 2 involves using two pine glulam board. The first one having the dimension $500\ mm \cdot 1200\ mm$ and the second one the dimension is $300\ mm \cdot 800\ mm$. The inner dimension then becomes $464\ mm \cdot 300\ mm \cdot 300\ mm$. This alternative is 14 mm longer than the correct 1/8 scale. Cost for building one room is about 350 kr.

The room is assembled as Figure 32 illustrates and the different elements is cut as Figure 31Figure 30 shows.

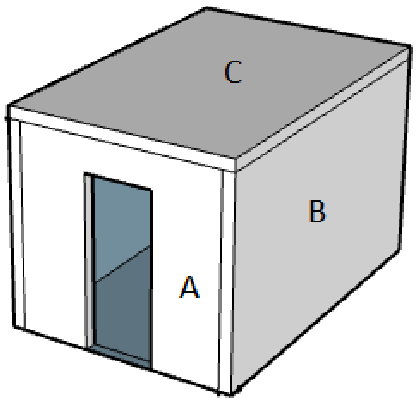


Figure 32 Alternative 2

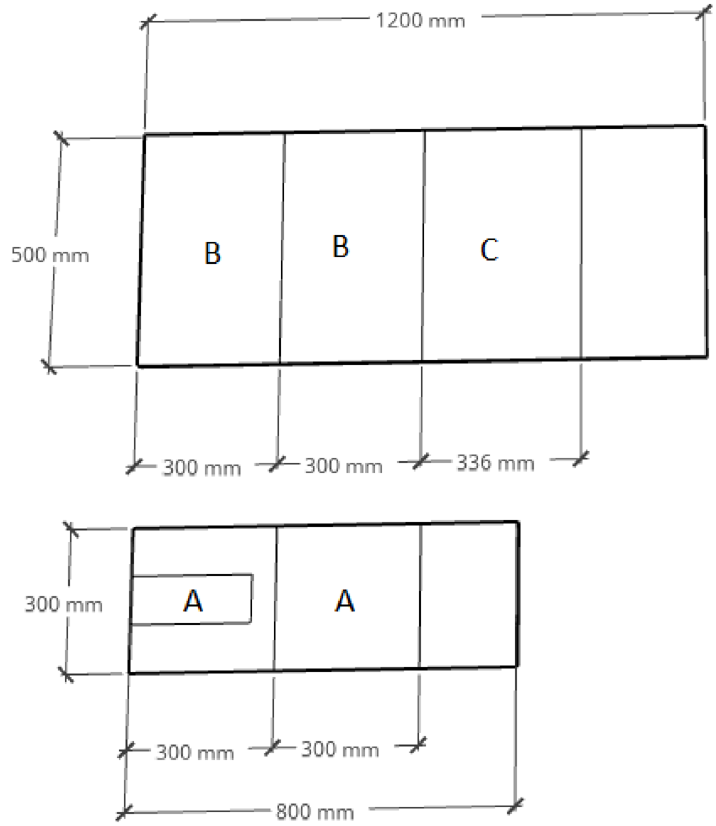


Figure 31 Alternative 2, Dimensions of the elements

9.3.3 Alternative 3

This alternative has not been tested. Alternative 3 involves building a room in light concrete plates without the ceiling. Then build a construction where only the walls, where the start fire is located, is made out of pine glulam boards. In addition, the ceiling consists of pine glulam board. This alternative is the cheapest alternative if many experiments are to be done. The light concrete room is a one-time investment and can be used many times and costs about 300-400 kr. For two experiments you need one pine glulam board with dimension $400\ mm \cdot 1200\ mm$ and one with dimension $300\ mm \cdot 1200\ mm$. The cost for one experiment is about 170 kr.

Step one:

Make the light concrete room in the same dimensions as shown in Figure 33. In this case its used 50 mm thick plates.

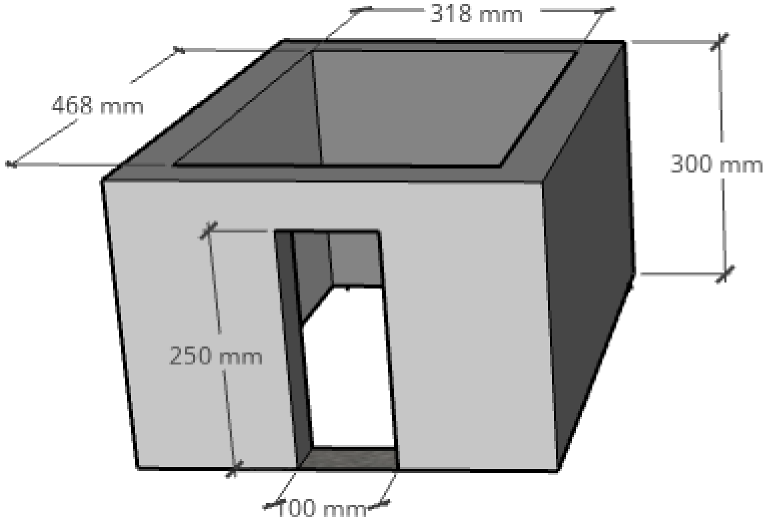


Figure 33 Light concrete room

Step two:

Cut the plates as shown in Figure 34 and assemble the construction as shown in Figure 35.

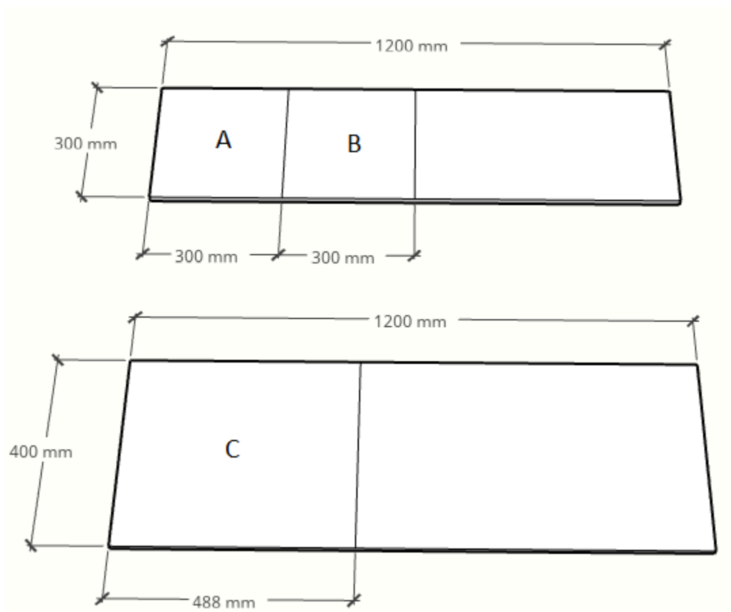


Figure 34 Alternative 3, Cut list

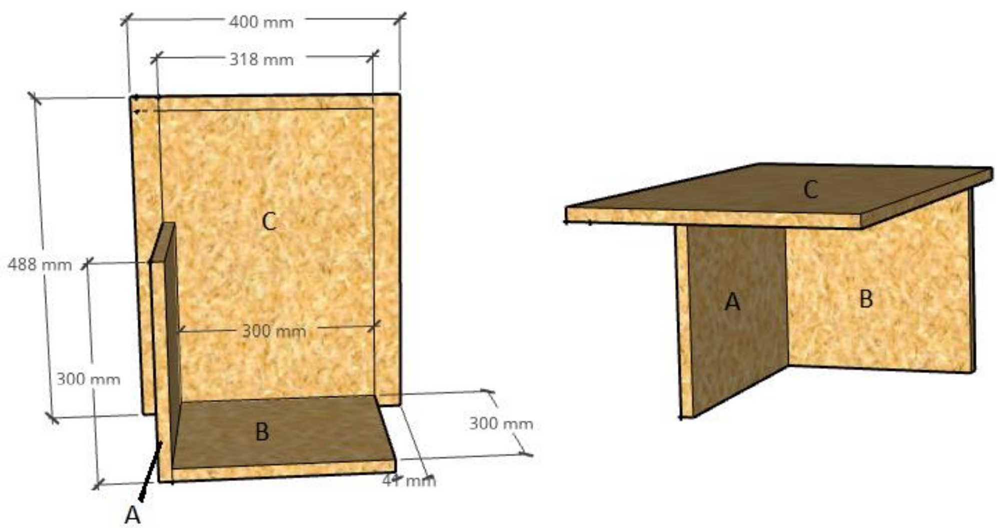


Figure 35 Alternative 3, assembling

Step three:

Place the construction in the light concrete room as shown in Figure 36.

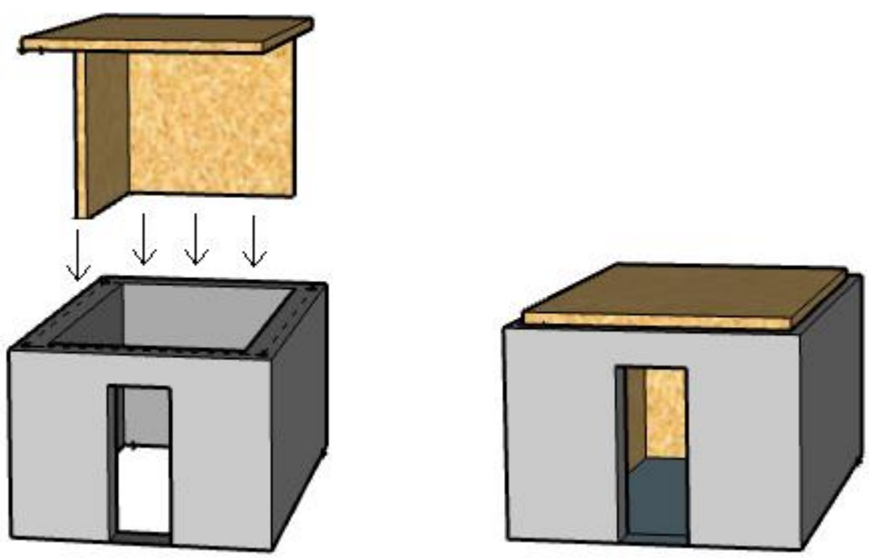


Figure 36 Alternative 3, final product

9.4 Appendix 4, Burner size

Test of the burner was done by placing the burner inside a room made out of non-combustible material (see Figure 4). The mass was measured from start to end and the mass loss rate was calculated. The HRR was calculated using Eq. 2 and properties of methanol from Table 1 Fuel properties methanol Table 1. Table 14, Table 15 and Table 16 shows the burner sizes which were tested before doing the experiment in 1/16 scale.

Table 14 Burner size for experiment 12

Burner size [mm]	Methanol [g]	Time [min:sec]	Mass loss rate [g/s] $(\dot{m})$	HRR [kW]$(\dot{Q})$
$21 \cdot 21 \cdot 19$	5	09:38	0,0087	0,17
$21 \cdot 21 \cdot 19$	5	09:19	0,0089	0,175

Table 15 Burner size for experiment 13

Burner size [mm]	Methanol [g]	Time [min:sec]	Mass loss rate [g/s] $(\dot{m})$	HRR [kW]$(\dot{Q})$
$24 \cdot 24 \cdot 19$	7	11:21	0,01	0,2

Table 16 Burner size for experiment 14-17

Burner size [mm]	Methanol [g]	Time [min:sec]	Mass loss rate [g/s] $(\dot{m})$	HRR [kW]$(\dot{Q})$
$24 \cdot 24 \cdot 29$	11,6	16:22	0,012	0,232
$24 \cdot 24 \cdot 29$	11,53	18:17	0,01	0,2

9.5 Response time thermocouple

During the experiments it was used thermocouples of the type K 1mm [33], to measure the temperature. The response time for 1 mm thermocouples was found to be 5 seconds when temperature increases and 10 seconds when temperature decreases. The increase was determined by inserting a thermocouple coming from air at 21,5°C into an oven with temperature of 800°C. The decrease was determined by removing the thermocouple from 800°C to 21,5°C. The response time refer to the time taken for the thermocouple to achieve 63% of the instantaneous step change. The reader is referred to [37] for why it's used 63%. 63% of the instantaneous step change from 21,5°C to 800°C is 492°C. From 800°C to 21,5°C this becomes 287°C.

Table 17 Results response time thermocouples

	Time [s] 21,5°C to 492°C	Time [s] 800°C to 287°C
Test 1	5	9,6
Test 2	5,6	9,5
Test 3	5,5	10
Average	**5,4**	**9,7**

Figure 37 Oven used for determine response time