

**Fire development in insulated
compartments:**
Effects from improved thermal insulation

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Abstract

New construction solutions, such as low energy buildings and lightweight ship constructions in FRP composite, are designed with more insulation than regular constructions. This may affect the fire development, leading to dangerous conditions for occupants and firemen. Will increased thermal insulation of a compartment affect the fire development so that a higher heat release rate is reached; does it lead to higher gas temperatures or earlier flashover compared to in a non-insulated compartment? In this study, hand calculations, experiments and simulations in FDS were performed, which show that the gas temperature reaches a higher level in an insulated compartment than in a non-insulated compartment. It was also shown that larger and quicker heat release rates are reached in compartments with increased thermal insulation where the fuel source is sensitive to incident radiation. The results of the study are limited since only a standard 20 feet container was studied as a representative compartment.

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It is not hard to make decisions when
you know what your values are

- *Roy Disney*

PREFACE

Finally! Detta blir de sista orden jag skriver i denna rapport, I'm sorry this has to be in Swedish.

Jag vill rikta ett speciellt tack till Håkan Frantzich vid Lunds universitet och Franz Evegren på SP Sveriges Tekniska Forskningsinstitut för att ni varit ett par stöttande handledare som funnits där för att vägleda och uppmuntra mig genom hela detta arbete.

Jag vill också tacka alla på SP Brandteknik som funnits där för att svara på frågor, och de snälla teknikerna som hjälpte mig med mina experiment.

Det har varit en lång resa att få detta arbete klart och jag har lärt mig många saker på vägen, både inom ämnet brand och om mig själv personligen. Det känns skönt att äntligen kunna säga att jag är klar. Förhoppningsvis kommer detta arbete kunna vara till nytta för någon mer än mig själv och jag hoppas att du som läser detta kommer uppskatta arbetet som ligger bakom.

Enjoy!



Stockholm, April 2012

EXECUTIVE SUMMARY

New design solutions are always of interest and sometimes they are implemented in everyday life before going through more thorough evaluations. There are a number of new designs that involve increased thermal insulation, such as low energy buildings and novel ship constructions made out of plastic composite. From a fire safety perspective it is relevant to question how the increased thermal insulation affects the development of a fire? Is a higher heat release rate reached, leading to higher gas temperatures and earlier flashover compared to in a non-insulated compartment?

The purpose of this study is to create an understanding of how increased thermal insulation can affect the fire development in a compartment. It was also of interest to investigate the suitability of the use of hand calculation methods and simulations when carrying out the comparison between the fire development in an insulated compartment to a non-insulated compartment. The work was based on four research questions:

- Does increased thermal insulation lead to a significantly higher gas temperature in a fire compartment?
- Will increased thermal insulation lead to a significantly larger and quicker heat release rate of a fire?
- Is it plausible that the condition flashover is reached earlier in an insulated compartment than in a non-insulated compartment?
- Do hand calculations and simulations give similar results to full scale experiments when comparing the fire behaviour in an insulated compartment to the fire behaviour in a non-insulated compartment?

The fire development in a compartment consists of four stages; the growth period, flashover, fully developed fire and the decay period. How the fire develops depends on a number of factors. Most important for this study has been the law of conservation of energy that can be applied on a fire compartment. Energy is released by the fire and later transferred away from the compartment in a number of different ways. The temperature in a fire compartment depends on the balance between the heat produced by the fire and the heat losses to its surroundings. The energy balance in a fire compartment is described in the figure below.

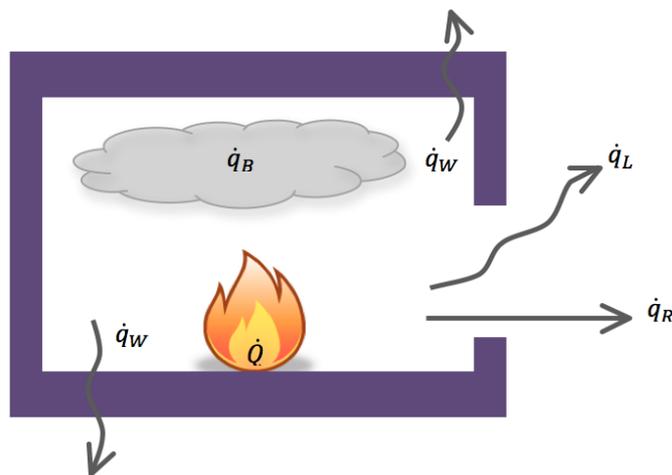
The evaluation was partly made through experiments, where full scale experiments were carried out at SP Technical Research Institute of Sweden, in Borås. Furthermore, pre- and post-experiment hand calculations (using the MQH method, Magnusson and Thelandersson method and EUROCODE method) and simulations using FDS were carried out. In the evaluation the size of the fire

compartment was kept constant. A standard 20 feet (6.1 m) container was used in experiments and calculations.

Four types of fire scenarios were evaluated to answer the above questions:

- Heptane pool fire in insulated container
- Heptane pool fire in non-insulated container
- Wood crib fire in insulated container
- Wood crib fire in non-insulated container

The heptane pool fire represent a fire in an engine room on a ship and the wood crib fire a fire in an ordinary room.



- \dot{Q} = Energy release rate due to combustion
 \dot{q}_w = Heat lost to compartment boundaries
 \dot{q}_L = Heat lost due to replacement of hot gases by cold
 \dot{q}_R = Heat lost by radiation through openings
 \dot{q}_B = Heat stored in the gas volume

Both hand calculations and simulations proved to be sensitive to input data. If there is a high uncertainty to the values of the heat release rate and properties of the boundary materials, the hand calculations using the MQH method give as good results as a FDS simulation, and is significantly less time consuming.

In each of the experiments with different fire sources, wood crib and heptane pool, the gas temperature reached a higher level in the insulated compartment than in the non-insulated compartment.

The results from the experiments do show that a higher heat release rate is reached in the insulated compartment compared to the non-insulated compartment. A quicker heat release rate is however only experienced in the experiment with the heptane pool fire.

As the heat release rate was reached quicker in the insulated compartment with the heptane pool fire, flashover would also be reached earlier in this compartment compared to the non-insulated compartment.

In the experiment with the wood crib fire on the other hand the heat release rate curve has the same shape both for the insulated and non-insulated compartment. It then comes down to if the heat release rate is high enough for flashover to be reached. In the conducted experiments flashover was reached in the insulated compartment however not in the non-insulated compartment.

SAMMANFATTNING

Nya konstruktionslösningar är alltid av intresse och ibland införs de i vardagen innan de genomgått mer grundliga utvärderingar. Det finns ett antal nya konstruktioner som involverar ökad termisk isolering, såsom lågenergihus och nya fartygskonstruktioner gjorda av plastkomposit. Från ett brand-skyddsperspektiv är det relevant att fråga sig hur den ökade termiska isoleringen påverkar en brands utveckling? Fås en högre effektutveckling som i sin tur kan leda till högre brandgastemperaturer och tidigare övertändning jämfört med i ett oisolerat utrymme?

Syftet med denna studie är att skapa en förståelse för hur ökad värmeisolering kan påverka brandförloppet i ett utrymme. Det har också varit av intresse att undersöka hur lämpligt det är att använda handberäkningar och simuleringar för att jämföra brandens utveckling i ett isolerat utrymme med dess utveckling i ett oisolerat. Arbetet var baserat på fyra forskningsfrågor:

- Leder ökad värmeisolering till att betydligt högre brandgastemperaturer nås i ett brandrum?
- Kommer ökad isolering leda till en betydligt större och snabbare effektutveckling?
- Är det sannolikt att övertändning nås tidigare i ett isolerat utrymme än i ett oisolerat utrymme?
- Ger handberäkningar och simuleringar liknande resultat som fullskaliga experiment när en jämförelse görs mellan brandens utveckling i ett isolerat utrymme och dess utveckling i ett oisolerat utrymme?

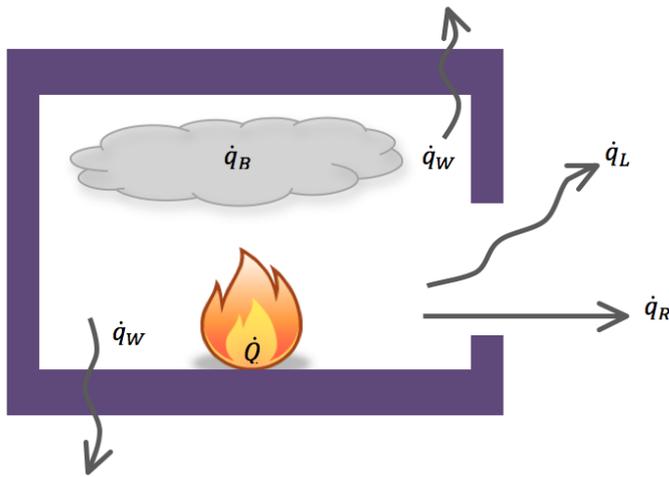
En brands utveckling i ett utrymme består av fyra faser, tillväxtfasen, övertändning, fullt utvecklade brand och avsvlningsfasen. Hur branden utvecklas beror på ett antal faktorer. Viktigast för denna studie har varit lagen om energins bevarande vilken kan appliceras på en brandcell. Energi frigörs av branden och förs sedan bort från utrymmet på en mängd olika sätt. Temperaturen i en brandcell beror på balansen mellan den värme som produceras av elden och värmeförluster till omgivningen. Energi-balansen i en brandcell beskrivs i figuren.

Utvärderingen har delvis gjorts genom experiment, där fullskaliga experiment utfördes vid SP Sveriges Tekniska Forskningsinstitut i Borås. Även pre- och post-experimentella handberäkningar (med hjälp av MQH metoden, Magnusson och Thelandersson metoden och EUROCODE metoden) och simuleringar med hjälp av FDS genomfördes. I utvärderingen hölls storleken på brandrummet konstant. En standard 20 fots (6.1 m) container användes vid försök och beräkningar.

Fyra brandscenarier har utvärderats:

- Pölbrand av heptan i isolerat utrymme
- Pölbrand av heptan i oisolerat utrymme
- Träribbstapel i isolerat utrymme
- Träribbstapel i oisolerat utrymme

Pölbranden av heptan representerar en brand i ett maskinrum på ett fartyg och träribbstapeln en brand i ett vanligt rum.



\dot{Q} = Värme producerad vid förbränning

\dot{q}_w = Värme förlorad till omslutande konstruktion

\dot{q}_L = Värme förlorad på grund av att varma brandgaser blir ersatta av kalla

\dot{q}_R = Värme förlorad genom strålning genom öppningar

\dot{q}_B = Värme lagrad i brandgaserna

Både handberäkningar och simuleringar visade sig vara känsliga för indata. Om det finns en stor osäkerhet i värdena för effektutvecklingen och den omslutande konstruktionens materialegenskaper så ger handberäkningar med hjälp av MQH metoden lika bra resultat som en FDS-simulering, vilken är betydligt mer tidskrävande.

I samtliga experiment med olika brandkällor, träribbstapel och pölbrand av heptan nåddes en högre gastemperatur i det isolerade utrymmet än i det oisolerade utrymmet.

Resultaten från experimenten visar även att en högre effektutveckling nås i det isolerade utrymmet jämfört med det oisolerade utrymmet. En snabbare effektutveckling nås dock bara i försöket med pölbranden av heptan.

Eftersom effektutvecklingen uppnåddes snabbare i det isolerade utrymmet med pölbranden av heptan är det rimligt att även övertändning nås tidigare i detta utrymme jämfört med det oisolerade utrymmet.

I experimentet med träribbstapeln hade effektutvecklingen däremot samma form för både det isolerade och oisolerade utrymmet. Där beror övertändning istället på om effektutvecklingen blir tillräckligt hög. I de experiment som genomfördes uppnåddes övertändning i det isolerade utrymmet, dock inte i det oisolerade utrymmet.

LIST OF SYMBOLS

A_f	horizontal burning area of the fuel [m ²]
A_i	area of the opening i [m ²]
A_O	total opening area [m ²]
A_T	total enclosure surface area (including the openings) [m ²]
C	heat capacity [J/m ² K]
c	specific heat [kJ/kg K]
D	diameter [m]
D_e	equivalent diameter of the fire [m]
g	gravitational acceleration [m/s ²]
ΔH_c	complete heat of combustion [kJ/kg]
h_c	effective heat convection coefficient [kW/m ² K]
ΔH_{eff}	effective heat of combustion [kJ/kg]
h_k	effective heat conduction coefficient [kW/m ² K]
h_i	height of the opening i [m]
H_O	weighted mean height of all the openings [m]
h_{PT}	heat transfer coefficient of the plate thermometer [W/m ² K]
h_r	effective heat radiation coefficient [kW/m ² K]
k	conductivity [kW/m K]
L	flame height [m]
m	mass of the fuel [kg]
\dot{m}	mass loss rate [kg/s]
\dot{m}''	mass loss rate per unit area [kg/m ² s]
\dot{m}''_{∞}	asymptotic diameter mass loss rate per unit area [kg/m ² s]
\dot{m}_a	mass flow rate of ambient air [kg/s]
\dot{q}''_{inc}	incident radiation [kW/m ²]

LIST OF SYMBOLS

\dot{Q}	heat release rate [kW]
\dot{Q}_{fo}	heat release rate needed to reach flashover [kW]
Q_t''	fire load density per total enclosure surface area [kJ/m ²]
t	time [s]
t^*	non dimensional time [-]
T_∞	temperature of the ambient air [K]
T_g	gas temperature [K]
T_{PT}	temperature measured by plate thermometer [K]
T_s	steel temperature [K]
δ	thickness of material [m]
ε_{PT}	emissivity of the plate thermometer [-]
$\kappa\beta$	material constant for liquid fuels [m ⁻¹]
ρ_∞	density of the ambient air [kg/m ³]
σ	Stefan-Boltzman constant [W/m ² K ⁴]
χ	combustion efficiency [-]

TABLE OF CONTENTS

1. Introduction	1
1.1 Purpose and objective	2
1.2 Limitations	3
1.3 Method	3
1.4 Outline.....	5
2. General Fire Dynamics.....	7
2.1 The development of a fire.....	7
2.2 Conservation of energy.....	10
2.3 Calculation methods for compartment temperatures	13
3. New Design Solutions	18
3.1 General effects of insulation on fire development	18
3.2 Low-energy houses.....	19
3.3 Lightweight ship constructions.....	20
4. Development of Fire Scenarios	24
4.1 Source of fire in experiments	24
4.2 Fire development in container	24
4.3 Fire scenario 1 to 4	28
5. Experimental set-up	30
5.1 Equipment and material	30
5.2 Measured properties	34
5.3 Experiment procedure	36
6. Simulations	38
6.1 FDS	38
6.2 Resources.....	38
6.3 Input data	38
6.4 Output data.....	41
7. Results	44
7.1 Pre-experiment hand calculations.....	44
7.2 Pre-experiment simulations.....	49
7.3 Experiments	59
7.4 Post-experiment hand calculations	71
7.5 Post-experiment simulations	73
7.6 Verification of simulations	82
8. Comparison of results.....	88
8.1 Heat release rate – heptane pool fire	88
8.2 Heat release rate – wood crib fire	89
8.3 Gas temperature – heptane pool fire	90

TABLE OF CONTENTS

8.4	Gas temperature – wood crib fire.....	92
8.5	Wall temperature – heptane pool fire	93
8.6	Wall temperature – wood crib fire	95
9.	Discussion	98
9.1	Result bias.....	98
9.2	Future research	101
10.	Conclusions	104
11.	References	106

Appendix A - Data for enclosed fires

Appendix B - Risk analysis

Appendix C - FDS-files

1. INTRODUCTION

Imagine a room in a building, and that there is a fire in the room. Now imagine the same room but coated with insulation. There is a fire in this room as well; the question is: Will this fire behave in a different way?

The National Research Council Canada published a report called *Effects of Insulation on Fire Safety* in 1981 (Lie 1981). The report lists various effects of increased insulation. Lie states that thermal insulation reduces the heat losses through the building boundaries and therefore reduces the loss of energy. Heat stays in the fire compartment and higher temperatures are reached which could lead to quicker fire development and earlier flashover.

Factors that are affected by increased thermal insulation could be summarised as follows:

- An increased thermal insulation will have influence on the fire growth (Lie 1981).
- Higher temperatures are reached in compartments with insulating boundaries (Pettersson et al. 1976; Latham 1987).
- The time until reaching flashover is shorter when the building products have high insulation capacities (Sundström, van Hees & Thureson 1998).
- Higher heat release rates are reached in compartments than in free burning tests (Sundström (ed.) 1995).

The impact on fire development from improved thermal insulation is a subject of interest in at least two current applications.

- Low-energy houses, and;
- Lightweight ship constructions

The interest for energy efficiency is growing and so is the development of low-energy houses, which use an increased amount of insulation to conserve energy. This type of construction is becoming more common in our cities for each year. However, there is a lack of knowledge and experience of fires in low-energy houses with improved thermal insulation and the constructions' effect on fire development.

Firemen are now getting increasingly worried about the new types of building constructions on the market. In the case with low-energy houses they are afraid that the fire development could be more rapid, which could create dangerous environment for the firemen and affect their rescue operation negatively (Ghent University 2010; Hartin 2008).

When it comes to lightweight ship constructions, changes in the safety regulations for ship constructions, SOLAS (Safety of Life at Sea), have made it possible to use other construction materials than steel, as long as the new design and fire safety arrangements provide the same level of safety. A new type of material that has been used in military ships is FRP composite (Fibre Reinforced Polymer). It is suggested to extend the use of this material to passenger ships, as it is lighter than steel and does not require the same level of maintenance. Yet FRP composite is combustible and a suitable safety measure is therefore to coat it with insulation to maintain the structural integrity (Evegren 2010). To evaluate the safety of a ship design with such well-insulated structures, it is important to investigate whether it could lead to differences in fire behaviour compared to when using steel structures.

There is not much information about how FRP composite with increased thermal insulation affects the fire, as this is a new area being explored. Previous fire experiments have been carried out by Hertzberg (2009) to investigate effects of the fire on the material, however, not what the material can do to the fire.

Boundary materials have also been tested by Sundström, van Hees & Thureson (1998). Those experiments were carried out as an ISO 9705 room/corner test with a propane gas burner giving constant heat release rate. As mentioned earlier, it showed that the time until reaching flashover is shorter when the building products have high insulation capacities. It was however, the boundary materials taking fire that affected the conditions in the compartment. It is therefore not possible to evaluate how the fire source was affected by the insulating capacity.

It is important to understand how the boundary materials affect the heat release rate since the heat release rate is used as an input in both hand calculations and simulations when determining compartment temperatures. These methods can therefore not take into account the possible increase in heat release rate, in a well-insulated compartment. It is possible to calculate changes in compartment temperatures however not possible to deduce any changes in heat release rates.

1.1 Purpose and objective

The purpose and objective for this study is presented below.

1.1.1 Purpose

The purpose of this study is to create an understanding for how increased thermal insulation can affect the fire development in a compartment.

1.1.2 Objective

The objective of this study is to investigate the fire development in an insulated compartment and compare it to the fire development in a non-insulated compartment. A fire source that can be affected by incident radiation from hot gases and boundary materials will therefore be used. This might lead to a larger

and quicker heat release rate, which is the input to hand calculations and simulations. It is hence of interest to investigate the suitability of the use of hand calculation methods and simulations when carrying out the comparison between the fire development in an insulated compartment to a non-insulated compartment. The research questions to be answered are:

- Does increased thermal insulation lead to a significantly higher gas temperature in a fire compartment?
- Will increased thermal insulation lead to a significantly larger and quicker heat release rate of a fire?
- Is it plausible that the condition flashover is reached earlier in an insulated compartment than in a non-insulated compartment?
- Do hand calculations and simulations give similar results to full scale experiments when comparing the fire behaviour in an insulated compartment to the fire behaviour in a non-insulated compartment?

The top three questions could be seen as a snowball effect, where they all affect each other. If the rise in gas temperature in the fire compartment is significant, the heat release rate will be affected; in case the heat release rate increases significantly, the time to flashover will be affected.

1.2 Limitations

To narrow down the size of this study, a number of limitations were set. Increased thermal insulation could affect several parameters. However it is only the temperature in the compartment, time to flashover and the heat release rate that are measured and evaluated in this study. In line with the measured parameters, focus lies upon the pre-flashover and flashover stage in the fire development. The maximum heat release rate in the experiments was limited to 1.5 MW as that is the upper limit for the hood extracting the hot gases.

The size and shape of the compartment as well as the thickness and type of insulation could also affect the fire development. In this study, a standard 20 feet container with inside measurements of 19'4"(l) x 7'8"(w) x 7'10"(h) was used to represent a normal sized compartment, which limits the applicability of the results. Rock wool with a thickness of 0.095 m was used as insulation for the insulated cases.

1.3 Method

This report is the result of research involving both computer simulations and full-scale experiments. The study has been carried out in collaboration with SP Technical Research Institute of Sweden.

Firstly a literature study was carried out. Studies were made of both general fire dynamics involving the factors that can be affected by increased thermal

insulation and new design solutions where increased thermal insulation is used. Thereafter a scenario identification was carried out, in order to find the appropriate scenarios where the questions listed above could be evaluated.

When the fire scenarios were found hand calculations were carried out. Three different methods were used to calculate the compartment temperature in a non-insulated compartment and an insulated compartment. The methods used were the MQH-method (SFPE 2002), the Magnusson and Thelandersson method (Magnusson & Thelandersson 1970) and the EUROCODE method (SS-EN 1991-1-2). In parallel with the hand calculations, pre-experiment simulations were carried out using FDS, Fire Dynamics Simulator (NIST 2011).

When results from the hand calculations and simulations had been presented and a difference in compartment temperature between the non-insulated and insulated case could be shown, full-scale experiments were scheduled. Four set-ups of experiments were carried out at SP's large scale test facility in Borås between the 6th and 8th of December 2011.

The four scenarios tested were:

1. Heptane pool fire in insulated container
2. Heptane pool fire in non-insulated container
3. Wood crib fire in insulated container
4. Wood crib fire in non-insulated container

With the results from the experiments post-experiment hand calculations and simulations were carried out. Finally the results from the hand calculations, simulations and experiments were compared and evaluated.

1.4 Outline

The outline of this thesis is presented in figure 1.1.

The first three chapters are descriptive and aim to give a detailed background to the effects of increased thermal insulation and its practical applications. In chapter 4, the fire scenarios that will be investigated are presented. Following are chapters 5 and 6, two parallel chapters where background information to the FDS simulations and the experiments is presented. Chapter 7 contains results from the pre-experiment hand calculations, the pre-experiment simulations, the experiments and the post-experiment hand calculations and simulations. Thereafter the results from each source are compared to each other in chapter 8. The final chapters, 9 and 10, tie it all together through discussion and conclusions.

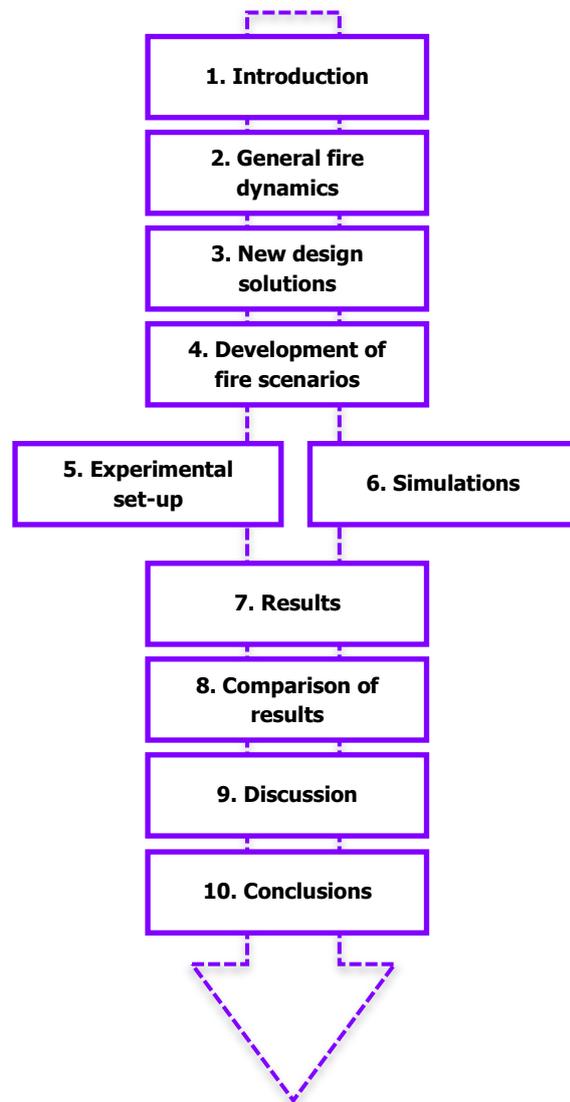


Figure 1.1: Outline.

2. GENERAL FIRE DYNAMICS

It is necessary to have an understanding of fire dynamics to comprehend the factors that improved thermal insulation could affect. First a short description of the development of a fire is presented, followed by a description of the conservation of energy in enclosures. Finally some calculation models for compartment temperatures are presented.

2.1 The development of a fire

A fires' development in an enclosure depends on a number of factors (Karlsson & Quintiere 2000):

- The size and location of the fire source,
- The type, amount, spacing and surface area of the fuel,
- The material properties of the enclosure boundaries,
- The size and location of the compartment openings, and;
- The size and shape of the enclosure.

In room-like compartments, the fire development could be divided into three stages: the growth period, the fully developed fire and the decay period (Drysdale 1998). The figure below shows schematically the heat release rate as a function of time for the different stages. Note that the growth period stage and the fully developed fire stage are separated by a flashover phase.

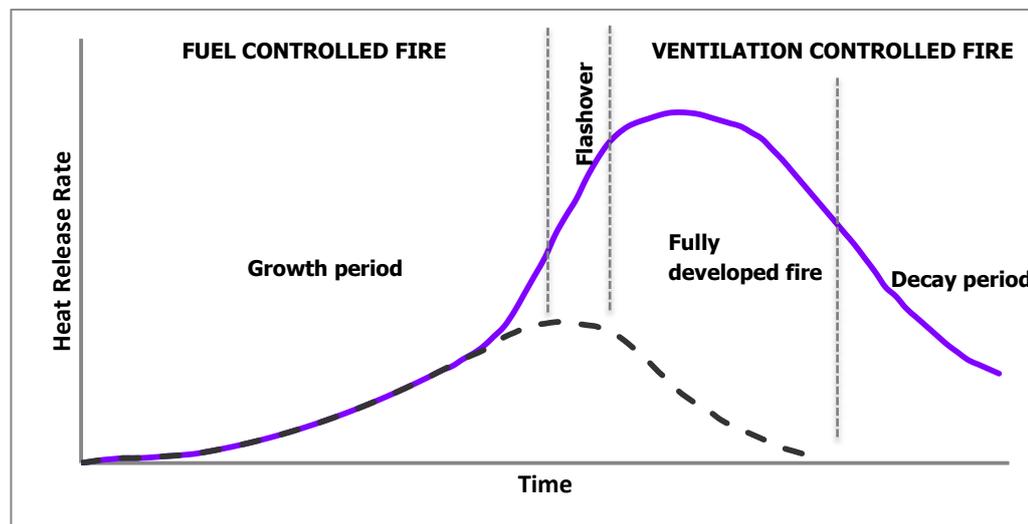


Figure 2.1: Schematic figure of the heat release rate as a function of time. The dashed line represents a ventilation controlled fire.

During the beginning of the **growth period**, the fire will be free burning and the source of fuel will only be in close proximity from where the fire ignited. The fire

will slowly start to grow larger. The average temperature of the compartment will be relatively low during this stage.

The fire development could thereafter develop in three different ways (Drysdale 1998):

1. If the origin of the fire is not situated close to any other combustible material or does not contain enough combustible material itself, the fire will extinct due to lack of fuel before the flashover stage is reached.
2. If the amount of oxygen available is limited, the fire becomes ventilation controlled or self-extinguishes.
3. If both oxygen and combustible materials are available, the fire can grow larger and proceed to the next stage of development.

Fuel controlled fire

The growth of the fire is controlled by the amount and type of fuel

(Karlsson & Quintiere 2000)

Ventilation controlled fire

It is the amount of oxygen that controls the growth of the fire

(Karlsson & Quintiere 2000)

The next stage of a fires' development is the **fully developed fire**. However, before that stage is reached, the fire accelerates rapidly in a phase called **flashover**. The duration of the flashover is normally short as it is only a transition between the growth period and the fully developed fire (Drysdale 1998). It is therefore not referred to as a stage in the fire development. During flashover all surfaces in the compartment are heated by radiation from flames, hot objects and the upper layer of smoke. The combustible surfaces ignite rapidly and the whole compartment is quickly involved in the fire (Spearpoint 2008). This phase is also used to indicate the point where the fire goes from being fuel controlled to being ventilation controlled (Karlsson & Quintiere 2000). People that have not escaped before flashover occurs have a very small chance of surviving (Drysdale 1998).

One of the definitions for flashover is when the hot gas layer reaches 500-600°C and the radiation towards the floor is 15-20 kW/m² (Brandteknik, LTH 2005). Another definition of flashover is when flames emerge from the openings (Drysdale 1998).

As stated above, the second stage of the fire development is the **fully developed fire**. All the compartment boundaries are involved in the fire at this stage and there will be flames throughout the whole compartment. It is during this stage of the fire that the highest temperatures are reached and also when structural damage to the construction could occur (Drysdale 1998).

After this stage the fire proceeds in a **decay** period, which is the last stage. During the decay period the average temperature in the compartment soon decreases to

about 80% of its peak value. The fire grows smaller and leaves behind smouldering coal that maintains the heat in the compartment locally (Drysdale 1998).

2.1.1 Estimating the heat release rate

To estimate the heat release rate of a fire is hard. There are two general ways to do it: either by using tabulated data or by making calculations. Tabulated data for heat release rates and fire loads are presented in appendix A.

A common way to calculate the heat release rate is to use equation 2.1 below. The mass loss rate of the fuel can be obtained from measuring the weight of the fuel while it is burning. The effective heat of combustion for the burning material does also need to be known (Karlsson & Quintiere 2000).

$$\dot{Q} = \dot{m} \cdot \Delta H_{eff} \quad (\text{eq. 2.1})$$

Where \dot{m} is the mass loss rate [kg/s] and ΔH_{eff} is the effective heat of combustion [kJ/kg]. The effective heat of combustion for many materials has been tabulated in the *SFPE Handbook of Fire Protection Engineering* (2002). However, it is sometimes easier to find the tabulated value for the complete heat of combustion, ΔH_c . The relation between the effective heat of combustion and the complete heat of combustion is called the combustion efficiency and is denoted, χ (Karlsson & Quintiere 2000). The combustion efficiency for organic materials is generally 0.7 and for alcohols 0.9.

$$\chi = \frac{\Delta H_{eff}}{\Delta H_c} \quad (\text{eq. 2.2})$$

The mass loss rate for different materials could also be found in tables, but it is most often presented as mass loss rate per unit area. Equation 2.1 above could therefore be modified to include the complete heat of combustion and the mass loss rate per unit area. The new equation is presented below (Karlsson & Quintiere 2000).

$$\dot{Q} = A_f \cdot \dot{m}'' \cdot \chi \cdot \Delta H_c \quad (\text{eq. 2.3})$$

Where A_f is the horizontal burning area of the fuel [m²], χ is the combustion efficiency, ΔH_c is the complete heat of combustion [kJ/kg] and \dot{m}'' is the mass loss rate per unit area [kg/m² s]. Equation 2.3 above is often used to calculate the theoretical heat release rate for liquid pool fires. For pool fires with a large diameter (>1 m) the mass loss rate per unit area is relatively constant. For liquid pool fires with smaller diameter the mass loss rate per unit area increases with its diameter. The mass loss rate per unit area is not only dependent of the diameter; it also depends on the irradiative heat flux from the flame toward the fuel surface. The following correlation equation is recommended to be used when calculating the mass loss rate per unit area for liquid pool fires with a diameter larger than 0.2 m (Drysdale 1998).

$$\dot{m}'' = \dot{m}''_{\infty} \cdot (1 - e^{-\kappa\beta D}) \quad (\text{eq. 2.4})$$

Where D is the diameter [m], \dot{m}''_{∞} is the asymptotic diameter mass loss rate per unit area [kg/m² s], $\kappa\beta$ is the material constant for liquid fuels [m⁻¹].

2.1.2 Maximum HRR as a function of available oxygen

As described above the development of a fire depends on the amount of oxygen available. The amount of oxygen available also affects the maximum heat release rate that could be reached. The heat release rate is therefore affected by the size of the room and the size of the openings to the room. The maximum heat release rate that can be reached in a room as a function of the amount of oxygen available can be calculated from equation 2.6. The expression has been derived from equation 2.5 (Karlsson & Quintiere 2000).

$$\dot{m}_a = 0.5 \cdot A_o \cdot \sqrt{H_o} \quad (\text{eq. 2.5})$$

Where \dot{m}_a is the mass flow rate of ambient air [kg/s], A_o is the total opening area [m²] and H_o is the weighted mean height of all the openings [m]. Multiplying 0.5, from equation 2.5, with 13.2 MJ/kg and 23%, the expression becomes (Karlsson & Quintiere 2000):

$$\dot{Q} = 1.518 \cdot A_o \cdot \sqrt{H_o} \quad (\text{eq. 2.6})$$

13.2 MJ/kg represents the amount of energy one kilo of oxygen can produce, assuming total combustion and 23% is the mass fraction of oxygen available in the air entering the compartment.

The weighted mean height of all the openings is calculated using equation 2.7, below (Karlsson & Quintiere 2000).

$$H_o = \frac{A_1 \cdot h_1 + A_2 \cdot h_2 + \dots + A_i \cdot h_i}{A_o} \quad (\text{eq. 2.7})$$

Where A_i is the area of the opening i [m²], h_i is the height of the opening i [m] and A_o is the total area of all the openings.

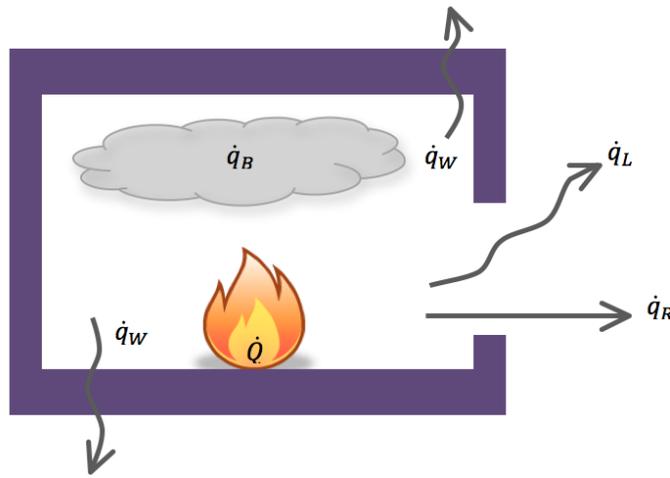
2.2 Conservation of energy

The conservation of energy plays an important role in many situations, among them the fire development.

Energy is always conserved, even if transformed into different forms. A fire compartment is an open energy system where both matter and energy can be exchanged with the surroundings. One way to change the internal energy of an open system is to increase or decrease the amount of internal matter, another way is to heat or cool the system (Jones & Atkins 2000).

The law of conservation of energy can be applied on a fire compartment. Energy is released by the fire and later transferred away from the compartment in a

number of different ways (Karlsson & Quintiere 2000). The temperature in a fire compartment depends on the balance between the heat produced by the fire and the heat losses to its surroundings (Latham 1987). The energy balance in a fire compartment is described in figure 2.2 and below.



- \dot{Q} = Energy release rate due to combustion
- \dot{q}_w = Heat lost to compartment boundaries
- \dot{q}_L = Heat lost due to replacement of hot gases by cold
- \dot{q}_R = Heat lost by radiation through openings
- \dot{q}_B = Heat stored in the gas volume

Figure 2.2: The energy balance in a fire compartment.

\dot{Q} - is the energy that is released in the compartment due to the combustion. This factor depends on the oxygen available, the amount of available combustible material and the physical properties of the material (Pettersson & Ödeen 1978). The burning rate will increase due to irradiative heat flux towards the burning fuel (Karlsson & Quintiere 2000). There are at least four sources of radiation: (1) the vertical flames from the fire, (2) the hot surfaces of the enclosure, (3) the flames under the ceiling and (4) the hot gas layer containing combustion products (Drysdale 1998).

\dot{q}_w - is the heat that is transferred through the compartment boundaries. The amount of heat transferred depends upon the thermal properties of the compartment material and the temperature difference between the inside and the outside of the compartment (Pettersson & Ödeen 1978). Drysdale (1998) describes that as a general rule, materials that are good electrical conductors are also good thermal conductors as they can transfer the heat through interaction between free electrons. Insulation materials on the other hand can only transfer heat through mechanical vibrations, which is a much less efficient process.

Heat losses to compartment boundaries depend on three factors: conduction, convection and radiation.

Conduction is heat transferred through materials, solids and fluids, though it is usually associated with solid materials. It is a transfer of energy that occurs between a particle with high temperature and a particle with low temperature (Wickström 2011).

Convection is heat transferred between a fluid (e.g. air) and a solid material. There are different types of convection: natural and forced. The forced convection involves a fluid flow affected by a fan and the natural convection is the fluid flow that occurs due to temperature differences between the solid surface and the fluid. The natural convection is generally most relevant in fire applications (Wickström 2011).

Radiation is the third type of heat transfer. Thermal radiation transmitted to a material is defined as the difference between absorbed radiation and emitted radiation (Wickström 2011).

\dot{q}_L - is the heat removed from the compartment due to replacement of hot gases with air of ambient temperature. This happens because of the difference in density between the hot gases and the cold air. Factors that affect this parameter are the temperatures of the different fluids and also the size of the opening area (Pettersson & Ödeen 1978).

\dot{q}_R - is the heat transferred out through the opening by radiation. The amount of transferred heat depends on the temperature of the gases and the opening area (Pettersson & Ödeen 1978).

\dot{q}_B - is the stored energy in the gas volume. In comparison with the other energy parameters it is relatively small and it is therefore often omitted (Pettersson & Ödeen 1978).

Applying the conservation of energy on a non-insulated compartment compared to an insulated compartment the major difference in heat loss is the heat losses to boundaries. The total heat lost to compartment boundaries in a non-insulated steel compartment is heavily dependent on the convection and radiation while the heat lost to compartment boundaries in an insulated compartment mostly depends on the conduction.

The energy balance could be summarised in the equation written in words below.

Energy release rate due to combustion = Heat lost due to replacement of hot gases + Heat lost to compartment boundaries + Heat lost by radiation through openings + Heat stored in the gas volume

To conclude, the fire development in an enclosure depends upon a number of factors. Among them, the boundary material will affect the temperature in the hot gas layer in the enclosure considerably. A well insulating boundary material will

limit the heat transfer so that most of the energy will be preserved in the hot gases (Karlsson & Quintiere 2000).

2.3 Calculation methods for compartment temperatures

Three calculation methods to estimate enclosure temperatures are presented below, namely the MQH method (SFPE 2002), the Magnusson and Thelandersson method (Magnusson & Thelandersson 1970) and the EUROCODE method (SS-EN 1991-1-2).

2.3.1 MQH

The MQH method has been named from the initials of McCaffrey, Quintiere and Harkleroad who developed this method of estimating the gas temperature in a ventilated fire compartment. The model uses a simplified energy balance taking into account the energy losses due to fluid flows through the opening and energy losses through the compartment boundaries (SFPE 2002). The equation is presented below.

$$\Delta T = 480 \left(\frac{\dot{Q}}{\sqrt{g} \cdot c \cdot \rho_{\infty} \cdot T_{\infty} \cdot A_0 \cdot \sqrt{H_0}} \right)^{2/3} \cdot \left(\frac{h_k \cdot A_T}{\sqrt{g} \cdot c \cdot \rho_{\infty} \cdot A_0 \cdot \sqrt{H_0}} \right)^{-1/3} \quad (\text{eq. 2.8})$$

Where \dot{Q} is the heat release rate of the fire source [kW], g is the gravitational acceleration [m/s^2], c is the specific heat [kJ/kg K], ρ_{∞} is the density of the ambient air [kg/m^3], T_{∞} is the ambient air temperature [K], A_0 is the total opening area [m^2], H_0 is the weighted mean height of all the openings [m], h_k is the effective heat conduction term for the solid boundaries [$\text{kW/m}^2 \text{K}$] and A_T is the total enclosure surface area (including the openings) [m^2].

The numbers 480, $2/3$ and $-1/3$ has been determined through correlation between the equation and data from over 100 experiments (SFPE 2002). If the values in equation 2.8 are substituted for ambient conditions of $g = 9.8$, $c = 1.05$, $\rho_{\infty} = 1.2$ and $T_{\infty} = 295$ the equation becomes more simple.

$$\Delta T = 6.85 \left(\frac{\dot{Q}^2}{h_k \cdot A_T \cdot A_0 \cdot \sqrt{H_0}} \right)^{1/3} \quad (\text{eq. 2.9})$$

The h_k term can be calculated in two ways, as per equation 2.9a or 2.9b below (McCaffrey et al. 1981).

$$h_k = \sqrt{\frac{k \rho c}{t}} \quad (\text{eq. 2.9a})$$

$$h_k = \frac{k}{\delta} \quad (\text{eq. 2.9b})$$

Where k is the conductivity of the boundary material [kW/m K], ρ is the density of the boundary material [kg/m^3], c is the specific heat of the boundary material [kJ/kg K], t is the time of exposure [s] and δ is the thickness of the wall [m].

Equation 2.9a is used when the boundary material could be assumed to be semi-infinite in thickness. Equation 2.9b is used when the boundary material is very thin or for very long exposure where the conduction becomes stable. Figure 2.3 shows a schematic of the temperature distribution in these two cases.

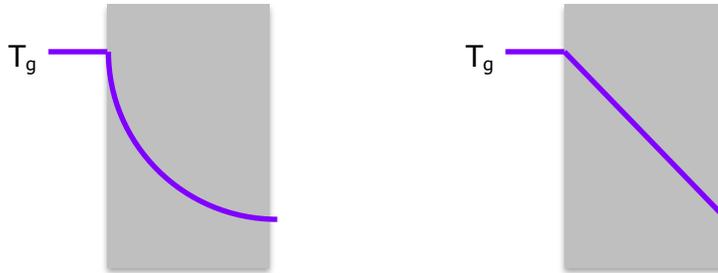


Figure 2.3: The temperature distribution in a wall. To the left is what could be assumed for a material semi-infinite in thickness and to the right what could be assumed for a very thin material.

In each of the equations the cooling effect from boundaries is not taken into account. This will make a large difference in case of a fire in a steel construction, since a large amount of energy will be lost on the outside of the compartment due to convection and radiation, as discussed above.

In order to take these parameters into account when carrying out calculations for steel constructions the h_k term can be modified. The h_k term in the equations above, representing the effective heat conduction through the boundaries, could be replaced by an h_c term and an h_r term which represent the convection and radiation, respectively, on the outside of the construction, see equation 2.8c below.

$$h_k = h_c + h_r \quad (\text{eq. 2.9c})$$

The h_r term could be estimated using the following approximation (Brandteknik, LTH 2007).

$$h_r = \frac{\sigma}{T_g - T_s} \cdot (T_g^4 - T_s^4) \cdot 10^{-3} \quad (\text{eq. 2.10})$$

Where σ is the Stefan-Boltzman constant, T_g is the gas temperature [K] and T_s is the steel temperature [K].

The h_c term could be estimated using equation 2.11 below (Pettersson & Ödeen 1978).

$$h_c = 8.7 + 0.033 \cdot T_\infty \quad (\text{eq. 2.11})$$

Where T_∞ is the ambient air temperature [K].

For an insulated compartment the conduction of heat is considered to be much larger than the convection and radiation and therefore equation 2.9a is used to determine the h_k term in the insulated case.

2.3.2 Magnusson & Thelandersson

Magnusson and Thelandersson have developed a method to predict temperature–time curves for fire compartments. They used both empirical and theoretical data to develop the model. This calculation method is focusing on the post-flashover period of a fire and indicates how the surrounding materials of the compartment affect the temperatures. This method has been developed for wood fuel fires and therefore has a limited area of applicability (Magnusson & Thelandersson 1970).

The temperature-time curves can be determined for compartments with different surrounding materials, listed from A to H in table 2.1 below (Magnusson & Thelandersson 1970).

Table 2.1: Construction type used in Magnusson and Thelandersson model (Magnusson & Thelandersson 1970)

Type	Description	Factor k_f *
A	Materials with thermal properties corresponding to average values for concrete, brick and lightweight concrete	1.0
B	Concrete	0.85
C	Lightweight concrete (density $\approx 500\text{kg/m}^3$)	3.0
D	50% concrete 50% lightweight concrete (density $\approx 500\text{kg/m}^3$)	1.35
E	50% lightweight concrete (density $\approx 500\text{kg/m}^3$) 33% concrete 17% composite construction comprising: gypsum (density $\approx 790\text{kg/m}^3$), mineral wool (density $\approx 50\text{kg/m}^3$) and brickwork (density $\approx 1800\text{kg/m}^3$)	1.65 – 1.50
F	80% non-insulated steel sheeting. 20% concrete. Typically a warehouse with non-insulated ceiling and walls of steel sheeting and a concrete floor	1.0 – 0.5
G	20% concrete 80% composite construction comprising double gypsum plasterboard, 2x13 mm (density $\approx 790\text{kg/m}^3$), 100 mm air gap, double gypsum plasterboard, 2x13 mm (density $\approx 790\text{kg/m}^3$)	1.5 – 1.45
H	Composite construction comprising: steel sheeting, 100mm mineral wool, steel sheeting	3.0

* For an actual opening factor of 0.02 – 0.04

Before the temperature can be determined, the actual opening factor and fire load for the compartment need to be calculated. The actual opening factor for the compartment is calculated using equation 2.12 below.

$$\text{Opening factor} = \frac{A_o \cdot \sqrt{H_o}}{A_T} \quad (\text{eq. 2.12})$$

Where A_o is the total opening area [m^2], A_T is the total enclosure surface area (including the openings) [m^2] and H_o is the weighted mean height of all the openings [m]. H_o is calculated using equation 2.7 (Karlsson & Quintiere 2000).

The fire load density per total enclosure surface area is calculated using the following equation.

$$Q_t'' = \frac{m \cdot \Delta H_{eff}}{A_T} \quad (\text{eq. 2.13})$$

Where A_T is the total enclosure surface area (including the openings) [m²], m is the mass of the fuel [kg] and ΔH_{eff} is the effective heat of combustion of the fuel [kJ/kg].

The actual opening factor and fire load can be recalculated to fictitious values using the k_f -factor from table 2.1 as in equation 2.14 and 2.15 below.

$$\text{Equivalent opening factor} = \text{Actual opening factor} \cdot k_f \quad (\text{eq. 2.14})$$

$$\text{Equivalent fire load density} = \text{Actual fire load density} \cdot k_f \quad (\text{eq. 2.15})$$

The fictitious values can then be used to find the right table from which values are collected for the temperature curve. Tables for the Magnusson and Thelandersson model can be found in *Brandteknisk dimensionering* (Pettersson & Ödeen 1978).

2.3.3 EUROCODE

The EUROCODE method is used to calculate temperature-time curves according to the European Committee for Standardization, similar to the Magnusson and Thelandersson method presented above. The temperature is calculated using equation 2.16 below (SS-EN 1991-1-2).

$$T_g = 273 + 1325(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}) \quad (\text{eq. 2.16})$$

Where t^* is a non dimensional time that can be calculated using equation 2.17.

$$t^* = t \cdot \left[\left(\frac{A_0 \cdot \sqrt{H_0}}{A_t} \right) / \sqrt{k\rho c} \right]^2 / \left[\frac{0.04}{1160} \right]^2 \quad (\text{eq. 2.17})$$

Where t is the time [h], $\frac{A_0 \cdot \sqrt{H_0}}{A_t}$ is the opening factor, which needs to be within the range of 0.02 m^{1/2} and 0.2 m^{1/2}. The $k\rho c$ -term is the conductivity, density and specific heat of the boundary material. This term needs to be within the range of $100 \leq \sqrt{k\rho c} \leq 2200$ (SS-EN 1991-1-2). Note that the time is in hours.

2.4 Estimating the critical heat release rate for flashover

When the compartment temperature has been calculated it can be used to estimate the likelihood of flashover. The three most commonly used equations to predict the critical heat release rate for flashover are presented below. The results from using these hand calculation models in the present case are presented in chapter 7.1 and 7.4.

2.4.1 Babrauskas' flashover equation

Babrauskas uses the same simplified energy balance as McCaffrey, Quintiere and Harkleroad as a base for the equation. In Babrauskas equation the primary energy loss is assumed to be radiation to 40 percent of the wall area which is at approximately ambient temperature. The hot gas layer temperature needed to reach flashover is set to 600°C. Comparing the results to fire tests the following equation was derived (SFPE 2002).

$$\dot{Q}_{fo} = 750 \cdot A_o \cdot \sqrt{H_o} \quad (\text{eq. 2.18})$$

Where \dot{Q}_{fo} is the heat release rate needed to reach flashover [kW], A_o is the total opening area [m²], H_o is the weighted mean height of all the openings [m].

2.4.2 MQH flashover equation

The MQH flashover equation is generally an extended version of the MQH-method used to calculate compartment temperatures. The hot gas layer temperature needed to reach flashover is set to 500°C and the following equation is derived (SFPE 2002).

$$\dot{Q}_{fo} = 610(h_k \cdot A_T \cdot A_o \cdot \sqrt{H_o}) \quad (\text{eq. 2.19})$$

Where \dot{Q}_{fo} is the heat release rate needed to reach flashover [kW], A_o is the total opening area [m²], H_o is the weighted mean height of all the openings [m], h_k is the effective heat conduction term for the solid boundaries [kW/m² K] and A_T is the total enclosure surface area (including the openings) [m²]

2.4.3 Thomas' flashover equation

Thomas also uses the same simplified energy balance as McCaffrey, Quintiere and Harkleroad as a base for the equation. The energy loss is generally assumed to be through heat transfer to surfaces and through radiation. From experimental data Thomas developed the following equation for the minimum rate of energy release for flashover.

$$\dot{Q}_{fo} = 378A_o \cdot \sqrt{H_o} + 7.8A_T \quad (\text{eq. 2.20})$$

Where \dot{Q}_{fo} is the heat release rate needed to reach flashover [kW], A_o is the total opening area [m²], H_o is the weighted mean height of all the openings [m] and A_T is the total enclosure surface area (including the openings) [m²].

3. NEW DESIGN SOLUTIONS

In the previous chapter the theory behind the fire development and how to calculate heat transfer through different boundary materials, such as thermal insulation, were explained. In this chapter the practical applications for increased thermal insulation will be described.

First, some general effects of increased thermal insulation are described. It is a short summary of results from different research projects involving differences in heat release rate and temperature due to insulating materials. This is followed by the description of two of the applications for increased thermal insulation: low-energy houses and lightweight ship constructions.

3.1 General effects of insulation on fire development

Already in 1981 the National Research Council Canada published a report called *Effects of Insulation on Fire Safety*. The report lists various effects of increased insulation; influence on growth of fire and failure of structural elements during fire are two of them (Lie 1981).

Thermal insulation reduces the heat transfer through the building boundaries and therefore reduces the loss of energy. Heat will stay in the fire compartment, implying increased temperatures which could result in a quicker fire development and earlier flashover. The increased temperature might also add to the risk of structural failure due to higher fire temperatures (Lie 1981).

In Pettersson et al. (1976) a temperature-time graph for different types of construction materials is presented. The highest temperature (approximately 1150°C) was calculated for a lightweight concrete construction with high insulation properties and the lowest temperature (approximately 700°C) for a construction with 80% non-insulated steel sheeting and 20% concrete. Similar results were found by Latham (1987) whose studies show that the type of fuel and lining material has an effect on the gas temperature in the hot smoke layer. Studies also show that the fire severity increases with at least two factors: increased fire load and, to a certain extent, a decrease in ventilation.

Latham (1987) also describes that experiments were carried out in a compartment with inner walls of insulating fire bricks. The high insulating properties of the lining material increased the temperature of the hot gas layer. However, when applying sheets of Gyproc 'Fireline' plasterboard to the inner walls this gave a lower maximum average compartment temperature compared to the case without plasterboards. It is the release of free water and water crystallization in plasterboards that provide additional fire protection (Latham 1987).

It has furthermore been reported that the building products could affect the time to flashover. In the report "*Results and Analysis from Fire Tests of Building Products in ISO 9705, the Room/Corner Test*" that was published by SP Technical

Research Institute of Sweden, results from a number of building products tested in the Room/Corner test are presented. For example, a paper faced glass wool was tested and flashover was reached after 18 seconds. This is explained by the high insulation capacity of the glass wool. The same paper put on a concrete substrate would probably, give an insignificant fire development (Sundström, van Hees & Thureson 1998).

SP was also coordinating a research project evaluating the fire safety of upholstered furniture, resulting in a handbook called "Fire Safety of Upholstered Furniture – the final report on the CBUF research programme" (Sundström (ed.) 1995). During experiments carried out in the project it was found that the heat release rate of chairs in a room fire is about 1.2 times higher than in free burning conditions, such as in Furniture Calorimeter. The difference in HRR is probably a result of the radiated heat from walls and the hot upper layer (Sundström (ed.) 1995).

The different factors mentioned above imply that an increased thermal insulation will affect the temperature in the compartment and also the time until flashover.

3.2 Low-energy houses

The interest and development of well-insulated buildings, or low-energy houses, is growing. This type of construction is becoming more common in our cities for each year. Reading about low-energy houses there are many concerns raised that have been thoroughly investigated, such as fear for humidity and mould. Although the concerns about how increased thermal insulation can have an effect on fire safety has been discussed by firemen and fire safety engineers for many years, the concerns have not yet reached the general public and have therefore not been investigated further. There is nevertheless a lack of knowledge and experience of fires in 'low-energy houses' with improved thermal insulation and the constructions' effects on fire development.

3.2.1 Construction components

For a house to be classified as a low-energy house the consumption of energy per square meter and year need to be half or less of what is accepted for a standard house of today. For this to be achieved the walls of the construction need to be coated with at least 50 mm extra insulation (Paroc 2007). An example of a wall for low-energy houses is presented in Paroc's folder *Energy sound constructions. Higher quality, lower energy consumption (sv. Energikloka konstruktioner. Högre kvalitet, lägre energiförbrukning)* (2007). The wall is provided with insulation having a total thickness of 285 mm. It is important to remember though; it is not just the increased thermal insulation that makes the house a low energy house. All the components of a house make a difference to the energy consumption, such as the windows and other thermal bridges.

The different types of insulation that can be used when constructing a house are uncountable as there are very many different manufacturers. Each type of

insulation has certain specialties. However, they all have one thing in common, their ability to reduce heat transfer.

Low-energy houses are also constructed to be air-tight and not as leaky as a standard house. This, as well as the consumption of energy, is regulated by the requirements for low-energy houses (Energikontoret Skåne 2010).

3.2.2 Issues with low energy buildings

Firemen around the world are getting increasingly worried about the new types of building constructions on the market, especially those for 'low-energy houses'. They are afraid that the fire development could affect their rescue operation negatively and create a dangerous environment for the firemen.

There are mainly two points of concern mentioned (Ghent University 2010; Hartin 2008):

- the conservation of energy during the fire development; and
- ventilation controlled fires.

A ventilation controlled fire occurs when there is a lack of oxygen available. This could be the case in 'low-energy buildings' as they are not as "leaky" as older structures. The new type of windows can also make a difference, as they are less likely to fail, which changes the ventilation profile (Hartin 2008).

3.3 Lightweight ship constructions

SOLAS (Safety of Life at Sea) contains provisions of how ships shall be constructed to be considered safe, covering everything from fire protection to structural stability and evacuation (Swedish Transport Agency 2009). The regulations have recently been updated to contain a number of new regulations, among them Regulation 17 in the fire safety chapter which allows for alternative design and arrangements, e.g. use of other construction materials than steel (SOLAS II-2/17).

SP Technical Research Institute of Sweden is involved in research on the possibility to replace the steel structures on ships with FRP composite. A common risk reducing measure is to provide the FRP composite panels with thermal insulation. In the research by SP it is hence important to determine if the improved thermal insulation would have any impact on a fire development (Evegren 2010).

There are obviously also positive aspects to thermally insulated constructions. With less heat conducted through the construction, well-insulated constructions will significantly reduce the probability of fire spread due to heat transfer. Another positive side is that surrounding areas adjacent to the fire compartment may provide an escape-friendly environment for a longer time period (Evegren 2011a).

3.3.1 Construction components

The construction material under investigation by SP is a FRP (fibre-reinforced polymer) composite. It is a sandwich construction that has a core of either PVC foam or balsa wood and is coated with carbon or glass fibre reinforced polymer laminate on each side of the core. Figure 3.1 show how the FRP is built up.

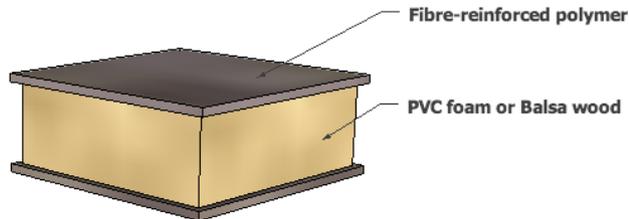


Figure 3.1: Fibre-reinforced composite (FRP).

It has been shown that the interface between the core and the fire-reinforced polymer softens and the structural performance deteriorates when the temperature in the joint becomes critical; typically at 130-140°C (Hertzberg 2009). To protect the composite from reaching high temperatures it is coated with insulation on each side. The thickness of the insulation depends on the desired classification. A FRP composite with approximately 0.1 m insulation on each side can be classified as a FRD60, which is a fire resisting division that can maintain structural integrity for 60 minutes. Figure 3.2 shows how the FRD is made up.

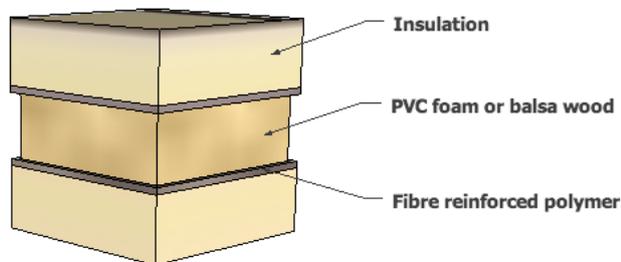


Figure 3.2: Fire resisting division (FRD).

A fire resisting division is defined in the HSC code, as a division formed by bulkheads and decks which shall be constructed of non-combustible or fire-restricting materials which by insulation or inherent fire-resisting properties satisfy the following requirements (IMO 2000):

- They shall be suitably stiffened.
- They shall be so constructed as to be capable of preventing the passage of smoke and flame up to the end of the appropriate fire protection time.

- Where required they shall maintain load-carrying capabilities up to the end of the appropriate fire protection time.
- They shall have thermal properties such that the average temperature on the unexposed side will not rise more than 140°C above the original temperature, nor will the temperature, at any one point, including any joint, rise more than 180°C above the original temperature during the appropriate fire protection time.
- A test of a prototype bulkhead or deck in accordance with the Fire Test Procedures Code shall be required to ensure that it meets the above requirements.

3.3.2 Issues with ship constructions in FRP composite

For the FRP composite to maintain structural integrity it is suggested to coat it with insulation, as described above. Improved thermal insulation will provide better containment of the fire but it could also lead to higher temperatures in the compartment. In an extreme case, the increased temperature could theoretically even lead to more heat transferring through the insulation to the division (in this case a FRP composite). Temperatures higher than 100°C could affect its structural stability and lead to collapse (Hertzberg 2009).

There are also other concerns that have been brought up regarding FRP composite constructions. Compared to a steel construction the combustible materials are not restricted on external surfaces and the ignitability of combustible external surfaces is not limited. As the FRP composite structure is combustible it could after a while take part in the fire and add fuel to the fire. In case of an uncontrolled fire that breaks out through a window the fire could spread on the outside of the construction and cause fire spread between decks and fire zones (Evegren 2011b).

4. DEVELOPMENT OF FIRE SCENARIOS

In theory the temperature seems to get higher and the heat release rate may become larger in an enclosure with a boundary material having good insulation qualities. A critical question is if it a significant difference that could affect the time to flashover?

In order to study the effects of increased thermal insulation, full-scale experiments were carried out. However, before carrying out the experiments the type and size of fire needed to be determined to get the most out of the experiments. That invoked an investigation which is presented below followed by descriptions of the four different fire scenarios that were developed.

4.1 Source of fire in experiments

Available data on fire load densities and heat release rates in different rooms were found and are presented in Appendix A. Based on that data it was decided that a wood crib and a heptane pool fire would be used as fire sources in the experiments. They represent a fire in a building where the most common room of ignition is the kitchen. Lots of combustible material is available there and most of it is organic fuel. The heptane pool fire represents a fire in an engine room where a liquid pool fire is the most common source of fire.

The fire sources chosen will be affected by the incoming radiation from the hot gas layer. This is good as it is of interest to investigate how an increased thermal insulation could affect the fire development. Therefore a gas burner with a constant heat release rate would not be adequate to use in this situation. The fire behaviour of a wood crib is also closer to a real fire development in a compartment than any other fire source (Xu et al. 2008).

It is of importance that the experiments are repeatable for this study to be robust. A wood crib and a heptane pool fire are considered good fire sources since they are considered to give similar fire developments in experiments if repeated. The size of the wood crib and heptane pool fire should be of sufficient size to give flashover in a room representing a ship compartment and an ordinary room in a building. Judging by the data presented in Appendix A, the fire load density and peak heat release rate in rooms differ a lot depending on occupancy. Each fire source is discussed further under the following headlines.

4.2 Fire development in container

Before deciding the size of the fire source it is important to decide the fire load needed to get the fire development necessary to investigate the effects of increased thermal insulation.

The hood that was to be used to measure the heat release rate during the experiments had a maximum measuring limit of approximately 1 500 kW. This

was therefore the absolute highest limit of heat release rate that could be used in the experiments.

As discussed in chapter 2 a fire can become ventilation controlled if the openings of the enclosure are not large enough. The maximum heat release rate as a function of oxygen available can be calculated using equation 2.6, presented in chapter 2.

$$\dot{Q} = 1.518 \cdot A_o \cdot \sqrt{H_o} \quad (\text{eq. 2.6})$$

The container that was used in the experiments had an open end where a temporary wall was built, leaving an opening 2 m high and 1 m wide, which is the typical size of a door opening. For these measurements a maximum heat release rate of approximately 4 000 kW can be expected. A maximum heat release rate of 1 500 kW (the maximum measuring limit of the hood) would therefore not be limited by the amount of oxygen available.

It was however, also of interest to decide on the lowest useful heat release rate for the experiments. One of the parameters that were going to be investigated in the experiments was the time to flashover. Therefore, it was necessary that flashover be reached in the experiments. The heat release rate needed to reach flashover can generally be calculated using one of three different methods. If calculated using Babrauskas' equation for flashover (eq. 2.18) the predicted heat release rate is calculated to 2120 kW. Using Thomas' equation (eq. 2.19) the heat release rate needed to reach flashover is calculated to be 1580 kW. The MQH flashover equation includes the effective heat conduction term (h_k) however this term changes over time, which makes this method hard to apply in this case.

Both of the calculated heat release rates, using Babrauskas and Thomas equations, are larger than the maximum measuring limit of the hood, however results in the study carried out by R. Huo, X.H. Jin, C.L. Shi and W.K. Chow (2001) show that the methods to calculate \dot{Q}_{fo} overestimate the heat release rate needed to reach flashover. Qualitative reasoning was therefore also used in this process, as follows.

When carrying out standard testing in the ISO 9705 Room Corner Test the heat release rate needed to reach flashover is approximately 1 000 kW (SP 2011). The size of the room is 3.6 m x 2.4 m x 2.4 m (l x w x h) with a door opening 2 m high and 0.8 m wide. The heat release rate needed to reach flashover depends on the size of the opening(s) providing oxygen to a room (SFPE 2002). The size of the door opening in the ISO 9705 Room Corner Test is slightly smaller than the one to be used in the experiments. Therefore, the heat release rate needed to reach flashover in the experiments could be expected to be a bit over 1 000 kW.

The heat release rate in the experiments should therefore range between 1 000 kW (needed to reach flashover) and 1 500 kW (maximum measuring limit of the hood).

4.2.1 Heptane

Heptane is a flammable liquid often used in standardised testing. It is for example used when testing foam equipment and liquid concentrates (SFPE 2002).

To reach a heat release rate between 1 000 kW (which was needed to reach flashover) and 1 500 kW (limit of the hood) the diameter of the tray needed to be 0.82 m – 0.96 m, calculated using equation 2.3 and 2.4 in chapter 2. The equation was solved using a combustion efficiency of 0.7, as heptane is a fuel that soot. The complete heat of combustion was set to 44.6 MJ/kg, the modified value for mass loss rate to 0.101 kg/m² s and $k\beta$ to 1.1 m⁻¹, according to table 3.3 in *Enclosure Fire Dynamics* (Karlsson & Quintiere 2000). A tray with a diameter of 0.89 m was chosen and thus theoretically a maximum heat release rate of 1 200 kW could be expected.

4.2.2 Wood crib

Wood cribs have been used for a long time to investigate fire growth and propagation (Delichatsios 1976). It has most often the shape of a three-dimensional cube and is constructed of wooden sticks that are placed in alternating rows where the sticks on each row are separated by an air gap. Figure 4.1 shows the typical layout of a wood crib.

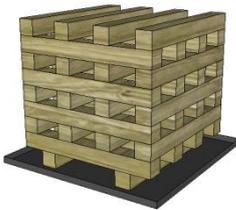


Figure 4.1: Typical layout of a wood crib.

As described in the SFPE Handbook of Fire Protection Engineering (3rd edition), the burning rate for uniformly ignited wood cribs is governed by one of three conditions: (1) the natural limit of stick surfaces burning freely; this limit applies to cribs with wide interstick spacings, (2) the maximum flow rate of air and combustion products through the air holes in the crib; this applies to tightly packed cribs, and (3) the maximum oxygen that can be supplied to the room (SFPE 2002).

It is also stated that wood cribs burn slower and produce less excess fire load than furnishing and other combustibles found in practical fire loads (SFPE 2002).

Xu et al. (2008) has carried out calibration burning of wood cribs that were later on used in water mist suppression tests. The results from the calibrating fire tests show that their wood crib of 31 kg, with an exposed surface area of 5.23 m², gives a maximum heat release rate of approximately 500 kW after 900 s. It also shows that if the size of the crib is doubled or tripled, then so is the fire growth rate.

Wood crib tests have also been carried out by Heskestad (2006). The wood crib reached a maximum heat release rate of 467 kW after 420 s. The heat release rate has been calculated from the maximum mass loss rate of 58 g/s multiplied by the heat of combustion 11.5 kJ/g and the combustion efficiency 0.7 using equation 2.1 and 2.2 presented in chapter 2.

Data from the wood crib experiments carried out by Xu and Heskestad are presented in table 4.1 below.

Table 4.1: Data from wood crib experiments

	Heskestad	Xu
Weight [kg]	21*	31.5
Stick length [m]	0.762	0.5
Stick width [m]	0.0159	0.035
Stick height [m]	0.0159	0.035
Sticks/layer	14	8
Layers	15	12
Exposed surface area [m²]	8.9	5.23
Peak HRR [kW]	467	500
Peak HRR time [s]	420	900

* Calculated from the volume using a density of 520 kg/m³

The data of the wood cribs used in the experiments carried out by Xu et al. (2008) are well documented and possible to repeat. The wood crib could be doubled or tripled to get twice or three times as high heat release rates and therefore it was chosen to be used when carrying out the current experiments.

The heat release rate curves from the experiments carried out by Xu et al. (2008) are presented below in figure 4.2. The dashed line, with a maximum of 1 600 kW, represents the heat release rate used in hand calculations and simulations. This is more than the 1 000 kW needed to reach flashover and just above the maximum limit of the hood (1 500 kW).

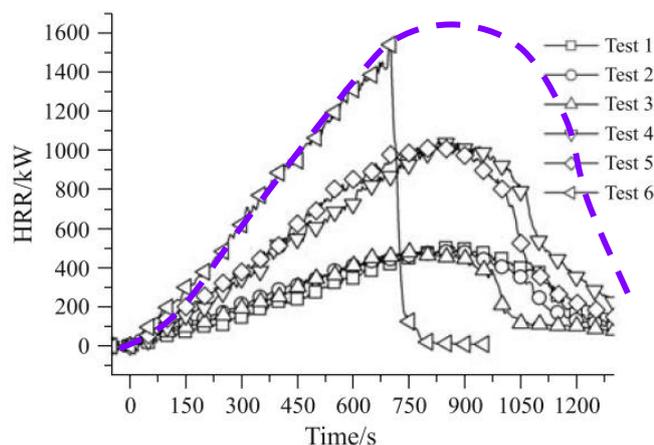


Figure 4.2: Heat release rate for wood crib experiments. The dashed line represent the heat release rate used in hand calculations and simulations.

4.3 Fire scenario 1 to 4

Four fire scenarios have been chosen to represent the fire development in a house and ship compartment. Data for enclosed fires, appendix A, show that the maximum heat release rate that could be expected from a normal room is often larger than 1 500 kW. The amount of fuel also exceeds what is going to be used in the experiments. However, to be able to measure the effects of increased thermal insulation the heat release cannot be too large, because of the limitations to the hood. The chosen scenarios are considered representable of fires in compartments in houses and on ships.

Each of the following fire scenarios has also been simulated in FDS, both before and after carrying out the experiments. The expected heat release rate was also used in hand calculations.

4.3.1 Scenario 1 – heptane pool fire in insulated container

A tray with heptane was placed inside the 20 feet container that was covered with 0.095 m insulation on the outside. The heptane represented a fire in an engine room on a ship. The tray had a diameter of 0.89 m and the expected heat release rate was approximately 1 200 kW. A schematic drawing of the tray is shown in figure 4.3.

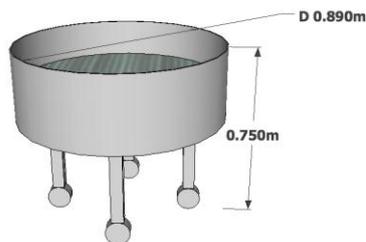


Figure 4.3: Schematic drawing of the tray with heptane used in the heptane pool fire experiments.

4.3.2 Scenario 2 – heptane pool fire in non-insulated container

A tray with heptane was placed inside the container that was bare on the outside. The heptane represented a fire in an engine room on a ship. The tray had a diameter of 0.89 m and the expected heat release rate was approximately 1 200 kW.

4.3.3 Scenario 3 – wood crib fire in insulated container

A wood crib was placed inside the 20 feet container that was covered with 0.095 m insulation on the outside. The wood crib represented a fire in a normal room in a building. The wood crib was formed as three cubes placed into an L-shape, see figure 4.4 below, as in the experiments carried out by Xu et al. (2008). The expected maximum heat release rate was approximately 1 600 kW, as described in the report by Xu et al. (2008).

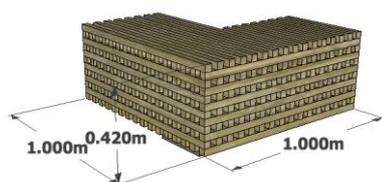


Figure 4.4: Schematic drawing of the wood crib used in the wood crib fire experiments.

4.3.4 Scenario 4 – wood crib fire in non-insulated container

A wood crib was placed inside the container that was bare on the outside. The wood crib represented a fire in an ordinary room in a building. The wood crib was formed as three cubes placed into an L-shape, see figure 4.4. The expected maximum heat release rate was approximately 1 600 kW, as described in the report by Xu et al. (2008).

5. EXPERIMENTAL SET-UP

It is of importance that each parameter is the same for each experiment to be able to compare the results. Below the set-ups of the performed experiments are described. The experiments took place in SP's facility for large scale experimental tests.

5.1 Equipment and material

The types of equipment and material used in the experiments are presented below.

5.1.1 Container

The container used in the experiments was a standard 20 ft container made out of corrugated steel. The inner measurements of the container are 5.9 m x 2.35 m x 2.4 m (l x w x h). Figure 5.1 shows a schematic drawing of the container. In two of the experiments the outside was covered with a layer of rock wool (Rockwool FlexiBatts®) which was 0.095 m thick. In the other two experiment configurations the container was left without insulation. The floor was left uninsulated in all configurations. However, the floor on the inside was originally made out of wood and to omit it from igniting it was covered with noncombustible plaster boards. The plaster boards were replaced after the two insulated experiments had been carried out.

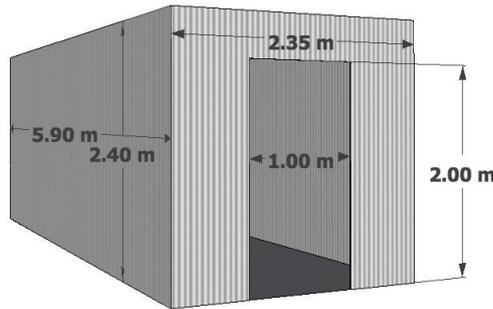


Figure 5.1: The container dimensions.

5.1.2 Fire source – heptane pool fire

In two of the four experiments a heptane pool fire was used as fire source. The heptane was poured into a circular tray with legs. The diameter of the tray was 0.89 m and the height 0.75 m. The tray was filled with some water and 50 litres of heptane, placing the surface of the fuel at an approximate height of 0.60 m from the floor, see figure 5.2.

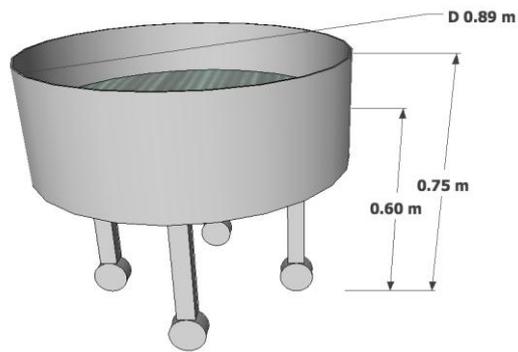


Figure 5.2: The heptane tray with its measurements.

The fire source was placed right behind the centre of the container, as shown in figure 5.3 below. Both the heptane pool and the wood crib were placed with the edge of the fire source 2.95 m from the opening of the container.

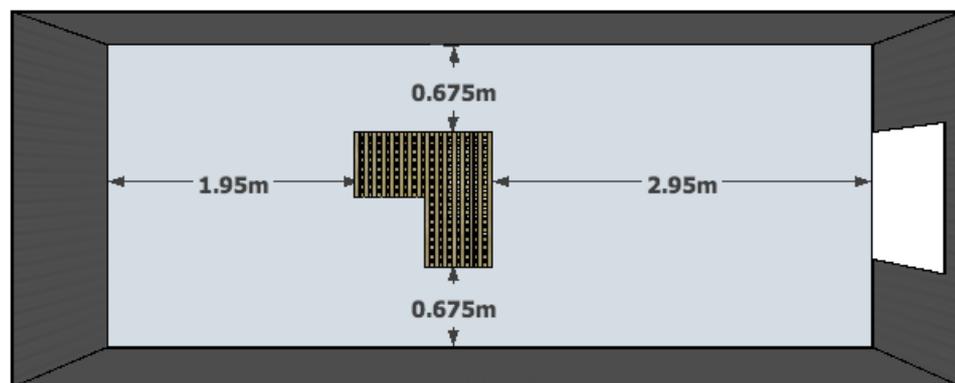


Figure 5.3: Placing of the fire source in the experiments.

5.1.3 Fire source – wood crib

In two of the four experiments wood cribs were used as fire source. The calibration burning of wood cribs carried out by Xu et al. (2007) has been used as reference. Data from the experiment is presented in a report detailed enough to be recreated. It was chosen to use the largest of the wood cribs tested, which provided a heat release rate of 1.6 MW.

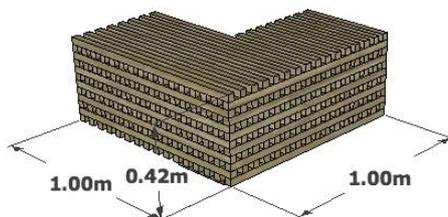


Figure 5.4: The wood crib with its measurements.

The wood crib used in the experiments carried out at SP Technical Research Institute of Sweden was built with sticks made out of pine. The crib had a total of

12 layers with 8 short sticks (0.035 m x 0.035 m x 0.500 m) and 8 long sticks (0.035 m x 0.035 m x 1.00 m) per layer. The dimensions of the wood crib are shown in figure 5.4.

Three trays, each one with the dimensions 0.30 m x 0.30 m (l x w) two of them having a height of 0.10 m and the third 0.07 m, were placed underneath the crib. The trays were filled with 1.0 litre of heptane each. The trays with heptane were used to get a simultaneous lighting of the wood crib that is easily repeatable.

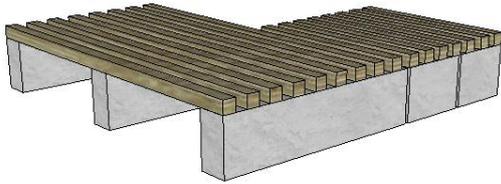


Figure 5.5: The first layer of sticks in the wood crib that were placed upon lightweight concrete blocks.

The wood crib was placed upon lightweight concrete blocks that were 0.15 m high and approximately 0.07 m wide. Figure 5.5 shows the first layer of wood sticks placed on top of the lightweight concrete blocks. The concrete blocks were placed along the length of the container and the first layer of sticks resting upon the blocks following the width of the container. The fire source was situated 2.95 m from the opening of the container, at the same distance as the heptane pool.

The moisture content of the wood ranged from 10.5% to 12.5%. The short sticks weighed from 0.32 kg to 0.36 kg and the long sticks 0.64 kg to 0.74 kg giving the wood crib a calculated total weight of 92 kg to 106 kg. Note that the wood had not been dried nor conditioned before the experiments. Some samples of the sticks were tested for moisture content and weight. With the constant weather conditions outside and temperature in the hall there is a relatively low probability that the properties of the wood will have changed between the experiments.

5.1.4 Insulation

The container was in two of the experiments covered with insulation. All long sides were covered on the outside, apart from the floor which was left uncovered. The closed end of the container was also covered on the outside and in the end with an opening a temporary wall was built, leaving an opening of 2 x 1 m. The temporary wall was constructed of wooden joist covered with plasterboards on the inside and filled with insulation on the outside. Figure 5.6 below shows the temporary wall.

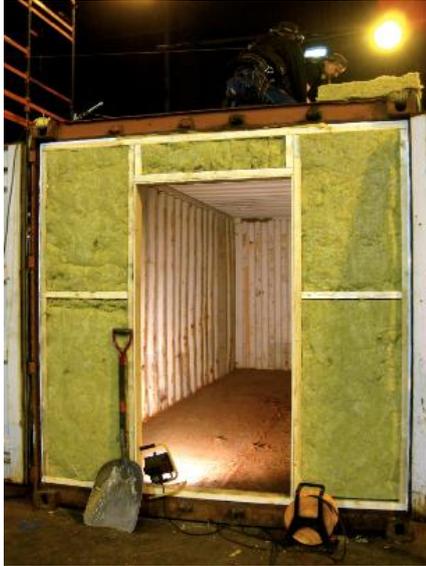


Figure 5.6: Temporary wall constructed in the open end of the container.

The insulation used to cover the container was Rockwool FlexiBatts®. The sheets of insulations were 1.170 m x 0.58 m x 0.095 m and had the following physical properties (Rockwool):

$$k = 0.037 \text{ W/m K}$$

$$\rho = 30 \text{ kg/m}^3$$

Steel pins were welded to the container indentations and the mineral wool threaded upon them and attached with locking devices. Figure 5.7 shows how the insulation was attached.

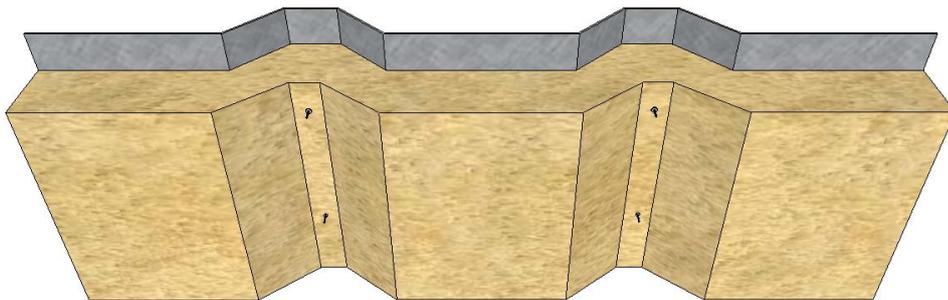


Figure 5.7: Schematic drawing of how the insulation was attached to the container.

Each sheet of insulation was attached with six pins. The pins were situated at six different heights: 0.13 m, 0.48 m, 1.03 m, 1.31 m, 1.66 m and 2.21 m from the roof. Approximately 60 m² of insulation was used to cover the container. The container looked as in figure 5.8 below when it was ready to be used.



Figure 5.8: Coated container, ready to be used in the experiments.

5.2 Measured properties

The different types of parameters measured and the devices used for the measurements are described below. The aim was to also weigh the fuel while it was burning. However, if a scale would have been placed inside the container it would have been damaged. Another option was to make a hole in the bottom of the container for the scale, though this would have been considered too large of an operation.

5.2.1 Heat release rate

The calorimeter in SP's large test facility was used to measure the heat release rate in each experiment. It was calibrated beforehand using a tray with a diameter of 0.72 m that was placed on scales. The tray was filled with heptane and left burning for 20 minutes. The calibration results were within the limits for the ISO 24473 standard.

5.2.2 Gas temperature

To measure the gas temperature in the container, 0.25 mm type K thermocouples were used. The thermocouples were situated in three thermocouple trees, with six thermocouples in each tree. The measuring points were situated 0.30 m apart, the highest one at 2.1 m from the floor and the lowest one at 0.60 m from the floor.

The three trees were placed along the centreline of the container, as shown in figure 5.9. The first one was situated between the fire and the back wall, 0.975 m from the wall, the second one between the fire and the door opening, 1.475 m from the opening, and the third in the door opening, 0.1 m in from the opening. Note that even in the door opening there was a measuring point situated at 2.1 m from the floor even though the door was only 2.0 m high.

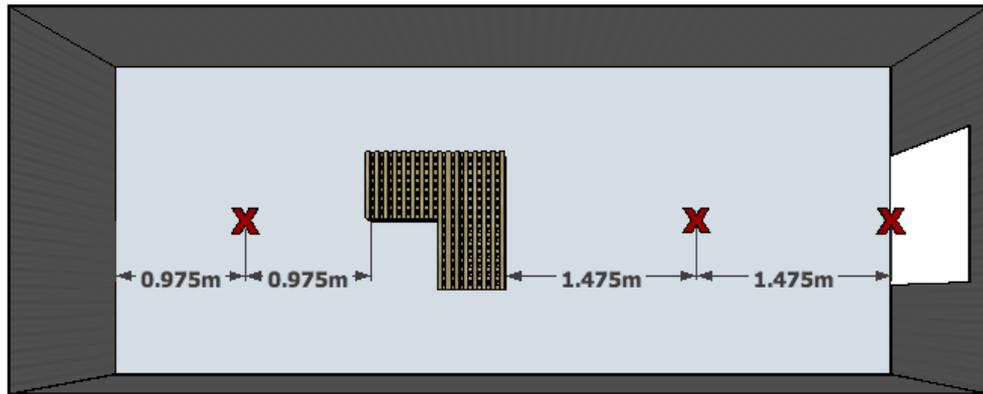


Figure 5.9: Placing of the thermo couple trees for measuring of the gas temperature. The gas temperature was measured at the heights: 0.6 m, 0.9 m, 1.2 m, 1.5 m, 2.1 m.

5.2.3 Wall temperature

Thermocouples, 0.25 mm type K, were also used to measure the temperature of the walls of the compartment. In total 9 measuring points were used. The measuring points were divided into groups of three. In each group the measuring points were distributed over three heights: 0.90 m, 1.5 m and 2.1 m.

The first group of measuring points were situated across from the fire on the wall left of the fire source (when viewed from the opening of the container). The second group of measuring points were situated on the wall right of the fire source, between the fire and the back wall. The last group of measuring points were also situated on the wall right of the fire source, between the fire and the door opening. Figure 5.10 below shows where the measuring points were situated.

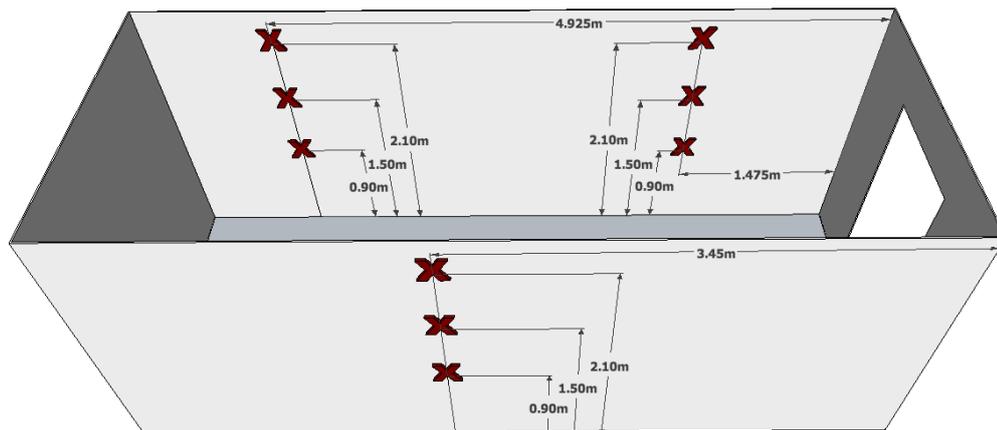


Figure 5.10: Placing of the thermo couples for measuring the wall temperature.

In all four experiments thermocouples soldered to the inside and outside of the steel were used. In the experiments where the container was coated with insulation, thermocouples were also placed in the middle of the insulation and on the outside of the insulation. The locations of the measuring points are shown in

figure 5.11, below. In total, 18 measuring points were used in the experiment without insulation and 36 in the one with insulation.

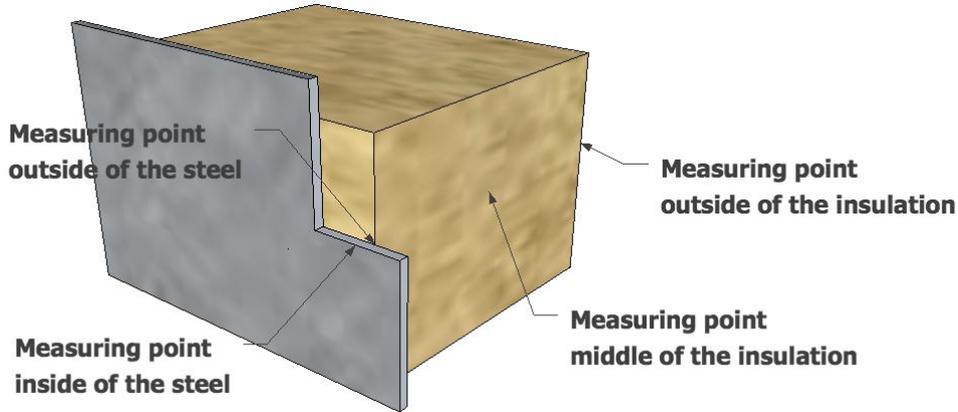


Figure 5.11: Locations for the measuring points of the wall temperature.

5.2.4 Radiation

To measure the radiation towards the floor, two plate thermometers were used. They were placed on the floor next to the thermocouple trees inside the container. The plate thermometers measure the temperature of a surface which cannot absorb any heat. This temperature is called the *Adiabatic Surface Temperature*. From the measured temperature the incident radiation can be obtained using the following equation (Wickström 2011):

$$\dot{q}_{inc}'' = \sigma T_{PT}^4 - \frac{1}{\varepsilon_{PT}} \left[(h_{PT} + h_k) \cdot (T_g - T_{PT}) - C \frac{dT_{PT}}{dt} \right] \quad (\text{eq. 5.1})$$

Where σ is the Stefan-Boltzman constant, T_{PT} is the temperature measured by the plate thermometer [K], ε_{PT} is the emissivity of the plate thermometer [-], h_{PT} is the heat transfer coefficient of the plate thermometer [$W/m^2 K$], h_k is the effective heat conduction coefficient [$W/m^2 K$], T_g is the gas temperature surrounding the plate thermometer [K], C is the heat capacity [$J/m^2 K$] and $\frac{dT_{PT}}{dt}$ is the transient term [K/s]. Note that the effective heat conduction coefficient is in $W/m^2 K$.

Typical values for the constants are, $\varepsilon_{PT} = 0.9$, $h_{PT} = 12 W/m^2 K$, $h_k = 8.4 W/m^2 K$ and $C = 4200 J/m^2 K$ (Wickström 2011). The surrounding gas temperature was not measured at floor level, instead the gas temperature measured at a height of 0.6 m from the floor has been used in the calculations.

5.3 Experiment procedure

Below it is described how the experiments were carried out.

5.3.1 Risk analysis

Before experiments are carried out at SP Technical Research Institute of Sweden the staff carries out a risk analysis to prevent any accidents. One was therefore carried out before the experiments of this study could start. In the risk analysis all the phases of the experiment were analysed: the preparation, the experimental process and also the cleaning up afterwards. The risk analysis is attached in Appendix B.

5.3.2 Test procedure

The wood crib was put in place and the three trays underneath were filled up with heptane. In the experiments with the heptane pool fire the circular tray was put into place and a foam extinguisher installed on the edge of the tray. As soon as possible after the trays had been filled with heptane the test was started, this to omit too much evaporation of the heptane before the experiment.

0 minutes – The stopwatch was started as well as the measuring devices.

1.5 minutes – The recording was started.

2 minutes – The fire source was ignited.

Throughout the experiments the time of occurrence of (1) flames reaching the ceiling, (2) flames emerging from the opening and (3) when the fire was extinct were noted as well as any unexpected events.

One minute after flashover was reached the fire was extinguished with water for the wood crib and with foam for the heptane pool fire. The walls inside the container also had to be cooled down. After each experiment was finished a fan was put in the door opening to ventilate.

The results from the carried out experiments are presented in section 7.3.

6. SIMULATIONS

FDS, Fire Dynamics Simulator, version 5.5.3 (NIST 2011) has been used to carry out simulations both before and after the experiments. The idea is to compare the results from the simulations with the results from the experiment and see how the results correspond.

Both set-ups was simulated two times. The first run, before the experiments were carried out, with an estimated heat release rate and the second run, after the experiments were carried out, using the heat release rate recorded in the experiments.

Apart from the four fire scenarios described in chapter 4, a fifth scenario was simulated of a “wood crib fire in a non-insulated container situated in a large room”. The fifth set-up was constructed as a validation configuration to investigate if the hood would have any effect on the results from the simulation, due to increased convection on the outside of the container. The results from this scenario are therefore only presented in section 7.6 Verification of simulations.

6.1 FDS

FDS is a type of CFD model (Computational Fluid Dynamics) that has been created by the National Institute of Standards and Technology (NIST) to simulate fires in rooms. The first version was published in 2000 and has since then been frequently updated. The software numerically solves Navier-Stokes equations that are suitable for smoke and heat transport from fires. The core algorithm is an explicit predictor-corrector scheme and the turbulence is solved using Large Eddy Simulation (NIST 2010).

6.2 Resources

The CFD simulations were performed at the Lunarc system (Lunarc 2012) using a multiprocessor version of FDS version 5.5.3. Simulations were carried out in December 2011 and January 2012. Lunarc is a centre for scientific and technical computing for research at Lund University. The system has several clusters. When carrying out the simulations, the Platon cluster was used. Platon is a HP solution with a total of 1728 processors.

6.3 Input data

The input data defines what is going to be calculated in FDS and are therefore of great importance. Below are some of the most important input data described. The whole FDS-files are found in Appendix C. A verification of the simulations including a grid independence analysis is presented in section 7.6 Verification of simulations.

6.3.1 Geometry and meshes

The geometry of the container was kept as identical to the actual container as possible. However the walls and roof of the container were simplified. In the actual container they are corrugated, though in the model they were kept plane. The size of the cells was chosen to be 0.05 m x 0.05 m x 0.05 m.

The model was divided into six meshes, as shown in figure 6.1 below. The mesh borders are marked in pink. All meshes had the same dimensions and amount of cells. The meshes are numbered 1 to 6 from the back of the container placing the fire source in mesh 3.

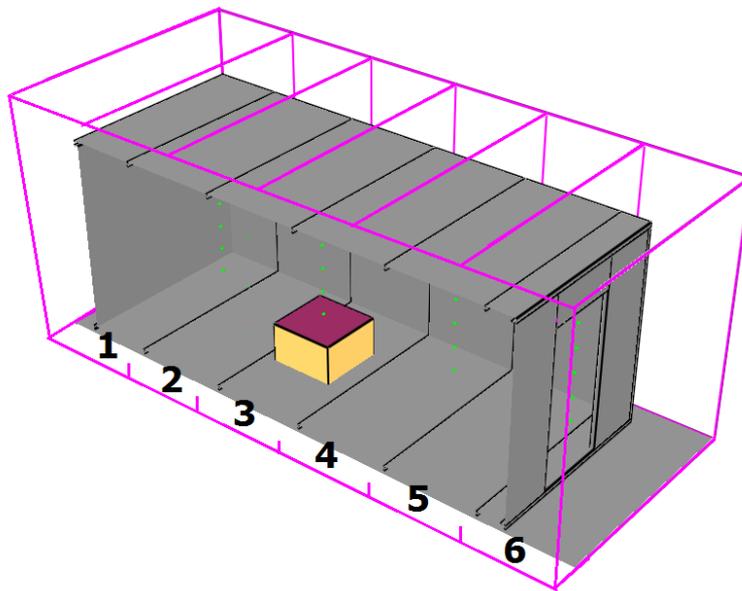


Figure 6.1: Distribution of meshes, simulation of original set-ups.

In the fifth simulation, with the larger room, the room was divided into five meshes as shown in figure 6.2 below. The mesh borders are marked in pink. The cell size was changed to 0.10 m x 0.10 m x 0.10 m in mesh 1 and 2, containing the container, and in mesh 3, 4 and 5, surrounding the container, the cell size was set to 0.20 m x 0.20 m x 0.20 m. The hood that was there to collect the smoke was situated in mesh 2.

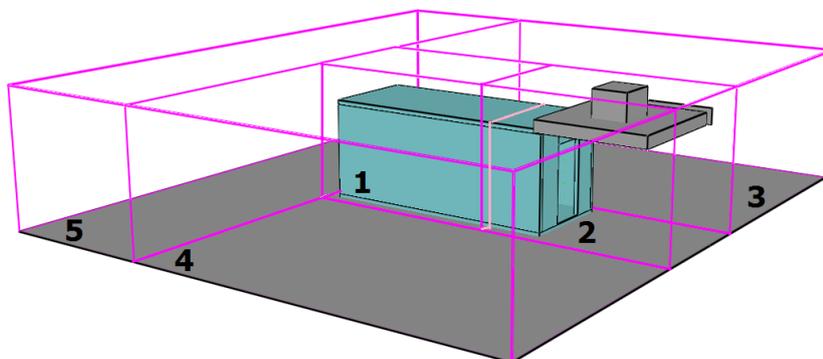


Figure 6.1: Distribution of meshes, simulation of verification set-up.

6.3.2 Boundary conditions

All boundaries apart from the one at the floor were open to allow for air to enter the calculation domain. The walls, floor and ceiling of the construction were given material properties for steel or steel and insulation. Boundary conditions for the fire are described below.

6.3.3 The fire

The types of fire sources were discussed in chapter 4. Two fire sources were used in the experiments. (1) Heptane in a circular tray with a diameter of 0.89 m. The maximum heat release rate has been calculated to 1 200 kW and (2) a wood crib with a maximum heat release rate of 1 600 kW as described in the report by Xu et al. (2008).

It is not possible to create circular objects in FDS and therefore a square object with a surface area of 0.64 m² represented the circular tray for the heptane. Figure 6.3 below shows drawings of the circular tray and the square object.

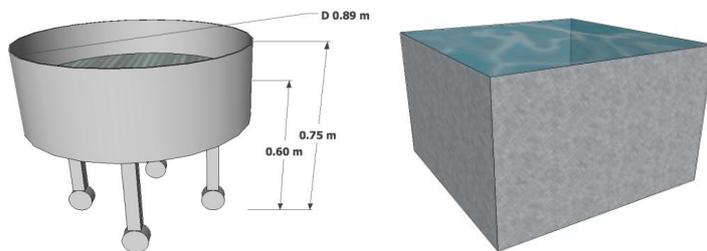


Figure 6.3: The heptane tray used in the experiments and the square obstruction used in the FDS simulations.

The wood crib fire that is shaped as three 0.5 m x 0.5 m x 0.5 m cubes placed in an “L-shape” was represented by a rectangular block with an area of 0.5 m x 1.5 m, see figure 6.4 below. Making a rectangular block to represent a “L-shaped” formation is a rough approximation, which adds uncertainty to the results.

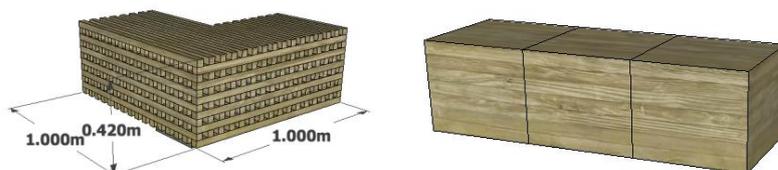


Figure 6.4: The wood crib used in the experiments and the rectangular obstruction used in the FDS simulations.

The chemical composition for wood was chosen to C=3.4, H=6.2, O=2.5 (Ritchie et al. 1997) and for heptane C=7, H=16. The soot yield was set to 0.015 kg_{soot}/kg_{fuel} for both fire sources (Robbins & Wade 2008). The fire properties were applied to the top blocks representing the fire source while the sides of the blocks were set to inert.

The default combustion model used in FDS is a single step chemical reaction with a two-parameter mixture fraction model where the mass fraction of unburned fuel and the mass fraction of burned fuel are computed.

6.3.4 Lining materials

In the non-insulated simulations each obstacle was given a steel surface, 0.003 m thick, with the following properties (Karlsson & Quintiere 2000):

CONDUCTIVITY_RAMP	= 45
SPECIFIC_HEAT	= 0.460
DENSITY	= 7820

In the simulations with the insulated container insulation with a thickness of 0.1 m was added to all the steel surfaces apart from the floor. The insulation had the following properties (Karlsson & Quintiere 2000):

CONDUCTIVITY_RAMP	= 'K_RAMP' *
SPECIFIC_HEAT	= 0.800
DENSITY	= 100

* the conductivity was changed with temperature (Engineering toolbox).

6.4 Output data

The output data is to be used when comparing results from the simulations to experiments and hand calculations. When running FDS two result files are created: one that displays the heat release rate and one with the results from the devices that have been used in the model. The heat release rate is registered automatically while other measuring tools have to be defined. The following output parameters have been chosen:

- Slicefiles for both temperature and velocity, to verify that the results from the simulation are reliable.
- Devices measuring the temperature in the container at the same position and height as measured in the experiment, to be able to compare the gas temperature to the results from the experiments.
- Devices measuring the temperature of the walls of the container. The positions are the same as in the experiment, to be able to compare the wall temperatures to the results from the experiments. In FDS the wall temperature is calculated using one-dimensional heat conduction equations. This may however lead to errors in the end result if the lateral heat conduction within the solid is significant (NIST 2010). The radiation was displayed using boundary files.
- Boundary file to measure the wall temperature, to be able to compare the wall temperatures to the results from the experiments.
- Boundary file to measure the radiation, to be able to compare the radiation to the results from the experiments.

- Heat detectors that go off at 600°C, to be able to compare the time to flashover and compare it to the results from the experiments.

The results from the carried out simulations are presented in section 7.2 and 7.5.

7. RESULTS

As described in the previous chapters the effect of increased thermal insulation is evaluated through hand calculations, simulations and full-scale experiments. In this chapter results from these are presented.

In sections 7.1 and 7.2 the results from the pre-experiment hand calculations and simulations are presented. In the following section, 7.3, the results from the experiments are presented and finally the results from the post-experiment hand calculations and simulations are presented in sections 7.4 and 7.5.

7.1 Pre-experiment hand calculations

Three methods to calculate the temperature in an enclosure were used, the MQH method, the Magnusson and Thelandersson method and the EUROCODE method. In each calculation method the compartment dimensions presented in table 7.1 were used. Values for the heat release rate used in the calculations were gathered from literature as described in section 4.2.

Table 7.1: Compartment dimensions used in the hand calculations

Parameter	Variable	Value	Unit
Length of compartment	l	5.90	m
Width of compartment	w	2.35	m
Height of compartment	h	2.40	m
Opening width	-	1.00	m
Opening height	-	2.00	m
Opening area	A_o	2.00	m ²
Internal surface area	A_t	65.33	m ²
Floor area	A_f	13.87	m ²

7.1.1 MQH

When carrying out calculations using the MQH method, the material properties presented in table 7.2 below have been used.

Table 7.2: Material properties for steel and insulation used in MQH calculations

Material	Variable	Value	Unit	Reference
Steel	h_c	10	W/m ² K	Calculated for an ambient temperature of 25°C using eq. 2.11
	h_r	30	W/m ² K	Calculated for a steel temperature of 800°C and an ambient temperature of 25°C using eq. 2.10
Insulation	$k\rho c$	3300	W ² s/m ⁴ K ²	Karlsson & Quintiere 2000

Equation 2.9 in chapter 2 was used to calculate the temperature-time curve for the four fire scenarios presented in chapter 4.

$$\Delta T = 6.85 \left(\frac{\dot{Q}^2}{h_k \cdot A_T \cdot A_o \cdot \sqrt{H_o}} \right)^{1/3} \quad (\text{eq. 2.9})$$

For the insulated case equation 2.9a were used to calculate h_k since the insulation can be considered semi infinite in thickness. For the non-insulated case equation 2.9c were used, as the steel most likely is affected by the convection and radiation on the outside of the construction.

$$h_k = \sqrt{\frac{k\rho c}{t}} \quad (\text{eq 2.9a})$$

$$h_k = (h_c + h_r) \quad (\text{eq 2.9c})$$

As all the parameters were known the temperature for each time step could easily be calculated.

Figure 7.1 displays the temperature time curve for the heptane pool fire, both for the non-insulated and the insulated container. The maximum average gas temperature reached in the non-insulated construction is 400°C and in the insulated construction 1 150°C.

Figure 7.2 displays the temperature time curve for the wood crib fire, both for the non-insulated and the insulated container. The maximum average gas temperature reached in the non-insulated construction is 500°C and in the insulated construction 1 300°C.

It is although important to remember that the MQH method only is applicable to a rise in temperature of maximum 600°C, pre flashover (indicated with a dotted blue line in the figures).

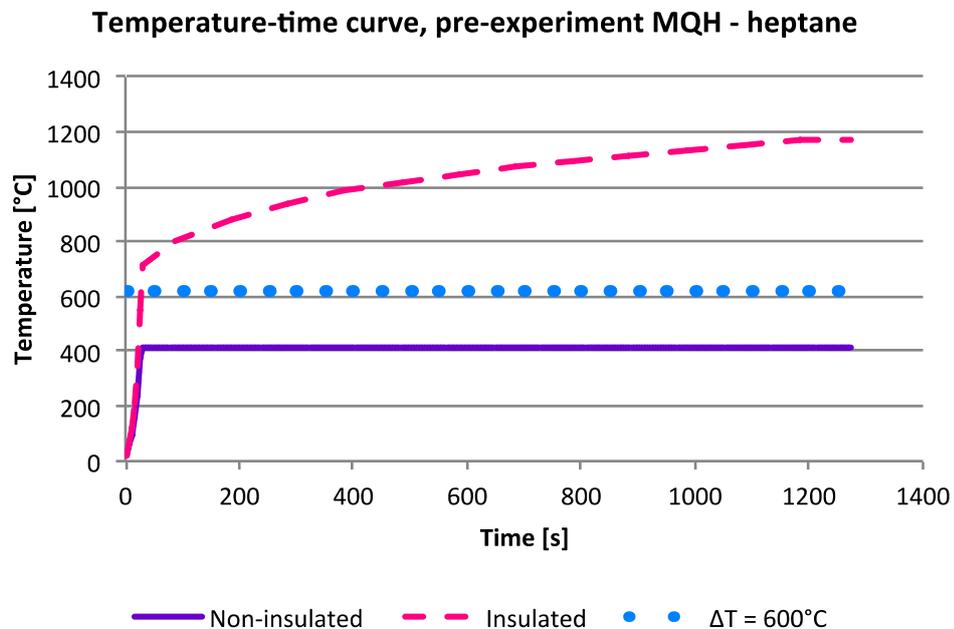


Figure 7.1: Temperature-time curve for the hot gases in a non-insulated construction and an insulated construction with a heptane pool fire as fire source using the MQH method. The method is valid until $\Delta T=600^\circ\text{C}$, which is marked with a dotted blue line.

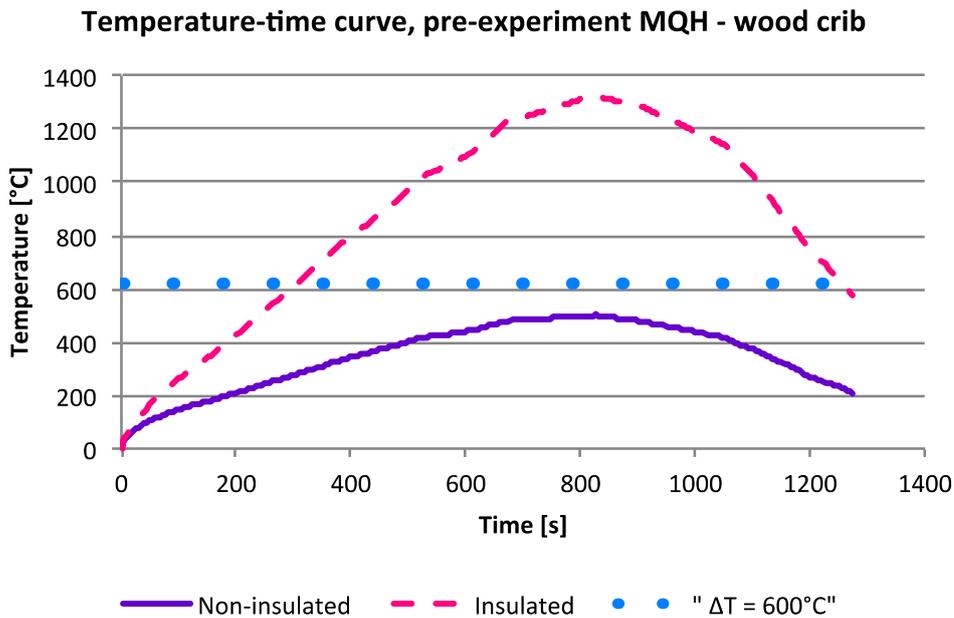


Figure 7.2: Temperature-time curve for the hot gases in a non-insulated construction and an insulated construction with a wood crib fire as fire source using the MQH method. The method is valid until $\Delta T=600^{\circ}\text{C}$, which is marked with a dotted blue line.

7.1.2 Magnusson and Thelandersson

Another method that has been used to calculate the compartment temperature is the Magnusson and Thelandersson method. As described in chapter 2 the temperature-time curve is determined from tabulated values for different type of surrounding materials. The Magnusson and Thelandersson method has been developed for wood fuel fires and calculations have therefore not been carried out for the heptane pool fire.

Of the surrounding materials presented in table 2.1 in chapter 2, the materials that are most similar to a non-insulated steel construction and an insulated steel construction are type F and type H, respectively. Type F represents 80% non-insulated steel sheeting and 20% concrete, a typical warehouse construction with non-insulated ceiling and walls of steel sheeting and a concrete floor. Type H represents a composite construction of: steel sheeting, 100 mm mineral wool, steel sheeting.

The actual opening factor was calculated to $0.042 \text{ m}^{1/2}$ using equation 2.11 in chapter 2. To obtain the fire load density per total enclosure surface area equation 2.12 in chapter 2 was used. The mass of wood and the heat of combustion for wood, found in the report by Xu et al. (2008), were divided by the total enclosure surface of the compartment. The mass of the wood crib was 91 kg and the heat of combustion for wood 12 MJ/kg. Dividing this by an enclosure surface area of 65.33 m^2 results in a fire load density of approximately 16.40 MJ/m^2 . The equations for the opening factor and fire load density are presented below.

$$\text{Opening factor} = \frac{A_0 \cdot \sqrt{H_0}}{A_T} \quad (\text{eq. 2.11})$$

$$Q_t'' = \frac{m \cdot \Delta H_{eff}}{A_T} \quad (\text{eq. 2.12})$$

The opening factor and fire load density were recalculated using the k_f factor for each type of construction, 1.0 for the type F construction (non-insulated) and 3.0 for the type H construction (insulated). This results in a fictitious opening factor of $0.042 \text{ m}^{1/2}$ and a fire load density of 16.40 MJ/m^2 for the non-insulated compartment. The fictitious opening factor and the fire load density for the insulated compartment are $0.126 \text{ m}^{1/2}$ and 49.20 MJ/m^2 , respectively. Values for the temperature-time curve were thereafter interpolated from the Magnusson and Thelandersson tables presented in Pettersson & Ödeen (1978).

Temperature-time curves for the non-insulated and insulated constructions are presented below in figure 7.3. The maximum average gas temperature reached in the non-insulated construction is 500°C and in the insulated construction 650°C .

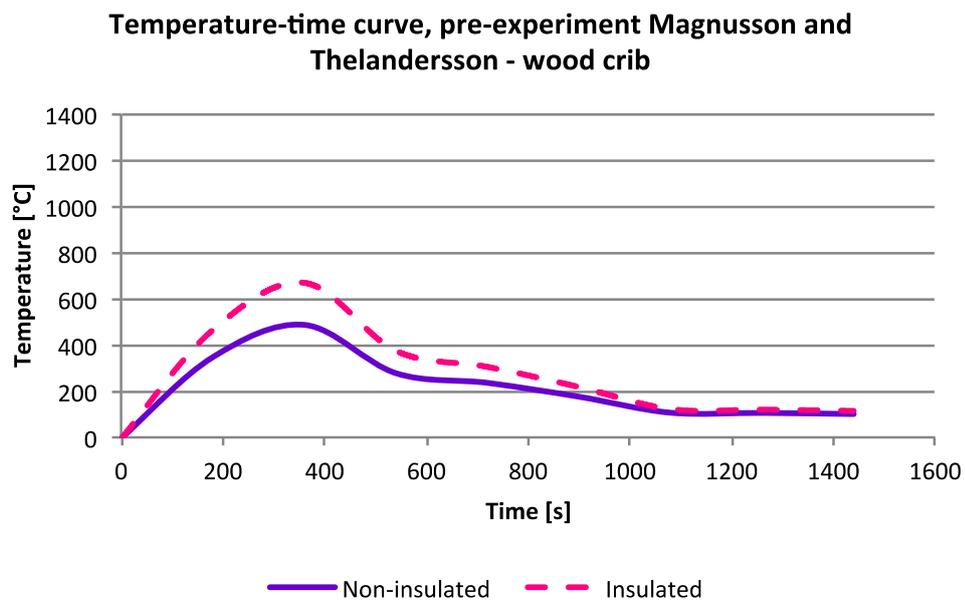


Figure 7.3: Temperature-time curve for the hot gases in a non-insulated construction and an insulated construction with a wood crib fire as fire source using the Magnusson and Thelandersson method.

7.1.3 EUROCODE

The EUROCODE method does not take in to account the heat release rate and the results for the two different types of fuel are therefore the same.

When carrying out calculations using the EUROCODE method, the intention was to use the material properties presented in table 7.3 below.

Table 7.3: Material properties for steel and insulation used in EUROCODE calculations

Material	Variable	Value	Unit	Reference
Steel	$k\rho c$	1.6×10^8	$\text{W}^2\text{s}/\text{m}^4\text{K}^2$	Karlsson & Quintiere 2000
Insulation	$k\rho c$	3.3×10^3	$\text{W}^2\text{s}/\text{m}^4\text{K}^2$	Karlsson & Quintiere 2000

However, there are at least two limitations to this method (SS-EN 1991-1-2):

1. The opening factor needs to be within the range of $0.02 \text{ m}^{1/2}$ and $0.2 \text{ m}^{1/2}$
2. The $\sqrt{k\rho c}$ -term needs to be within the range of $100 \text{ J}/\text{m}^2\text{s}^{1/2}\text{K}$ and $2\,200 \text{ J}/\text{m}^2\text{s}^{1/2}\text{K}$

As for the Magnusson and Thelandersson method the opening factor was calculated to $0.042 \text{ m}^{1/2}$, which is within the range of applicability. However the $\sqrt{k\rho c}$ -term for steel is calculated to $12650 \text{ J}/\text{m}^2\text{s}^{1/2}\text{K}$ and for insulation $57 \text{ J}/\text{m}^2\text{s}^{1/2}\text{K}$. Nor the $\sqrt{k\rho c}$ -term for steel nor the one for insulation is within the range of applicability. This method is therefore not applicable to any of the boundary materials.

Calculations were instead carried out using the highest and lowest value of the $\sqrt{k\rho c}$ -term, within the range of applicability. This resulted in figure 7.4 below, with a maximum average temperature of 1350°C for the construction with insulating boundary material and 600°C for the construction with non-insulating material.

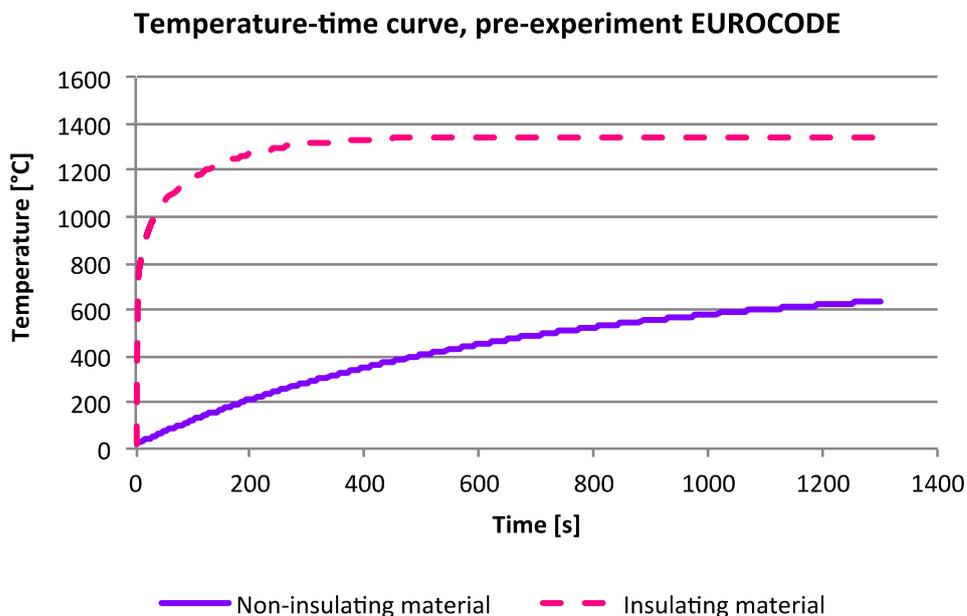


Figure 7.4: Temperature-time curve for the hot gases in a non-insulated construction and an insulated construction using the EUROCODE method.

7.1.4 Summary of results from the pre-experiment hand calculations

The maximum average temperatures for each construction, derived from the different calculation methods, are presented in table 7.4 below. The gas temperature in the insulated enclosure was higher than in the non-insulated enclosure for all calculation methods. The difference in temperature between the two boundary materials range from 200°C to 800°C.

Flashover, according to the criterion: hot gas layer reaching 500-600°C, was obtained in each of the insulated enclosure calculations.

Table 7.4: Summary of the results received from the pre-experiment hand calculations

Method	Maximum average temperature	
	Non-insulated construction	Insulated construction
Heptane pool fire		
MQH	400°C	1 150°C
EUROCODE*	600°C	1350°C
Wood crib fire		
MQH	500°C	1 300°C
Magnusson and Thelandersson	400°C	600°C
EUROCODE*	600°C	1350°C

* The boundary materials were not applicable to this method and therefore other values for $k\rho c$ have been used

7.2 Pre-experiment simulations

FDS simulations were carried out before the experiments, using values for the heat release rate gathered from literature as described in section 4.2. The results from the simulations are presented below under separate headlines for each parameter measured.

7.2.1 Heat release rate – heptane pool fire

The heat release rate used in the pre-experiment simulations of the heptane pool fires was chosen from the theoretically calculated value for a 0.96 m² pool diameter of a liquid heptane pool fire, as described in chapter 4. Figure 7.5 shows the heat release rate from the heptane pool fire simulations.

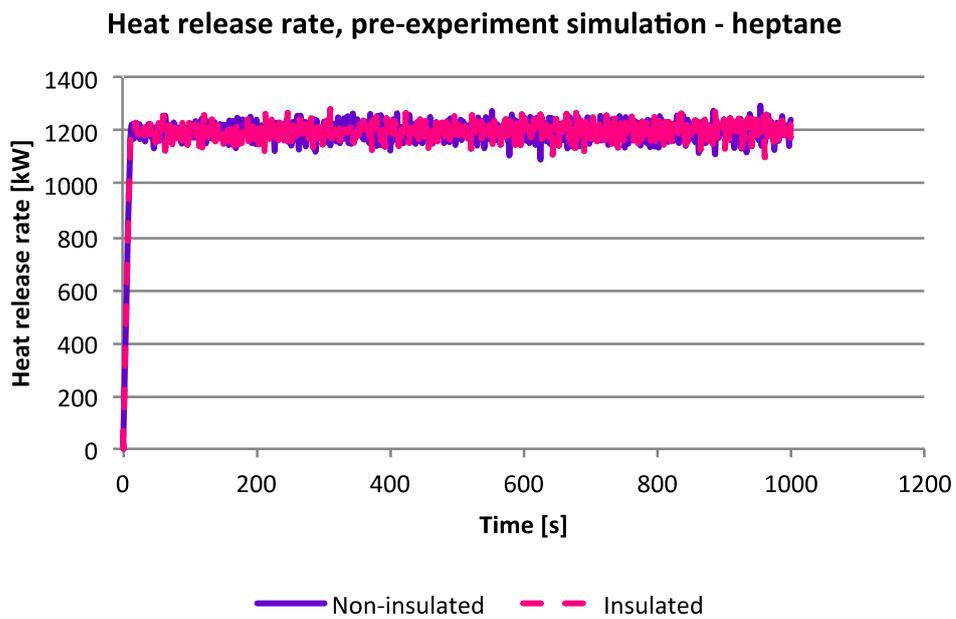


Figure 7.5: The heat release rate recorded in the pre-experiment heptane pool fire simulations.

The heat release rate reached a maximum of 1 200 kW. The same heat release rate was used for the non-insulated and insulated case.

7.2.2 Heat release rate – wood crib fire

The heat release rate used in the pre-experiment simulations of the wood crib fires was chosen from the report by Xu et al (2008), as described in chapter 4. Figure 7.6 shows the heat release rate from the wood crib fire simulations.

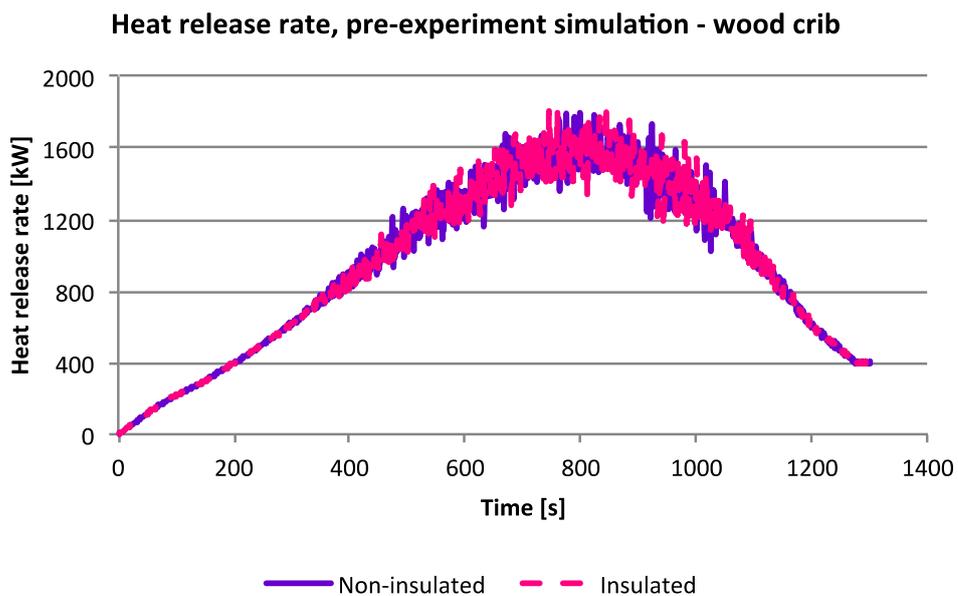


Figure 7.6: The heat release rate recorded in the pre-experiment wood crib fire simulations.

The maximum heat release rate was 1 600 kW. The same heat release rate was used for the non-insulated and insulated case.

7.2.3 Gas temperature – heptane pool fire

The gas temperature was measured in three thermocouple trees situated in the container at the same positions as in the full-scale experiments.

The highest temperatures were reached at the position between the fire and the door opening at a height of 2.1 m. Figure 7.7 below show the temperature measurements from this position in the non-insulated and insulated compartment. The maximum average temperature in the non-insulated compartment was approximately 530°C, reached after approximately 700 s. The maximum average temperature reached in the insulated compartment was 720°C, after approximately 1 000 s.

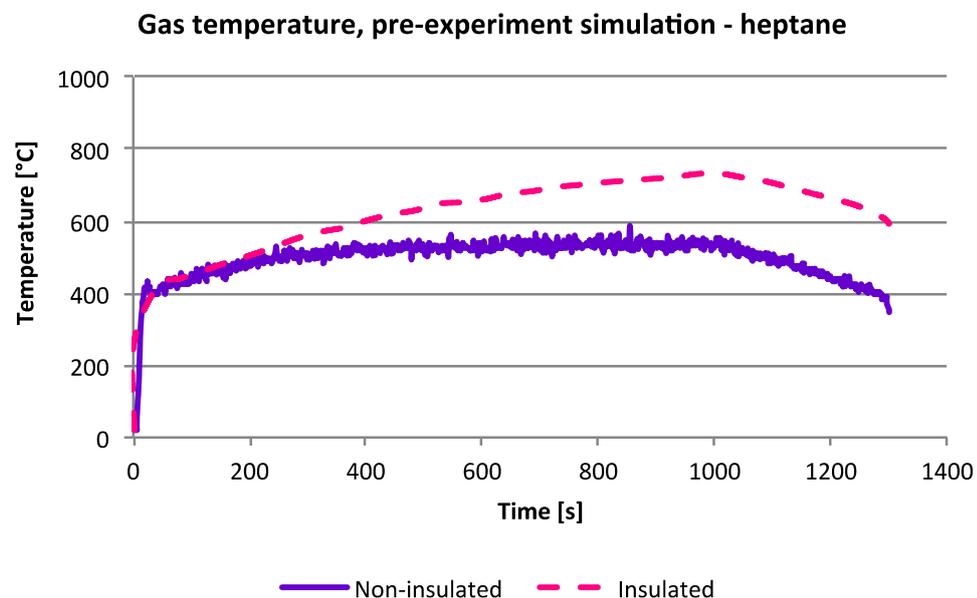


Figure 7.7: The gas temperature recorded between the fire and the door opening, at 2.1 m height, in the pre-experiment heptane pool fire simulations.

7.2.4 Gas temperature – wood crib fire

Figure 7.8 below shows the temperature measurements from the position between the fire and the door opening in the non-insulated and insulated compartment. The maximum average temperature in the non-insulated compartment was approximately 580°C, reached after approximately 850 s. The maximum average temperature reached in the insulated compartment was 670°C, after approximately 900 s.

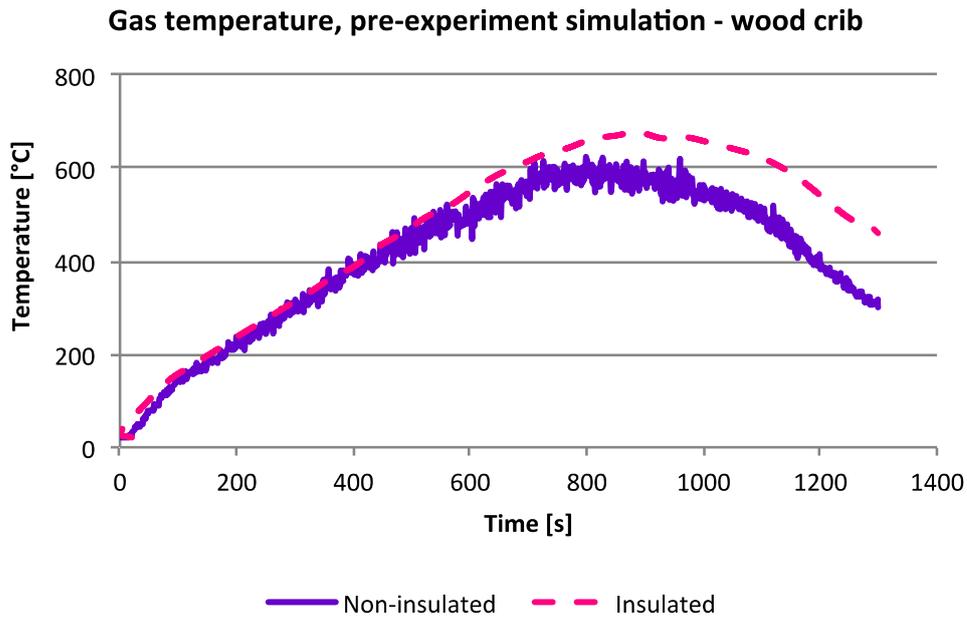


Figure 7.8: The gas temperature recorded between the fire and the door opening, at 2.1 m height, in the pre-experiment wood crib fire simulations.

7.2.5 Wall temperature – heptane pool fire

The wall temperature was registered at three positions on the wall of the container. In each position the temperature was measured at three different heights and two or four depths, depending on if the container was insulated or not, as described in section 5.2. At one of the positions in the insulated container the temperature was also measured at 20 different depths.

The highest wall temperature was reached at the position across from the fire at a height of 2.1 m. However, to be able to compare the wall temperature to the gas temperature, the temperature from the position between the fire and the door opening are displayed in figure 7.9 below. The graph displays the wall temperature and gas temperature from the same position at 2.1 m from the floor from both the non-insulated and the insulated simulation. The displayed wall temperatures are the ones measured on the outside of the steel.

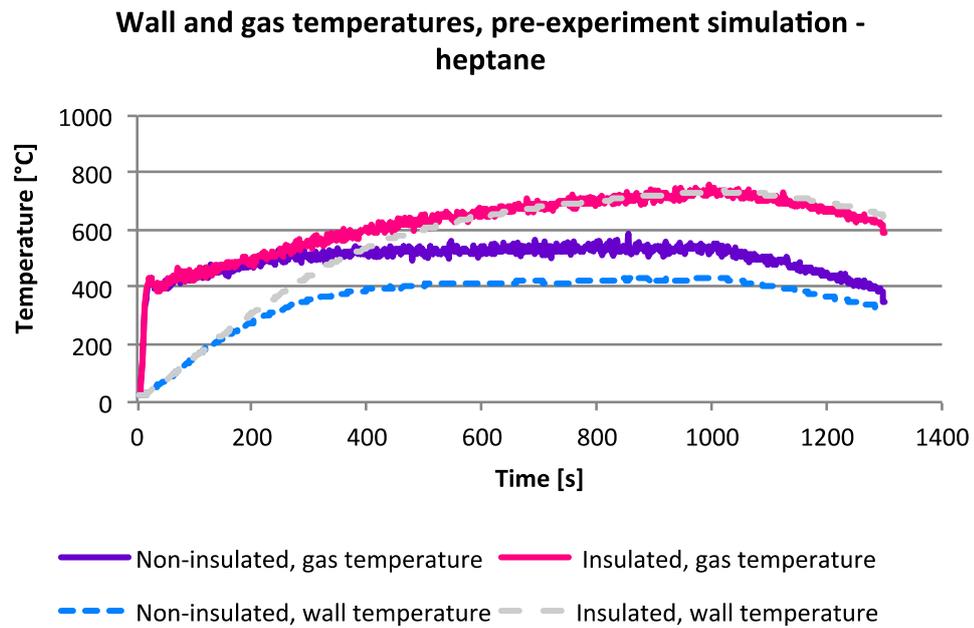


Figure 7.9: The wall and gas temperature recorded between the fire and the door opening, at 2.1 m height, in the pre-experiment heptane pool fire simulations.

The maximum average wall temperature reached in the non-insulated container, between the fire and the door opening, was 420°C and was recorded after approximately 950 s. The maximum average wall temperature reached in the insulated container was 720°C and was recorded after approximately 950 s. The maximum average wall temperature was higher in the insulated case than in the non-insulated. The maximum average wall temperature was reached at the same time in the non-insulated as in the insulated compartment.

As mentioned above, the wall temperature was measured at 20 different depths in one measuring point. The measuring point was situated between the fire and the back wall at a height of 2.1 m. Figure 7.10 below show a cross section taken at 1 040 s. The dot to the left of the wall in the graph represents the gas temperature registered at the thermocouple tree in the compartment, between the fire and back wall at a height of 2.1 m. The dot to the right of the wall in the graph represents the ambient temperature surrounding the compartment.

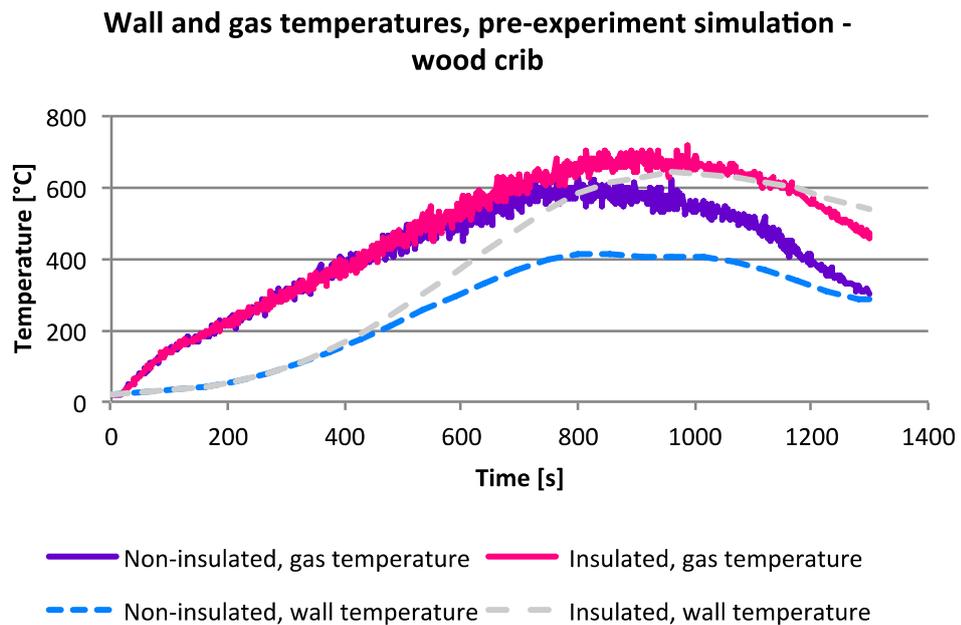


Figure 7.11: The wall and gas temperature recorded between the fire and the door opening, at 2.1 m height, in the pre-experiment wood crib fire simulations.

The maximum average wall temperature reached in the non-insulated container, between the fire and the door opening, was 410°C and was recorded after approximately 900 s. The maximum average wall temperature reached in the insulated container was 620°C and was recorded after approximately 950 s. The maximum average wall temperature was higher in the insulated case than in the non-insulated. The maximum average wall temperature was reached slightly earlier in the insulated compartment than in the non-insulated compartment.

Figure 7.12 below show a cross section taken at 990 s at the position between the fire and the back wall at 2.1 m height. The dot to the left of the wall in the graph represents the gas temperature registered at the thermocouple tree in the compartment, between the fire and back wall at a height of 2.1 m. The dot to the right of the wall in the graph represents the ambient temperature surrounding the compartment.

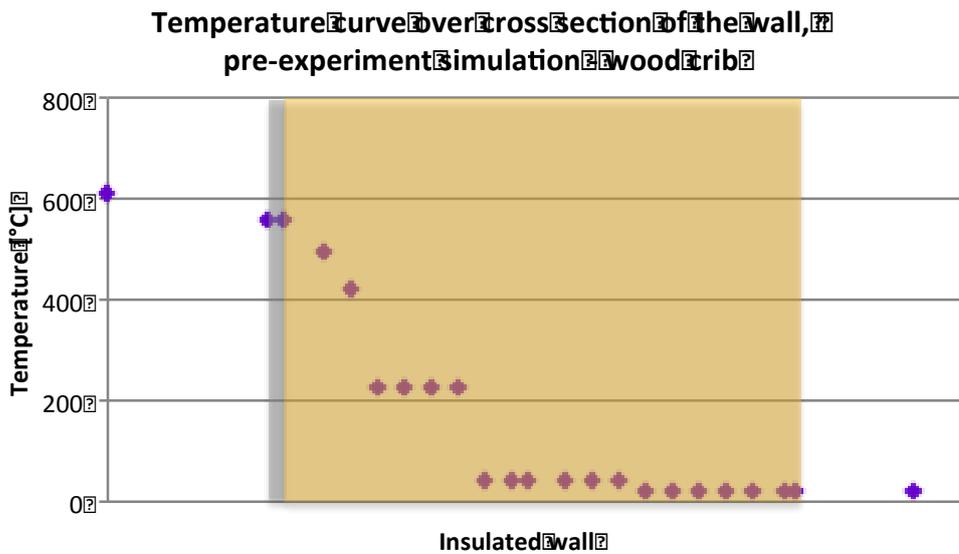


Figure 7.12: Temperature curve over the cross section of the insulated wall taken at 990 s in the wood crib fire. Measuring point situated between the fire and the back wall at a height of 2.1 m.

Note that none of the temperature curves correlate with the general opinion of how the temperature distribution in a wall is depicted, as described in section 2.6. This is discussed further in chapter 9.

7.2.7 Radiation – heptane pool fire

Boundary files were used in the model to measure the radiation. Figure 7.13 and 7.14 below show the incident radiation towards the floor in the non-insulated and insulated compartment with a heptane pool fire. The figures show the container from above, with the opening to the right. The snapshots are taken from the time step where the maximum average temperature was measured, after 700 s for the non-insulated compartment and 1 000 s for the insulated compartment. The black contours represent a radiation of 15.0 kW/m², which is one of the criteria for flashover.

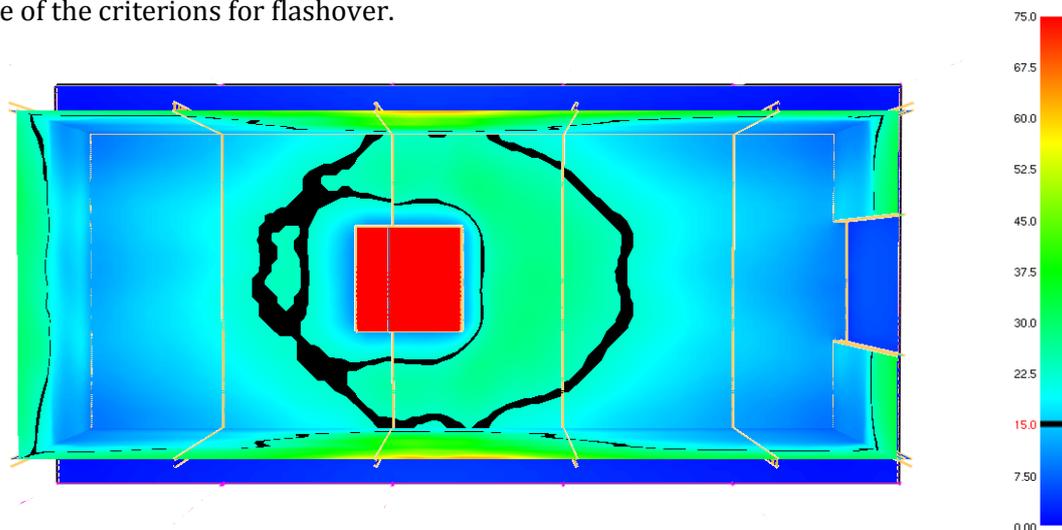


Figure 7.13: Measured radiation in the pre-experiment simulation with a heptane pool fire in a non-insulated compartment. The black contour represents a radiation of 15.0 kW/m².

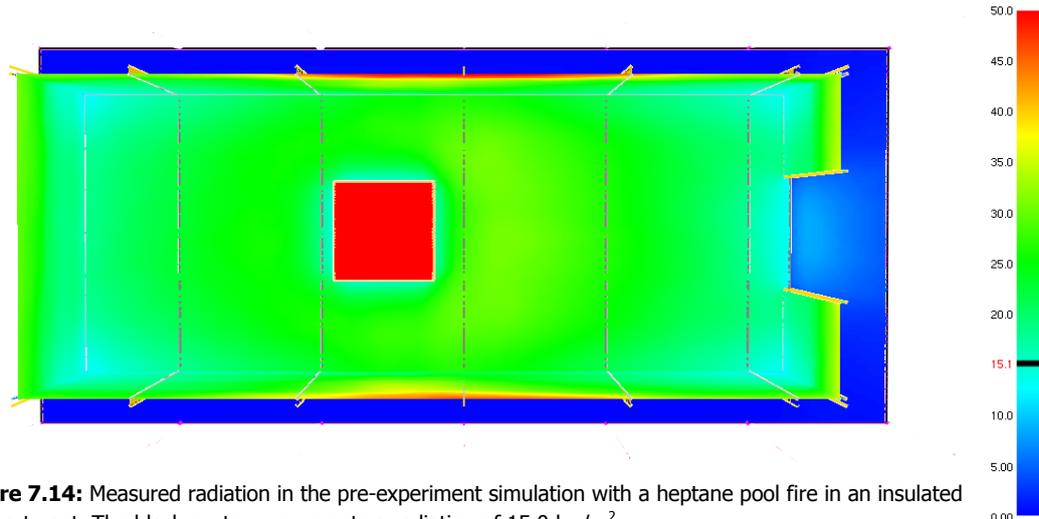


Figure 7.14: Measured radiation in the pre-experiment simulation with a heptane pool fire in an insulated compartment. The black contour represents a radiation of 15.0 kW/m^2 .

The radiation exceeds 15 kW/m^2 in the whole compartment in the insulated case. In the non-insulated case 15 kW/m^2 is only reached around the fire.

7.2.8 Radiation – wood crib fire

Figures 7.15 and 7.16 below show the incident radiation towards the floor in the non-insulated and insulated compartment with a wood crib fire. The figures are taken from the time step where the maximum average temperature was measured, after 850 s for the non-insulated compartment and 900 s for the insulated compartment. The black contours represent a radiation of 15.0 kW/m^2 .

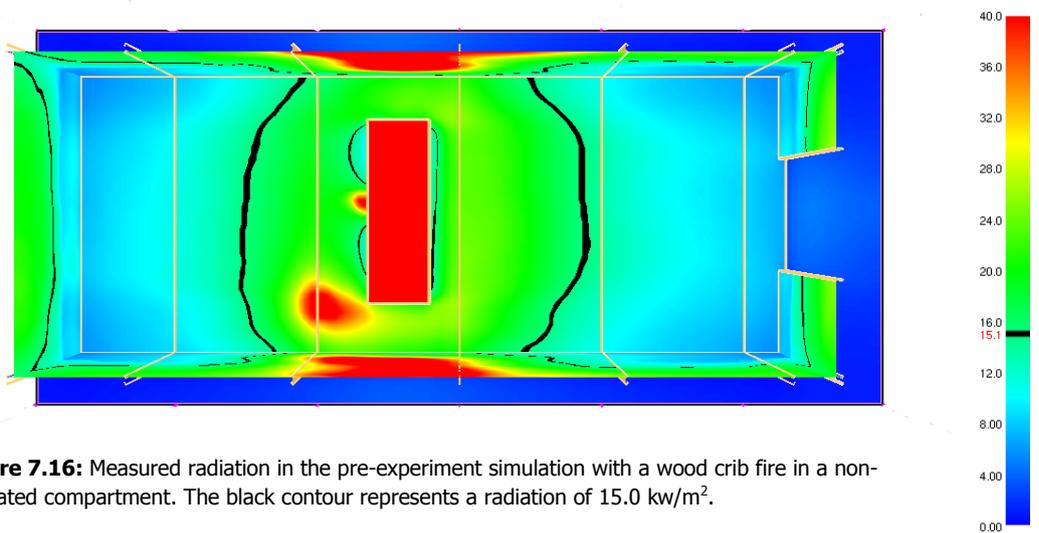


Figure 7.16: Measured radiation in the pre-experiment simulation with a wood crib fire in a non-insulated compartment. The black contour represents a radiation of 15.0 kW/m^2 .

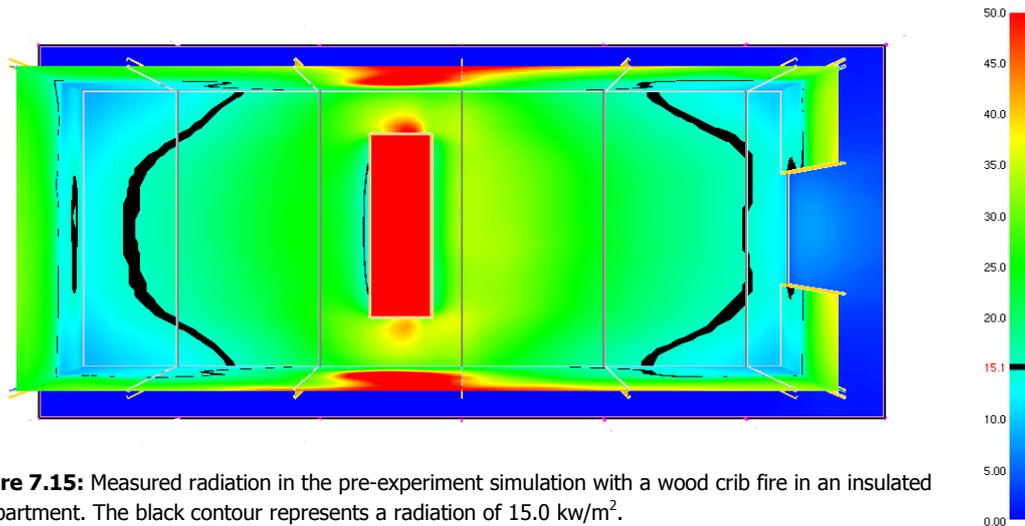


Figure 7.15: Measured radiation in the pre-experiment simulation with a wood crib fire in an insulated compartment. The black contour represents a radiation of 15.0 kW/m².

The radiation exceeds 15 kW/m² in almost the whole compartment in the insulated case. In the non-insulated case 15 kW/m² is reached around the fire.

7.2.9 Summary of results from the pre-experiment simulations

Flashover, according to the criterion: hot gas layer reaching 500-600°C, was attained in all the simulations. However, in the two non-insulated cases the temperature just exceeded 500°C. The gas temperature differs between the non-insulated and insulated cases, though not as much in the wood crib experiment as in the heptane pool fire experiment. A summary of the results is found in table 7.5 below.

Table 7.5: Summary of the results received from the pre-experiment simulations

	Non-insulated container with heptane pool fire	Insulated container with heptane pool fire	Non-insulated container with wood crib fire	Insulated container with wood crib fire
Extinction of fire	1 300 s	1 300 s	1 300 s	1 300 s
Max. average temperature in compartment	530°C	720°C	580°C	670°C
Time until max. average temperature in compartment was reached	700 s	1 000 s	850 s	900 s
Maximum heat release rate	1 200 kW	1 200 kW	1 550 kW	1 550 kW
Time until maximum heat release rate was reached	13 s	13 s	800 s	800 s

7.3 Experiments

Below the results from the experiments are presented. First observations from the experiments are described. They are followed by the results from each measured parameter. Finally, a discussion about whether flashover was reached or not and a summary of the results from the experiments is presented.

7.3.1 Observations – heptane pool fire experiments

At the first attempt to light the heptane in the experiment with the heptane pool fire in the non-insulated container, it only blazed up quickly and then died out. At the second try it lit up as expected. The flames reached the ceiling after 10 s and as in the insulated case the fire grew large quickly. From 635 s and onwards, small flames sporadically emerged from the opening in intervals of 15 s to 30 s sometimes it was even longer in between. The fire was extinguished with foam after 960 s since flames were emerging from the opening.

In the experiment with the heptane pool fire in the insulated container the flames reached the ceiling after 10 s. The fire grew large quickly and already after 375 s flames emerged from the door opening. Heavy smoke came off the roof and a small flame was also seen on the roof. After approximately 465 s the hood could not swallow all the gases from the fire and smoke escaped on the outside of the hood. The fire was extinguished with foam after 520 s since flames were emerging from the opening. The walls were then so hot that they were red.

7.3.2 Observations – wood crib fire experiments

In the experiment with the wood crib fire in a non-insulated container the flames reached the ceiling after 90 s. As in the insulated experiment the heptane burnt heavily and lit the wood in the wood crib without problems. The heptane in the trays was finished after 395 s and afterwards the fire slowly grew larger. No flames emerged from the door opening and the fire started to decrease after 1 200 s. The fire was extinguished after 1 620 s, using water, since the heat release rate had started to stagnate.

The heptane trays under the wood crib in the insulated wood crib fire experiment were lit with a torch. The heptane burnt heavily and lit the wood crib. Flames reached the ceiling after 100 s and the heptane was consumed after 430 s. The fire slowly grew larger and flames emerged from the door opening after 1 050 s. At 1 200 s the fire was extinct using water since flames were emerging from the opening. During the experiment smoke was coming from the roof of the container and the soffit of the door opening had started to smoulder.

7.3.3 Heat release rate – heptane pool fire experiments

The heat release rate from the heptane pool fire experiments is displayed in figure 7.17 below. In the insulated case the heat release rate increased rapidly, compared to the non-insulated case where it increased slowly and almost stagnated after 500 seconds. The peak in the end of both of the graphs is a result of the foam applied onto the heptane to extinguish the fire.

The maximum average heat release rate reached in the non-insulated container was approximately 990 kW and in the insulated container approximately 1140 kW, this occurred after 900 s and 380 s, respectively.

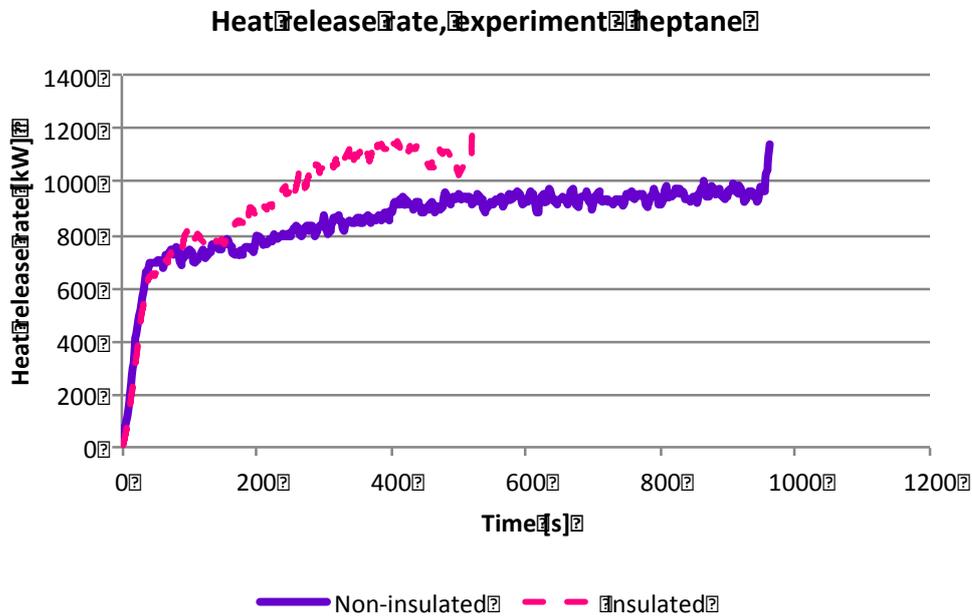


Figure 7.17: The heat release rate recorded in the heptane pool fire experiments.

7.3.4 Heat release rate – wood crib fire experiments

The heat release rate from the wood crib fire experiments is displayed in figure 7.18 below. In both cases the shape of the graph follows the same arc. However, the heat release rate in the insulated container is approximately 100 kW to 200 kW higher than in the non-insulated container throughout the whole experiment.

The peak that occurs in the beginning of both graphs is a result of the heptane in the trays underneath the wood crib being finished. The maximum average heat release rate reached in the non-insulated container was approximately 780 kW and in the insulated container approximately 800 kW, this occurred after 1170 s and 1160 s respectively.

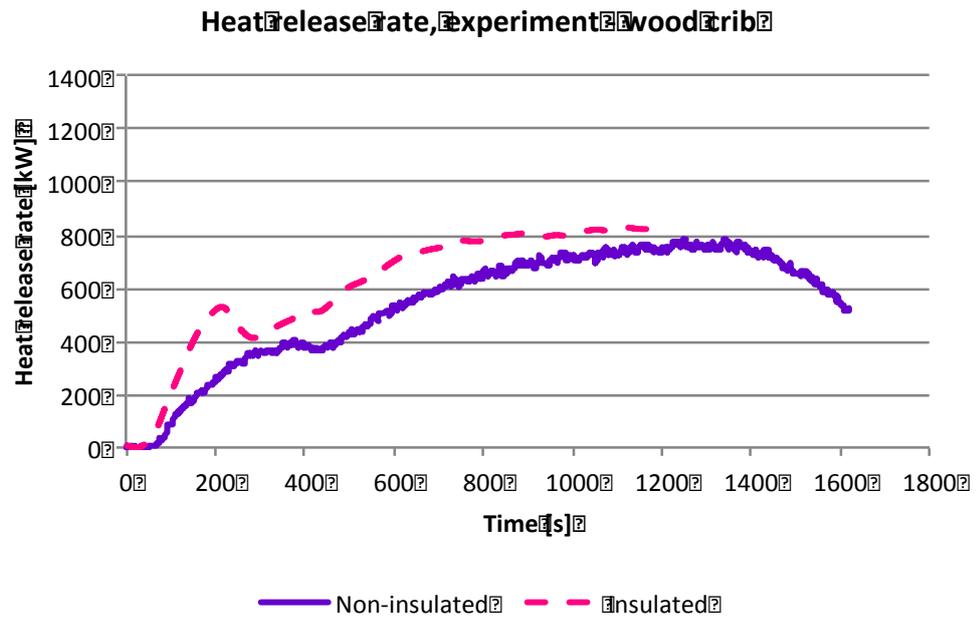


Figure 7.18: The heat release rate recorded in the wood crib fire experiments.

7.3.5 Gas temperature – heptane fire experiments

As described in chapter 6, the gas temperature was measured at three positions on the floor in the container. In each position the temperature was measured at six different heights.

The highest temperatures were reached at a height of 2.1 m around the thermocouple tree, positioned between the fire and the door opening. Figure 7.19 below show the temperature measurements from this position in the non-insulated and insulated compartments. The lowest temperatures were generally reached at the position between the fire and back wall.

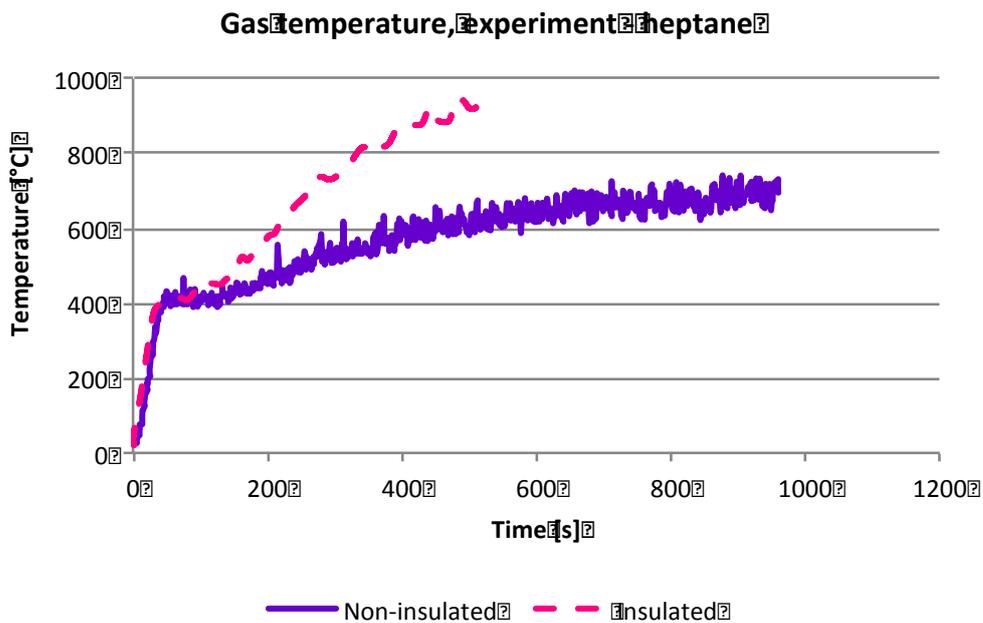


Figure 7.19: The gas temperature recorded between the fire and the door opening, at 2.1 m height, in the heptane pool fire experiments.

The maximum average gas temperature reached in the non-insulated compartment was 670°C and was recorded after approximately 800 s. The maximum average gas temperature reached in the insulated compartment is 900°C and was recorded after approximately 450 s. The maximum average gas temperature is higher in the insulated case than in the non-insulated case. The maximum average temperature is also reached earlier in the insulated case than in the non-insulated case.

7.3.6 Gas temperature – wood crib fire experiments

The highest temperatures were reached at a height of 2.1 m around the thermocouple tree, positioned between the fire and the door opening. Figure 7.20 below shows the temperature measurements from this position in the non-insulated and insulated compartments.

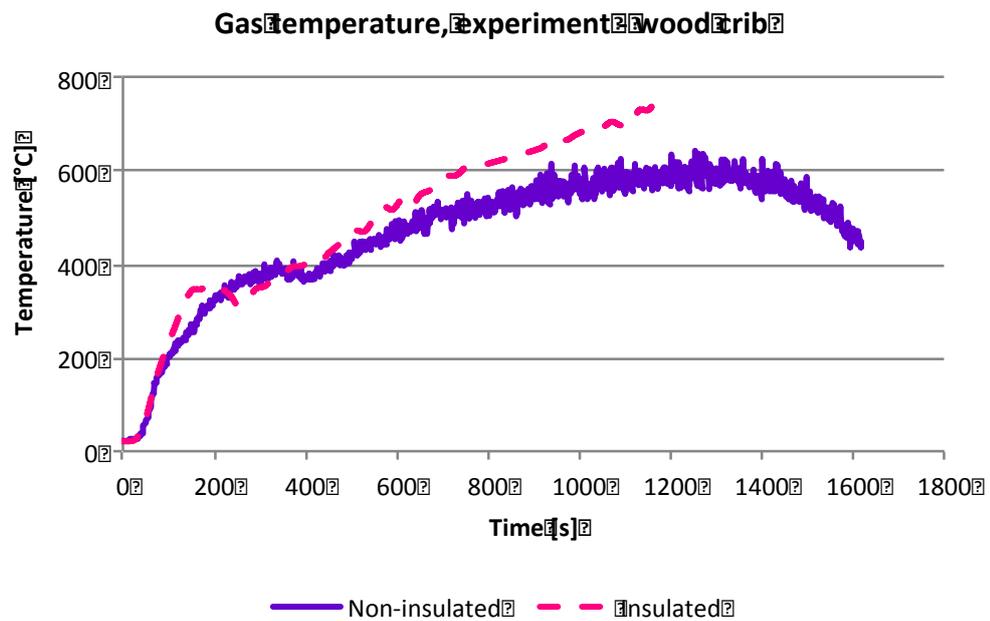


Figure 7.20: The gas temperature recorded between the fire and the door opening, at 2.1 m height, in the wood crib fire experiments.

The maximum average gas temperature reached in the non-insulated compartment was 580°C and was recorded after approximately 1 100 s. The maximum average gas temperature reached in the insulated compartment was 710°C and was recorded after approximately 1 100 s. The maximum average gas temperature is higher in the insulated case than in the non-insulated case. The maximum average temperatures were reached at the same time in both the insulated and the non-insulated case.

7.3.7 Wall temperature – heptane pool fire experiments

The wall temperature was measured at three locations on the wall of the container. At each location it was measured at three different heights and two or four depths, depending on if the container was insulated or not, as described in section 5.2.

The highest wall temperature was reached between the fire and door opening at a height of 2.1 m. Figure 7.21 shows the wall temperatures at this position for both the non-insulated and the insulated cases. The gas temperature from the same position at 2.1 m from the floor is also presented in the graph together with the wall temperatures. The displayed wall temperatures are the ones measured on the outside of the steel (i.e in-between the steel and the insulation for the insulated case).

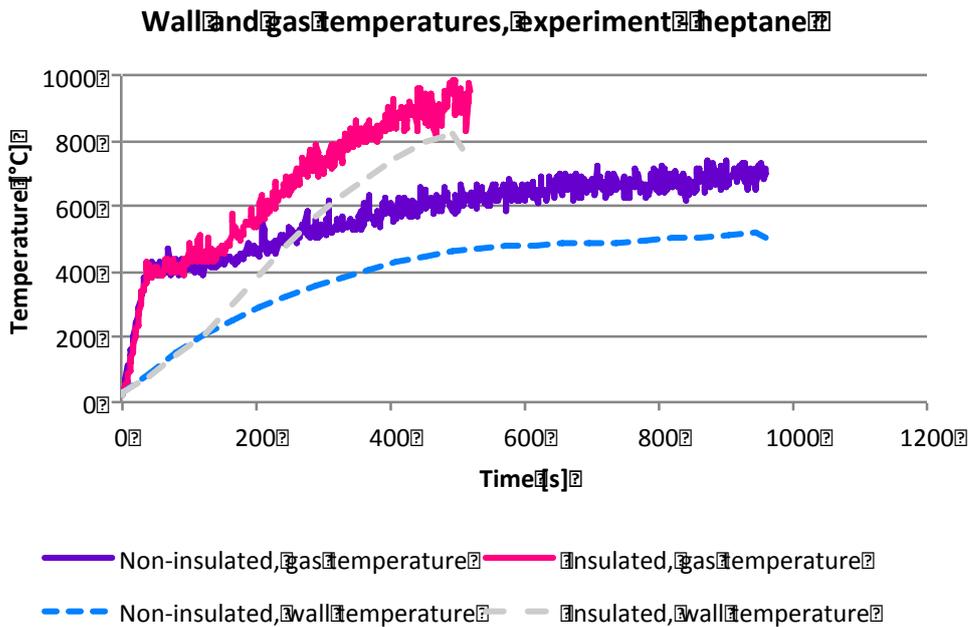


Figure 7.21: The wall and gas temperature recorded between the fire and the door opening, at 2.1 m height, in the heptane pool fire experiments.

The maximum average wall temperature reached in the non-insulated container was 500°C and was recorded after approximately 750 s. The maximum average wall temperature of the steel reached in the insulated container was 800°C and was recorded after approximately 450 s. The maximum average wall temperature is higher in the insulated case than in the non-insulated. The maximum average wall temperature is also reached earlier in the insulated case than in the non-insulated case.

Figure 7.22 below show the cross section with a temperature graph from the insulated experiment. The wall temperature was measured on each side of the steel and also within the insulation and on the outside of the insulation. The temperatures are taken from measuring devices situated between the fire and the door opening at 2.1 m from the floor. The temperature to the left in the graph is the gas temperature registered at the thermocouple tree in the compartment, between the fire and door opening at a height of 2.1 m. The temperature to the right is the ambient temperature surrounding the compartment.

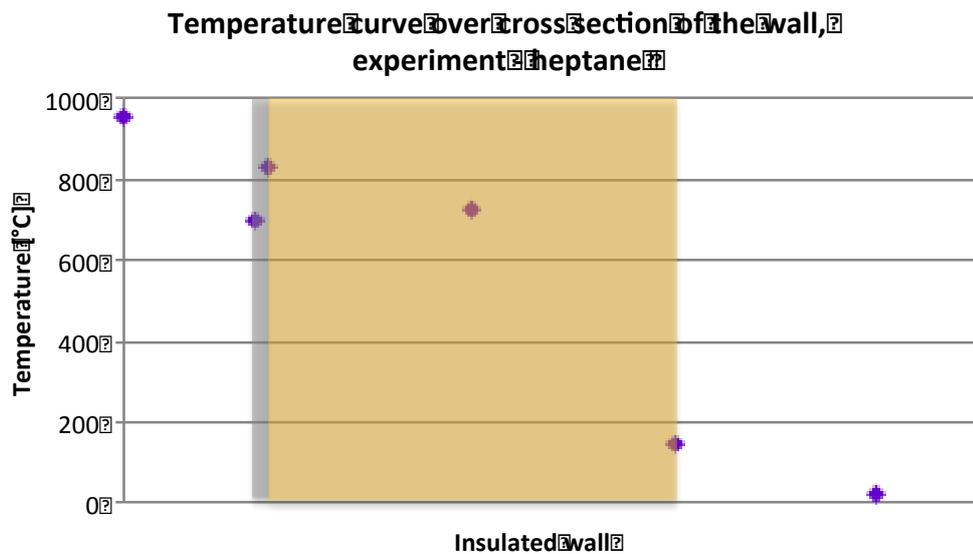


Figure 7.22: Temperature curve over the cross section of the insulated wall taken at 520 s in the heptane pool fire. Measuring points situated between the fire and the door opening at a height of 2.1 m.

The cross section from the insulated container is taken at 520 s after the heptane was lit. The difference in temperature between the steel and the hot gases in the room is approximately 120°C. There is a significant difference in temperature between the steel and the outside of the insulation, approximately 685°C.

Note that none of the temperature curves correlate with the general opinion of how the temperature distribution in a wall is depicted, as described in section 2.6. This is discussed further in chapter 9.

7.3.8 Wall temperature – wood crib fire experiments

The highest wall temperature was reached at the position by the fire at 2.1 m from the floor in the non-insulated case. In the insulated case the highest temperature was reached at the position between the fire and the door opening at a height of 2.1 m.

When comparing the wall and gas temperatures between the non-insulated and insulated case the measurements from the position between the fire and the door opening are used. Figure 7.23 shows the wall temperatures and gas temperatures at this position. The displayed wall temperatures are the ones measured on the outside of the steel.

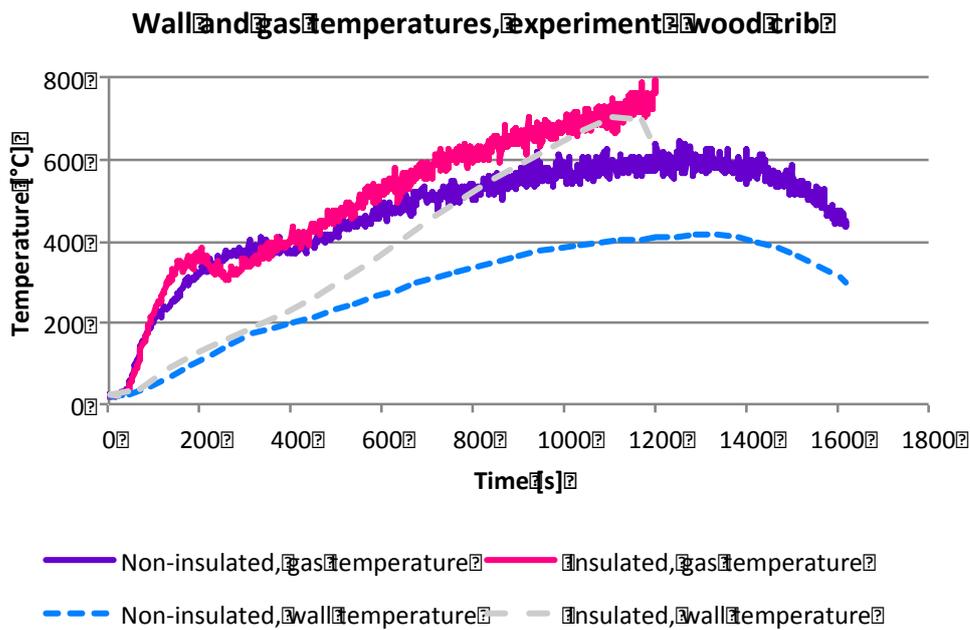


Figure 7.23: The wall and gas temperature recorded between the fire and the door opening, at 2.1 m height, in the wood crib fire experiments.

The maximum average wall temperature reached in the non-insulated container was approximately 410°C and was recorded after approximately 1 250 s. The maximum average wall temperature reached in the insulated container was 680°C and was recorded after approximately 1 100 s. The maximum average wall temperature is higher in the insulated case than in the non-insulated. The maximum average wall temperatures are reached at approximately the same time in both the insulated and the non-insulated cases.

Figure 7.24 below show the cross section with a temperature graph from the insulated experiment. The wall temperature was measured on each side of the steel and also inside the insulation and on the outside of the insulation. The temperatures are taken from measuring devices situated between the fire and the door opening at 2.1 m from the floor. The dot to the left of the wall in the graph represents the gas temperature registered at the thermocouple tree in the compartment, between the fire and the door opening at a height of 2.1 m. The dot to the right of the wall in the graph represents the ambient temperature surrounding the compartment.

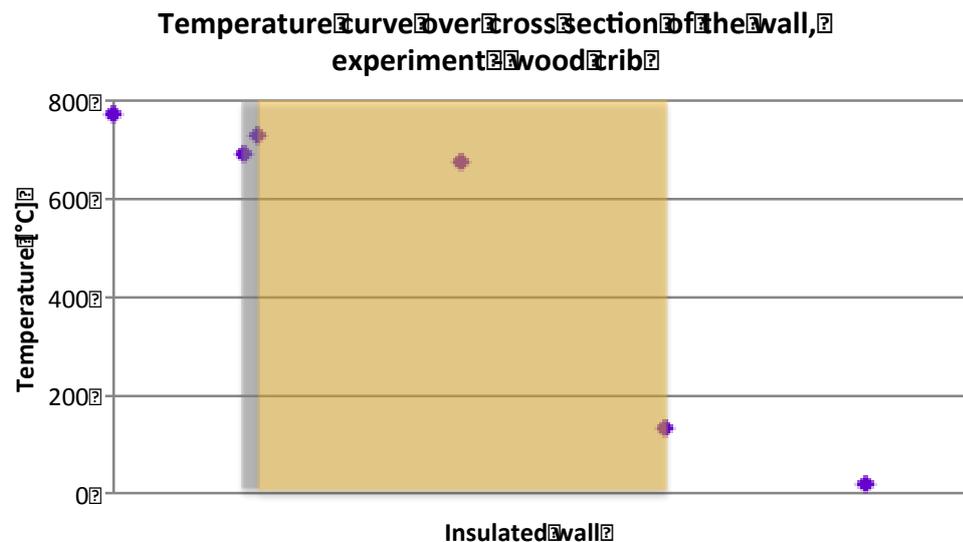


Figure 7.24 Temperature curve over the cross section of the insulated wall taken at 1 200 s in the wood crib fire. Measuring points situated between the fire and the door opening at a height of 2.1 m.

The cross section from the insulated container is taken at 1 200 s after the heptane was lit. The difference in temperature between the steel and the hot gases in the room is approximately 50°C. There is a significant difference in temperature between the steel and the outside of the insulation, approximately 600°C.

Note that none of the temperature curves correlate with the general opinion of how the temperature distribution in a wall is depicted, as described in section 2.6. This is discussed further in chapter 9.

7.3.9 Radiation – heptane pool fire experiments

The radiation towards the floor was measured at the bottom of the thermocouple trees situated in the container, positioned between the fire and the back wall and between the fire and the door opening. Figure 7.30 below shows the incident radiation from the heptane pool experiments.

The highest radiation was measured at the position between the fire and the door opening. In the non-insulated container the maximum average radiation towards the floor was 7.1 kW/m² and in the insulated container 14.9 kW/m². The highest radiation is reached quicker in the insulated than in the non-insulated container.

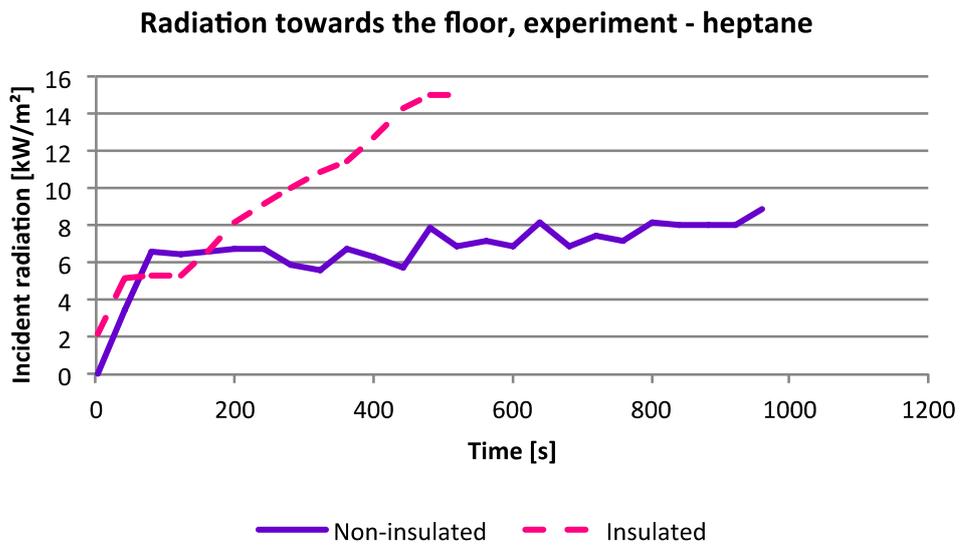


Figure 7.30: Incident radiation towards the floor recorded in the heptane pool fire experiment. Measuring device situated between the fire and the door opening.

7.3.10 Radiation – wood crib fire experiments

Figure 7.31 below show the incident radiation from the wood crib experiments. The maximum average radiation towards the floor measured in the non-insulated container was 5.5 kW/m^2 and in the insulated container 7.2 kW/m^2 . The maximum average radiation was reached approximately at the same time in the insulated as in the non-insulated container.

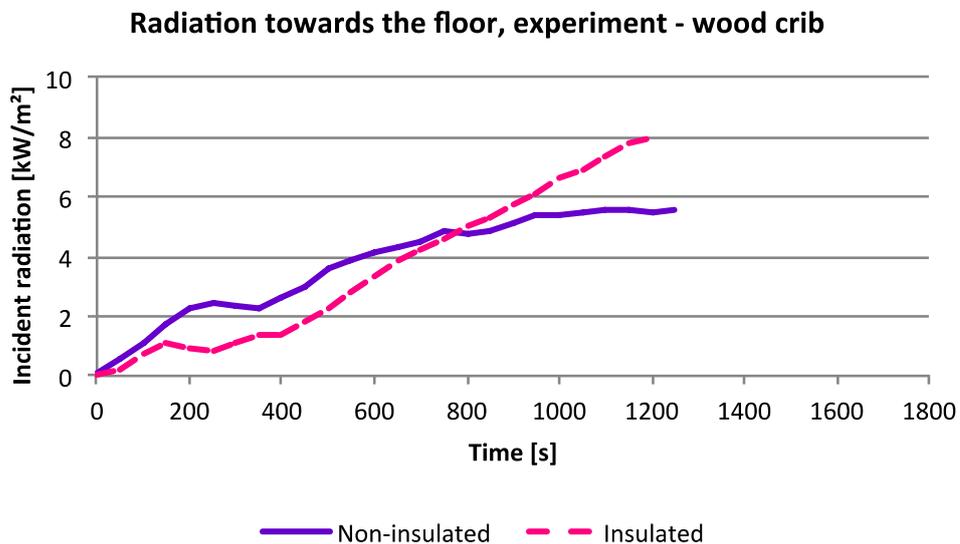


Figure 7.31: Incident radiation towards the floor recorded in the wood crib fire experiment. Measuring device situated between the fire and the door opening.

7.3.11 Flashover

The criteria for flashover was mentioned in chapter 2, one of them was that the temperature of the hot gas layer need to reach 500-600°C (Brandteknik, LTH 2005). The gas temperature reached 600°C at 2.1 m from the floor in all four experiments. Though, in the wood crib experiment without insulation the 600°C was just reached. In the insulated experiments 600°C was also reached at 1.8 m from the floor.

Criterion number two was that the radiation towards the floor needs to be 15-20 kW/m² to reach flashover (Brandteknik, LTH 2005). The radiation towards the floor was 15 kW/m² in one of the experiments, the insulated heptane pool fire experiment. The maximum average radiation level reached in the insulated wood crib fire was 7.2 kW/m².

The last flashover criterion, flames emerging from the opening (Drysdale 1998) was reached in the experiments where the container was coated with insulation but not in the two non-insulated cases.

7.3.12 Summary of results from the experiments

There is a visible difference in heat release rate between the non-insulated and insulated cases for both the wood crib and the heptane pool fire experiments. The gas temperature also differs between the non-insulated and insulated cases, although not as much in the wood crib experiments as in the heptane pool fire experiments. Flashover, according to the criterion: flames emerging from the opening, was reached in the experiments where the container was coated with insulation and not in the two non-insulated cases. A summary of the results is found in table 7.6 below.

Table 7.6: Summary of the results received from the experiments

	Non-insulated container with heptane pool fire	Insulated container with heptane pool fire	Non-insulated container with wood crib fire	Insulated container with wood crib fire
Flames reaching the ceiling	10 s	10 s	90 s	100 s
Time until flames emerged from the opening	635 s, sporadic flames	375 s	<i>Not achieved</i>	1050 s
Extinction of fire	960 s	520 s	1620 s	1200 s
Max. average temperature in compartment	670°C	900°C	580°C	710°C
Time until max. average temperature in compartment was reached	800 s	450 s	1 100 s	1 100 s

	Non-insulated container with heptane pool fire	Insulated container with heptane pool fire	Non-insulated container with wood crib fire	Insulated container with wood crib fire
Max. average heat release rate	990 kW	1 140 kW	780 kW	800 kW
Time until max. average heat release rate was reached	900 s	380 s	1170 s	1160 s
Comments	<p>At the first attempt to ignite the heptane it did not work. However at the second attempt there was no problem to ignite the fuel.</p> <p>Sporadic flames were exiting through the door in intervals of 15 to 30 seconds starting at 635s.</p>	<p>There were lots of smoke coming from the roof, also a small flame was visible.</p> <p>After 465s the hood cannot extract all the gases.</p> <p>The top tube for the gas measurement burned off at 520s.</p> <p>Walls were red because of the heat when the experiment was finished.</p>	<p>The thermocouple trees were not stretched out before the experiment started.</p> <p>The heptane in the trays underneath the wood crib burned out at 395s.</p> <p>A flame was close to exiting the door at 1360 s however faded before reaching the door.</p>	<p>Smoke was coming off the roof, however not as much as in the first experiment.</p> <p>The heptane in the trays underneath the wood crib burned out at 430s.</p> <p>The soffit of the door opening had started to smoulder.</p>

7.4 Post-experiment hand calculations

Hand calculations were carried out after the experiments, using the heat release rate measured in the experiment as input data. The results from the hand calculations are presented below. The results from the post-experiment hand calculations are compared to the results from pre-experiment hand calculations, experiments and simulations in chapter 8.

7.4.1 MQH

Post-experiment hand calculations were carried out using the MQH-method with the heat release rate that had been recorded in the experiments instead of an estimated heat release rate. Other parameters were kept the same as in the pre-experiment hand calculations.

Figure 7.32 displays the temperature time curve for the heptane pool fire, both the non-insulated and the insulated container. The maximum average gas temperature reached in the non-insulated container is 360°C and in the insulated container 950°C.

Figure 7.33 displays the temperature time curve for the wood crib fire, both insulated and non-insulated container. The maximum average gas temperature reached in the non-insulated construction is 300°C and in the insulated construction 900°C.

As for the pre-experiment calculations it is important to remember that the MQH method only is applicable to a rise in temperature of maximum 600°C, pre flashover (indicated with a dotted blue line in the figures).

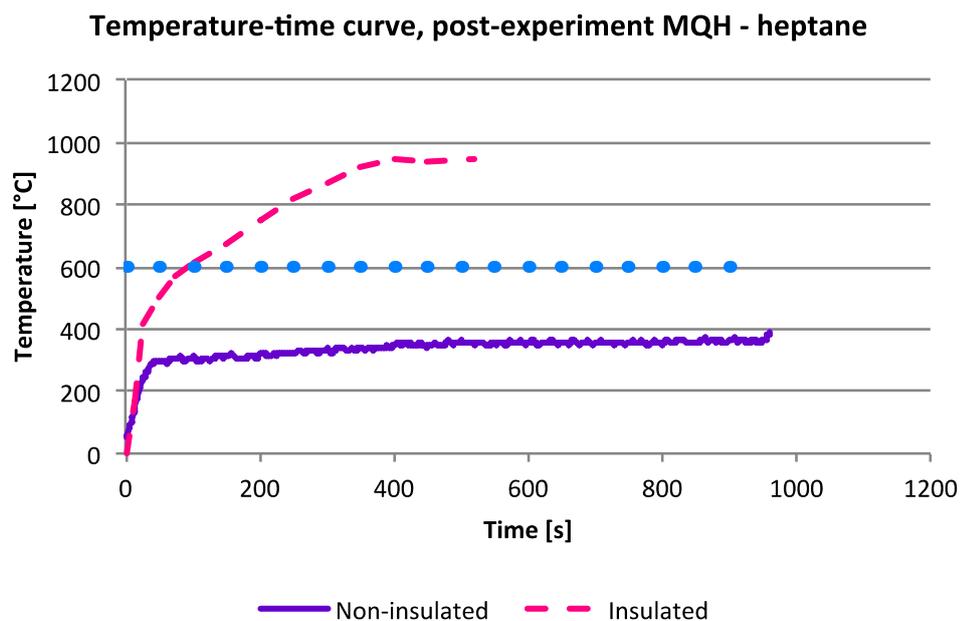


Figure 7.32: Temperature-time curve from the post-experiment hand calculations for the heptane pool fire using the MQH method. The method is valid until $\Delta T=600^\circ\text{C}$, which is marked with a dotted blue line.

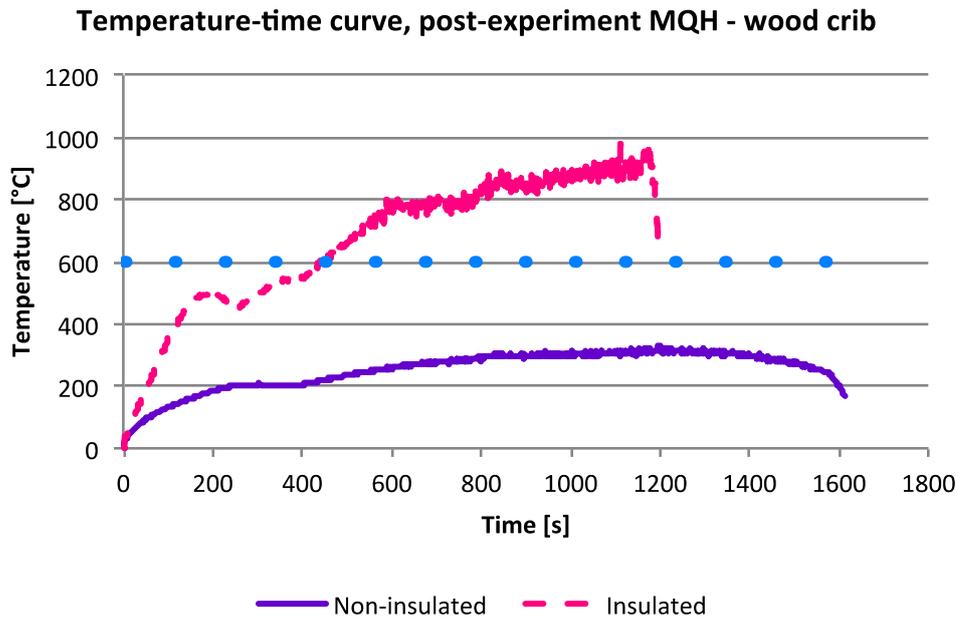


Figure 7.33: Temperature-time curve from the post-experiment hand calculations for the wood crib fire using the MQH method. The method is valid until $\Delta T=600^{\circ}\text{C}$, which is marked with a dotted blue line.

7.4.2 Magnusson and Thelandersson and EUROCODE

The results from the Magnusson and Thelandersson method and the EUROCODE method are not dependant on the heat release rate and there are therefore no new results from these methods.

7.4.3 Summary of results from the post-experiment hand calculations

The maximum average temperatures for each construction, derived from the MQH method, are presented in table 7.7 below. The temperature in the insulated compartment was higher than the one in the non-insulated compartment in each case. The difference in temperature between the two enclosure types are about 600°C . Flashover, according to the criterion: hot gas layer reaching $500\text{-}600^{\circ}\text{C}$, was attained in both cases with insulated compartments.

Only results from the MQH method are presented in the table below, as the other two models are not applicable to post-experiment calculations.

Table 7.7: Summary of the results received from the post-experiment hand calculations

Method	Maximum average temperature	
	Non-insulated construction	Insulated construction
Heptane pool fire		
MQH	360°C	950°C
Wood crib fire		
MQH	300°C	900°C

7.5 Post-experiment simulations

FDS simulations were carried out after the experiments, using the heat release rate measured in the experiment as input data. The results from the simulations are presented below under separate headlines for each parameter measured. The results from the post-experiment simulations are compared to the results from pre-experiment hand calculations, experiments and simulations in chapter 8.

7.5.1 Heat release rate – heptane pool fire

Figure 7.34 below shows the heat release rate from the post-experiment heptane pool fire simulations.

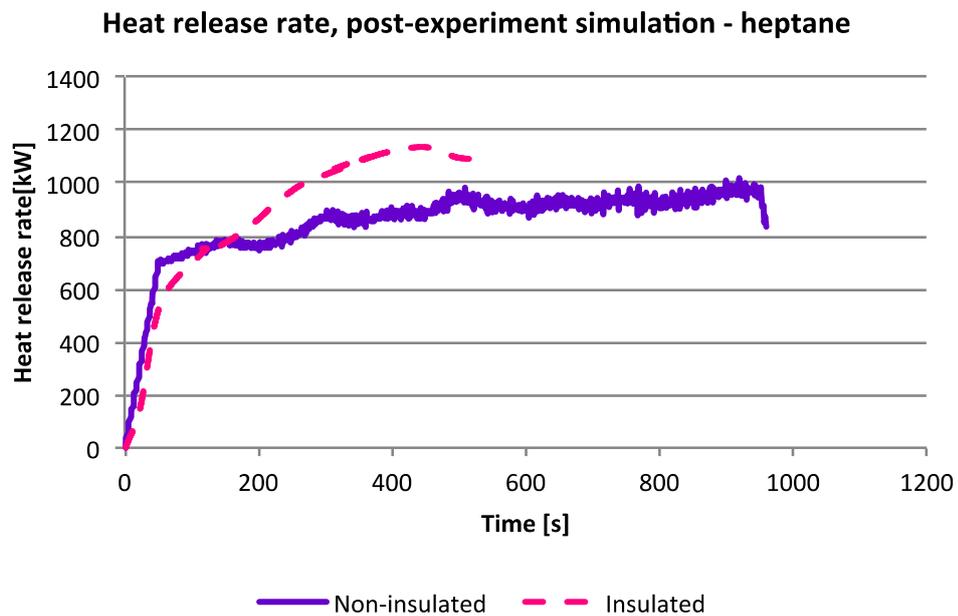


Figure 7.34: The heat release rate recorded in the post-experiment heptane pool fire simulations.

The maximum heat release rate reached in the non-insulated container was approximately 1 000 kW and in the insulated container approximately 1 200 kW, this occurred after 900 s and 450 s, respectively.

7.5.2 Heat Release rate – wood crib fire

Figure 7.35 below shows the heat release rate from the post-experiment wood crib fire simulations.

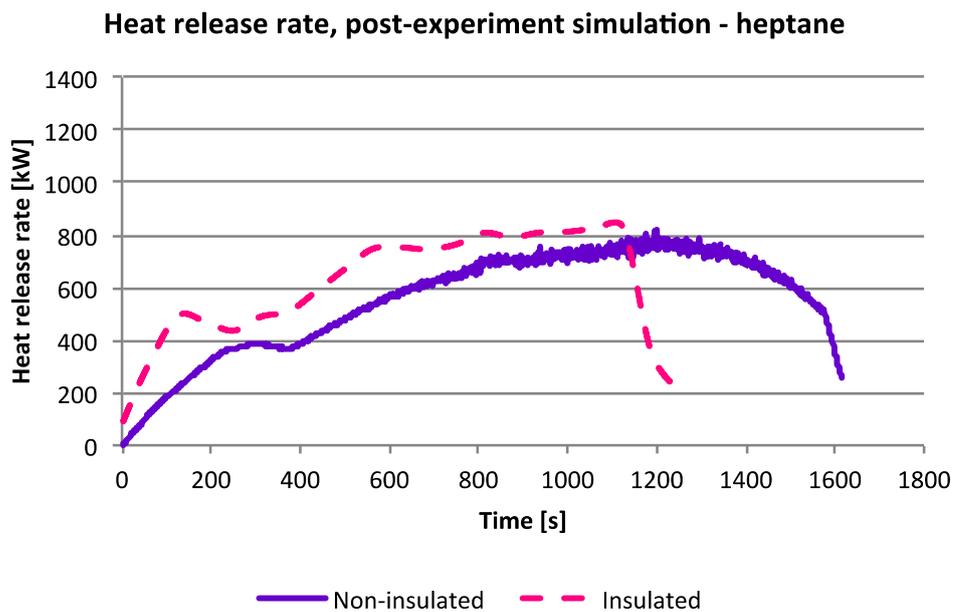


Figure 7.35: The heat release rate recorded in the post-experiment heptane pool fire simulations.

The maximum heat release rate reached in the non-insulated container was approximately 760 kW and in the insulated container approximately 800 kW, this occurred after 1 200 s and 1 100 s, respectively.

7.5.3 Gas temperature – heptane pool fire

The gas temperature was measured in thermocouple trees at three positions on the floor in the container. In each position the temperature was measured at six different heights, same as in the pre-experiment simulations.

The highest temperatures were reached at the measuring points positioned between the fire and the door opening at a height of 2.1 m. Figure 7.36 below shows the temperature measurements from this position in the non-insulated and insulated compartments.

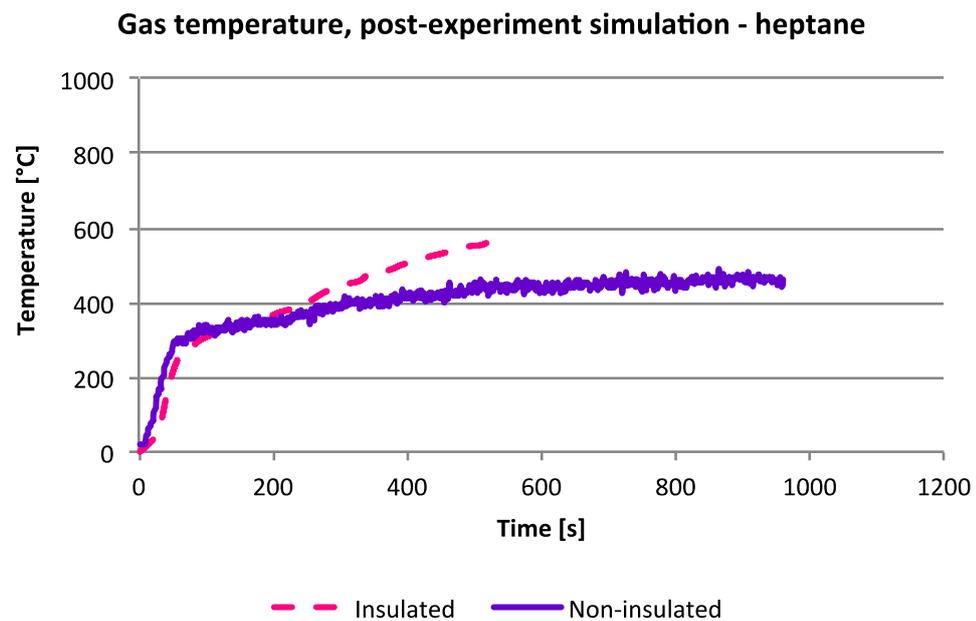


Figure 7.36: The gas temperature recorded in the post-experiment heptane pool fire simulations. Measuring point situated at 2.1 m height between the fire and the door opening.

The maximum average gas temperature reached in the non-insulated compartment was 460°C and was recorded after approximately 830 s. The maximum average gas temperature reached in the insulated compartment was 530°C and was recorded after approximately 450 s. The maximum average gas temperature was higher in the insulated case than in the non-insulated case. The maximum average temperature in the insulated compartment was reached before the maximum average temperature in the non-insulated compartment.

7.5.4 Gas temperature – wood crib fire

The highest temperatures in the wood crib fire simulations were reached at the measuring points positioned between the fire and the door opening at a height of 2.1 m. Figure 7.37 below show the temperature measurements from this position in the non-insulated and insulated compartment.

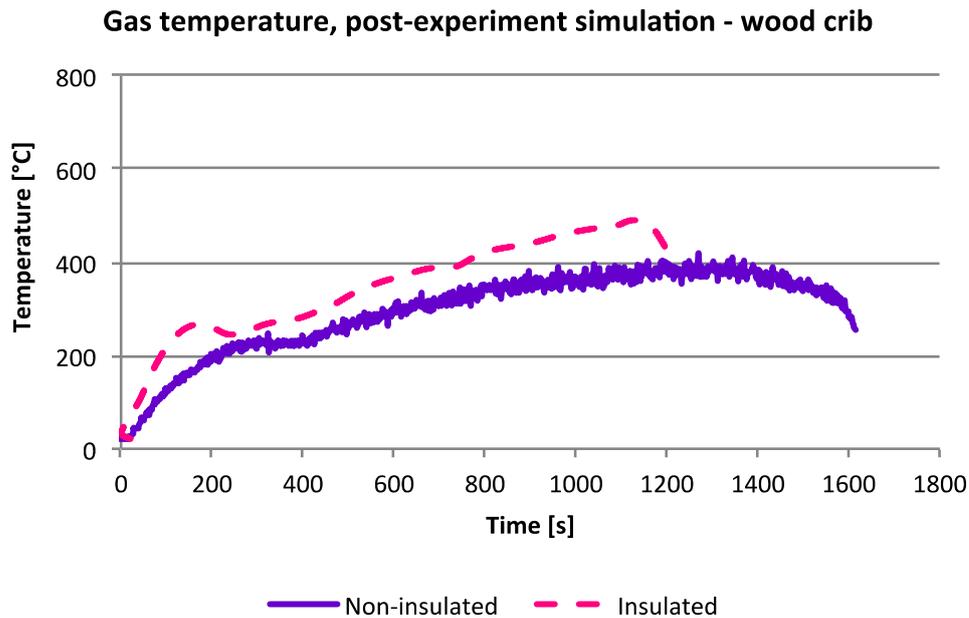


Figure 7.37: The gas temperature recorded in the post-experiment wood crib fire simulations. Measuring point situated at 2.1 m height between the fire and the door opening.

The maximum average gas temperature reached in the non-insulated compartment was 380°C and was recorded after approximately 1 200 s. The maximum average gas temperature reached in the insulated compartment was 480°C and was recorded after approximately 1 150 s. The maximum average gas temperature is higher in the insulated case than in the non-insulated case. The maximum average temperature in the insulated compartment is reached approximately at the same time as the maximum average temperature in the non-insulated compartment.

7.5.5 Wall temperature – heptane pool fire

The wall temperature was registered at three positions on the wall of the container. In each position it was measured at three different heights and two or four depths, depending on if the container was insulated or not. At one of the positions in the insulated container the temperature was measured at 20 different depths, same as in the pre-experiment simulations.

The highest wall temperature was reached at the position across from the fire at a height of 2.1 m. When comparing the wall and gas temperatures between the non-insulated and insulated case the measurements from the position between the fire and the door opening are used. Figure 7.38 shows the wall temperatures and gas temperatures at this position. The graph displays the wall temperature and gas temperature from the same position at 2.1 m from the floor from both the non-insulated and the insulated case. The displayed wall temperatures are the ones measured on the outside of the steel.

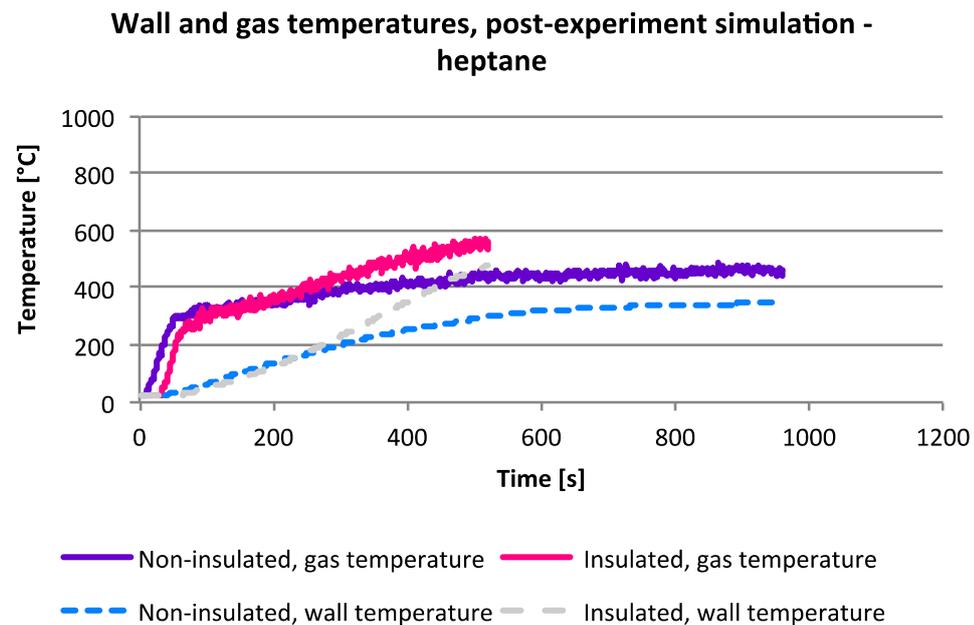


Figure 7.38: The wall and gas temperature recorded between the fire and back wall opening, at 2.1 m height, in the post-experiment heptane pool fire simulations.

The maximum average wall temperature reached in the non-insulated container between the fire and the door opening was 340°C and was recorded after approximately 820 s. The maximum average wall temperature reached in the insulated container was 440°C and was recorded after approximately 480 s. The maximum average wall temperature was higher in the insulated case than in the non-insulated. The maximum average wall temperature in the insulated compartment was reached before the maximum temperature in the non-insulated compartment.

The wall temperature that was measured at 20 different depths in one measuring point was situated between the fire and the back wall at a height of 2.1 m. Figure 7.39 below shows a cross section taken at 520 s. The dot to the left of the wall in the graph represents the gas temperature registered at the thermocouple tree in the compartment, between the fire and back wall at a height of 2.1 m. The dot to the right of the wall in the graph represents the ambient temperature surrounding the compartment.

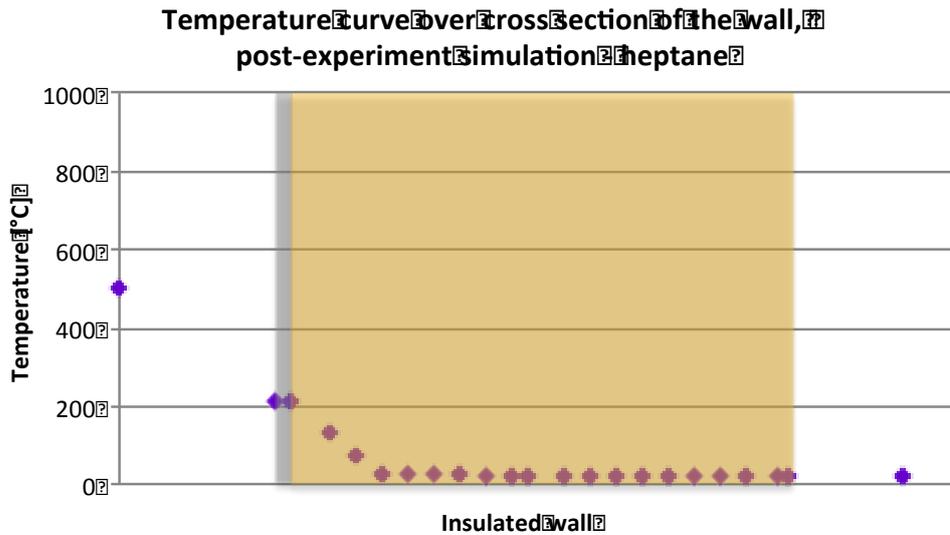


Figure 7.39: Temperature curve over the cross section of the insulated wall taken at 520 s in the wood crib fire. Measuring point situated between the fire and the back wall at a height of 2.1 m.

Note that none of the temperature curves correlate with the general opinion of how the temperature distribution in a wall is depicted, as described in section 2.6. This is discussed further in chapter 9.

7.5.6 Wall temperature – wood crib fire

Figure 7.40 below, displays the wall and gas temperature from the between the fire and the door opening position at 2.1 m from the floor, from both the non-insulated and the insulated case. The wall temperatures displayed are the ones registered on the outside of the steel.

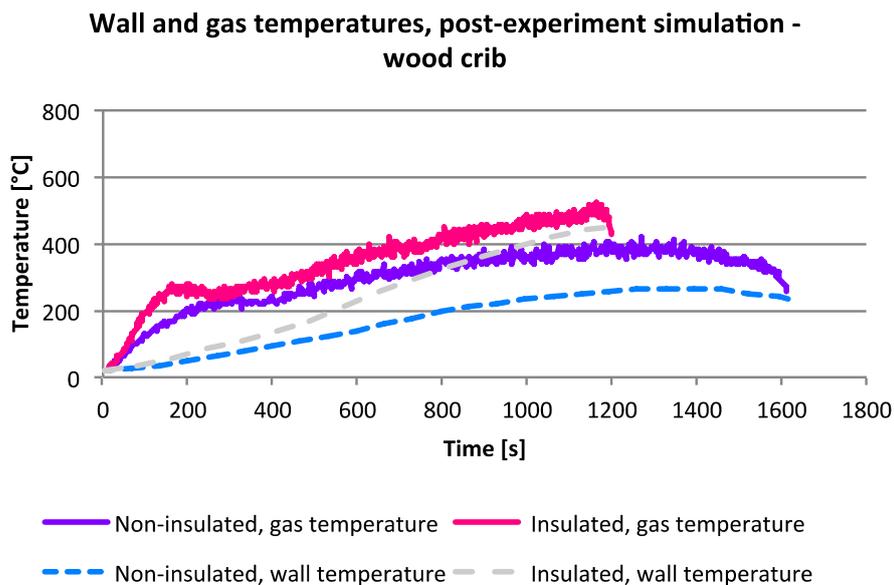


Figure 7.40: The wall and gas temperature recorded between the fire and the back wall, at 2.1 m height, in the post-experiment wood crib fire simulations.

The maximum average wall temperature reached in the non-insulated container at the position between the fire and the door opening was 260°C and was recorded after approximately 1 400 s. The maximum average wall temperature reached in the insulated container was 420°C and was recorded after approximately 1 100 s. The maximum average wall temperature was higher in the insulated case than in the non-insulated. The maximum average wall temperature was reached almost at the same time in both compartments.

The wall temperature that was measured at 20 different depths in one measuring point was situated between the fire and the back wall at a height of 2.1 m. Figure 7.41 below show a cross section taken at 1 180 s. The dot to the left of the wall in the graph represents the gas temperature registered at the thermocouple tree in the compartment, between the fire and back wall at a height of 2.1 m. The dot to the right of the wall in the graph represents the ambient temperature surrounding the compartment.

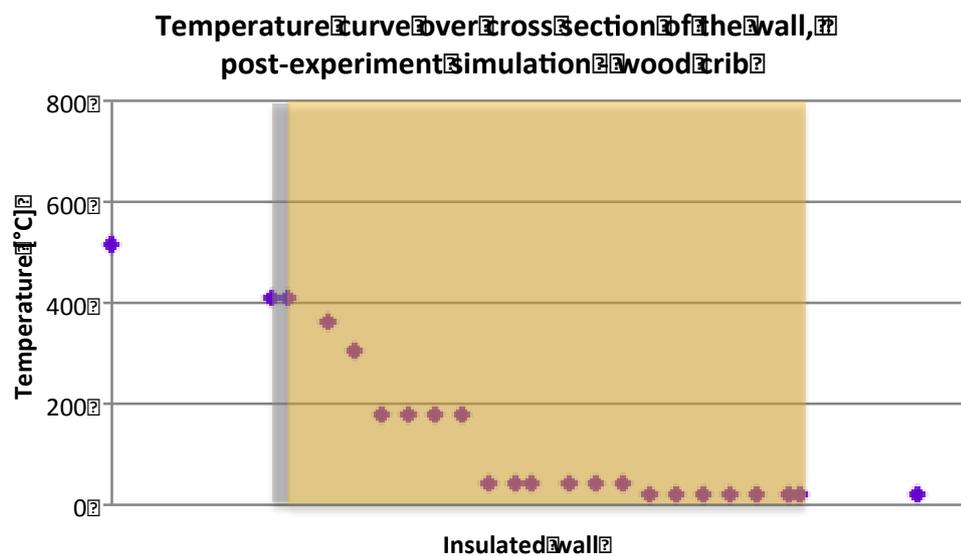


Figure 7.41: Temperature curve over the cross section of the insulated wall taken at 1 180 s in the wood crib fire. Measuring point situated between the fire and the back wall at a height of 2.1 m.

Note that none of the temperature curves correlate with the general opinion of how the temperature distribution in a wall is depicted, as described in section 2.6. This is discussed further in chapter 9.

7.5.7 Radiation – heptane pool fire

Boundary files were used in the model to measure the radiation. Figures 7.42 and 7.43 below show the radiation in the non-insulated and insulated compartment with a heptane pool fire. The figures are taken from the time step where the maximum average temperature was measured, after 830 s for the non-insulated compartment and 450 s for the insulated compartment. The black contours represent a radiation of 15.0 kW/m², which is one of the criteria for flashover.

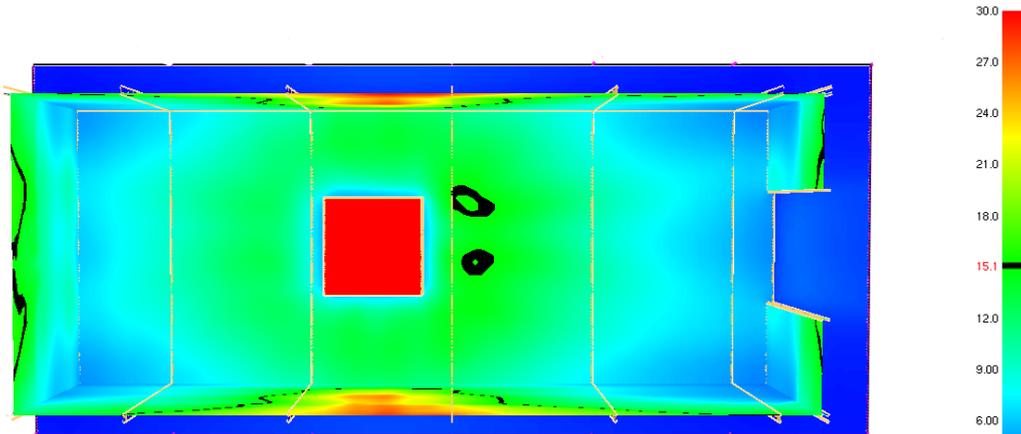


Figure 7.43: Measured radiation in the post-experiment simulation with a heptane pool fire in a non-insulated compartment. The black contour represents a radiation of 15.0 kW/m^2 .

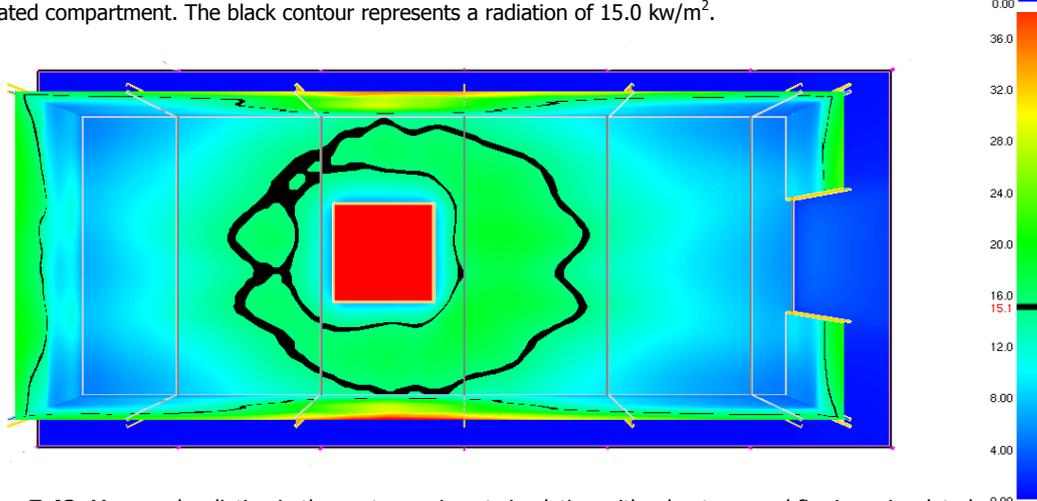


Figure 7.42: Measured radiation in the post-experiment simulation with a heptane pool fire in an insulated compartment. The black contour represents a radiation of 15.0 kW/m^2 .

The radiation reaches 15 kW/m^2 around the fire in the insulated case. In the non-insulated case 15 kW/m^2 is barely reached.

7.5.8 Radiation – wood crib fire

Figure 7.44 and 7.45 below show the radiation in the non-insulated and insulated compartment with a wood crib fire. The figures are taken from the time step where the maximum average temperature was measured, after 1 200 s for the insulated compartment and 1 150 s for the non-insulated compartment. The black contours represent a radiation of 15.0 kW/m^2 .

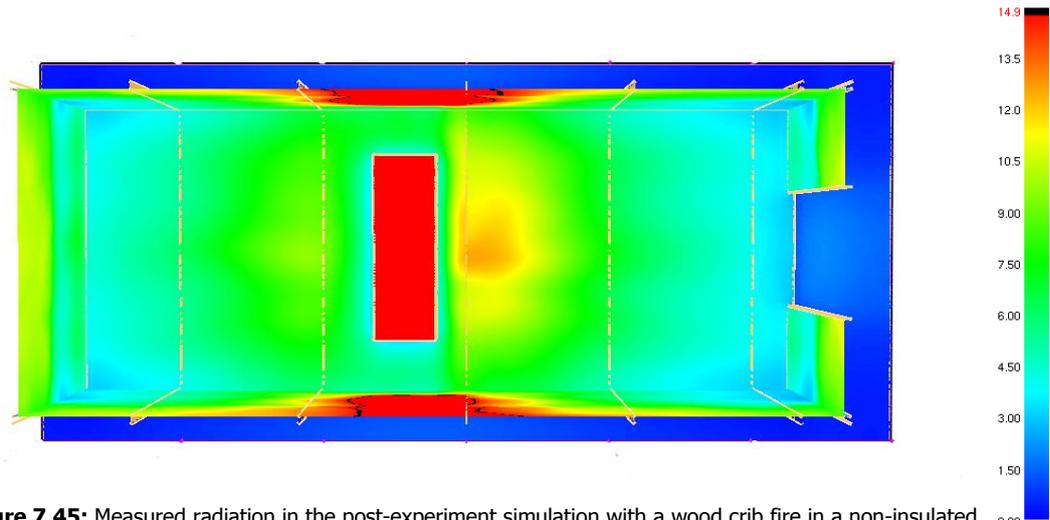


Figure 7.45: Measured radiation in the post-experiment simulation with a wood crib fire in a non-insulated compartment. The black contour represents a radiation of 15.0 kW/m^2 .

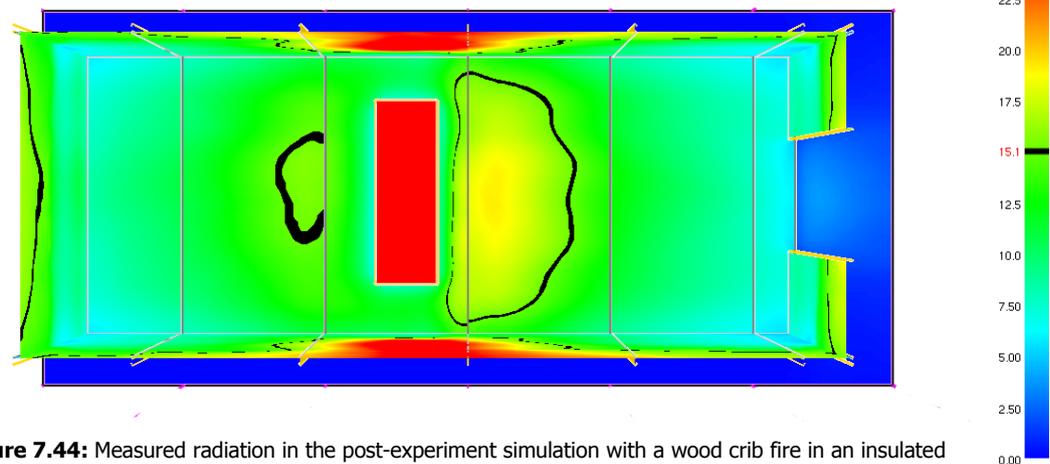


Figure 7.44: Measured radiation in the post-experiment simulation with a wood crib fire in an insulated compartment. The black contour represents a radiation of 15.0 kW/m^2 .

The radiation barely reaches 15 kW/m^2 around the fire in the insulated case. In the non-insulated case 15 kW/m^2 is not reached, only on the fire source and on the walls directly across from the fire.

7.5.9 Summary of results from the post-experiment simulations

Flashover, according to the criterion: hot gas layer reaching $500\text{-}600^\circ\text{C}$, was attained in the simulation with the heptane pool fire in an insulated enclosure. However, the temperature just exceeded 500°C . The gas temperature differs between the non-insulated and insulated cases with approximately 100°C in both the heptane pool fire and the wood crib fire simulations. A summary of the results is found in table 7.8 below.

Table 7.8: Summary of the results received from the post-experiment simulations

	Non-insulated container with heptane pool fire	Insulated container with heptane pool fire	Non-insulated container with wood crib fire	Insulated container with wood crib fire
Extinction of fire	960 s	520 s	1 620 s	1 200 s
Max. average temperature in compartment	460°C	530°C	380°C	480°C
Time until max. average temperature in compartment was reached	830 s	450 s	1 200 s	1 150 s
Maximum heat release rate	1 000 kW	1 200 kW	760 kW	800 kW
Time until maximum heat release rate was reached	900 s	450 s	1 200 s	1 100 s

7.6 Verification of simulations

The simulations have been verified through a number of analyses. They have been verified through mesh resolution analysis, dimensionless heat release rate analysis, flame height analysis, grid independence analysis and room size analysis. Each type of verification method is described below.

7.6.1 Mesh resolution

To be certain that the grid would be fine enough to record information, on a sufficiently detailed level, verification calculations of the mesh resolution were carried out. According to the FDS Users guide, version 5 (2010), the characteristic fire diameter divided by the normal size of a mesh cell in meters ($D^*/\delta x$) should be within the range of 4 to 16, as shown in equation 7.1 below. However, it should preferably be chosen to a number larger than 10 (Jakobsen et al. 2009).

$$4 < D^*/\delta x < 16 \quad (\text{eq. 7.1})$$

The characteristic diameter is calculated using equation 7.2 below.

$$D^* = \left(\frac{\dot{Q}}{\rho_{\infty} \cdot c \cdot T_{\infty} \cdot \sqrt{g}} \right)^{2/5} \quad (\text{eq. 7.2})$$

Where \dot{Q} is the heat release rate [kW], ρ_{∞} is the density of the ambient air [kg/m³], c is the specific heat of the hot gases [kJ/kg K], T_{∞} is the temperature of the ambient air [K] and g is the gravitational acceleration [m/s²]. If the characteristic diameter divided by the cell size is smaller than 4, not enough

information will be extracted and if larger than 16 no extra information will be extracted, it will only be more time consuming.

Standard values were chosen for the constants, $\rho_{\infty} = 1.2 \text{ kg/m}^3$, $c_p = 1.0 \text{ kJ/kg K}$, $T_{\infty} = 297 \text{ K}$, $g = 9.81 \text{ m/s}^2$ and the size of the cells (δx) to 0.05 m and 0.10 for both the pre-experiment and post-experiment simulations.

The results for each simulation are presented in table 7.9 and 7.10 below.

Table 7.9: Mesh resolution, pre-experiment simulations

	Heptane pool fire, non-insulated	Heptane pool fire, insulated	Wood crib fire, non-insulated	Wood crib fire, insulated
Maximum heat release rate	1 200 kW	1 200 kW	1 600 kW	1 600 kW
$D^*/\delta x$ $\delta x = 0.05 \text{ m}$	20.60	20.60	23.10	23.10
$D^*/\delta x$ $\delta x = 0.10 \text{ m}$	10.29	10.29	11.55	11.55

Although 20.6 and 23.10 are higher than 16, and knowing that it could be time consuming the simulations were carried out keeping the chosen cell size of 0.05 m x 0.05 m x 0.05 m.

Table 7.10: Mesh resolution, post-experiment simulations

	Heptane pool fire, non-insulated	Heptane pool fire, insulated	Wood crib fire, non-insulated	Wood crib fire, insulated
Maximum heat release rate	970 kW	1 140 kW	780 kW	860 kW
$D^*/\delta x$ $\delta x = 0.05 \text{ m}$	18.91	20.17	17.33	18.02
$D^*/\delta x$ $\delta x = 0.10 \text{ m}$	9.45	10.08	8.66	9.01

7.6.2 Dimensionless heat release rate

Verification calculations were also carried out for the fire sources. The heat release rate should be in relation to the surface it is applied to. The dimensionless heat release rate could be calculated using equation 7.3 below. It should be within the range of 0.3 to 2.5 (Jakobsen et al. 2009). If smaller than 0.3 the fire will be too weak and if larger than 2.5 it will be more like a jet flame, which is appropriate in case of gas leak simulations.

$$Q^* = \frac{\dot{Q}}{\rho_{\infty} \cdot c \cdot T_{\infty} \cdot \sqrt{g D_e} \cdot D_e^2} \quad (\text{eq. 7.3})$$

\dot{Q} is the heat release rate [kW], ρ_{∞} is the density of the ambient air [kg/m^3], c is the specific heat at constant pressure [kJ/kg K], T_{∞} is the temperature of the ambient air [K], g is the gravitational acceleration [m/s^2] and D_e is the equivalent diameter of the fire [m] which could be calculated using equation 7.4 below.

$$D_e = 2\sqrt{A/\pi} \quad (\text{eq. 7.4})$$

Where A is the area of the fire [m^2].

Standard values were chosen for the constants, $\rho_\infty = 1.2 \text{ kg/m}^3$, $c_p = 1.0 \text{ kJ/kg K}$, $T_\infty = 298 \text{ K}$, $g = 9.81 \text{ m/s}^2$ for both the pre-experiment and post-experiment simulations. The areas of the fires were set to 0.64 m^2 for the heptane pool fire and 0.75 m^2 for the wood crib fire, as discussed in chapter 6.

The results for each simulation are presented in table 7.11 and 7.12 below. The dimensionless heat release rate for both the pre-experiment simulations and the post-experiments simulations are within the range of applicability for the relation between surface and heat release rate.

Table 7.11: Dimensionless heat release rate, pre-experiment simulations

	Heptane pool fire, non-insulated	Heptane pool fire, insulated	Wood crib fire, non-insulated	Wood crib fire, insulated
Maximum heat release rate	1 200 kW	1 200 kW	1 600 kW	1 600 kW
D	0.90	0.90	0.98	0.98
Q^*	1.39	1.39	1.52	1.52

Table 7.12: Dimensionless heat release rate, post-experiment simulations

	Heptane pool fire, non-insulated	Heptane pool fire, insulated	Wood crib fire, non-insulated	Wood crib fire, insulated
Maximum heat release rate	970 kW	1 140 kW	780 kW	860 kW
D	0.90	0.90	0.98	0.98
Q^*	1.12	1.32	0.74	0.82

7.6.3 Flame height

It is also important that the flames of the fire reach a reasonable height. The flame height could be calculated using the Heskestad flame height correlation, equation 7.5 below (Heskestad 1998).

$$L = 0.253 \cdot \dot{Q}^{2/5} - 1.02 \cdot D_e \quad (\text{eq. 7.5})$$

Where \dot{Q} is the heat release rate [kW] and D_e is the equivalent diameter of the fire [m]. Using values as presented above, L becomes 3.09 m for the heptane pool fire and 3.50 m for the wood crib fire, which is considered reasonable. The results for each simulation are presented in table 7.13 and 7.14 below.

Table 7.13: Flame height, pre-experiment simulations

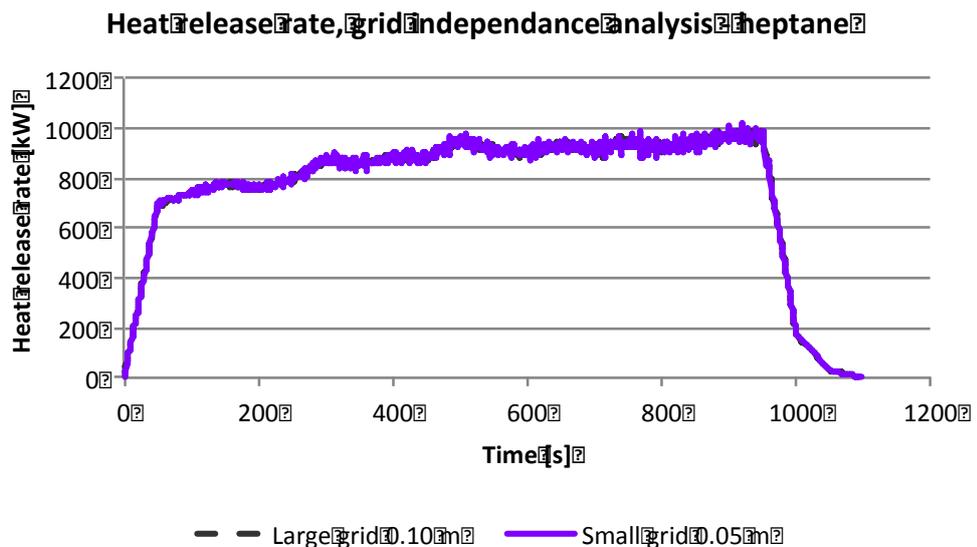
	Heptane pool fire, non-insulated	Heptane pool fire, insulated	Wood crib fire, non-insulated	Wood crib fire, insulated
Maximum heat release rate	970 kW	1 140 kW	780 kW	860 kW
D	0.90	0.90	0.98	0.98
Flame height	3.09 m	3.09 m	3.50 m	3.50 m

Table 7.14: Flame height, post-experiment simulations

	Heptane pool fire, non-insulated	Heptane pool fire, insulated	Wood crib fire, non-insulated	Wood crib fire, insulated
Maximum heat release rate	970 kW	1 140 kW	780 kW	860 kW
D	0.90	0.90	0.98	0.98
Flame height	2.76 m	3.00 m	2.38 m	2.51 m

7.6.4 Grid independence

A grid independence analysis of the simulations has been carried out. The simulations with a heptane pool fire in a non-insulated container and the wood crib fire in a non-insulated container were run a second time. The cell size was enlarged to 0.10 m instead of 0.05 m as in the previous simulations. The graphs below compare the heat release rate curves from the simulations with the coarser grid to the base simulation. The comparison has been made between post-experiment simulations. Figure 7.46 shows the heat release rate from the heptane pool fire in the non-insulated compartment and graph 7.39 shows the heat release rate from the wood crib fire in the non-insulated compartment.

**Figure 7.46:** Grid independence analysis. Heat release rates from the heptane pool fire in the non-insulated compartment, large grid 0.01 m and small grid 0.05 m.

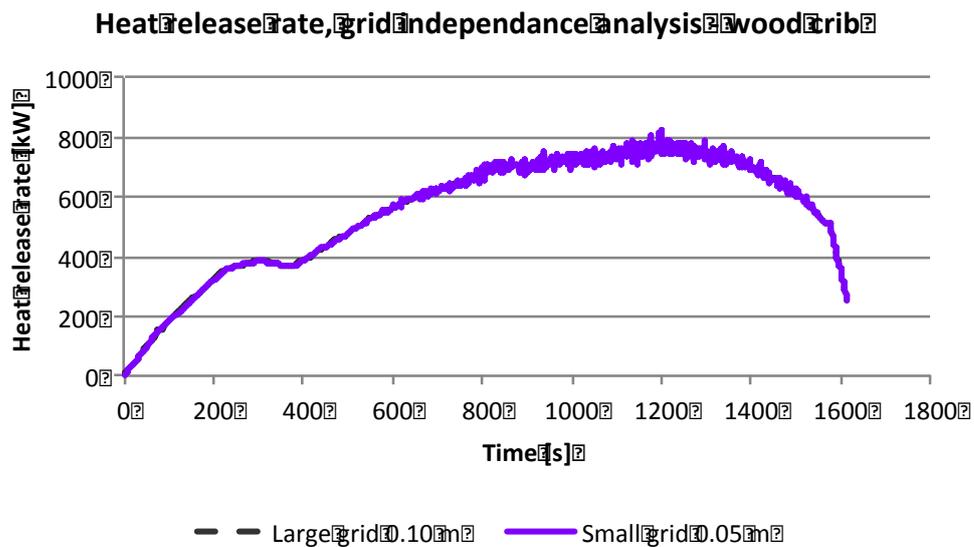


Figure 7.47: Grid independence analysis. Heat release rates from the wood crib fire in the non-insulated compartment, large grid 0.01 m and small grid 0.05 m.

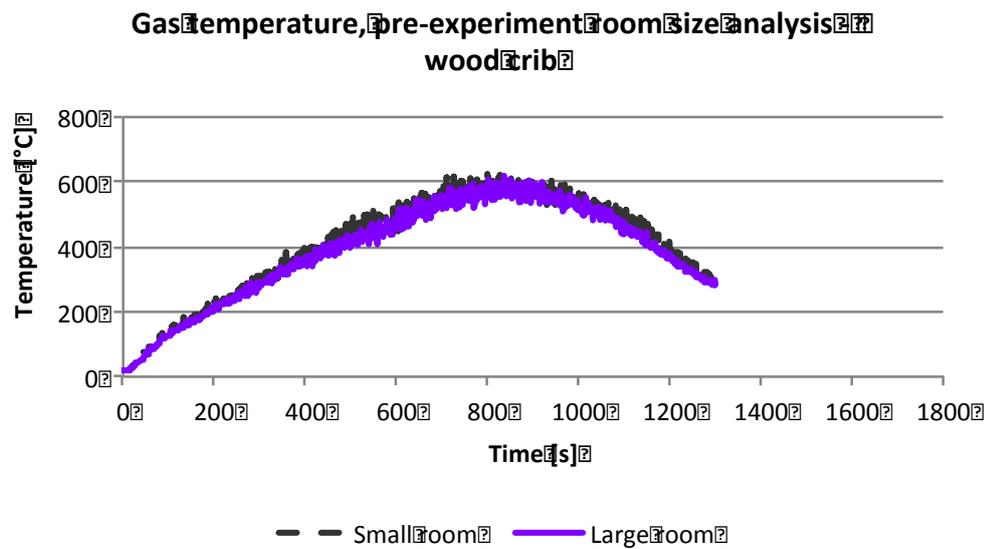
In both the heptane pool fire simulation and the wood crib fire simulation the heat release rate curve for the large and the small grid size is the same.

7.6.5 Room size and hood

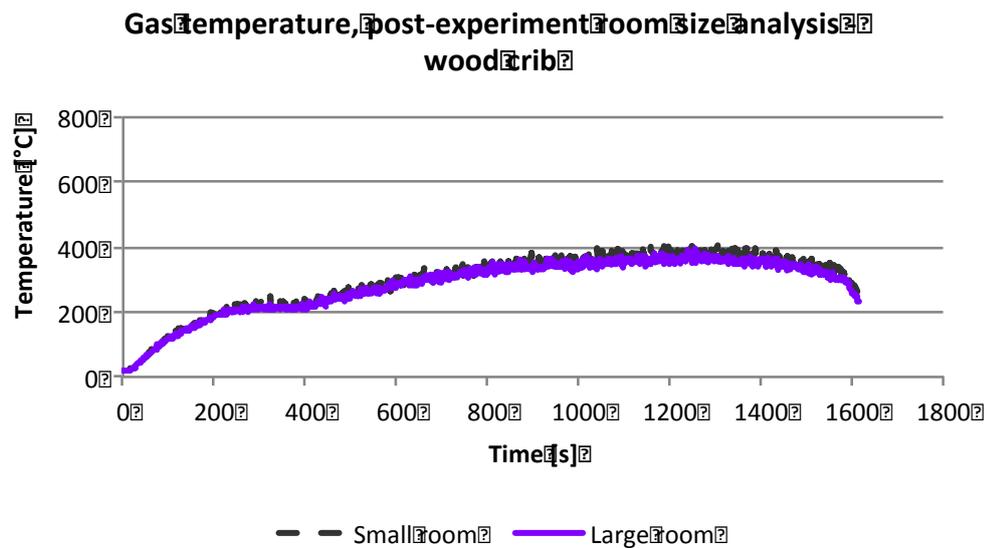
A fifth simulation was carried out to evaluate how the hood can affect the convection on the outside of the container, and thereby the amount of heat that is transferred through the compartment boundaries.

In the fifth simulation the container was situated in a large room with a hood. In the previous simulations the container was situated in a smaller room with no hood. It is only the non-insulated case that has been evaluated since that is the case where the convection might affect the conditions in the compartment. Both the pre- and post-experiment simulations were evaluated.

Temperature time curves from each simulation are presented in figures 7.48 and 7.49 below.



Graph 7.48: Room size and hood analysis. Gas temperature from pre-experiment simulation of the wood crib fire in the non-insulated compartment.



Graph 7.49: Room size and hood analysis. Gas temperature from post-experiment simulation of the wood crib fire in the non-insulated compartment.

The gas temperatures recorded in both the pre- and post-experiment simulations give the same results.

8. COMPARISON OF RESULTS

In the previous chapter the results from each method of calculating the differences between a non-insulated and an insulated compartment were presented. The focus lied on how the increased insulation affects the conditions in the enclosure. In this chapter the results from each method will be compared to each other. The focus lies upon comparing the methods to each other instead of an insulated compartment to a non-insulated one.

8.1 Heat release rate – heptane pool fire

The heat release rates for the heptane pool fire that were used in the hand calculations, recorded during the experiments and recorded in the simulations are displayed in figures 8.1 and 8.2 below. The heat release rates for the pre-experiment hand calculations were the same for both methods (no heat release rate was used for the EUROCODE method). The heat release rate has therefore only been displayed once in the graphs. Furthermore, the heat release rate recorded in the experiments was used as an input when carrying out the post-experiment hand calculations. The heat release rate for the post-experiment hand calculations is therefore not displayed in the graph, as it was the same as the one for the experiment.

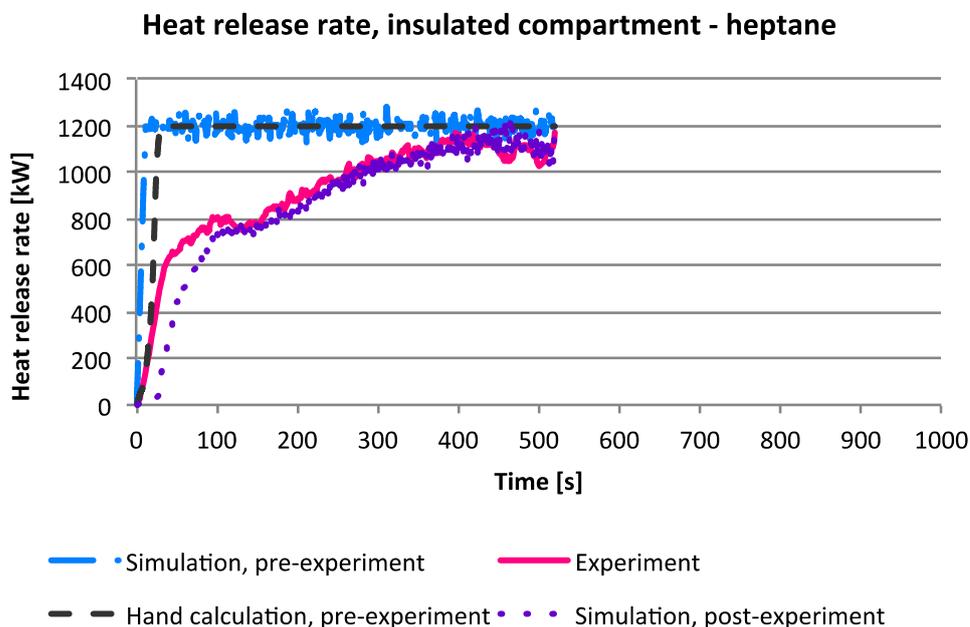


Figure 8.1: The heat release rates recorded for the heptane pool fire in the insulated compartment. Results from simulations, hand calculations and experiment.

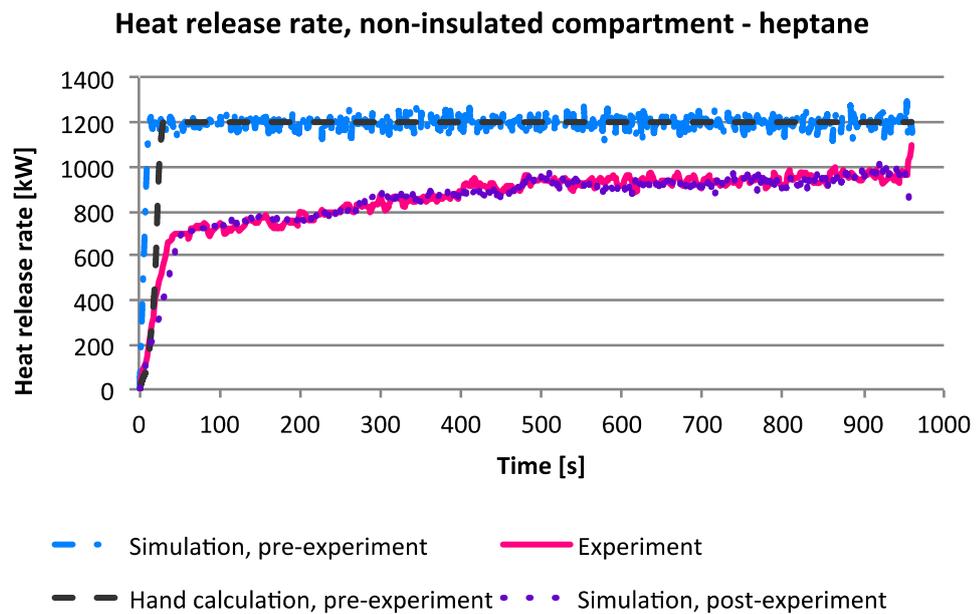


Figure 8.2: The heat release rates recorded for the heptane pool fire in the non-insulated compartment. Results from simulations, hand calculations and experiment.

The estimated heat release rate used in the pre-experiment hand calculations and simulations does not correspond to the ones recorded in the experiments, not for the insulated nor for the non-insulated case. In both cases the estimated heat release rates reaches a high level more quickly than the recorded heat release rate. However they tend to reach the same level in the end of the test-time.

8.2 Heat release rate – wood crib fire

The heat release rates for the wood crib fire used in the hand calculations, recorded during the experiments and recorded in the simulations, are displayed in figures 8.3 and 8.4 below. The heat release rates for the pre-experiment hand calculations were the same for all methods (no heat release rate was used for the EUROCODE method). The heat release rates from hand calculations are therefore only displayed once in the graphs. As for the heptane pool fire the heat release rate for the post-experiment hand calculations were the same as for the experiment, and therefore not displayed in the graph.

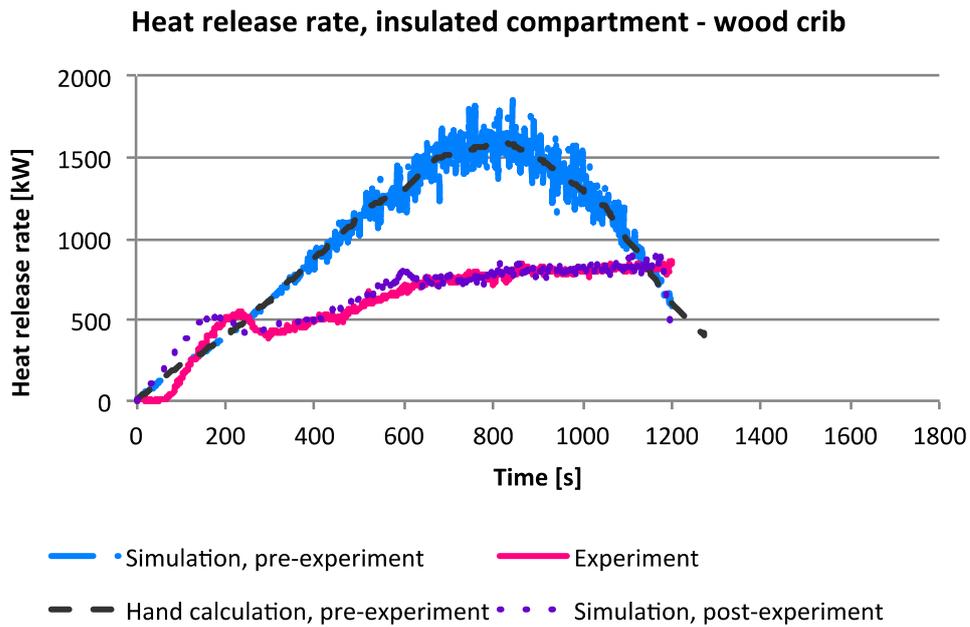


Figure 8.3: The heat release rates recorded for the wood crib fire in the insulated compartment. Results from simulations, hand calculations and experiment.

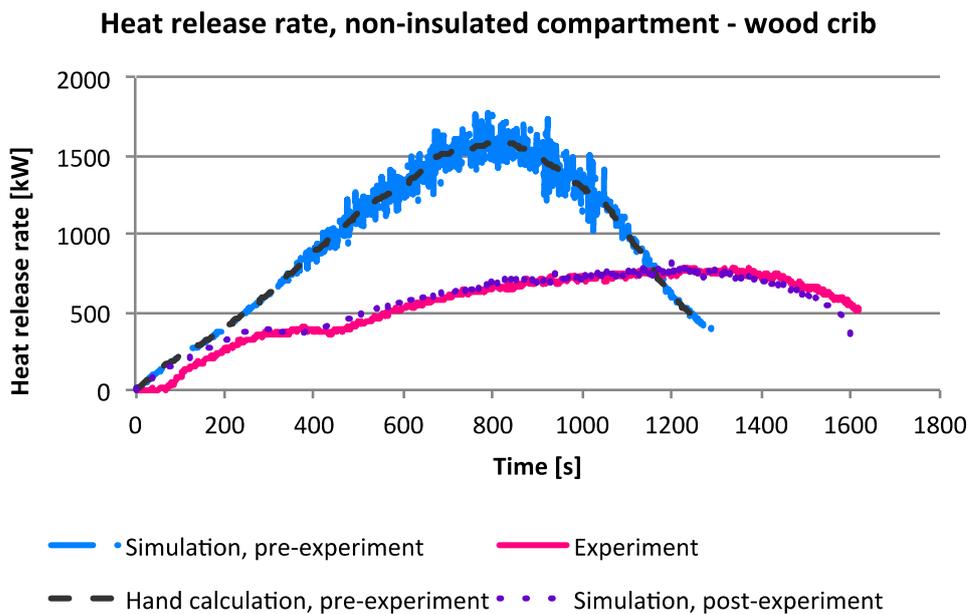


Figure 8.4: The heat release rates recorded for the wood crib fire in the non-insulated compartment. Results from simulations, hand calculations and experiment.

The estimated heat release rate used in the pre-experiment simulations and hand calculations reaches a level about twice the size of the recorded heat release rate.

8.3 Gas temperature – heptane pool fire

The gas temperatures from the heptane pool fire tests are displayed in figures 8.5 and 8.6 below. The results from each method, hand calculations, simulations and experiments, are compared to each other.

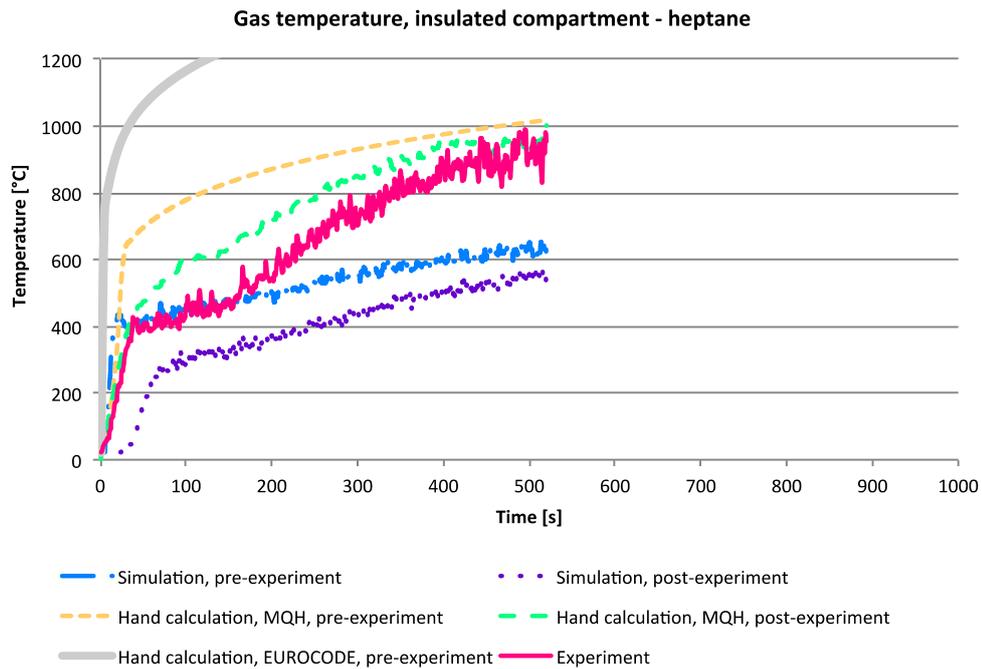


Figure 8.5: The gas temperatures recorded for the heptane pool fire in the insulated compartment. Results from simulations, hand calculations (MQH and EUROCODE) and experiment.

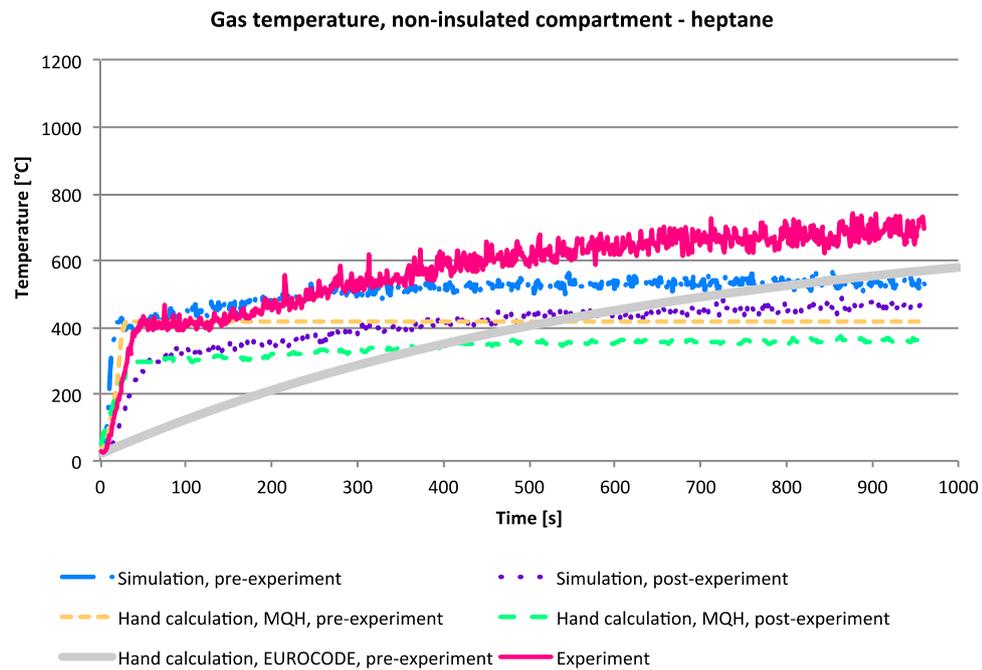


Figure 8.6: The gas temperature recorded for the heptane pool fire in the non-insulated compartment. Results from simulations, hand calculations (MQH and EUROCODE) and experiment.

The gas temperature in the insulated compartment differs a lot between the different methods. The hand calculations tend to overestimate the gas temperature while the simulations tend to underestimate the gas temperature in the insulated compartment. The results from the non-insulated compartment do

not differ as much. However, both hand calculations and simulations seem to underestimate the gas temperature.

8.4 Gas temperature – wood crib fire

The gas temperatures from the wood crib fire tests are displayed in figure 8.7 and 8.8 below. The results from each method, hand calculations, simulations and experiments, are compared to each other. In addition to the methods used in the heptane pool fire evaluation the Magnusson and Thelandersson method has been used.

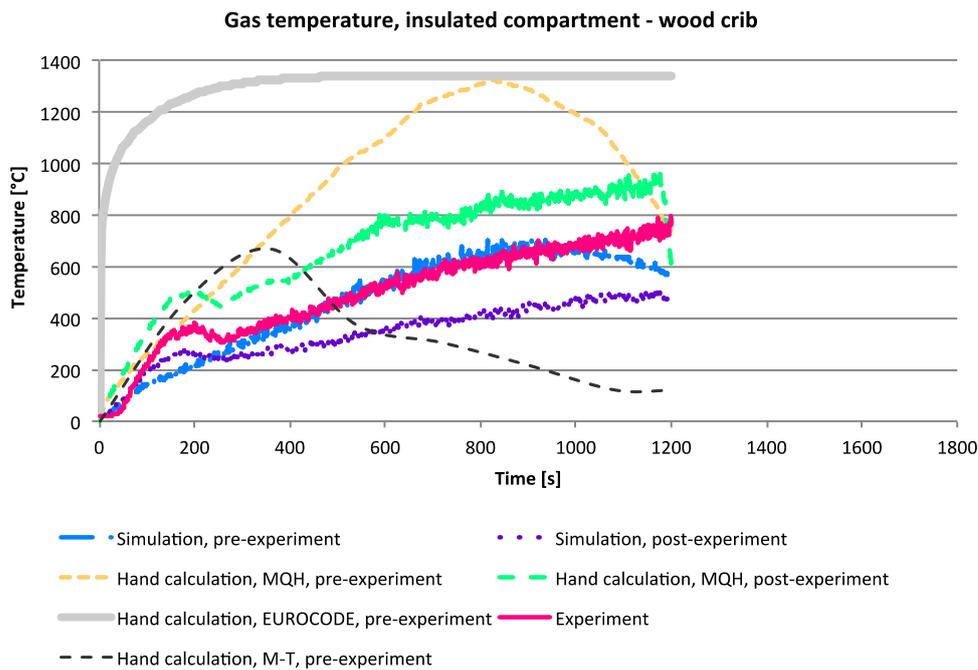


Figure 8.7: The gas temperature recorded for the wood crib fire in the insulated compartment. Results from simulations, hand calculations (MQH, EUROCODE and M-T) and experiment.

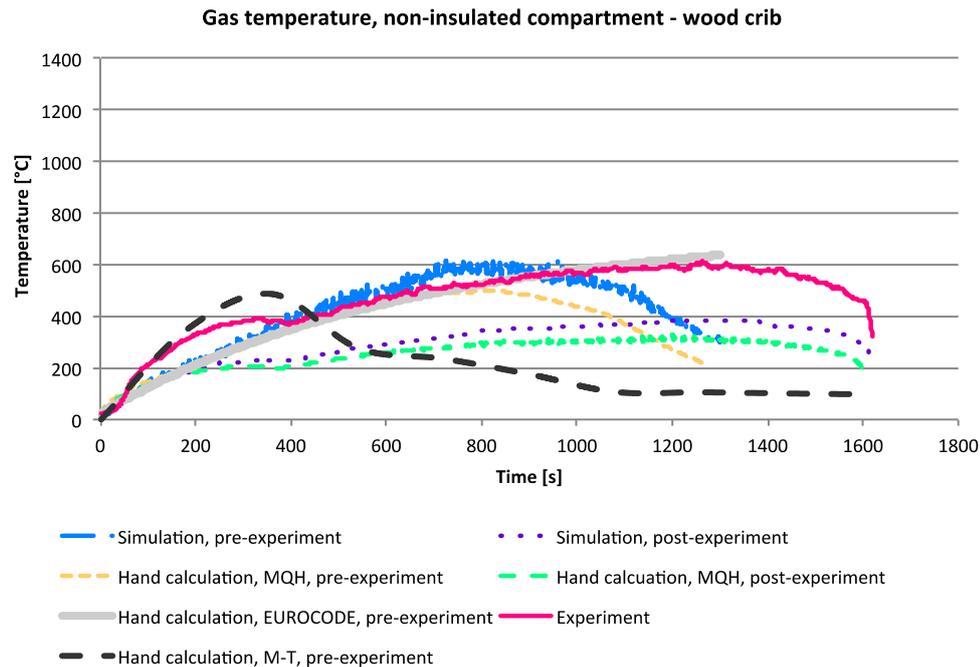


Figure 8.8: The gas temperature recorded for the wood crib fire in the non-insulated compartment. Results from simulations, hand calculations (MQH, EUROCODE and M-T) and experiment.

The gas temperatures in the insulated compartment differ a lot between the different methods. The hand calculations tend to overestimate the gas temperature while the simulations tend to underestimate the gas temperature. However, the pre- and post-experiment simulation, the post-experiment hand calculation and the result from the experiment follow the same shape.

The results from the non-insulated enclosure do not differ as much. However all methods apart from the MQH and EUROCODE pre-experiment calculation seem to underestimate the gas temperature. The post-experiment simulation and hand calculation (MQH-method) follows the same arc and diverge only slightly.

8.5 Wall temperature – heptane pool fire

The wall temperatures from the heptane pool fire tests are displayed in figures 8.9 and 8.10 below. The wall temperatures displayed are the ones recorded in the experiments and also the temperatures registered in both the pre- and post-experiment simulations. The wall temperature was not calculated using hand calculations. The wall-temperatures displayed in the graphs below were recorded on the outside of the steel-construction between the fire and the back wall.

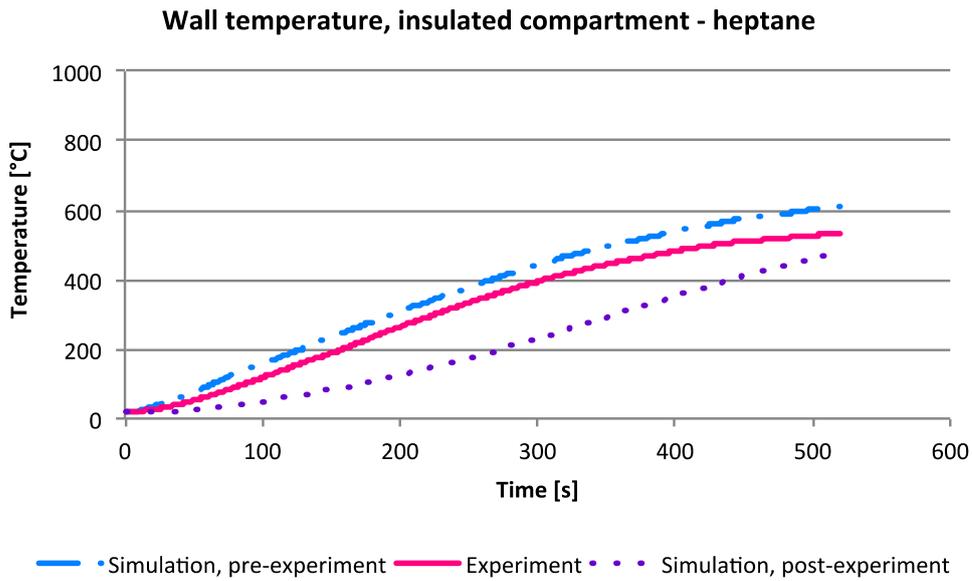


Figure 8.9: The wall temperature recorded for the heptane pool fire in the insulated compartment. Results from simulations and experiment.

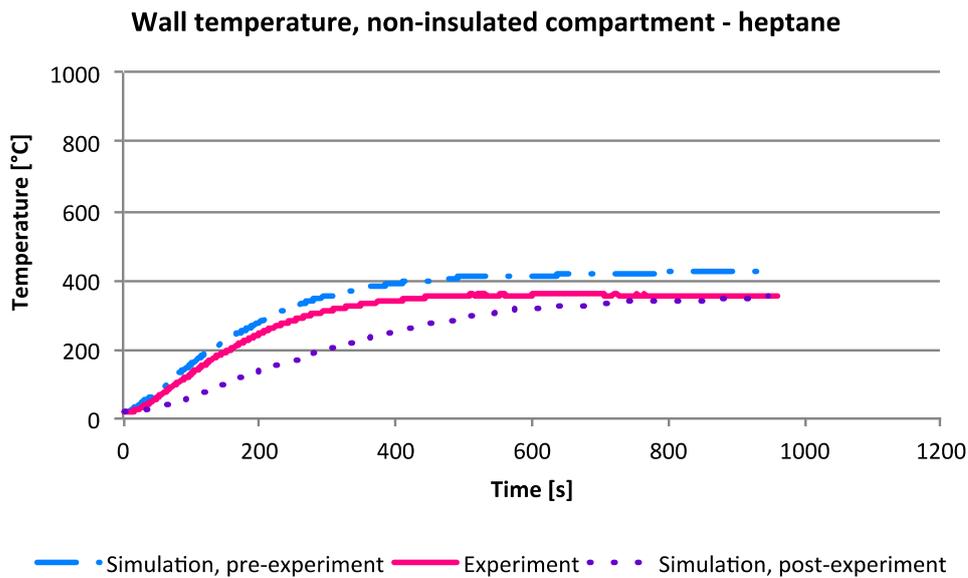


Figure 8.10: The wall temperature recorded for the heptane pool fire in the non-insulated compartment. Results from simulations and experiment.

Figure 8.11 displays the cross section of an insulated wall with the temperatures recorded in the simulations and the experiment after 520 s. The measuring devices were situated between the fire and the back wall at a height of 2.1 m. The temperature to the left in the graph is the gas temperature registered at the thermocouple tree in the compartment, between the fire and back wall at a height of 2.1 m. The temperature to the right is the ambient temperature surrounding the compartment.

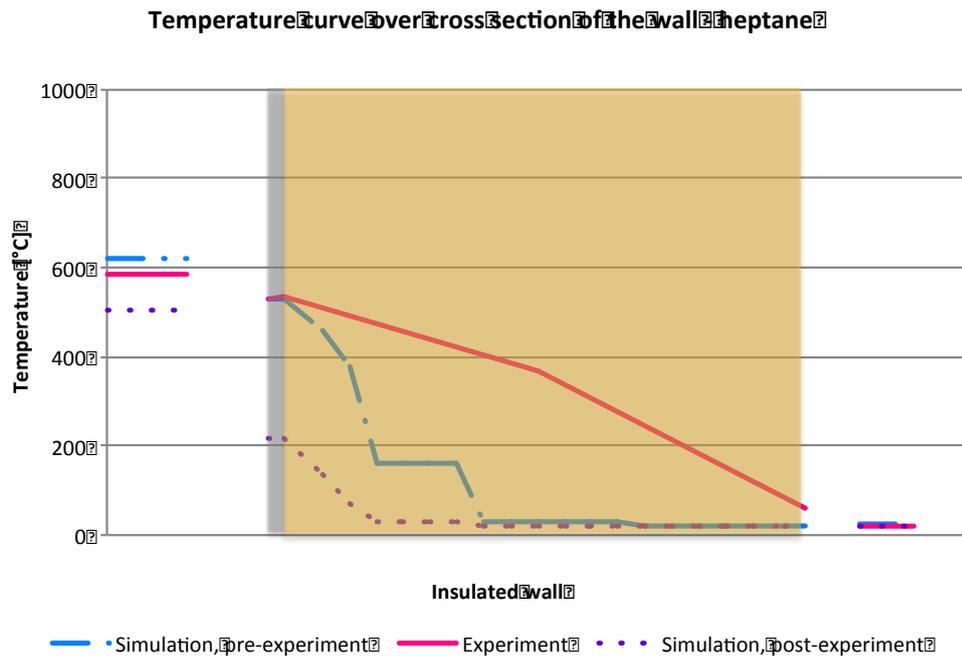


Figure 8.11: Temperature curve over the cross section of the insulated wall taken at 520 s in the heptane pool fire. Measuring point situated between the fire and the back wall at a height of 2.1 m. Displayed are results from simulations and experiment.

Note that none of the temperature curves correlate with the general opinion of how the temperature distribution in a wall is depicted, as described in section 2.6. This is discussed further in chapter 9.

8.6 Wall temperature – wood crib fire

The wall temperatures from the wood crib fire tests are displayed in figures 8.12 and 8.13 below. The wall temperatures displayed are the ones recorded in the experiments and also the temperatures registered in both the pre- and post-experiment simulations. The wall temperature was not calculated using hand calculations. The wall temperatures displayed in the graphs below were recorded on the outside of the steel-construction between the fire and the back wall.

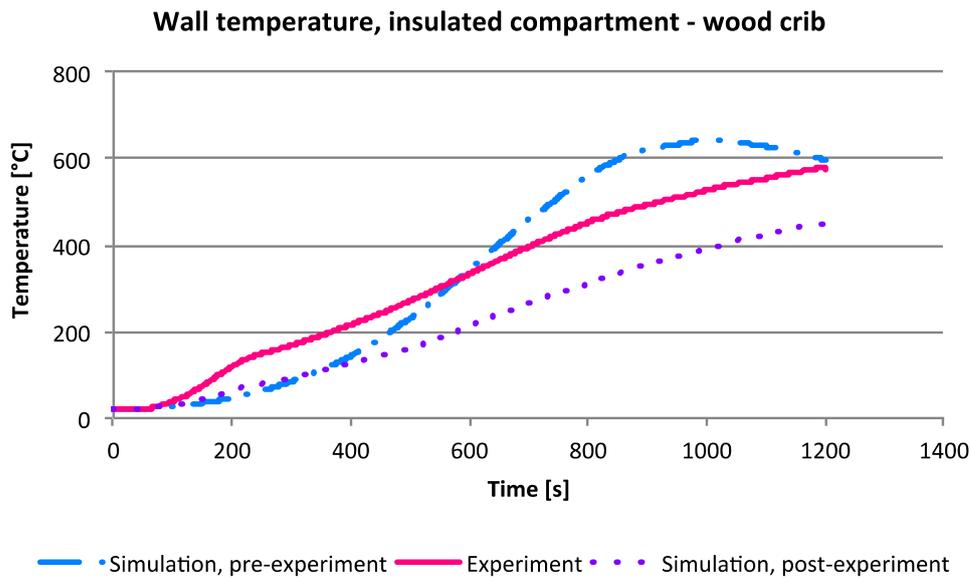


Figure 8.11: The wall temperature recorded for the wood crib fire in the insulated compartment. Results from simulations and experiment.

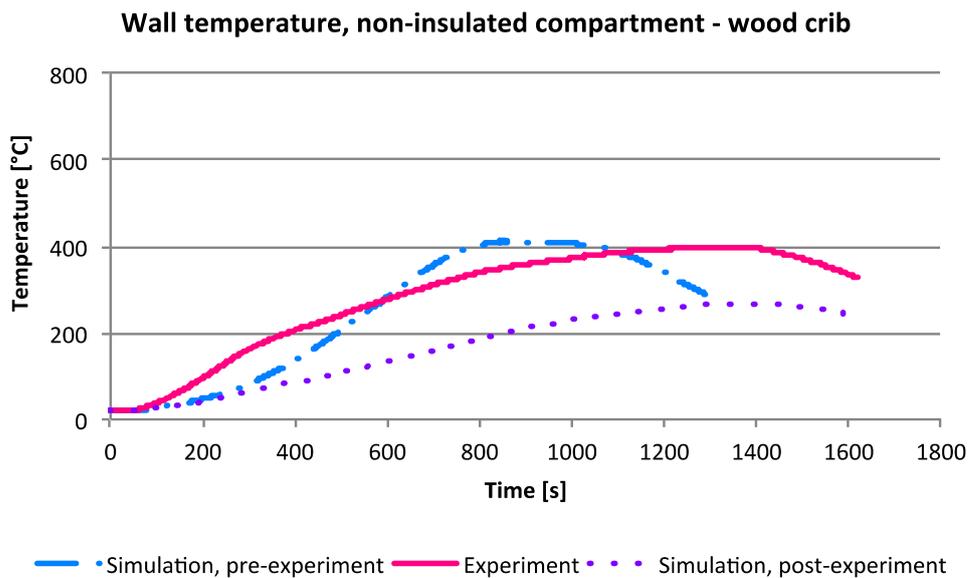


Figure 8.12: The wall temperature recorded for the wood crib fire in the non-insulated compartment. Results from simulations and experiment.

Figure 8.13 display the cross section of an insulated wall with the wall temperatures recorded in the simulations and the experiment after 520 s. The measuring devices were situated between the fire and the back wall at a height of 2.1 m. The temperature to the left in the graph is the gas temperature registered at the thermocouple tree in the compartment, between the fire and back wall at a height of 2.1 m. The temperature to the right is the ambient temperature surrounding the compartment.



Figure 8.13: Temperature curve over the cross section of the insulated wall taken at 1 180 s in the wood crib fire. Measuring point situated between the fire and the back wall at a height of 2.1 m. Displayed are results from simulations and experiment.

Note that none of the temperature curves correlate with the general opinion of how the temperature distribution in a wall is depicted, as described in section 2.6. This is discussed further in chapter 9.

9. DISCUSSION

In this chapter the findings from the project are discussed with regards to the result bias and sensitivity analysis. There is also a discussion about whether the objectives have been met. Finally, future areas of research are suggested.

9.1 Result bias

In all studies carried out, not just this one, there are lots of factors that could affect the end result. It is therefore of importance to discuss what uncertainties there are connected to each method.

9.1.1 Hand calculations

For any hand calculation carried out, the hardest part is to estimate the inputs.

The results from the MQH method differ a lot depending on the heat release rate used in the calculations. The heat release rate for the pre-experiment hand calculations for the wood crib was unknown, hence the large difference in the end result between the pre- and post-experiment hand calculations. The results from the hand calculations for the heptane pool fire on the other hand are more similar to each other probably because there is more knowledge how to estimate the heat release rate for a liquid pool fire than for an organic burning material.

Based on the results from the hand calculations, using the MQH method gives a higher gas temperature in the insulated compartment but a lower gas temperature in the non-insulated compartment compared to the experiments. The dimensions of the enclosure were kept the same in the hand calculations as in the experiments and are therefore the only other factor, apart from the heat release rate, that could have affected the results is the effective heat conduction coefficient, h_k .

An increase in $k\rho c$ or $h_r + h_c$ lead to an increase in heat transfer and therefore lower compartment temperatures. It is therefore likely that the $k\rho c$ -term must have been given a too low value and the $h_r + h_c$ a too high value.

In both the calculations for, insulated and non-insulated compartment, constant values were chosen for the $k\rho c$ and $h_r + h_c$ terms even though both the thermal properties of the insulation and the convection and radiation depend on the gas and wall temperatures. As no analysis of this has been performed it is uncertain how the results are affected.

The calculations according to the Magnusson and Thelandersson method do not correspond to the results from any other used method. This is in line with what was expected as it is a post-flashover method and this study focuses on the pre-flashover phase of the fire development. It does, however, still show that a change in boundary material to a more insulating one does increase the gas temperature in the compartment.

The EUROCODE method was not applicable to the boundary materials used in the study. To be able to compare it with the other methods, maximum and minimum values were used, within the range of applicability. The results do not correspond to the results from any other method used, apart from for the non-insulated wood crib fire where it is surprisingly similar to the result from the experiment. However, this is considered a coincidence. It does however confirm that a change in boundary material to a more insulating one does increase the gas temperature in the compartment.

9.1.2 Simulations

The input data defines what is going to be calculated in the simulations and are therefore of great importance.

If the size of the grid is too large there might not be enough data processed in the calculations, which could lead to lower temperatures. A large grid size could also lead to a quicker smoke spread as the information of each cell is transferred in the boundaries of the cells. However, according to the verification calculations carried out it is considered that the cell size used in the simulations is coarse enough to perform sufficiently detailed calculations.

Relatively few inputs have been used in the simulations that could affect the gas temperature of the compartment. It is the heat release rate and the thermal properties of the boundary materials. As for the heat release rate, this was the only input to be changed between the pre- and post-experiment simulations. Looking at the results, the change in heat release rate to a lower value made the gas temperature drop. Which is what would be expected to happen.

Suppose that FDS with the correct input data provides the correct results. In the post-experiment calculations, the heat release rate recorded in the experiments was used as an input, it could therefore not have been this input that made the gas temperatures reaching such a low level compared to the experiments. This indicates that the values for the thermal properties of the boundary materials were not correct.

Comparing the results from the simulations with the results from the experiments shows that the gas temperatures in the simulations are very low. The thermal properties for the boundary material must have been given a too high value as it seems like too much heat is transferred from the compartment through the boundaries. It is likely to believe it is through the boundaries the heat is lost and not through the door opening. The loss should in that case have been smaller in the post-experiment simulation compared to the pre-experiment simulation due to lower gas temperatures. It can be concluded that the simulations are sensitive to the thermal properties of boundary materials.

There is a larger difference between the gas and wall temperature in the experiment than in the simulations. This could indicate that gas temperature in FDS is more uniform through out the whole plane compared to the experiments

where the temperature could be more inhomogeneous throughout the compartment.

The difference in gas temperature in the pre-experiment simulations was approximately 200°C, between the insulated and non-insulated heptane pool fire experiments. For the wood crib fire the difference was only 100°C. The difference in temperature is probably a result of the large difference in heat release rate curves between the two cases. For the heptane pool fire the heat release rate reaches a high level quickly and therefore has more time to build up a higher temperature.

The temperature curves over the cross section of the walls have an ordinary shape and do not correlate with what would be theoretically expected. The temperature measurements in the wall should not be relied on.

It is hard to compare the results from the simulations to the results from the experiments since the results from the simulations only are given in pictures. It is however possible to conclude that the radiation levels in the simulations are in the same order of magnitude as the ones recorded in the experiments. Higher levels of radiation towards the floor are measured in the pre-experiment simulations than in the post-experiment simulations. This is possibly a result of the gas temperatures being higher in the pre-experiment simulations.

9.1.3 Experiments

The insulation was not changed between the heptane pool fire experiment and the wood crib fire experiment. High temperatures were reached in the heptane pool fire experiment and there were lots of smoke coming from the container surfaces and insulation. It was probably the binding material in the insulation that vaporised. The outside surface of the container even seemed to catch fire in some places, which was probably the insulation or old paint on the container burning. How this affected the insulating capacity in the wood crib experiment is unknown.

The wood sticks were not conditioned before the experiment and therefore it is not certain that the moisture content was the same in both experiments or even throughout the cribs in each experiment. Yet, all the wood sticks were kept in the testing hall for a couple of days before the experiment. Even though the experiments were not carried out on the same day it is reasonable to believe that the variety in moisture content was minor and did not have a large effect on the end result.

The differences in gas temperature and heat release rate were larger between the two heptane pool fire experiments than between the two wood crib fire experiments. This indicates that the heptane is more sensitive to incident radiation than the wood crib.

In the graphs with the temperature curve over the cross section of the wall there is a dip showing a lower temperature on the inside of the steel than on the outside (figure 7.22 and figure 7.24). This is not realistic. The thermocouple must have been damaged, which sometimes occurs in fire tests.

The temperature distribution over the cross section has more of a convex shape and not the concave shape that would be theoretically expected. This is probably a result of the conductivity increasing with rising temperatures.

It was earlier in the report stated that flashover in accordance with the criteria flames emerging from the opening was reached in the two experiments where the container was coated with insulation. The non-insulated heptane pool fire experiment was however stopped before the fuel was finished. If the experiment would have continued for longer, flashover might have been reached even in this experimental set-up.

9.1.4 General

Neither hand calculations nor simulations are able to reflect the incident radiation towards the fire source and therefore not the increase in heat release rate. As seen in graphs over the heat release rate, it does reach a higher level in the insulated compartment compared to the non-insulated compartment which likely occurs due to the incident radiation from the hot gas layer and the hot compartment surfaces. This is not possible to recreate in FDS simulations as the heat release rate is defined in the input file. The same applies to the hand calculations, where the heat release rate is one of the inputs needed to be able to calculate the gas temperature.

Both hand calculations and simulations are very sensitive to the chosen inputs. If there is a high uncertainty to the heat release rate and properties of the boundary materials, hand calculations using the MQH method give as good results as the FDS simulation, and is far less time consuming.

9.2 Future research

This study has identified a few areas for which future research will be beneficial for similar studies.

- In this research the same dimensions of the compartment has been used as well as the opening area. It would also be of interest to make research of how the compartment dimensions affect the temperature of the compartment and time to flashover.
- An evaluation could also be made on how much insulation is needed to change the conditions in a compartment. In the experiments carried out in this study insulation with a thickness of 0.095 m was used. How would the results have changed if a 0.005 m thick insulation had been used?

- In case of a fire in the insulation, toxic gases are produced. It could be of interest to evaluate the increase of risk of injury or death due to the increase of toxic gases as a result of increased thermal insulation.
- As discussed earlier the thermal properties for the materials used in this study were not within the range of applicability for the EUROCODE method. This is something that could be investigated further and an evaluation of the EUROCODE method could be useful.
- In this study the conservation of energy theory has been described. It could be of interest to develop a “Conservation of energy equation” that accounts for convection and radiation, which is now missing in the MQH-method.

10. CONCLUSIONS

This chapter summarises the findings from the project, based on its purposes and objectives.

The purpose of this project was to create an understanding for how increased thermal insulation can affect the fire development in a compartment. The objective was to compare the fire development in an insulated compartment to a non-insulated compartment. The possibility to carry out hand calculations and simulations were also to be evaluated. The following four questions were therefore answered:

Does increased thermal insulation lead to significantly higher gas temperature in the fire compartment?

In each of the experiments with different fire sources, wood crib and heptane pool, the gas temperature reached a higher level in the insulated compartment than in the non-insulated compartment. In the insulated heptane pool fire experiment the maximum average gas temperature was 26% higher than in the non-insulated experiment. For the wood crib fire experiment the maximum average gas temperature was 18% higher in the insulated compartment.

Even in the hand calculations and simulations higher gas temperatures were obtained in the insulated compartments. Therefore, increased thermal insulation does lead to significantly higher gas temperatures in the fire compartment.

Will increased thermal insulation lead to a significantly larger and quicker heat release rate of a fire?

This was only possible to investigate in the experiment as the heat release rate is used as an input in both hand calculations and simulations.

The results from the heptane pool fire experiments show that a larger heat release rate is reached in the insulated compartment compared to the non-insulated compartment. The maximum average heat release rate reached in the insulated compartment was 13% higher than in the non-insulated compartment. A higher fire growth rate is also experienced in the experiment with the heptane pool fire. The fire growth rate in the insulated compartment is approximately twice as large as the fire growth rate in the non-insulated compartment.

In the insulated wood crib fire experiment the maximum heat release rate was only 2.5% higher than in the non-insulated compartment and the fire growth rate did not change between the insulated and non-insulated experiment.

Larger and quicker heat release rates are reached in compartments with increased thermal insulation where the fire source is sensitive to incident radiation.

Is it plausible that the condition flashover is reached earlier in an insulated compartment than in a non-insulated compartment?

This question stands in connection with the question above. As the heat release rate increased faster in the insulated compartment with the heptane pool fire, flashover would also be reached earlier in this compartment compared to the non-insulated compartment.

In the experiment with the wood crib fire on the other hand, the heat release rate curve has the same shape for both the insulated and non-insulated compartment. It then comes down to if the heat release rate is high enough for flashover to be reached. In the experiments carried out, flashover was reached in the insulated compartment but not in the non-insulated compartment. Hence, the provided insulation resulted in an increased heat release rate, sufficient for flashover to occur. This implies that improved thermal insulation could make the difference of whether flashover occurs or not.

Do hand calculations and simulations give similar results to full scale experiments when comparing the fire behaviour in an insulated compartment to a non-insulated compartment?

Both hand calculations and simulations are very sensitive to the chosen inputs and the results did therefore not correspond to the ones from the experiments.

Calculations using the MQH method give as good results as the FDS simulation, and are far less time consuming, if there is a high uncertainty to the heat release rate and properties of the boundary materials.

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APPENDIX A. DATA FOR ENCLOSED FIRES

A fire could develop in many different ways, depending on e.g. what type of room the fire has started in and on the amount and sort of fuel in the room. Below are some data that has been collected on enclosed fires.

Fire load densities

Fire loads for compartments with different usage areas are listed in the *International Fire Engineering Guidelines* (ABCB 2005) and *Brandbelastning* (Boverket 2008). Different usage areas have been listed together with their fire load per square meter floor area in table A.1 below. The fire load ranges from 238 MJ/m² to 800 MJ/m², which in a 20 feet container would add up to a total fire load of 3 300 MJ to 11 100 MJ.

Table A.1: Fire loads for different types of compartments

Type of compartment	Fire load per m ² floor area	Fractile	Reference
Dwelling (sv. Bostad)	800 MJ	80 %	Boverket 2008
Office (sv. Kontor)	520 MJ	80 %	Boverket 2008
Hotel room (sv. Hotellrum)	400 MJ	80 %	Boverket 2008
Hotel bedroom	400 MJ	80 %	ABCB 2005
Office	570 MJ	80 %	ABCB 2005
Homes	413 MJ *	80 %	ABCB 2005
Navy Cabin (A)	238 MJ **	-	Arvidson, Axelsson & Hertzberg 2008
Mechanical workshop	275 MJ *	80 %	ABCB 2005
Machinery manufacturing	275 MJ *	80 %	ABCB 2005

* Calculated, average value x 1.375, as per guidance in the IFEG

** Calculated from the total fire load and the floor area of the cabin, value from experimental report

Heat release rates

The heat release rate in a room depends on the type and amount of furniture in the room and also on the coating of walls, ceiling and floor. The total heat release rate could either be determined from tests or by adding up the heat release rates for a number of pieces of furniture. In table A.2 and A.3 below, occupancies and a number of pieces of furniture have been listed together with their heat release rates.

Table A.2: Heat release rates for different occupancies

Occupancy	Heat Release Rate	Reference
Navy Cabin	1 650 kW	Särdqvist 1993
Office	1 500 – 2 000 kW	Särdqvist 1993
Engine room (ship)	- *	-

* No data has been found for this type of occupancy

Table A.3: Heat release rates for different pieces of furniture

Piece of furniture	Heat release rate	Reference
Sofa	1 000 – 3 000 kW	Särdqvist 1993
Easy Chair	1 000 – 2 000 kW	Särdqvist 1993
Three Panel Workstation	6 800 kW	NIST 2011
Office Storage	1 000 kW	Särdqvist 1993
Wardrobe	2 000 – 3 000 kW	Särdqvist 1993
Curtain	500 – 1 500 kW	Särdqvist 1993

Note, that a single piece of furniture could give a higher peak heat release rate than set ups of occupancies.

Recommendations in legislation

In the *General advice by Swedish National Board of Housing, Guidance in performance-based design of fire safety in buildings (2011)*, (sv. *Boverkets allmänna råd om analytisk dimensionering av byggnaders brandskydd*) there is a list of set values for fire growth rate, maximum heat release rate and heat of combustion for a number of occupancies. The values listed are as stated in table A.4.

Table A.4: Set values for analytical dimensioning of buildings' fire protection

Occupancy	Fire growth rate [kW/s]	Maximum heat Release Rate [kW]	Heat of combustion [MJ/kg]
Dwelling, Hotel and Healthcare facilities	0,047	5 000	20
Office and School	0,012	5 000	16
Assembly building	0.047	10 000	20

The recommendations give higher heat release rates than the ones displayed in the tables above. However, this could be because of the need for a safety margin when creating a design fire scenario.

Room of ignition

A fire in a room could be caused by a number of factors and it could start in a number of different rooms. In a building it is most common that the fire starts in the kitchen (forgotten stove) and in an industry because of technical faults (MSB 2011). On ships it is most common that the fire starts in the engine room (LeBlanc 1998). In buildings the fire load consist of furniture and organic materials and in an engine room on a ship of oil and liquid fuels.

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APPENDIX B. RISK ANALYSIS

Risikanalys för släckhallarna BR

Risikanalys för *"Fire development in insulated compartments: Effects from improved thermal insulation"*

Mötesdeltagare:

Michael Magnusson (Tekniskt ansvarig)

Franz Evegren (Projektledare)

Anna Back (Observatör och allt i allo)

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Sven-Gunnar Gustafsson (Tekniker)

Bakgrund

Försöken utförs för att undersöka hur ökad isolering av ett brandrum kan påverka brandförloppet. Fyra olika uppställningar kommer köras:

1. Isolerad container med träribbstapel som brandkälla
2. Isolerad container med heptanbrand
3. Container (utan isolering) med träribbstapel som brandkälla
4. Container (utan isolering) med heptanbrand

Det är även av intresse att köra fristående tester där träribbstapeln samt heptanbranden testas separat.

Det som ska undersökas är om temperaturen i brandrummet kommer bli högre i det isolerade än i det oisolerade fallet samt om tid till övertändning påverkas.

Testet kan avslutas 1 minut efter att övertändning inträffat.

Testförlopp

Bränsle fylls på i kärl (ett eller tre, beroende på försök) – Tarmo

0min - Start av mätutrustning – Sven-Gunnar

0min – Start av tidtagarur – Anna och Tarmo

1.5min - Start av videokamera – Anna

2min - Antändning av bränsle med hjälp av tändpinne – Tarmo

Tänk på att inte vänta för länge mellan upphällning av bränsle och antändning då bränslet förångas.

Observera och notera när:

- flammor når taket – Anna
- när övertändning nås – Anna
- när flammor börjar slå ut genom dörröppningen – Anna

En minut efter övertändning inträffat släcks branden med:

- Vatten utifrån, träribbstapel – Tarmo
- Skum med gåshuvud, heptan – Tarmo

När träribbstapeln syns utifrån görs sista släckningen genom att gå in och vattenbegjuta resterande glödränder.

Efter varje försök ställs en fläkt in i containern för att vädra ut brandgaserna.

Riskidentifiering

Nedan följer vid mötet identifierade risker i försökens olika moment och hur dessa hanteras.

Moment	Risk	Åtgärd
Förberedelse	Få metallpinnar (för att fästa upp isolering) i ögon	Använda skyddsglasögon
	Andningsobehag i samband med hantering av mineralull	Bära skyddskläder och andningsskydd
	Tunga lyft, flytt av container (någon kan hamna i vägen)	Var alltid minst två personer vid flytt får att ge god uppsikt
	Olycka vid användning av mobil plattform	Skall utföras av person med utbildning
Instrumentering	-	
Försök	Spill och läckage av heptan ut i rummet	Se till att ha funktionellt kärl utan hål och sprickor.
	Brandspridning/För hög effektutveckling	Gåsacke på heptankärlet, backup med skum utanför + vatten för omgivande ytor
	Obehöriga som tillträder platsen, t.ex. genom dörr mot konstruktionshallen	Spärra av dörr, t.ex. med frystejp eller kedja
	Värme från container blir för varm för närliggande väggar	Ha omgivningen i åtanke när containern placeras ut
Efter försök	Heta ytor där man kan bränna sig	Se till så att alla vet vilka ytor som kommer att bli varma
	Brandgaser	Använda fläkt för att få ut brandgaser ur rum. Användning av ansiktsmasker vid behov.
Resthantering	Inandning och obehag i samband med hantering av mineralull	Bära skyddskläder och andningsskydd
	Skada vid borttagning av metallpinnar och igensvetsning av hål	Använd skyddskläder och glasögon
Övrigt	Vattenavbrott	Ha pulversläckare som backup
		Bär alltid skyddskläder, hjälm och skor

Före provning

Övriga åtgärder och kommentarer angående riskhantering:

- Obligatorisk genomgång av försöken och riskhanteringen med all inblandad personal före start
- Definiera entydigt vem som bestämmer säkerhetsnivån under försöket, t.ex. vem som avbryter provningen om så behövs: Tarmo.
- Obligatorisk separat genomgång med kunder och besökare om hur provningen skall ske och vilka säkerhetsregler som gäller: inga kunder aktuella för tillfället.

APPENDIX C. FDS-FILES

Below are the full FDS-files that were used in the post-experiment simulations. The only change to the pre-experiment simulations was the heat release rate. The heat release rates for the pre-experiment simulations are presented separately.

The FDS-file for the insulated and non-insulated compartment is shown under the same headline. The extra text that was added for the insulated cases is highlighted in grey. If it has not been possible to highlight the changes, the changes are added within brackets marked in grey next to the original text.

Pre-experiment heat release rate - heptane

----Burner----

&REAC ID='HEPTANE',

C = 7,

H = 16,

SOOT_YIELD=0.015/

&SURF ID='BURNER',

HRRPUA=1875,

RAMP_Q='Heptane'

COLOR='RASPBERRY' /

&RAMP ID='Heptane', T=0.000, F=0.00000 /

&RAMP ID='Heptane', T=5.000, F=0.5 /

&RAMP ID='Heptane', T=10.00, F=1.0 /

&RAMP ID='Heptane', T=500.0, F=1.0 /

&RAMP ID='Heptane', T=1300.0, F=1.0 /

&OBST XB= 3.25, 4.05, 1.7, 2.5, 0.9, 1.4, SURF_IDS='BURNER','INERT','INERT' /

Pre-experiment heat release rate – wood crib

----Burner----

&REAC ID='WOOD',

FYI='Ritchie, et al., 5th IAFSS, C_3.4 H_6.2 O_2.5'

O = 2.5,

C = 3.4,

H = 6.2,

SOOT_YIELD=0.015/ Robbins A.P & Wade C.A (2008) Soot Yield Values for Modelling Purposes-
Residential Occupancies

&SURF ID='BURNER',

HRRPUA=2133.33333,

RAMP_Q='Wood cribs'

COLOR='RASPBERRY' /

&RAMP ID='Wood cribs', T=0.00, F=0.00000 /

&RAMP ID='Wood cribs', T=75.0, F=0.10938 /

&RAMP ID='Wood cribs', T=150., F=0.18750 /

&RAMP ID='Wood cribs', T=225., F=0.28125 /

&RAMP ID='Wood cribs', T=300., F=0.38750 /

&RAMP ID='Wood cribs', T=375., F=0.51250 /

&RAMP ID='Wood cribs', T=450., F=0.62500 /

&RAMP ID='Wood cribs', T=525., F=0.75000 /

&RAMP ID='Wood cribs', T=600., F=0.81250 /

&RAMP ID='Wood cribs', T=675., F=0.93750 /

&RAMP ID='Wood cribs', T=750., F=0.96875 /

&RAMP ID='Wood cribs', T=825., F=1.00000 /

&RAMP ID='Wood cribs', T=900., F=0.93750 /

&RAMP ID='Wood cribs', T=975., F=0.84375 /

&RAMP ID='Wood cribs', T=1050, F=0.75000 /

&RAMP ID='Wood cribs', T=1125, F=0.56250 /

&RAMP ID='Wood cribs', T=1200, F=0.37500 /

&RAMP ID='Wood cribs', T=1275, F=0.25000 /

&OBST XB= 3.55, 4.05, 1.35, 2.85, 0.9, 1.4, SURF_IDS='BURNER','INERT','INERT' /

FDS-file - heptane pool fire

Container06-03 – heptane pool fire with HRR from experiments

&HEAD CHID='Insulation-Heptane-exp', TITLE='Insulation-Heptane-exp' /

&MESH IJK = 24, 64, 64, XB= 0.70, 1.90, 0.45, 3.65, 0.8, 4.0, MPI_PROCESS=0 /

&MESH IJK = 24, 64, 64, XB= 1.90, 3.10, 0.45, 3.65, 0.8, 4.0, MPI_PROCESS=1 /

&MESH IJK = 24, 64, 64, XB= 3.10, 4.30, 0.45, 3.65, 0.8, 4.0, MPI_PROCESS=2 /

&MESH IJK = 24, 64, 64, XB= 4.30, 5.50, 0.45, 3.65, 0.8, 4.0, MPI_PROCESS=3 /

&MESH IJK = 24, 64, 64, XB= 5.50, 6.70, 0.45, 3.65, 0.8, 4.0, MPI_PROCESS=4 /

&MESH IJK = 24, 64, 64, XB= 6.70, 7.90, 0.45, 3.65, 0.8, 4.0, MPI_PROCESS=5 /

&TIME T_END = 1100.0 / (=750.0)

&DUMP DT_RESTART = 100.00/ saves the out file each 100s

&MISC SURF_DEFAULT = 'STEEL WALL', ('STEEL-INSULATION WALL')

BNDF_DEFAULT =.TRUE.

RADIATION=.TRUE.

TMPA=20 /

&MATL ID = 'STEEL'

CONDUCTIVITY = 45

SPECIFIC_HEAT = 0.460

DENSITY = 7820 /

&MATL ID = 'INSULATION'

CONDUCTIVITY_RAMP = 'K_RAMP'

SPECIFIC_HEAT = 0.800

DENSITY = 100 / Conductivity

(konduktivitet/värmeledningstal W/mK), Specific heat (värmekapacitet J/kgK). When using conductivity ramp, parameter T means Temperature and F is the given value (http://www.engineeringtoolbox.com/mineral-wool-insulation-k-values-d_815.html)

&RAMP ID = 'K_RAMP', T= 38.00, F=0.04 /

&RAMP ID = 'K_RAMP', T= 121.0, F=0.05 /

&RAMP ID = 'K_RAMP', T= 177.0, F=0.06 /

&RAMP ID = 'K_RAMP', T= 218.0, F=0.07 /

&RAMP ID = 'K_RAMP', T= 260.0, F=0.08 /

&RAMP ID = 'K_RAMP', T= 301.0, F=0.09 /

&RAMP ID = 'K_RAMP', T= 329.0, F=0.10 /

IV | APPENDIX C. FDS-FILES

```

&RAMP ID                                ='K_RAMP', T= 357.0, F=0.11 /
&RAMP ID                                ='K_RAMP', T= 385.0, F=0.12 /
&RAMP ID                                ='K_RAMP', T= 427.0, F=0.13 /
&RAMP ID                                ='K_RAMP', T= 441.0, F=0.14 /
&RAMP ID                                ='K_RAMP', T= 482.0, F=0.15 /
&RAMP ID                                ='K_RAMP', T= 510.0, F=0.16 /
&RAMP ID                                ='K_RAMP', T= 538.0, F=0.17 /
&RAMP ID                                ='K_RAMP', T= 552.0, F=0.18 /
&RAMP ID                                ='K_RAMP', T= 579.0, F=0.19 /
&RAMP ID                                ='K_RAMP', T= 607.0, F=0.20 /
&RAMP ID                                ='K_RAMP', T= 621.0, F=0.21 /
&RAMP ID                                ='K_RAMP', T= 649.0, F=0.22 /

```

```

&SURF ID                                ='STEEL-INSULATION WALL'
  BACKING                                ='EXPOSED',
  MATL_ID                                ='STEEL','INSULATION'
  THICKNESS                              =0.003,0.1
  COLOR                                  =SILVER/
&SURF ID                                ='INSULATION-STEEL WALL',
  BACKING                                ='EXPOSED',
  MATL_ID                                ='INSULATION','STEEL'
  THICKNESS                              =0.1,0.003
  COLOR                                  =GOLD/

```

```

&SURF ID                                ='STEEL WALL',
  BACKING                                ='EXPOSED',
  MATL_ID                                ='STEEL',
  THICKNESS                              =0.003
  COLOR                                  =GRAY/

```

----Burner----

```

&REAC ID='HEPTANE',
  C = 7,
  H = 16,

```

SOOT_YIELD=0.015/

&SURF ID='BURNER',

HRRPUA=1936.5,

RAMP_Q='Heptane'

COLOR='RASPBERRY'/

&RAMP ID='Heptane', T=0.000, F=0.0 / (&RAMP ID='Heptane', T=0.000, F=0.00 /)

&RAMP ID='Heptane', T=50.00, F=0.72 / (&RAMP ID='Heptane', T=25.00, F=0.01 /)

&RAMP ID='Heptane', T=100.0, F=0.76 / (&RAMP ID='Heptane', T=50.00, F=0.37 /)

&RAMP ID='Heptane', T=150.0, F=0.80 / (&RAMP ID='Heptane', T=100.0, F=0.60 /)

&RAMP ID='Heptane', T=200.0, F=0.78 / (&RAMP ID='Heptane', T=150.0, F=0.61 /)

&RAMP ID='Heptane', T=250.0, F=0.82 / (&RAMP ID='Heptane', T=200.0, F=0.68 /)

&RAMP ID='Heptane', T=300.0, F=0.90 / (&RAMP ID='Heptane', T=250.0, F=0.77 /)

&RAMP ID='Heptane', T=350.0, F=0.88 / (&RAMP ID='Heptane', T=300.0, F=0.83 /)

&RAMP ID='Heptane', T=400.0, F=0.91 / (&RAMP ID='Heptane', T=350.0, F=0.87 /)

&RAMP ID='Heptane', T=450.0, F=0.91 / (&RAMP ID='Heptane', T=400.0, F=0.90 /)

&RAMP ID='Heptane', T=500.0, F=0.98 / (&RAMP ID='Heptane', T=450.0, F=0.92 /)

&RAMP ID='Heptane', T=550.0, F=0.94 / (&RAMP ID='Heptane', T=500.0, F=0.90 /)

&RAMP ID='Heptane', T=600.0, F=0.93 / (&RAMP ID='Heptane', T=525.0, F=0.84 /)

&RAMP ID='Heptane', T=650.0, F=0.96 / (&RAMP ID='Heptane', T=550.0, F=1.00 /)

&RAMP ID='Heptane', T=700.0, F=0.94 / (&RAMP ID='Heptane', T=600.0, F=0.13 /)

&RAMP ID='Heptane', T=750.0, F=0.97 / (&RAMP ID='Heptane', T=650.0, F=0.03 /)

&RAMP ID='Heptane', T=800.0, F=0.95 / (&RAMP ID='Heptane', T=700.0, F=0.01 /)

&RAMP ID='Heptane', T=850.0, F=0.97 / (&RAMP ID='Heptane', T=750.0, F=0.00 /)

&RAMP ID='Heptane', T=900.0, F=1.00 /

&RAMP ID='Heptane', T=950.0, F=1.00 /

&RAMP ID='Heptane', T=1000., F=0.18 /

&RAMP ID='Heptane', T=1050., F=0.03 /

&RAMP ID='Heptane', T=1100., F=0.00 /

&OBST XB= 3.25, 4.05, 1.7, 2.5, 0.9, 1.4, SURF_IDS='BURNER','INERT','INERT' /

----Detectors----

&PROP ID='HD',

VI | APPENDIX C. FDS-FILES

```

QUANTITY='LINK TEMPERATURE',

ACTIVATION_TEMPERATURE=600.00/

&DEVC      ID='Heat detector1',          PROP_ID='HD',
           XYZ=1.6,2.75,3.25 / By the wall (top)

&DEVC      ID='Heat detector2',          PROP_ID='HD',
           XYZ=1.6,1.4,3.25 / By the wall

&DEVC      ID='Heat detector3',          PROP_ID='HD',
           XYZ=3.95,2.1,3.25 / Above fire

&DEVC      ID='Heat detector4',          PROP_ID='HD',
           XYZ=6.5,2.75,3.25 / By the door (top)

&DEVC      ID='Heat detector5',          PROP_ID='HD',
           XYZ=6.5,1.4,3.25 / By the door

----Container-----

&OBST XB   = 1.05, 7.05, 0.85, 3.30, 0.85, 0.90, SURF_ID='STEEL WALL' /      --- golv ---

&OBST XB   = 1.05, 7.05, 0.85, 3.30, 3.30, 3.35,

SURF_ID6=   'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
           'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
           'STEEL-INSULATION WALL','INSULATION-STEEL WALL' /      --- tak ---

&OBST XB   = 1.05, 7.05, 0.85, 0.90, 0.90, 3.30,

SURF_ID6=   'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
           'INSULATION-STEEL WALL','STEEL-INSULATION WALL',
           'INSULATION-STEEL WALL','INSULATION-STEEL WALL' /      --- vägg 1 ---

&OBST XB   = 1.05, 1.10, 0.90, 3.25, 0.90, 3.30,

SURF_ID6=   'INSULATION-STEEL WALL','STEEL-INSULATION WALL',
           'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
           'INSULATION-STEEL WALL','INSULATION-STEEL WALL' /      --- vägg 2 ---

&OBST XB   = 1.05, 7.05, 3.25, 3.30, 0.90, 3.30,

SURF_ID6=   'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
           'STEEL-INSULATION WALL','INSULATION-STEEL WALL',
           'INSULATION-STEEL WALL','INSULATION-STEEL WALL' /      --- vägg 3 ---

&OBST XB   = 7.00, 7.05, 2.55, 3.25, 0.90, 3.30,

SURF_ID6=   'STEEL-INSULATION WALL','INSULATION-STEEL WALL',
           'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
           'INSULATION-STEEL WALL','INSULATION-STEEL WALL' /      --- vägg 4 ---

&OBST XB   = 7.00, 7.05, 1.60, 2.55, 2.90, 3.30,

SURF_ID6=   'STEEL-INSULATION WALL','INSULATION-STEEL WALL',
           'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
           'INSULATION-STEEL WALL','INSULATION-STEEL WALL' /      --- vägg 5 ---
door opening

&OBST XB   = 7.00, 7.05, 0.90, 1.60, 0.90, 3.30,

```

SURF_ID6= 'STEEL-INSULATION WALL','INSULATION-STEEL WALL',
 'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
 'INSULATION-STEEL WALL','INSULATION-STEEL WALL' / --- vägg 6 ---

----Vents----

&VENT XB = 0.70,7.90, 0.45,3.65, 4.0,4.0, SURF_ID='OPEN' / --z1--

&VENT XB = 0.70,0.70, 0.45,3.65, 0.8,4.0, SURF_ID='OPEN' / --x1--

&VENT XB = 7.90,7.90, 0.45,3.65, 0.8,4.0, SURF_ID='OPEN' / --x2--

&VENT XB = 0.70,7.90, 0.45,0.45, 0.8,4.0, SURF_ID='OPEN' / --y1--

&VENT XB = 0.70,7.90, 3.65,3.65, 0.8,4.0, SURF_ID='OPEN' / --y2--

----Measuring devices----

----Thermocouple tree door----

&DEVC ID = 'Temp_door_1', QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 1.5/

&DEVC ID = 'Temp_door_2', QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 1.8/

&DEVC ID = 'Temp_door_3', QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 2.1/

&DEVC ID = 'Temp_door_4', QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 2.4/

&DEVC ID = 'Temp_door_5', QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 2.7/

----Thermocouple tree fire-back wall----

&DEVC ID = 'Temp_container_1.1', QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 1.5/

&DEVC ID = 'Temp_container_1.2', QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 1.8/

&DEVC ID = 'Temp_container_1.3', QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 2.1/

&DEVC ID = 'Temp_container_1.4', QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 2.4/

&DEVC ID = 'Temp_container_1.5', QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 2.7/

&DEVC ID = 'Temp_container_1.6', QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 3.0/

----Thermocouple tree door-fire----

&DEVC ID = 'Temp_container_2.1', QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 1.5/

&DEVC ID = 'Temp_container_2.2', QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 1.8/

&DEVC ID = 'Temp_container_2.3', QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 2.1/

&DEVC ID = 'Temp_container_2.4', QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 2.4/

&DEVC ID = 'Temp_container_2.5', QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 2.7/

&DEVC ID = 'Temp_container_2.6', QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 3.0/

----Thermocouple tree fire----

&DEVC ID = 'Temp_fire_1', QUANTITY='TEMPERATURE', XYZ= 3.65, 2.1, 1.5/

&DEVC ID = 'Temp_fire_2', QUANTITY='TEMPERATURE', XYZ= 3.65, 2.1, 1.8/

&DEVC ID = 'Temp_fire_3', QUANTITY='TEMPERATURE', XYZ= 3.65, 2.1, 2.1/

VIII | APPENDIX C. FDS-FILES

&DEVC ID = 'Temp_fire_4', QUANTITY='TEMPERATURE', XYZ= 3.65, 2.1, 2.4/

&DEVC ID = 'Temp_fire_5', QUANTITY='TEMPERATURE', XYZ= 3.65, 2.1, 2.7/

&DEVC ID = 'Temp_fire_6', QUANTITY='TEMPERATURE', XYZ= 3.65, 2.1, 3.0/

----Thermocouple tree outside----

&DEVC ID = 'Temp_out_1', QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 1.5/

&DEVC ID = 'Temp_out_2', QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 1.8/

&DEVC ID = 'Temp_out_3', QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 2.1/

&DEVC ID = 'Temp_out_4', QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 2.4/

&DEVC ID = 'Temp_out_5', QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 2.7/

&DEVC ID = 'Temp_out_6', QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 3.0/

----Wall and ceiling temperature (BOUNDARY FILES)----

&BNDF QUANTITY = 'WALL TEMPERATURE'

----Radiation----

&BNDF QUANTITY = 'RADIATIVE HEAT FLUX' /

&BNDF QUANTITY = 'CONVECTIVE HEAT FLUX' /

&BNDF QUANTITY = 'GAUGE HEAT FLUX' / use when to compare predicted heat flux with measured

---- Wall and ceiling temperatures (DEVICES)----

&DEVC ID = 'Temp_wall1.1.1.1', XYZ=3.65,0.9,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.000, IOR=2 / 35

&DEVC ID = 'Temp_wall1.1.1.2', XYZ=3.65,0.9,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.003, IOR=2 /

&DEVC ID = 'Temp_wall1.1.1.3', XYZ=3.65,0.9,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.048, IOR=2 /

&DEVC ID = 'Temp_wall1.1.1.4', XYZ=3.65,0.9,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.096, IOR=2 /

&DEVC ID = 'Temp_wall1.1.1.b', XYZ=3.65,0.9,3.0, QUANTITY='BACK WALL TEMPERATURE', IOR=2 / situated on wall 1 (2.1m)

&DEVC ID = 'Temp_wall1.1.2.1', XYZ=3.65,0.9,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.000, IOR=2 / 40

&DEVC ID = 'Temp_wall1.1.2.2', XYZ=3.65,0.9,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.003, IOR=2 /

&DEVC ID = 'Temp_wall1.1.2.3', XYZ=3.65,0.9,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.048, IOR=2 /

&DEVC ID = 'Temp_wall1.1.2.4', XYZ=3.65,0.9,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.096, IOR=2 /

&DEVC ID = 'Temp_wall1.1.2.b', XYZ=3.65,0.9,2.4, QUANTITY='BACK WALL TEMPERATURE', IOR=2 / situated on wall 1 (1.5m)

&DEVC ID = 'Temp_wall1.1.3.1', XYZ=3.65,0.9,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.000, IOR=2 / 45

&DEVC ID = 'Temp_wall1.1.3.2', XYZ=3.65,0.9,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.003, IOR=2 /

&DEVC ID = 'Temp_wall1.1.3.3', XYZ=3.65,0.9,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.048, IOR=2 /

&DEVC ID = 'Temp_wall1.1.3.4', XYZ=3.65,0.9,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.096, IOR=2 /

&DEVC ID = 'Temp_wall1.1.3.b', XYZ=3.65,0.9,1.8, QUANTITY='BACK WALL TEMPERATURE', IOR=2 / situated on wall 1 (0.9m)

&DEVC ID = 'Temp_wall3.1.1.1', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.000, IOR=-2 / 50

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.003, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.010, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.015, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.020, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.025, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.030, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.035, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.040, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.045, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.3', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.048, IOR=-2 / 60

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.055, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.060, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.065, IOR=-2 /

```
&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.070, IOR=-2 /
```

```
&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.075, IOR=-2 /
```

```
&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.080, IOR=-2 /
```

```
&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.085, IOR=-2 /
```

```
&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.090, IOR=-2 /
```

```
&DEVC ID = 'Temp_wall3.1.1.4', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.096, IOR=-2 /
```

```
&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.100, IOR=-2 / 70
```

```
&DEVC ID = 'Temp_wall3.1.1.b', XYZ=2.075,3.25,3.0, QUANTITY='BACK
WALL TEMPERATURE', IOR=-2 / situated on wall 3 (2.1m)
```

```
&DEVC ID = 'Temp_wall3.1.2.1', XYZ=2.075,3.25,2.4, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.000, IOR=-2 / 72
```

```
&DEVC ID = 'Temp_wall3.1.2.2', XYZ=2.075,3.25,2.4, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.003, IOR=-2 /
```

```
&DEVC ID = 'Temp_wall3.1.2.3', XYZ=2.075,3.25,2.4, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.048, IOR=-2 /
```

```
&DEVC ID = 'Temp_wall3.1.2.4', XYZ=2.075,3.25,2.4, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.096, IOR=-2 /
```

```
&DEVC ID = 'Temp_wall3.1.2.b', XYZ=2.075,3.25,2.4, QUANTITY='BACK
WALL TEMPERATURE', IOR=-2 / situated on wall 3 (1.5m)
```

```
&DEVC ID = 'Temp_wall3.1.3.1', XYZ=2.075,3.25,1.8, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.000, IOR=-2 / 77
```

```
&DEVC ID = 'Temp_wall3.1.3.2', XYZ=2.075,3.25,1.8, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.003, IOR=-2 /
```

```
&DEVC ID = 'Temp_wall3.1.3.3', XYZ=2.075,3.25,1.8, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.048, IOR=-2 /
```

```
&DEVC ID = 'Temp_wall3.1.3.4', XYZ=2.075,3.25,1.8, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.096, IOR=-2 /
```

```
&DEVC ID = 'Temp_wall3.1.3.b', XYZ=2.075,3.25,1.8, QUANTITY='BACK
WALL TEMPERATURE', IOR=-2 / situated on wall 3 (0.9m)
```

```
&DEVC ID = 'Temp_wall3.2.1.1', XYZ=5.55,3.25,3.0, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.001, IOR=-2 / 82
```

&DEVC ID = 'Temp_wall3.2.1.2', XYZ=5.55,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.003, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.1.3', XYZ=5.55,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.048, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.1.4', XYZ=5.55,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.096, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.1.b', XYZ=5.55,3.25,3.0, QUANTITY='BACK WALL TEMPERATURE', IOR=-2 / situated on wall 3 (2.1m)

&DEVC ID = 'Temp_wall3.2.2.1', XYZ=5.55,3.25,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.000, IOR=-2 / 87

&DEVC ID = 'Temp_wall3.2.2.2', XYZ=5.55,3.25,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.003, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.2.3', XYZ=5.55,3.25,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.048, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.2.4', XYZ=5.55,3.25,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.096, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.2.b', XYZ=5.55,3.25,2.4, QUANTITY='BACK WALL TEMPERATURE', IOR=-2 / situated on wall 3 (1.5m)

&DEVC ID = 'Temp_wall3.2.3.1', XYZ=5.55,3.25,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.000, IOR=-2 / 92

&DEVC ID = 'Temp_wall3.2.3.2', XYZ=5.55,3.25,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.003, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.3.3', XYZ=5.55,3.25,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.048, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.3.4', XYZ=5.55,3.25,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.096, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.3.b', XYZ=5.55,3.25,1.8, QUANTITY='BACK WALL TEMPERATURE', IOR=-2 / situated on wall 3 (0.9m)

&DEVC ID = 'Temp_c.1', XYZ=3.65,2.1,3.3, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.000, IOR=-3 / 97

&DEVC ID = 'Temp_c.2', XYZ=3.65,2.1,3.3, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.003, IOR=-3 /

&DEVC ID = 'Temp_c.3', XYZ=3.65,2.1,3.3, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.048, IOR=-3 /

&DEVC ID = 'Temp_c.4', XYZ=3.65,2.1,3.3, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.096, IOR=-3 /

&DEVC ID = 'Temp_c.b', XYZ=3.65,2.1,3.3, QUANTITY='BACK WALL TEMPERATURE', IOR=-3 /

----Slicefiles----

```
&SLCF PBX          = 2.10, QUANTITY = 'TEMPERATURE' /
&SLCF PBX          = 3.95, QUANTITY = 'TEMPERATURE' /
&SLCF PBZ          = 3.00, QUANTITY = 'TEMPERATURE' /
&SLCF PBZ          = 2.70, QUANTITY = 'TEMPERATURE' /
&SLCF PBZ          = 2.40, QUANTITY = 'TEMPERATURE' /
&SLCF PBY          = 1.25, QUANTITY = 'V-VELOCITY', VECTOR=.TRUE./
&SLCF PBY          = 2.05, QUANTITY = 'V-VELOCITY', VECTOR=.TRUE./
&SLCF PBY          = 2.90, QUANTITY = 'V-VELOCITY', VECTOR=.TRUE./
&TAIL /
```

FDS-file - wood crib fire

Container06-04 - wood crib fire with HRR from experiments

```
&HEAD CHID='Insulation-Woodcrib-exp', TITLE='Insulation-Woodcrib-exp' /
```

```
&MESH      IJK          = 24, 64, 64, XB= 0.70, 1.90, 0.45, 3.65, 0.8, 4.0, MPI_PROCESS=0 /
&MESH      IJK          = 24, 64, 64, XB= 1.90, 3.10, 0.45, 3.65, 0.8, 4.0, MPI_PROCESS=1 /
&MESH      IJK          = 24, 64, 64, XB= 3.10, 4.30, 0.45, 3.65, 0.8, 4.0, MPI_PROCESS=2 /
&MESH      IJK          = 24, 64, 64, XB= 4.30, 5.50, 0.45, 3.65, 0.8, 4.0, MPI_PROCESS=3 /
&MESH      IJK          = 24, 64, 64, XB= 5.50, 6.70, 0.45, 3.65, 0.8, 4.0, MPI_PROCESS=4 /
&MESH      IJK          = 24, 64, 64, XB= 6.70, 7.90, 0.45, 3.65, 0.8, 4.0, MPI_PROCESS=5 /
```

```
&TIME T_END          = 1615.0 / (1250.0)
```

```
&DUMP      DT_RESTART  = 100.00/ saves the out file each 100s
```

```
&MISC      SURF_DEFAULT = 'STEEL WALL', ('STEEL-INSULATION WALL')
```

```
BNDF_DEFAULT =.TRUE.
```

```
RADIATION    =.TRUE.
```

```
TMPA         =20 /
```

```
&MATL ID          = 'STEEL'
```

```
CONDUCTIVITY    = 45
```

```
SPECIFIC_HEAT   = 0.460
```

```
DENSITY         = 7820 /
```

&MATL ID = 'INSULATION'

CONDUCTIVITY_RAMP = 'K_RAMP'

SPECIFIC_HEAT = 0.800

DENSITY = 100 / Conductivity (konduktivitet/värmeläsningsstal W/mK), Specific heat (värmekapacitet J/kgK). When using conductivity ramp, parameter T means Temperature and F is the given value (http://www.engineeringtoolbox.com/mineral-wool-insulation-k-values-d_815.html)

&RAMP ID = 'K_RAMP', T= 38.00, F=0.04 /

&RAMP ID = 'K_RAMP', T= 121.0, F=0.05 /

&RAMP ID = 'K_RAMP', T= 177.0, F=0.06 /

&RAMP ID = 'K_RAMP', T= 218.0, F=0.07 /

&RAMP ID = 'K_RAMP', T= 260.0, F=0.08 /

&RAMP ID = 'K_RAMP', T= 301.0, F=0.09 /

&RAMP ID = 'K_RAMP', T= 329.0, F=0.10 /

&RAMP ID = 'K_RAMP', T= 357.0, F=0.11 /

&RAMP ID = 'K_RAMP', T= 385.0, F=0.12 /

&RAMP ID = 'K_RAMP', T= 427.0, F=0.13 /

&RAMP ID = 'K_RAMP', T= 441.0, F=0.14 /

&RAMP ID = 'K_RAMP', T= 482.0, F=0.15 /

&RAMP ID = 'K_RAMP', T= 510.0, F=0.16 /

&RAMP ID = 'K_RAMP', T= 538.0, F=0.17 /

&RAMP ID = 'K_RAMP', T= 552.0, F=0.18 /

&RAMP ID = 'K_RAMP', T= 579.0, F=0.19 /

&RAMP ID = 'K_RAMP', T= 607.0, F=0.20 /

&RAMP ID = 'K_RAMP', T= 621.0, F=0.21 /

&RAMP ID = 'K_RAMP', T= 649.0, F=0.22 /

&SURF ID = 'STEEL-INSULATION WALL',

BACKING = 'EXPOSED',

MATL_ID = 'STEEL','INSULATION'

THICKNESS = 0.003,0.1

COLOR = SILVER/

&SURF ID = 'INSULATION-STEEL WALL',

BACKING = 'EXPOSED',

```

MATL_ID = 'INSULATION', 'STEEL'
THICKNESS = 0.1, 0.003
COLOR = GOLD/

```

```

&SURF ID = 'STEEL WALL',
BACKING = 'EXPOSED',
MATL_ID = 'STEEL',
THICKNESS = 0.003
COLOR = GRAY/

```

----Burner----

```

&REAC ID='WOOD',
FYI='Ritchie, et al., 5th IAFSS, C_3.4 H_6.2 O_2.5'
O = 2.5,
C = 3.4,
H = 6.2,
SOOT_YIELD=0.015/

```

```

&SURF ID='BURNER',
HRRPUA=1173.2,
RAMP_Q='Wood cribs'
COLOR='RASPBERRY'/

```

```

&RAMP ID='Wood cribs', T=0.000, F=0.00 / (&RAMP ID='Wood cribs', T=0.000, F=0.00 /)
&RAMP ID='Wood cribs', T=75.00, F=0.19 / (&RAMP ID='Wood cribs', T=50.00, F=0.17 /)
&RAMP ID='Wood cribs', T=150.0, F=0.33 / (&RAMP ID='Wood cribs', T=100.0, F=0.40 /)
&RAMP ID='Wood cribs', T=225.0, F=0.46 / (&RAMP ID='Wood cribs', T=150.0, F=0.58 /)
&RAMP ID='Wood cribs', T=300.0, F=0.50 / (&RAMP ID='Wood cribs', T=200.0, F=0.58 /)
&RAMP ID='Wood cribs', T=375.0, F=0.47 / (&RAMP ID='Wood cribs', T=250.0, F=0.46 /)
&RAMP ID='Wood cribs', T=450.0, F=0.56 / (&RAMP ID='Wood cribs', T=300.0, F=0.52 /)
&RAMP ID='Wood cribs', T=525.0, F=0.65 / (&RAMP ID='Wood cribs', T=350.0, F=0.57 /)
&RAMP ID='Wood cribs', T=600.0, F=0.73 / (&RAMP ID='Wood cribs', T=400.0, F=0.56 /)
&RAMP ID='Wood cribs', T=675.0, F=0.79 / (&RAMP ID='Wood cribs', T=450.0, F=0.65 /)
&RAMP ID='Wood cribs', T=750.0, F=0.83 / (&RAMP ID='Wood cribs', T=500.0, F=0.71 /)
&RAMP ID='Wood cribs', T=825.0, F=0.91 / (&RAMP ID='Wood cribs', T=550.0, F=0.80 /)
&RAMP ID='Wood cribs', T=900.0, F=0.90 / (&RAMP ID='Wood cribs', T=600.0, F=0.87 /)

```

&RAMP ID='Wood cribs', T=975.0, F=0.93 / (&RAMP ID='Wood cribs', T=650.0, F=0.85 /)
 &RAMP ID='Wood cribs', T=1050., F=0.94 / (&RAMP ID='Wood cribs', T=700.0, F=0.86 /)
 &RAMP ID='Wood cribs', T=1125., F=0.96 / (&RAMP ID='Wood cribs', T=750.0, F=0.83 /)
 &RAMP ID='Wood cribs', T=1200., F=1.00 / (&RAMP ID='Wood cribs', T=800.0, F=0.90 /)
 &RAMP ID='Wood cribs', T=1275., F=0.97 / (&RAMP ID='Wood cribs', T=850.0, F=0.93 /)
 &RAMP ID='Wood cribs', T=1350., F=0.94 / (&RAMP ID='Wood cribs', T=900.0, F=0.89 /)
 &RAMP ID='Wood cribs', T=1425., F=0.88 / (&RAMP ID='Wood cribs', T=950.0, F=0.92 /)
 &RAMP ID='Wood cribs', T=1500., F=0.79 / (&RAMP ID='Wood cribs', T=1000., F=0.92 /)
 &RAMP ID='Wood cribs', T=1575., F=0.65 / (&RAMP ID='Wood cribs', T=1050., F=0.93 /)
 &RAMP ID='Wood cribs', T=1615., F=0.32 / (&RAMP ID='Wood cribs', T=1100., F=0.94 /)
 &RAMP ID='Wood cribs', T=1150., F=0.93 /
 &RAMP ID='Wood cribs', T=1175., F=1.00 /
 &RAMP ID='Wood cribs', T=1200., F=0.45 /
 &RAMP ID='Wood cribs', T=1250., F=0.23 /
 &OBST XB= 3.55, 4.05, 1.35, 2.85, 0.9, 1.4, SURF_IDS='BURNER','INERT','INERT' /

----Detectors----

&PROP ID='HD',
 QUANTITY='LINK TEMPERATURE',
 ACTIVATION_TEMPERATURE=600.00/
 &DEVC ID='Heat detector1',
 PROP_ID='HD',
 XYZ=1.6,2.75,3.25 / By the wall (top)
 &DEVC ID='Heat detector2',
 PROP_ID='HD',
 XYZ=1.6,1.4,3.25 / By the wall
 &DEVC ID='Heat detector3',
 PROP_ID='HD',
 XYZ=3.95,2.1,3.25 / Above fire
 &DEVC ID='Heat detector4',
 PROP_ID='HD',
 XYZ=6.5,2.75,3.25 / By the door (top)
 &DEVC ID='Heat detector5',
 PROP_ID='HD',

XYZ=6.5,1.4,3.25 / By the door

----Container----

&OBST XB = 1.05, 7.05, 0.85, 3.30, 0.85, 0.90, SURF_ID='STEEL WALL' / --- golv ---

&OBST XB = 1.05, 7.05, 0.85, 3.30, 3.30, 3.35,

SURF_ID6= 'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
'STEEL-INSULATION WALL','INSULATION-STEEL WALL' / --- tak ---

&OBST XB = 1.05, 7.05, 0.85, 0.90, 0.90, 3.30,

SURF_ID6= 'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
'INSULATION-STEEL WALL','STEEL-INSULATION WALL',
'INSULATION-STEEL WALL','INSULATION-STEEL WALL' / --- vägg 1 ---

&OBST XB = 1.05, 1.10, 0.90, 3.25, 0.90, 3.30,

SURF_ID6= 'INSULATION-STEEL WALL','STEEL-INSULATION WALL',
'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
'INSULATION-STEEL WALL','INSULATION-STEEL WALL' / --- vägg 2 ---

&OBST XB = 1.05, 7.05, 3.25, 3.30, 0.90, 3.30,

SURF_ID6= 'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
'STEEL-INSULATION WALL','INSULATION-STEEL WALL',
'INSULATION-STEEL WALL','INSULATION-STEEL WALL' / --- vägg 3 ---

&OBST XB = 7.00, 7.05, 2.55, 3.25, 0.90, 3.30,

SURF_ID6= 'STEEL-INSULATION WALL','INSULATION-STEEL WALL',
'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
'INSULATION-STEEL WALL','INSULATION-STEEL WALL' / --- vägg 4 ---

&OBST XB = 7.00, 7.05, 1.60, 2.55, 2.90, 3.30,

SURF_ID6= 'STEEL-INSULATION WALL','INSULATION-STEEL WALL',
'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
'INSULATION-STEEL WALL','INSULATION-STEEL WALL' / --- vägg 5 ---

door opening

&OBST XB = 7.00, 7.05, 0.90, 1.60, 0.90, 3.30,

SURF_ID6= 'STEEL-INSULATION WALL','INSULATION-STEEL WALL',
'INSULATION-STEEL WALL','INSULATION-STEEL WALL',
'INSULATION-STEEL WALL','INSULATION-STEEL WALL' / --- vägg 6 ---

----Vents----

&VENT XB = 0.70,7.90, 0.45,3.65, 4.0,4.0, SURF_ID='OPEN' / --z1--

&VENT XB = 0.70,0.70, 0.45,3.65, 0.8,4.0, SURF_ID='OPEN' / --x1--

&VENT XB = 7.90,7.90, 0.45,3.65, 0.8,4.0, SURF_ID='OPEN' / --x2--

&VENT XB = 0.70,7.90, 0.45,0.45, 0.8,4.0, SURF_ID='OPEN' / --y1--

&VENT XB = 0.70,7.90, 3.65,3.65, 0.8,4.0, SURF_ID='OPEN' / --y2--

----Measuring devices----

thermocouple tree door

&DEVC ID = 'Temp_door_1' , QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 1.5/
 &DEVC ID = 'Temp_door_2' , QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 1.8/
 &DEVC ID = 'Temp_door_3' , QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 2.1/
 &DEVC ID = 'Temp_door_4' , QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 2.4/
 &DEVC ID = 'Temp_door_5' , QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 2.7/

thermocouple tree fire-back wall

&DEVC ID = 'Temp_container_1.1' , QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 1.5/
 &DEVC ID = 'Temp_container_1.2' , QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 1.8/
 &DEVC ID = 'Temp_container_1.3' , QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 2.1/
 &DEVC ID = 'Temp_container_1.4' , QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 2.4/
 &DEVC ID = 'Temp_container_1.5' , QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 2.7/
 &DEVC ID = 'Temp_container_1.6' , QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 3.0/

thermocouple tree door-fire

&DEVC ID = 'Temp_container_2.1' , QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 1.5/
 &DEVC ID = 'Temp_container_2.2' , QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 1.8/
 &DEVC ID = 'Temp_container_2.3' , QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 2.1/
 &DEVC ID = 'Temp_container_2.4' , QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 2.4/
 &DEVC ID = 'Temp_container_2.5' , QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 2.7/
 &DEVC ID = 'Temp_container_2.6' , QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 3.0/

thermocouple tree fire

&DEVC ID = 'Temp_fire_1' , QUANTITY='TEMPERATURE', XYZ= 3.8, 2.1, 1.5/
 &DEVC ID = 'Temp_fire_2' , QUANTITY='TEMPERATURE', XYZ= 3.8, 2.1, 1.8/
 &DEVC ID = 'Temp_fire_3' , QUANTITY='TEMPERATURE', XYZ= 3.8, 2.1, 2.1/
 &DEVC ID = 'Temp_fire_4' , QUANTITY='TEMPERATURE', XYZ= 3.8, 2.1, 2.4/
 &DEVC ID = 'Temp_fire_5' , QUANTITY='TEMPERATURE', XYZ= 3.8, 2.1, 2.7/
 &DEVC ID = 'Temp_fire_6' , QUANTITY='TEMPERATURE', XYZ= 3.8, 2.1, 3.0/

thermocouple tree outside

&DEVC ID = 'Temp_out_1' , QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 1.5/
 &DEVC ID = 'Temp_out_2' , QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 1.8/
 &DEVC ID = 'Temp_out_3' , QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 2.1/
 &DEVC ID = 'Temp_out_4' , QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 2.4/
 &DEVC ID = 'Temp_out_5' , QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 2.7/
 &DEVC ID = 'Temp_out_6' , QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 3.0/

----Wall and ceiling temperature (BOUNDARY FILES)----

&BNDF QUANTITY ='WALL TEMPERATURE' /

----Radiation----

&BNDF QUANTITY ='RADIATIVE HEAT FLUX' /

&BNDF QUANTITY ='CONVECTIVE HEAT FLUX' /

&BNDF QUANTITY ='GAUGE HEAT FLUX' / use when to compare predicted heat flux with measured

---- Wall and ceiling temperatures (DEVICES)----

&DEVC ID ='Temp_wall1.1.1.1', XYZ=3.65,0.9,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.000, IOR=2 / 35

&DEVC ID ='Temp_wall1.1.1.2', XYZ=3.65,0.9,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.003, IOR=2 /

&DEVC ID ='Temp_wall1.1.1.3', XYZ=3.65,0.9,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.048, IOR=2 /

&DEVC ID ='Temp_wall1.1.1.4', XYZ=3.65,0.9,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.096, IOR=2 /

&DEVC ID ='Temp_wall1.1.1.b', XYZ=3.65,0.9,3.0, QUANTITY='BACK WALL TEMPERATURE', IOR=2 / situated on wall 1 (2.1m)

&DEVC ID ='Temp_wall1.1.2.1', XYZ=3.65,0.9,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.000, IOR=2 / 40

&DEVC ID ='Temp_wall1.1.2.2', XYZ=3.65,0.9,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.003, IOR=2 /

&DEVC ID ='Temp_wall1.1.2.3', XYZ=3.65,0.9,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.048, IOR=2 /

&DEVC ID ='Temp_wall1.1.2.4', XYZ=3.65,0.9,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.096, IOR=2 /

&DEVC ID ='Temp_wall1.1.2.b', XYZ=3.65,0.9,2.4, QUANTITY='BACK WALL TEMPERATURE', IOR=2 / situated on wall 1 (1.5m)

&DEVC ID ='Temp_wall1.1.3.1', XYZ=3.65,0.9,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.000, IOR=2 / 45

&DEVC ID ='Temp_wall1.1.3.2', XYZ=3.65,0.9,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.003, IOR=2 /

&DEVC ID ='Temp_wall1.1.3.3', XYZ=3.65,0.9,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.048, IOR=2 /

&DEVC ID ='Temp_wall1.1.3.4', XYZ=3.65,0.9,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.096, IOR=2 /

&DEVC ID ='Temp_wall1.1.3.b', XYZ=3.65,0.9,1.8, QUANTITY='BACK WALL TEMPERATURE', IOR=2 / situated on wall 1 (0.9m)

&DEVC ID = 'Temp_wall3.1.1.1', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.000, IOR=-2 / 50

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.003, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.010, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.015, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.020, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.025, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.030, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.035, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.040, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.045, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.3', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.048, IOR=-2 / 60

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.055, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.060, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.065, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.070, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.075, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.080, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.085, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.090, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.4', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.096, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.2', XYZ=2.075,3.25,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.100, IOR=-2 / 70

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&DEVC      ID          ='Temp_wall3.1.1.b',  XYZ=2.075,3.25,3.0,  QUANTITY='BACK
WALL TEMPERATURE', IOR=-2 / situated on wall 3 (2.1m)

&DEVC      ID          ='Temp_wall3.1.2.1',  XYZ=2.075,3.25,2.4,  QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.000, IOR=-2 / 72

&DEVC      ID          ='Temp_wall3.1.2.2',  XYZ=2.075,3.25,2.4,  QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.003, IOR=-2 /

&DEVC      ID          ='Temp_wall3.1.2.3',  XYZ=2.075,3.25,2.4,  QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.048, IOR=-2 /

&DEVC      ID          ='Temp_wall3.1.2.4',  XYZ=2.075,3.25,2.4,  QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.096, IOR=-2 /

&DEVC      ID          ='Temp_wall3.1.2.b',   XYZ=2.075,3.25,2.4,  QUANTITY='BACK
WALL TEMPERATURE', IOR=-2 / situated on wall 3 (1.5m)

&DEVC      ID          ='Temp_wall3.1.3.1',  XYZ=2.075,3.25,1.8,  QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.000, IOR=-2 / 77

&DEVC      ID          ='Temp_wall3.1.3.2',  XYZ=2.075,3.25,1.8,  QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.003, IOR=-2 /

&DEVC      ID          ='Temp_wall3.1.3.3',  XYZ=2.075,3.25,1.8,  QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.048, IOR=-2 /

&DEVC      ID          ='Temp_wall3.1.3.4',  XYZ=2.075,3.25,1.8,  QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.096, IOR=-2 /

&DEVC      ID          ='Temp_wall3.1.3.b',   XYZ=2.075,3.25,1.8,  QUANTITY='BACK
WALL TEMPERATURE', IOR=-2 / situated on wall 3 (0.9m)

&DEVC      ID          ='Temp_wall3.2.1.1',  XYZ=5.55,3.25,3.0,   QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.001, IOR=-2 / 82

&DEVC      ID          ='Temp_wall3.2.1.2',  XYZ=5.55,3.25,3.0,   QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.003, IOR=-2 /

&DEVC      ID          ='Temp_wall3.2.1.3',  XYZ=5.55,3.25,3.0,   QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.048, IOR=-2 /

&DEVC      ID          ='Temp_wall3.2.1.4',  XYZ=5.55,3.25,3.0,   QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.096, IOR=-2 /

&DEVC      ID          ='Temp_wall3.2.1.b',  XYZ=5.55,3.25,3.0,   QUANTITY='BACK WALL
TEMPERATURE', IOR=-2 / situated on wall 3 (2.1m)

&DEVC      ID          ='Temp_wall3.2.2.1',  XYZ=5.55,3.25,2.4,   QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.000, IOR=-2 / 87

&DEVC      ID          ='Temp_wall3.2.2.2',  XYZ=5.55,3.25,2.4,   QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.003, IOR=-2 /

&DEVC      ID          ='Temp_wall3.2.2.3',  XYZ=5.55,3.25,2.4,   QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.048, IOR=-2 /

```

```
&DEVC      ID      = 'Temp_wall3.2.2.4', XYZ=5.55,3.25,2.4, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.096, IOR=-2 /
```

```
&DEVC      ID      = 'Temp_wall3.2.2.b', XYZ=5.55,3.25,2.4, QUANTITY='BACK WALL
TEMPERATURE', IOR=-2 / situated on wall 3 (1.5m)
```

```
&DEVC      ID      = 'Temp_wall3.2.3.1', XYZ=5.55,3.25,1.8, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.000, IOR=-2 / 92
```

```
&DEVC      ID      = 'Temp_wall3.2.3.2', XYZ=5.55,3.25,1.8, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.003, IOR=-2 /
```

```
&DEVC      ID      = 'Temp_wall3.2.3.3', XYZ=5.55,3.25,1.8, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.048, IOR=-2 /
```

```
&DEVC      ID      = 'Temp_wall3.2.3.4', XYZ=5.55,3.25,1.8, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.096, IOR=-2 /
```

```
&DEVC      ID      = 'Temp_wall3.2.3.b', XYZ=5.55,3.25,1.8, QUANTITY='BACK WALL
TEMPERATURE', IOR=-2 / situated on wall 3 (0.9m)
```

```
&DEVC      ID      = 'Temp_c.1', XYZ=3.65,2.1,3.3, QUANTITY='INSIDE WALL
TEMPERATURE', DEPTH=0.000, IOR=-3 / 97
```

```
&DEVC      ID      = 'Temp_c.2', XYZ=3.65,2.1,3.3, QUANTITY='INSIDE WALL
TEMPERATURE', DEPTH=0.003, IOR=-3 /
```

```
&DEVC      ID      = 'Temp_c.3', XYZ=3.65,2.1,3.3, QUANTITY='INSIDE WALL
TEMPERATURE', DEPTH=0.048, IOR=-3 /
```

```
&DEVC      ID      = 'Temp_c.4', XYZ=3.65,2.1,3.3, QUANTITY='INSIDE WALL
TEMPERATURE', DEPTH=0.096, IOR=-3 /
```

```
&DEVC      ID      = 'Temp_c.b', XYZ=3.65,2.1,3.3, QUANTITY='BACK WALL
TEMPERATURE', IOR=-3 /
```

```
----Slicefiles----
```

```
&SLCF PBX      = 2.10, QUANTITY = 'TEMPERATURE' /
```

```
&SLCF PBX      = 3.95, QUANTITY = 'TEMPERATURE' /
```

```
&SLCF PBZ      = 3.00, QUANTITY = 'TEMPERATURE' /
```

```
&SLCF PBZ      = 2.70, QUANTITY = 'TEMPERATURE' /
```

```
&SLCF PBZ      = 2.40, QUANTITY = 'TEMPERATURE' /
```

```
&SLCF PBX      = 1.25, QUANTITY = 'V-VELOCITY', VECTOR=.TRUE. /
```

```
&SLCF PBX      = 2.05, QUANTITY = 'V-VELOCITY', VECTOR=.TRUE. /
```

```
&SLCF PBX      = 2.90, QUANTITY = 'V-VELOCITY', VECTOR=.TRUE. /
```

```
&TAIL /
```


FDS-file, large room - wood crib fire

Container06-05 – wood crib fire with HRR from experiments, Large room with cone

```

&HEAD CHID='Steel-Woodcrib-largerroom-exp', TITLE='Steel-Woodcrib-largerroom-exp'

&MESH      IJK          = 50, 32, 36, XB= 0.70, 5.70, 0.40, 3.60, 0.8, 4.4, MPI_PROCESS=0 /
&MESH      IJK          = 50, 32, 36, XB= 5.70, 10.7, 0.40, 3.60, 0.8, 4.4, MPI_PROCESS=1 /
&MESH      IJK          = 50, 32, 18, XB= 0.70, 10.7, 3.60, 10.0, 0.8, 4.4, MPI_PROCESS=2 /
&MESH      IJK          = 50, 32, 18, XB= 0.70, 10.7, -6.0, 0.40, 0.8, 4.4, MPI_PROCESS=3 /
&MESH      IJK          = 20, 80, 18, XB= -3.3, 0.70, -6.0, 10.0, 0.8, 4.4, MPI_PROCESS=4 /

&TIME T_END          = 1615.0 /

&DUMP      DT_RESTART          = 100.00/ saves the out file each 100s

&MISC      SURF_DEFAULT ='STEEL WALL'

              BDNF_DEFAULT =.TRUE.

              RADIATION   =.TRUE.

              TMPA        =20.0 /

&MATL ID          = 'STEEL'

CONDUCTIVITY      = 45

SPECIFIC_HEAT     = 0.460

DENSITY           = 7820 /

&SURF ID          ='STEEL WALL',

      BACKING      ='EXPOSED',

      MATL_ID      ='STEEL',

      THICKNESS    =0.003/

----Burner----

&REAC ID='WOOD',

      FYI='Ritchie, et al., 5th IAFSS, C_3.4 H_6.2 O_2.5'

      O = 2.5,

      C = 3.4,

      H = 6.2,

      SOOT_YIELD=0.015/

```

&SURF ID='BURNER',

HRRPUA=1035.4,

RAMP_Q='Wood cribs'

COLOR='RASPBERRY'/

&RAMP ID='Wood cribs', T=0.000, F=0.00 /

&RAMP ID='Wood cribs', T=75.00, F=0.19 /

&RAMP ID='Wood cribs', T=150.0, F=0.33 /

&RAMP ID='Wood cribs', T=225.0, F=0.46 /

&RAMP ID='Wood cribs', T=300.0, F=0.50 /

&RAMP ID='Wood cribs', T=375.0, F=0.47 /

&RAMP ID='Wood cribs', T=450.0, F=0.56 /

&RAMP ID='Wood cribs', T=525.0, F=0.65 /

&RAMP ID='Wood cribs', T=600.0, F=0.73 /

&RAMP ID='Wood cribs', T=675.0, F=0.79 /

&RAMP ID='Wood cribs', T=750.0, F=0.83 /

&RAMP ID='Wood cribs', T=825.0, F=0.91 /

&RAMP ID='Wood cribs', T=900.0, F=0.90 /

&RAMP ID='Wood cribs', T=975.0, F=0.93 /

&RAMP ID='Wood cribs', T=1050., F=0.94 /

&RAMP ID='Wood cribs', T=1125., F=0.96 /

&RAMP ID='Wood cribs', T=1200., F=1.00 /

&RAMP ID='Wood cribs', T=1275., F=0.97 /

&RAMP ID='Wood cribs', T=1350., F=0.94 /

&RAMP ID='Wood cribs', T=1425., F=0.88 /

&RAMP ID='Wood cribs', T=1500., F=0.79 /

&RAMP ID='Wood cribs', T=1575., F=0.65 /

&RAMP ID='Wood cribs', T=1615., F=0.32 /

&OBST XB= 3.55, 4.05, 1.35, 2.85, 0.9, 1.4, SURF_IDS='BURNER','INERT','INERT' /

----Detectors----

&PROP ID='HD',

QUANTITY='LINK TEMPERATURE',
ACTIVATION_TEMPERATURE=600.00/

&DEVC ID='Heat detector1',
PROP_ID='HD',
XYZ=1.6,2.75,3.25 / By the wall (top)

&DEVC ID='Heat detector2',
PROP_ID='HD',
XYZ=1.6,1.4,3.25 / By the wall

&DEVC ID='Heat detector3',
PROP_ID='HD',
XYZ=3.95,2.1,3.25 / Above fire

&DEVC ID='Heat detector4',
PROP_ID='HD',
XYZ=6.5,2.75,3.25 / By the door (top)

&DEVC ID='Heat detector5',
PROP_ID='HD',
XYZ=6.5,1.4,3.25 / By the door

---Container----

&OBST XB	= 1.00, 7.10, 0.80, 3.30, 0.80, 0.90, /	--- golv ---
&OBST XB	= 1.00, 7.10, 0.80, 3.30, 3.30, 3.40, /	--- tak ---
&OBST XB	= 1.00, 7.10, 0.80, 0.90, 0.90, 3.30, /	--- vägg 1 ---
&OBST XB	= 1.00, 1.10, 0.90, 3.20, 0.90, 3.30, /	--- vägg 2 ---
&OBST XB	= 1.00, 7.10, 3.20, 3.30, 0.90, 3.30, /	--- vägg 3 ---
&OBST XB	= 7.00, 7.10, 2.60, 3.30, 0.90, 3.30, /	--- vägg 4 ---
&OBST XB	= 7.00, 7.10, 1.60, 2.60, 2.90, 3.30, /	--- vägg 5 --- door opening
&OBST XB	= 7.00, 7.10, 0.90, 1.60, 0.90, 3.30, /	--- vägg 6 ---
&OBST XB	= 8.10, 9.00, 1.40, 2.40, 3.70, 4.40, COLOR='GRAY'/	--- hood ---
&OBST XB	= 7.10, 10.0, 0.50, 3.50, 3.40, 3.70, COLOR='GRAY'/	--- hood ---

----Vents----

```
&VENT XB = -3.3,10.7, -6.0,10.0, 4.4,4.4, SURF_ID='OPEN' / --z1--
&VENT XB = -3.3,-3.3, -6.0,10.0, 0.8,4.4, SURF_ID='OPEN' / --y1--
&VENT XB = 10.7,10.7, -6.0,10.0, 0.8,4.4, SURF_ID='OPEN' / --y2--
&VENT XB = -3.3,10.7, -6.0,-6.0, 0.8,4.4, SURF_ID='OPEN' / --x1--
&VENT XB = -3.3,10.7, 10.0,10.0, 0.8,4.4, SURF_ID='OPEN' / --x2--
```

----Hood----

```
&SURF ID = 'EXHAUST', VOLUME_FLUX=3.0, COLOR='BLUE' /
&VENT XB = 7.10, 10.0, 0.50, 3.50, 3.40, 3.40, SURF_ID='EXHAUST' /
```

----Measuring devices----

thermocouple tree door

```
&DEVC ID = 'Temp_door_1', QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 1.5/
&DEVC ID = 'Temp_door_2', QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 1.8/
&DEVC ID = 'Temp_door_3', QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 2.1/
&DEVC ID = 'Temp_door_4', QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 2.4/
&DEVC ID = 'Temp_door_5', QUANTITY='TEMPERATURE', XYZ= 7.0, 2.1, 2.7/
```

thermocouple tree fire-back wall

```
&DEVC ID = 'Temp_container_1.1', QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 1.5/
&DEVC ID = 'Temp_container_1.2', QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 1.8/
&DEVC ID = 'Temp_container_1.3', QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 2.1/
&DEVC ID = 'Temp_container_1.4', QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 2.4/
&DEVC ID = 'Temp_container_1.5', QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 2.7/
&DEVC ID = 'Temp_container_1.6', QUANTITY='TEMPERATURE', XYZ= 2.075, 2.1, 3.0/
```

thermocouple tree door-fire

```
&DEVC ID = 'Temp_container_2.1', QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 1.5/
&DEVC ID = 'Temp_container_2.2', QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 1.8/
&DEVC ID = 'Temp_container_2.3', QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 2.1/
&DEVC ID = 'Temp_container_2.4', QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 2.4/
&DEVC ID = 'Temp_container_2.5', QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 2.7/
&DEVC ID = 'Temp_container_2.6', QUANTITY='TEMPERATURE', XYZ= 5.5, 2.1, 3.0/
```

thermocouple tree fire

```
&DEVC ID = 'Temp_fire_1', QUANTITY='TEMPERATURE', XYZ= 3.65, 2.1, 1.5/
&DEVC ID = 'Temp_fire_2', QUANTITY='TEMPERATURE', XYZ= 3.65, 2.1, 1.8/
```

```

&DEVC ID      ='Temp_fire_3', QUANTITY='TEMPERATURE', XYZ= 3.65, 2.1, 2.1/
&DEVC ID      ='Temp_fire_4', QUANTITY='TEMPERATURE', XYZ= 3.65, 2.1, 2.4/
&DEVC ID      ='Temp_fire_5', QUANTITY='TEMPERATURE', XYZ= 3.65, 2.1, 2.7/
&DEVC ID      ='Temp_fire_6', QUANTITY='TEMPERATURE', XYZ= 3.65, 2.1, 3.0/

thermocouple tree outside

&DEVC ID      ='Temp_out_1', QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 1.5/
&DEVC ID      ='Temp_out_2', QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 1.8/
&DEVC ID      ='Temp_out_3', QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 2.1/
&DEVC ID      ='Temp_out_4', QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 2.4/
&DEVC ID      ='Temp_out_5', QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 2.7/
&DEVC ID      ='Temp_out_6', QUANTITY='TEMPERATURE', XYZ= 0.85, 2.05, 3.0/

----Wall and ceiling temperature (BOUNDARY FILES)----

&BNDF          QUANTITY                          ='WALL TEMPERATURE' /

----Radiation----

&BNDF          QUANTITY                          ='RADIATIVE HEAT FLUX' /
&BNDF          QUANTITY                          ='CONVECTIVE HEAT FLUX' /
&BNDF          QUANTITY                          ='GAUGE HEAT FLUX' / use
when to compare predicted heat flux with measured

---- Wall and ceiling temperatures (DEVICES)----

&DEVC          ID                                ='Temp_wall1.1.1.1', XYZ=3.60,0.9,3.0, QUANTITY='INSIDE WALL
TEMPERATURE', DEPTH=0.0000, IOR=2 / 35

&DEVC          ID                                ='Temp_wall1.1.1.1', XYZ=3.60,0.9,3.0, QUANTITY='INSIDE WALL
TEMPERATURE', DEPTH=0.0015, IOR=2 /

&DEVC          ID                                ='Temp_wall1.1.1.b', XYZ=3.60,0.9,3.0, QUANTITY='BACK WALL
TEMPERATURE', IOR=2 / situated on wall 1 (2.1m)

&DEVC          ID                                ='Temp_wall1.1.2.1', XYZ=3.60,0.9,2.4, QUANTITY='INSIDE WALL
TEMPERATURE', DEPTH=0.0000, IOR=2 /

&DEVC          ID                                ='Temp_wall1.1.2.1', XYZ=3.60,0.9,2.4, QUANTITY='INSIDE WALL
TEMPERATURE', DEPTH=0.0015, IOR=2 /

&DEVC          ID                                ='Temp_wall1.1.2.b', XYZ=3.60,0.9,2.4, QUANTITY='BACK WALL TEMPERATURE',
IOR=2 / situated on wall 1 (1.5m)

&DEVC          ID                                ='Temp_wall1.1.3.1', XYZ=3.60,0.9,1.8, QUANTITY='INSIDE WALL
TEMPERATURE', DEPTH=0.0000, IOR=2 /

```

&DEVC ID = 'Temp_wall1.1.3.1', XYZ=3.60,0.9,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.0015, IOR=2 /

&DEVC ID = 'Temp_wall1.1.3.b', XYZ=3.60,0.9,1.8, QUANTITY='BACK WALL TEMPERATURE', IOR=2 / situated on wall 1 (0.9m)

&DEVC ID = 'Temp_wall3.1.1.1', XYZ=2.1,3.20,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.0000, IOR=-2 / 44

&DEVC ID = 'Temp_wall3.1.1.1', XYZ=2.1,3.20,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.0015, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.1.b', XYZ=2.1,3.20,3.0, QUANTITY='BACK WALL TEMPERATURE', IOR=-2 / situated on wall 3 (2.1m)

&DEVC ID = 'Temp_wall3.1.2.1', XYZ=2.1,3.20,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.0000, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.2.1', XYZ=2.1,3.20,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.0015, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.2.b', XYZ=2.1,3.20,2.4, QUANTITY='BACK WALL TEMPERATURE', IOR=-2 / situated on wall 3 (1.5m)

&DEVC ID = 'Temp_wall3.1.3.1', XYZ=2.1,3.20,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.0000, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.3.1', XYZ=2.1,3.20,1.8, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.0015, IOR=-2 /

&DEVC ID = 'Temp_wall3.1.3.b', XYZ=2.1,3.20,1.8, QUANTITY='BACK WALL TEMPERATURE', IOR=-2 / situated on wall 3 (0.9m)

&DEVC ID = 'Temp_wall3.2.1.1', XYZ=5.55,3.20,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.0000, IOR=-2 / 53

&DEVC ID = 'Temp_wall3.2.1.1', XYZ=5.55,3.20,3.0, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.0015, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.1.b', XYZ=5.55,3.20,3.0, QUANTITY='BACK WALL TEMPERATURE', IOR=-2 / situated on wall 3 (2.1m)

&DEVC ID = 'Temp_wall3.2.2.1', XYZ=5.55,3.20,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.0000, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.2.1', XYZ=5.55,3.20,2.4, QUANTITY='INSIDE WALL TEMPERATURE', DEPTH=0.0015, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.2.b', XYZ=5.55,3.20,2.4, QUANTITY='BACK WALL TEMPERATURE', IOR=-2 / situated on wall 3 (1.5m)

&DEVC ID = 'Temp_wall3.2.3.1', XYZ=5.55,3.20,1.8, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.0000, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.3.1', XYZ=5.55,3.20,1.8, QUANTITY='INSIDE
WALL TEMPERATURE', DEPTH=0.0015, IOR=-2 /

&DEVC ID = 'Temp_wall3.2.3.b', XYZ=5.55,3.20,1.8, QUANTITY='BACK WALL
TEMPERATURE', IOR=-2 / situated on wall 3 (0.9m)

&DEVC ID = 'Temp_c.1', XYZ=3.8,2.1,3.3, QUANTITY='INSIDE WALL
TEMPERATURE', DEPTH=0.0000, IOR=-3 / 62

&DEVC ID = 'Temp_c.1', XYZ=3.8,2.1,3.3, QUANTITY='INSIDE WALL
TEMPERATURE', DEPTH=0.0015, IOR=-3 /

&DEVC ID = 'Temp_c.b', XYZ=3.8,2.1,3.3, QUANTITY='BACK WALL
TEMPERATURE', IOR=-3 /

----Slicefiles----

&SLCF PBX = 2.10, QUANTITY = 'TEMPERATURE' /

&SLCF PBX = 3.95, QUANTITY = 'TEMPERATURE' /

&SLCF PBZ = 3.00, QUANTITY = 'TEMPERATURE' /

&SLCF PBZ = 2.70, QUANTITY = 'TEMPERATURE' /

&SLCF PBZ = 2.40, QUANTITY = 'TEMPERATURE' /

&SLCF PBX = 1.25, QUANTITY = 'V-VELOCITY', VECTOR=.TRUE./

&SLCF PBX = 2.05, QUANTITY = 'V-VELOCITY', VECTOR=.TRUE./

&SLCF PBX = 2.90, QUANTITY = 'V-VELOCITY', VECTOR=.TRUE./

&TAIL /