Simple temperature calculation models for compartment fires

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Preface

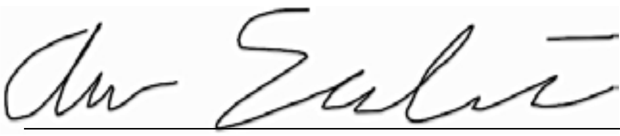
This thesis is about a new calculation model for different kinds of fire scenarios that has been developed in our final work to receive a Bachelor of Science in Fire Protection Engineering at Luleå University of Technology (LTU). The work corresponds to 15 ETCS (European Credit Transfer System).

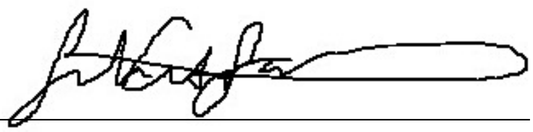
The project has helped us to receive a better understanding about fire behaviour for different fire scenarios. It has also given us a better insight in what uncertainties and problems there are in the calculation methods that are used in the industry today. In addition, the work has been very interesting.

We would like to give many thanks to our supervisor during this work, Professor Ulf Wickström, who has helped us through many different problems and issues when developing the new calculation model. We would also like to thank Anders Löfqvist who helped us programming our Excel-application and who always was there when questions were asked.

Thanks also to everyone else who were there for us and helped us through this final degree project.

Luleå, Sweden, september 2012





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Abstract

Models to calculate the fire temperature for compartments are of great importance when designing fire protection in buildings, both to save lives and to save money. There are a range of models that are good at estimating the fire temperatures for compartments with surrounding structures made of concrete, brick, wood and other similar building materials. However, there are very few simple models for compartments with thermally thin surrounding structures, with- or without insulation.

The purpose with this report is to show that it is possible to calculate the fire temperature within different types surrounding structures with simple models. The purpose is also to present the results in a pedagogical way.

This report presents simple models for semi-infinite surrounding structures and thermally thin surrounding structures with- or without insulation. These models have been derived in similar ways and indicate which parameters that affect the fire temperature development. A numerical solution for thermally thin surrounding structures has also been developed. These solutions are presented in an Excel spreadsheet that allows the user to change parameters input.

The new model for semi-infinite surrounding structures results in a similar fire temperature curve as the parametric fire curve according to EUROCODE 1 and the ISO-834 curve. The new model for thermally thin surrounding structures with- or without insulation results in fire temperatures that match experimentally measured fire temperatures.

Even though the new model gave good results, there are still a few things that need to be improved. More research on the different parameters used in the model, especially the combustion efficiency, is needed to set the right values for each parameter. The model should be compared with more varying experiments to conclude its limits and to validate the model.

Keywords: *Analytical solution, Numerical solution, Thermally thin, Semi-infinite, Fire temperature*

Sammanfattning

Modeller för att beräkna brandtemperaturen i olika utrymmen är viktiga när man designar brandskyddet i byggnader, både för att rädda liv och för att spara pengar. Det finns en stor mängd modeller som är bra på att bestämma brandtemperaturen i utrymmen med omgivande material av betong, tegel, trä och andra byggmaterial. Det finns dock väldigt få enkla beräkningsmodeller för utrymmen med tunna omgivande strukturer, så som tunt stål, med- eller utan isolering.

Syftet med den här rapporten är att visa att det är möjligt att beräkna brandtemperaturen inom olika typer av omgivande strukturer, med enkla modeller. Syftet är även att presentera resultatet på ett pedagogiskt sätt.

Den här rapporten presenterar enkla modeller för halvoändliga väggar samt tunna väggar med- eller utan isolering. Dessa modeller har härletts på liknande sätt och indikerar vilka parametrar som påverkar brandutvecklingen. En numerisk lösning för termiskt tunna strukturer har också utvecklats. Dessa lösningar är presenterade i ett Excelblad som tillåter användaren att ändra parametrarnas värden.

Den nya modellen för halvoändliga strukturer resulterar i en liknande brandtemperaturkurva som den parametriska brandkurvan enligt EUROCODE 1 samt ISO-834 kurvan. Den nya modellen för termiskt tunna strukturer med- eller utan isolering resulterar i brandtemperaturer som överensstämmer med experimentellt uppmätta brandtemperaturer.

Även om den nya modellen gav bra resultat, är det fortfarande några saker som måste utvecklas. De olika parametrarna i modellen behöver en närmre undersökning, särskilt förbränningseffektiviteten, för att ha möjlighet att ange rätt värden för respektive parameter. Modellen bör även jämföras med fler differentierande experiment för att kunna bestämma dess begränsningar samt kunna validera modellen.

Sökord: *Analytisk lösning, Numerisk lösning, Termiskt tunn, Halvoändlig, Brandtemperatur*

Nomenclature

List of symbols

A_0	opening area [m^2]
A_{tot}	total compartment boundary area, including the openings [m^2]
c	specific heat capacity [J/kgK]
c_p	specific heat capacity at constant pressure [J/kgK]
d	thickness [m]
h	heat transfer coefficient [W/m^2K]
h_c	convection heat transfer coefficient [W/m^2K]
h_r	radiation heat transfer coefficient [W/m^2K]
H_0	opening height [m]
H_c	compartment height [m]
k	thermal conductivity [W/mK]
L_c	compartment length [m]
$\dot{m}_a$	mass flow of air [kg/s]
$\dot{m}_o$	mass flow of air out from compartment [kg/s]
$\dot{m}_i$	mass flow of air in to the compartment [kg/s]
Θ	temperature difference $(T - T_i)$ [˚C]
O	opening factor for the compartment [$m^{1/2}$]
t	time [s]
t_d	critical time for treating a solids as semi-infinite [s]

R thermal resistance [m^{2}K/W]

T_{core} core temperature [˚C]

T_f fire temperature [˚C]

T_g gas temperature [˚C]

T_i initial temperature [˚C]

V_c compartment volume [m^3]

W_c compartment width [m]

q heat [J]

$\dot{q}$ heat flow rate [W]

$\dot{q}_b$ rate of heat being stored as gas [W]

$\dot{q}_c$ rate of heat released by combustion [W]

$\dot{q}_l$ rate of heat loss by convection through openings [W]

$\dot{q}_r$ rate of heat loss by radiation through openings [W]

$\dot{q}_w$ rate of heat loss conducted through the walls, ceiling and floor [W]

$\dot{q}''$ heat flux per unit area [W/m^2]

α_1 flow factor [kg/m$^{5/2}$s]

α_2 combustion yield [J/kg]

ε emissivity [-]

σ Stefan Boltzman´s constant [W/m^{2}K^4]

ρ density [kg/m^3]

τ time constant [s]

Superscripts

$\dot{}$	rate
$''$	per area unit
$'''$	per volume unit

Subscripts

i	fire exposed side
o	non-fire exposed side
$core$	core material in wall
f	fire
ins	insulation
max	maximal
s	surface
st	steel
tot	total
ult	ultimate

Table of Contents

1 Introduction

1.1 Background

How the fire temperature is changing with time and what effect different boundary conditions in a room have on the fire growth are of great importance when designing fire protection in buildings. It is difficult to find accurate results because of the complexity of fire development and the varying effects from different parameters.

Different methods to estimate the fire temperature have been developed, focusing on different fire-scenarios. The simplest models used are the two-zone model (pre-flashover) and the one-zone model (post-flashover). The main difference between these models is that the one-zone model has most influence on the construction and the two-zone model has most impact on lifesaving. (Harmath och Mehaffey 1983)

Most of the methods for calculating the fire temperature are relatively simple and more often used as a guideline for how the fire will develop. There are many assumptions and approximations made in order to derive simple methods, and these assumptions can sometimes be doubtful or might limit the methods validity to only a few fire scenarios. It can lead to bad interpretations about the fire development if the methods are used beyond their limitations.

The calculations can either be performed by computer programs or by hand. Even in simple methods, there is often much information and various parameters involved, which make the computer a helpful instrument. However, it takes long time for most computer programs to get results and knowledge about the programs is necessary. Computer applications, which are user-friendly, time-efficient and give trustworthy results, are consequently requested when analysing fire scenarios.

"United States Nuclear regulatory commission" has used the so-called MQH- method, based on the two-zone model, to make an excel-application that calculates the gas temperature. The Excel sheet provides opportunities to change materials, compartment boundaries, ambient conditions, the energy release rate and the thermal properties of the compartment enclosure surfaces. (Iqba, Salley and Weerakkody 2004)

1.2 Purpose and Objective

1.2.1 Purpose

The purpose of this work is to find relatively simple and trustworthy methods to calculate the fire temperature for different compartment properties and gain understanding for which parameters that have most influence on the fire development.

1.2.2 Objective

The objective of this work is to derive a new calculation method, applicable on post-flashover fire scenarios. A simple, user-friendly excel-application based on the new model should be created to make it easier for the user to receive quick results about a certain fire scenario.

Questions to be answered:

- What are the main uncertainties in the calculation methods used today?
- Is there a need for a new calculation method?
- What parameters are of significant importance in a fire scenario?

1.3 Limitations

When constructing the new calculation methods, a few limitations were introduced.

- The calculations on the fire temperature are based on the one-zone model and all of the assumptions are thereby made with that in mind.
- The new model is only verified in this study and will not be validated in the report.
- The new model will only be compared with the most frequently applied methods that are used for calculation of temperatures in fire scenarios.

1.4 Self-evaluation

This work has been performed in order to obtain a Bachelor of Science in Fire Protection Engineering at Luleå University of Technology (LTU) in accordance to the main requirements from the faculty.

The thesis is a beginning of a greater work to obtain a better approximation for a certain kind of fire temperature calculation and has been performed by us with guidance from our supervisor. All questions and problems were thereby formulated by us and discussed with the supervisor. The work has been planned and performed during 10 weeks of the summer of 2012, which corresponds to 15 ECTS and also shows our capability of structuring and performing a work within a given time.

Old calculation methods have been analyzed to identify weaknesses and strengths so as to formulate a new, improved calculation method. In this way we have shown capability of critically and systematically using knowledge and analyzing it in order to make the fire protection calculations better. This is also shown in the report where the result is critically questioned.

We have shown ability of presenting the thesis to a crowd when presenting it in both verbal- and written form. Working together and dividing work efforts evenly shows our capability of working as a group.

The report shows that we have used knowledge from the courses throughout the education but also that we had to take in new knowledge to achieve our objectives. The report is about a wide part of the fire-engineering field as well as for a more specific part.

The report also contains suggestions for further research and investigations in order to improve the model.

2 Method

The report has emanated from the work made by Ulf Wickström (Wickström, DRAFT - Heat transfer in fire technology 2012) and the close dialogue between the authors of this report and Ulf Wickström, as well as his DRAFT, has contributed to the main theories that has been used. Further references to Ulf Wickström and his DRAFT in this report will be limited.

A literature study has thereafter been made on the subject to give a deeper understanding in what problems and highlights there are in different calculation methods. The most occurring methods were the ones in focus in the study since they were considered to be the most accepted methods.

When it was clear what kind of issues that needed to be solved, the forming of the new model began. Ideas and speculations of how the model ought to be performed were discussed continuously with Wickström.

An Excel application was thereafter created with assistance of the embedded program VBA (Visual Basic for Applications) in Excel. The equations that were derived in the new model were used in the application with the purpose to create a user-friendly calculation program.

The results from the new model were finally compared with old calculation methods and executed experiments to be able to determine whether the new model was better or worse than the old methods.

3 Theories

To be able to understand the theories behind fire development calculations, it is necessary to know how a fire behaves in an enclosure. A description of how a fire develops in an enclosure is therefore defined below, followed by general assumptions made in a room fire and at last different calculation methods on fire-scenario used today are explained.

3.1 Enclosure fire development

A fire in an enclosure follows a significant pattern where the fire can be divided into different stages; ignition, growth, flashover, fully developed fire and decay. (Walton and Thomas 1995) Figure 1 shows a time-temperature curve for a typical enclosure fire.

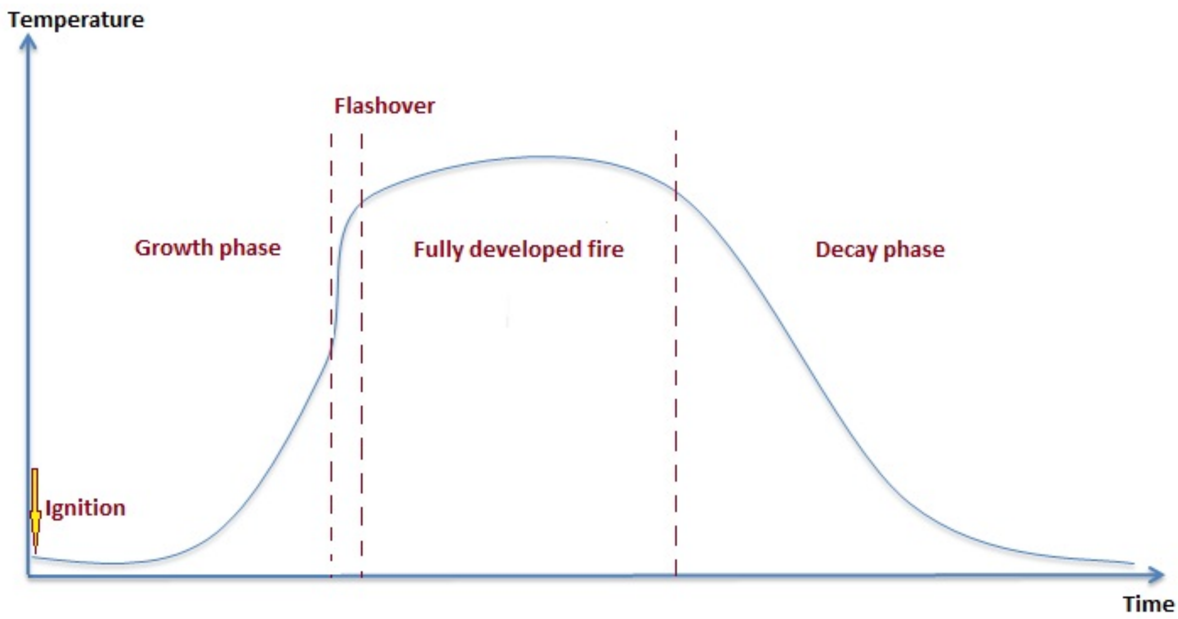

Figure 1 Schematic illustration of fire development.

The ignition stage is where the fire is initiated. The following step, the growth phase, is when the fire begins to grow and it is not significantly affected by how the compartment looks like. If the fire is fuel-controlled, i.e. have restricted access of fuel, it is most likely to stop growing at this stage, and the same if it is ventilation-controlled, i.e. have limited access of oxygen. However, if the fire has access to oxygen and fuel it will grow and flashover will occur. (Walton and Thomas 1995)

Flashover is the stage where all the combustible materials in the enclosure ignite. Flashovers appear between 500°C and 600°C, which is the ignition temperature for various building materials and furniture. After the flashover, the fire is fully developed. This is the stage where the fire has reached its peak and when it can be assumed ventilation-controlled. The heat release rate is peaking at this point, and the fire combust more material than it has access to oxygen, the combustion is therefore incomplete. (Walton and Thomas 1995)

When the fire has incinerated the fuel in the compartment it will reach the decay phase. This phase is where the fire is fuel-controlled, and it will therefore decrease during this stage (Walton and Thomas 1995).

3.2 The energy balance

In an enclosure fire, there will be an energy balance, which can be divided in very detailed processes, with some relatively small and large processes. The typical energy balance explains that all energy that is released from the combustion $\dot{q}_c$ will either transfer through the walls $\dot{q}_w$, leave the compartment as hot gases $\dot{q}_l$, radiate through the openings $\dot{q}_r$ or be stored as hot gas in the compartment $\dot{q}_b$, see equation (1), see e.g. (Karlsson and Quintiere 2000). An illustration of the energy balance is shown in Figure 2.

$$\dot{q}_c = \dot{q}_w + \dot{q}_l + \dot{q}_r + \dot{q}_b \quad (1)$$

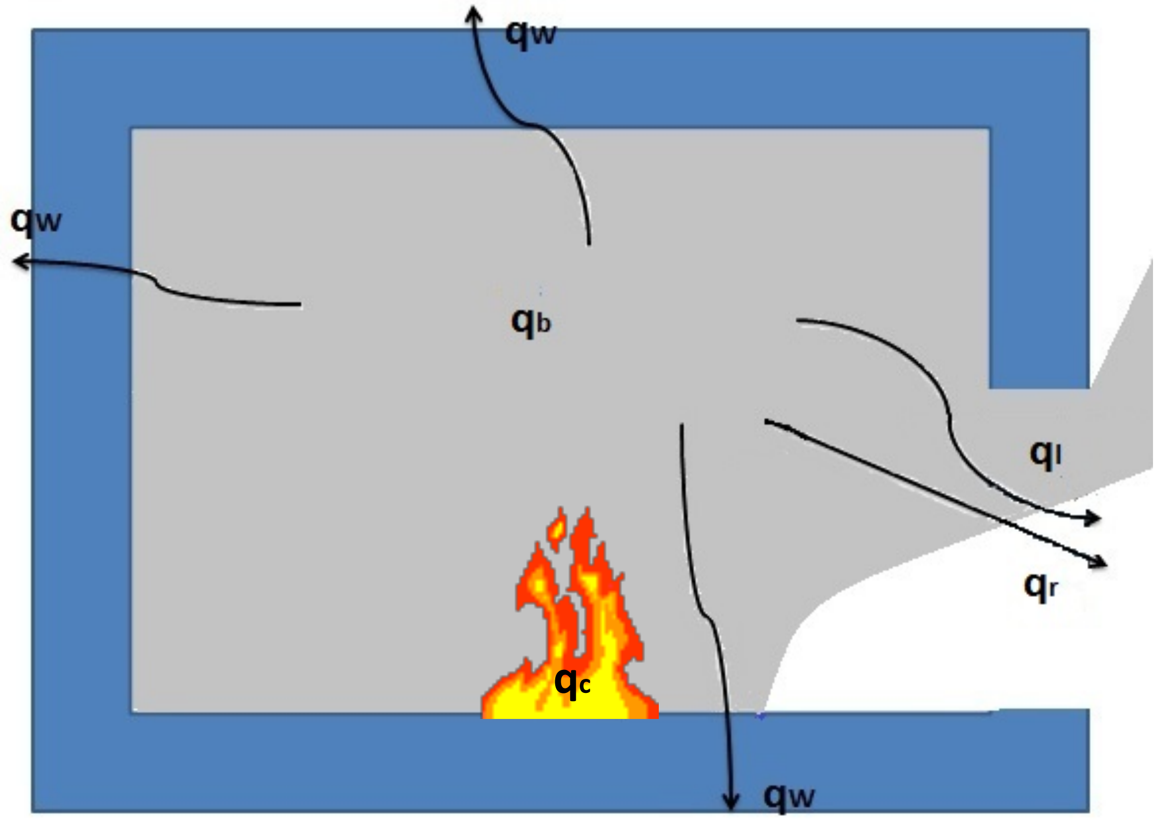

Figure 2 Energy balance illustrated for one-zone model.

Except from this, the mass flow must also be taken into consideration, since the mass flow into and out of the room will have an impact on the energy balance. This is called the mass balance where the amount of mass hot gas that leaves the room will be exchanged by the same amount of mass cold air that comes from the outside, equation (2), see e.g. (Karlsson and Quintiere 2000).

$$\dot{m}_o = \dot{m}_i = \dot{m}_a \quad (2)$$

$\dot{m}_o$ is the mass flow of hot gases out of the room, $\dot{m}_i$ the mass flow of ambient air into the room and $\dot{m}_a$ the overall mass flow of air in the room. The mass balance is illustrated in Figure 3.

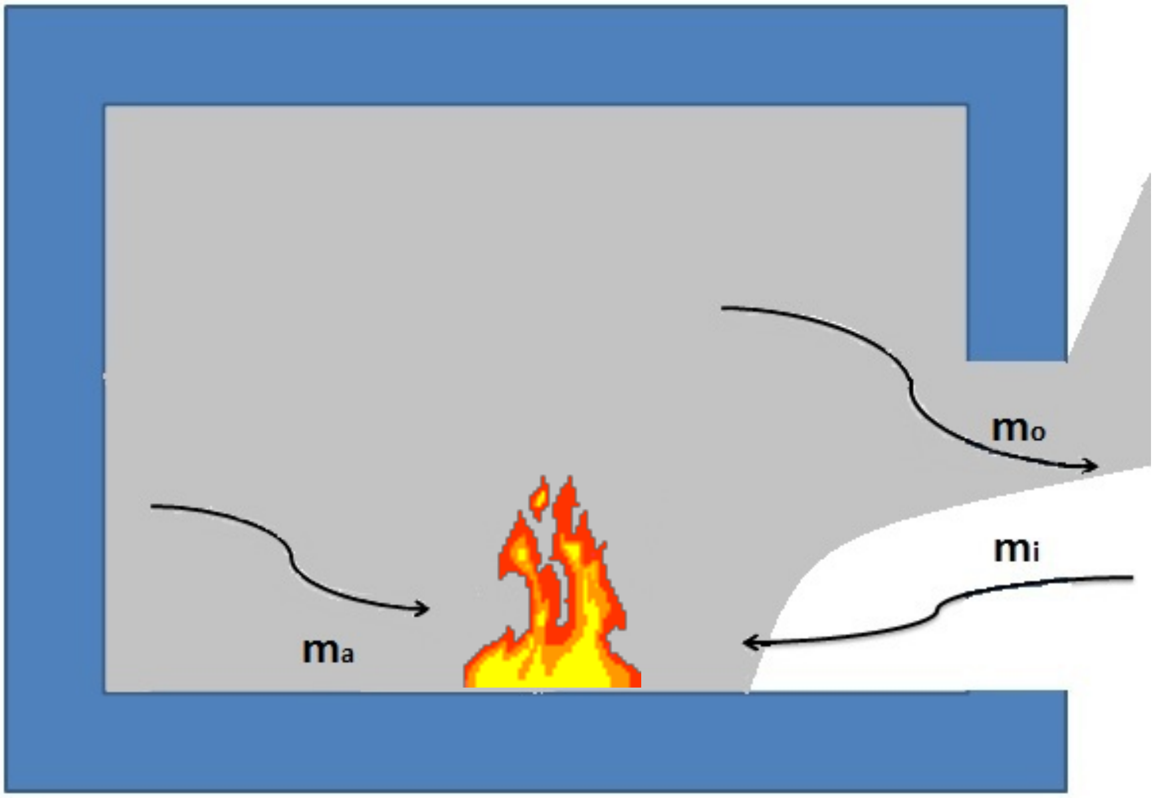

Figure 3 Mass flow for the one-zone model.

3.3 Time-temperature curves

Since the fire development depends on many different parameters, the developers of the methods for calculating the fire temperature in a room had to make some assumptions. These assumptions are the ones that make the time-temperature curves differ. However, the main-assumption that has to be done is whether to calculate on a two-zone model or one-zone model. (Harmath och Mehaffey 1983) Thereafter, it is possible to make different simplifications for the two models. The models are described more closely below, followed by a few examples of methods, which depend on the representing model. As mentioned before, a fire can also be calculated by assistance of a computer-program, which is described in section 3.6.

3.4 Two-zone model

A two-zone model is when the enclosure is divided into two parts where the upper part is filled with hot gas and the lower part with cold air. The layers are assumed to have uniform temperature throughout the whole layer and even though the lower air layer will be heated up, it will never get as warm as the upper layer. (Walton and Thomas 1995) The two-zone model focuses on the pre-flashover stage, the stage where there is plenty of oxygen and the combustion is good. The two-zone model is mainly a calculation method which has focus on life-saving in the buildings. (Harmath och Mehaffey 1983) The two-zone model is illustrated in Figure 4.

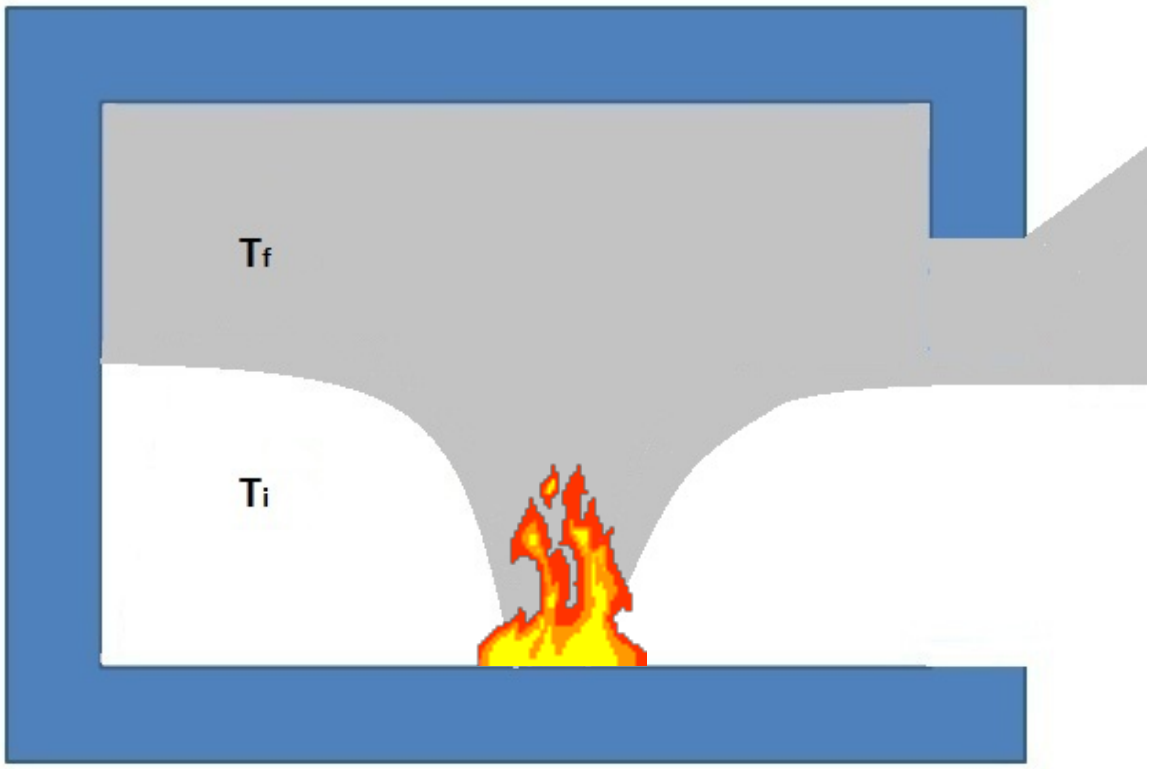

Figure 4 Illustration of two-zone model.

3.4.1 MQH-method

One two-zone model for estimating the gas temperature in a compartment was developed by McCaffrey, Quintiere and Harkleroad and is named the MQH-method. They simplified the energy balance by ignoring $\dot{q}_r$ and $\dot{q}_b$ since they are considered as relatively small processes in relation to the most dominate terms $\dot{q}_c$, $\dot{q}_w$ and $\dot{q}_l$. They also used dimensionless parameters and experimental results to determine constants so that the gas temperature could be calculated without the assistance of a computer (McCaffery, Quintiere och Harkleroad 1981)

Limitations with the MQH-method

The MQH- method has some limitations, listed below.

- The temperature rise, ΔT must be between 20°C and 600°C (McCaffery, Quintiere och Harkleroad 1981).
- The fire has to be fuel-controlled. However, if the energy release rate is estimated for the room and used in the equation, this problem can be ignored (McCaffery, Quintiere och Harkleroad 1981)
- The energy release rate has to be known (McCaffery, Quintiere och Harkleroad 1981)
- It is only applicable on situations when heat loss to mass is flowing out of the openings and when it does not take too long for the hot gases to leave the room. The method is therefore not applicable in large rooms (McCaffery, Quintiere och Harkleroad 1981).
- The values of the coefficients must also be changed if the burning fuel is next to a wall or a corner in the room (McCaffery, Quintiere och Harkleroad 1981).

The MQH-method is described more closely in Appendix A.

3.5 One-zone models

A one-zone model considers the compartment as totally filled with hot gas. The hot gas layer is assumed to be uniform with the same temperature throughout the whole layer (Harmath och Mehaffey 1983). The one-zone model is illustrated in Figure 5.

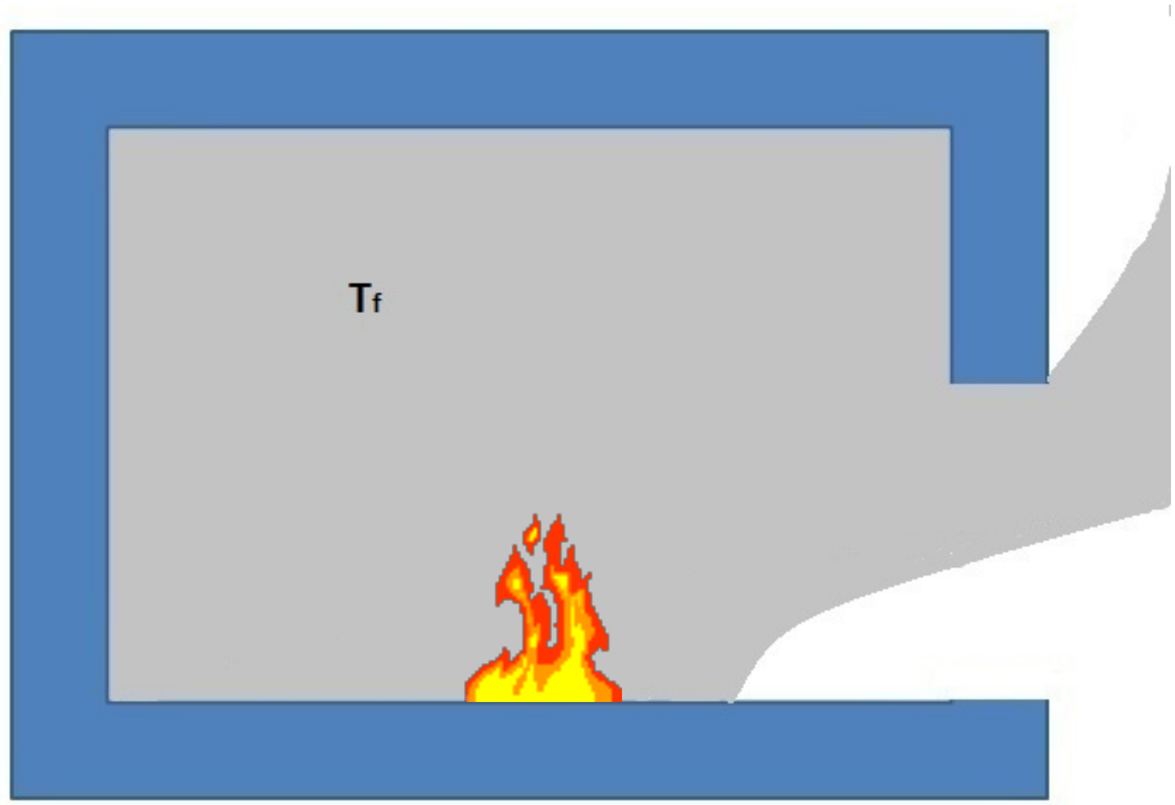

Figure 5 Illustration of one-zone model.

3.5.1 Method of Magnusson and Thelandersson

The method of Magnusson and Thelandersson is a one-zone model, which is applicable on post-flashover scenarios. They expressed the energy release as a function of time, which resulted in a time-temperature curve that a computer model solved from the energy balance. The result was compared with experimental tests to receive an energy release curve that corresponded with the experimental curves (Karlsson and Quintiere 2000). Totally 48 tests were performed with different settings where the fuel was wood (Magnusson och Thelandersson 1970).

Limitations of the method of Magnusson and Thelandersson

The method of Magnusson and Thelandersson are generally limited by the graphs that they have developed. The users have thereby seven different fire cases to choose from where the opening factor can vary between 0.02 $m^{1/2}$ and 0.12 $m^{1/2}$ and the fire load density can vary between 12.5 $MJ/m^2$and 1500 MJ/m^2 (Magnusson och Thelandersson 1970). The material of the surrounding structures can also be taken into account.

The method of Magnusson and Thelandersson is described more closely in Appendix B.

3.5.2 EUROCODE parametric fire exposure method

The EUROCODE method, adopted by CEN European Committee for Standardizations, is another well-known one-zone method. Wickström, who based his work on the time-temperature curves that were developed by Magnusson and Thelandersson, developed the concept of parametric fires, outlined in EN-1991-1-2 Appendix A. The method depends on the opening factor, the fire load and the thermal inertia of the boundaries and a time-altering gamma factor. Wickström's work was later introduced in EUROCODE 1 (Wickström, Temperature Calculation of Insulated Steel Columns Exposed to Natural Fire 1981/1982).

The method divided the fire development into one heating phase and one cooling phase. The heating phase is based on the standard curve, ISO 834, but is expressed with a sum of exponential terms. The cooling phase has three different linear time-temperature selections depending on the duration time of the fire, t_d (European Committee For Standardization 2002).

Limitations of the EUROCODE parametric fire exposure method

In EUROCODE 1 (European Committee For Standardization 2002) the following limitations are listed for the method.

- It is only valid if the floor area is less than 500 m^2, the room height is less than 4 m and there are no openings in the roof (European Committee For Standardization 2002).
- The method is limited to fire compartments with mainly cellulosic materials (European Committee For Standardization 2002).

- The thermal inertia should be between 100-2200 [$J/m^2s^{1/2}K$] and the opening factor between 0.02-0.20 (European Committee For Standardization 2002).

The EUROCODE parametric fire exposure method is described more in Appendix C.

3.6 Computer programs for calculations on room fire scenarios

The most sophisticated and advanced computer models in use are the CFD-models (Computational Fluid Dynamics). The CFD models solves the equations of the fluid flow which uses the Newton's second law, the first law of thermodynamics and also assume that the mass of fluid is conserved. (Bailey och Colin u.d.) One applied CFD-model is introduced below.

3.6.1 FDS

FDS (Fire Dynamics Simulator) is a CFD- model, which is used to calculate fluid flows created by fire. It is a computer model, which is using numerical methods for analysis of fluxes. A form of the Navier-Stokes equation is thereby solved numerically to be able to simulate a room-fire. (McGrattan, o.a. 2007)

The computer program uses a program called Smokeview (SMV), which visualizes the result, from a simulation, with different effects for the user to be able to understand the fires development in the compartment. (Peacock, o.a. 2005)

All the input parameters are written in a text file, which is called the input data file, to enable the program to simulate the specific fire scenario. (McGrattan, o.a. 2007) The user need to get familiar with the specific way of writing the input data file and reading the outputs before it is fully operational, due to the programs complexity.

4 New model for semi-infinite- and thermally thin surrounding structures with/without insulation

Since there are plenty of different methods to calculate temperatures, gas layer heights and other attributes of fire scenarios, this model focus on simplicity and what maximal fire temperature that can be obtained for different types of compartments. The maximal fire temperature occurs during the fully developed compartment fire, after long time, when the fire is ventilation controlled (Walton and Thomas 1995). Such a fully developed fire can be treated as a one-zone problem, see Figure 5. The general idea is that the fire curve, depending on heat release rate and time, is approaching a maximal fire temperature, which depends mainly on the combustion efficiency but also on thermal insulation in the surrounding structures and size of the openings. An ultimate fire temperature is also defined that is independent of the thermal properties of the surrounding structures, see Figure 6. The details of the model in Figure 6 are described throughout the rest of this report.

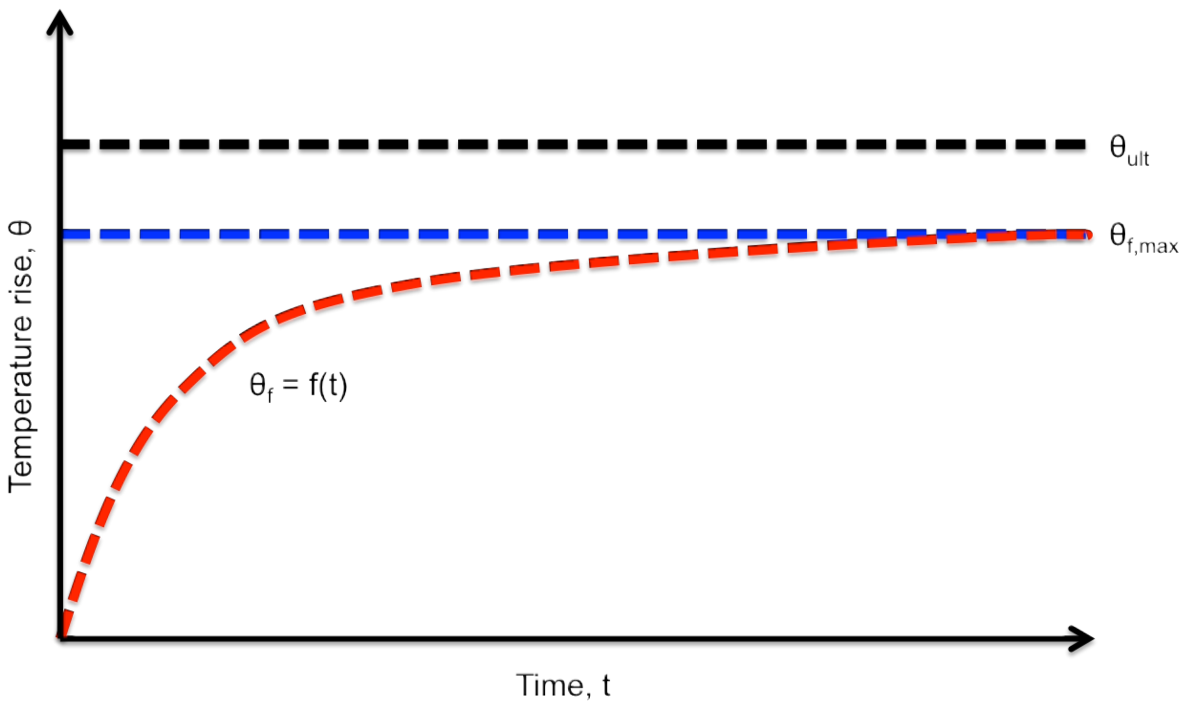

Figure 6 Schematic visualization of the new model.

4.1 Basic assumptions and simplification

- 50 % of oxygen flowing into the compartment is used for combustion
- Uniform gas temperature inside the compartment
- The combustion i.e. heat release rate is ventilation controlled
- Mass created from pyrolysis is neglected
- All combustion takes place inside the compartment
- The compartment is ventilated by natural convection independent of temperature

4.2 Limitations for the new model

This new model is based on models initially developed by Kawagoe, Ödeen, Magnusson and Thelandersson and others and can thereby be assumed to be held by the limitations for the parametric fires, according to Eurocode, which are derived from their work.

4.3 Basic theories

First, the energy balance in a fire compartment is examined as shown in chapter 3.2, equation (1). The amount of the energy released from combustion $\dot{q}_c$ during a ventilation-controlled fire depends on the amount of air that flows into the compartment $\dot{m}_i$ and the combustion yield α_2 i.e. the amount of energy released from the reaction with the oxygen that is used in the combustion, see equation (4). The amount of air flowing into the compartment, $\dot{m}_i$ depends on the opening area A_0, the square root of the opening height $\sqrt{H_0}$ and a flow factor α_1, see equation (3).

$$\dot{m}_i = \alpha_1 A_o \sqrt{H_o} \qquad (3)$$

$$\dot{q}_c = \alpha_2 \dot{m}_i = \alpha_1 \alpha_2 A_0 \sqrt{H_0} \qquad (4)$$

The flow factor α_1 is derived from the flow in- and out through a vertical opening and is often set to roughly 0.5 kg/m$^{5/2}$s (Thomas and Heselden 1972).

The combustion yield constant α_2 is derived from the ideal combustion yield for materials, which is relatively constant for various materials at 13.2*10^6 J/kg. The combustion efficiency is then assumed to be 50 % and the oxygen content in ambient air at 23 %. The combustion yield constant α_2 can therefore be calculated (Huggett 1980).

$$\alpha_2 = 0.5 * 0.23 * 13.2 * 10^6 = 1518000 \text{ J/kg} \quad (5)$$

The amount of energy conducted through the surrounding structure depends on the fire temperature on the inside of the compartment T_f, the initial temperature T_i of the surrounding air T_∞ and the total thermal resistance of the surrounding structures R_{tot}, including the heat transfer coefficient on the outside of the compartment. The heat flux is assumed equally high through the roof, the walls and the floor. The total compartment area will therefore be assumed to conduct heat (Anthony, o.a. 2008). The temperature rise is $\Theta = T - T_i$, but equation (6) is only valid when the fire has reached steady-state, i.e. $T_f = T_{f,max}$, so the temperature rise can be expressed as $\Theta_{f,max}$.

$$\dot{q}_w = A_{tot}\dot{q}''_w = A_{tot}\frac{\Theta_{f,max}}{R_{tot}} \quad (6)$$

For semi-infinite surrounding structures the heat flux to the structures is zero after long time since $R_{tot} \rightarrow \infty$ i.e.

$$\dot{q}_w = 0 \quad (7)$$

The amount of energy leaving as hot gases out of the compartment depends on the mass flow rate out from the compartment $\dot{m}_o$, specific heat of the hot gases which is assumed equal to air c_p and the temperature rise of the gas Θ_f. In fully developed fires, it is appropriate to assume that the fire temperature, gas temperature and radiation temperature are equal.

$$\dot{q}_l = c_p\dot{m}_o\Theta_f \quad (8)$$

The mass flow in $\dot{m}_i$ and the mass flow out $\dot{m}_o$ of the compartment are treated as equal to each other and by applying Bernoulli´s theorem the flow rate within the compartment can be derived, see Figure 3 and equation (2).

The energy leaving the compartment as hot gases can thereby be expressed as a function of how much mass that is flowing into the compartment for a fully developed fire.

$$\dot{q}_l = c_p \dot{m}_i \Theta_f = c_p \alpha_1 A_0 \sqrt{H_0} \Theta_f \quad (9)$$

The opening factor can be defined as a relation between the opening geometry and the total compartment area (Magnusson och Thelandersson 1970).

$$O = \frac{A_0 \sqrt{H_0}}{A_{tot}} \quad (10)$$

The amount of energy that is being stored, as heat inside the compartment, compared to the other energy terms, is relatively small and is neglected in this model to acquire the maximal temperature (Anthony, o.a. 2008). The amount of energy radiated through the openings can also be treated as relatively small and is ignored in this simple model (Karlsson and Quintiere 2000).

4.4 Maximum fire temperature

Equation (9), (6) and (4) are used in equation (1), with the assumption that $\dot{q}_r$ and $\dot{q}_b$ are relatively small, to give an expression for the maximal temperature rise $\Theta_{f,max}$ after a long time when the fire temperature has reached its maximum temperature. This maximal temperature depends on the opening factor of the compartment O, the flow factor α_1, the combustion yield α_2, the total thermal resistance of the walls R_{tot} and the specific heat of the hot gases c_p.

$$\alpha_1 \alpha_2 A_0 \sqrt{H_0} = A_{tot} \frac{\Theta_{f,max}}{R_{tot}} + c_p \alpha_1 A_0 \sqrt{H_0} \Theta_f \quad (11)$$

Equation (11) is simplified with equation (10) and the maximal fire temperature can be expressed.

$$\Theta_{f,max} = \frac{\alpha_2}{c_p + \frac{1}{R_{tot}\alpha_1 O}} \qquad (12)$$

When the surrounding structures are completely isolating, i.e. the total thermal resistance is infinitely high, the so-called ultimate fire temperature is developed. The term, $\frac{1}{R_{tot}\alpha_1 O}$ in equation (12) will thereby vanish and the ultimate fire temperature will depend on the combustion yield and the specific heat capacity of air.

$$\Theta_{ult} = \frac{\alpha_2}{c_p} \qquad (13)$$

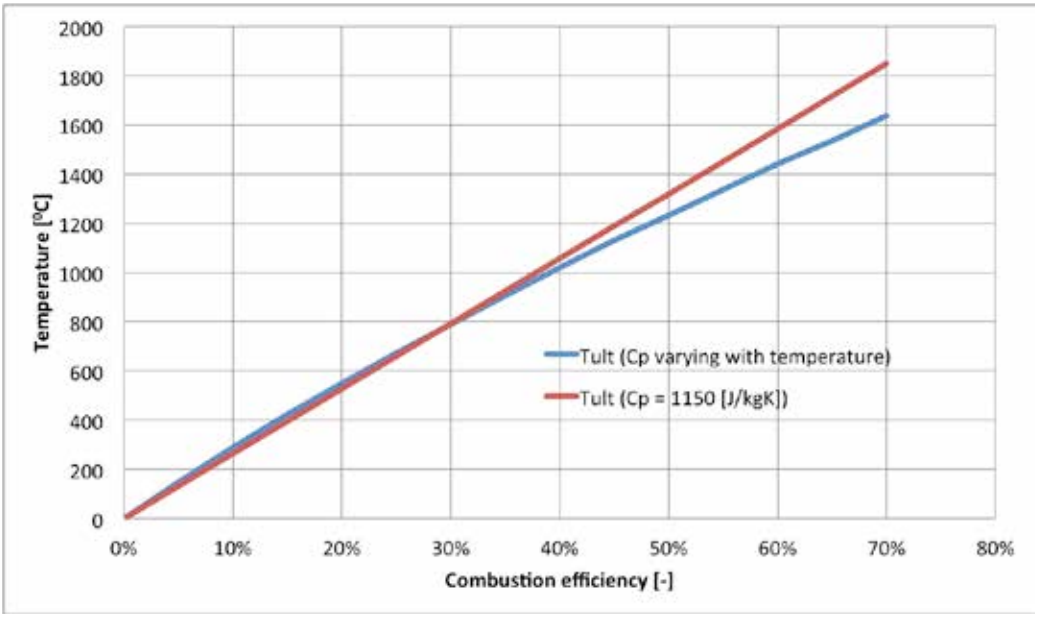

Figure 7 The ultimate temperature as a function of combustion efficiency with the specific heat capacity, c_p either depending on temperature or assumed constant.

The heat transfer through the surrounding structures, $\dot{q}_w^{"}$ can be described as a difference between the heat released from combustion, $\dot{q}_c$ and the heat that leaves the compartment as hot gases, $\dot{q}_l$. The heats exiting by radiation through the opening, $\dot{q}_r$ and the heat stored as hot gases, $\dot{q}_b$ are here neglected from equation (1) because they are relatively small. By using equation (4), (9), (10) and (13), an identification of the terms can be done, which results in a temperature difference between the ultimate temperature and the maximal fire temperature times the flow factor, the specific heat of air and the opening factor. See equation (14).

$$\dot{q}''_w = \dot{q}_c - \dot{q}_l = \alpha_1 \alpha_2 O - \alpha_1 c_p O \Theta_{f,max} = \alpha_1 c_p O (\Theta_{ult} - \Theta_{f,max}) \tag{14}$$

A fictive heat transfer coefficient can now be identified as the coefficient $h_f = \alpha_1 c_p O$ in equation (14), see equation (15) and (16). The thermal resistance between the ultimate fire temperature and the maximal temperature can also be identified, equation (17). The unit for this heat transfer coefficient and thermal resistance is the same as for any other e.g. [W/m^{2}K] and [m^{2}K/W].

$$\dot{q}''_w = \alpha_1 c_p O (\Theta_{ult} - \Theta_{f,max}) \leftrightarrow \dot{q}'' = h(\Theta_1 - \Theta_2) \tag{15}$$

$$h_f = \alpha_1 c_p O \tag{16}$$

$$R_f = \frac{1}{h_f} = \frac{1}{\alpha_1 c_p O} \tag{17}$$

With the new resistance in equation (17), the ultimate temperature in equation (13) and the maximal fire temperature in equation (12), the maximal fire temperature can be written as the relation between thermal resistances and the ultimate temperature.

$$\Theta_{f,max} = \left(\frac{R_{tot}}{R_{tot} + R_f} \right) \Theta_{ult} \tag{18}$$

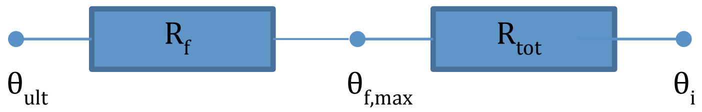

Figure 8 The series shows an electrical analogy with the resistances and the temperatures across the surrounding structures. R_{tot} includes the heat transfer resistances between the air and the surface.

4.4.1 Semi-infinite surrounding structure

The typical temperature distribution for semi-infinite surrounding structures and the positioning of thermal resistances can be seen in Figure 9. For thermally thick structures, the penetration time will be long and the non-fire exposed surface will be almost unaffected by the finite thickness of the structures during the fire development. After long time the semi-infinite surrounding structures are assumed completely insulating, see equation (13).

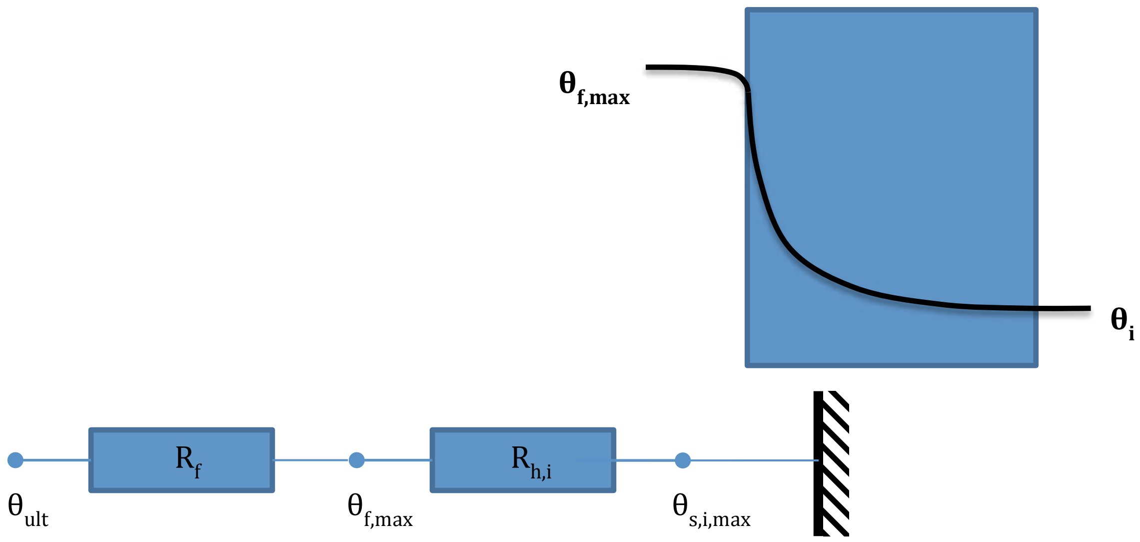

Figure 9 Temperature distribution within a semi-infinite surrounding structure. The series below shows an electrical analogy with the resistances and the temperatures across the surrounding structures after long time at steady state.

Whether a solid can be treated as semi-infinite or not depends on the material properties of the solid, the time it has been exposed to the fire and a criterion for when the non-fire exposed side is affected by the heat conduction through the solid. Basically, if a semi-infinite solid is exposed by fire on one side, the surface temperature on the non-fire exposed side should be relatively unchanged. Figure 10 illustrates a semi-infinite solid. Often, the fire temperature is approximated as equal to the surface temperature of the wall for semi-infinite solids, which is a good approximation, certainly after longer times and at higher temperatures (Wickström, DRAFT - Heat transfer in fire technology 2012).

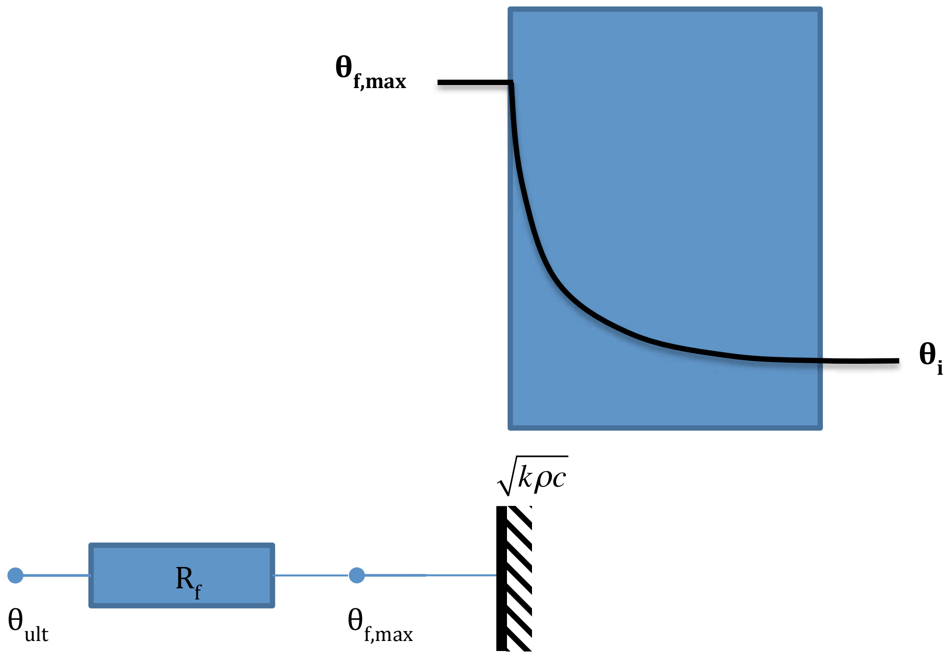

Figure 10 Temperature distribution within a semi-infinite surrounding structure with the approximation $\theta_f = \theta_s$. The series below shows an electrical analogy with the resistances and the temperatures across the surrounding structures after long time at steady state.

The maximal fire temperature is achieved after long time, and is in equation (19) identified the same way as equation (13).

$$\Theta_{f,max} = \Theta_{ult} = \frac{\alpha_2}{c_p} \quad (19)$$

4.4.2 Thermally thin surrounding structure without insulation

The typical temperature distribution for thermally thin surrounding structures without insulation and the positioning of thermal resistances can be seen in Figure 11.

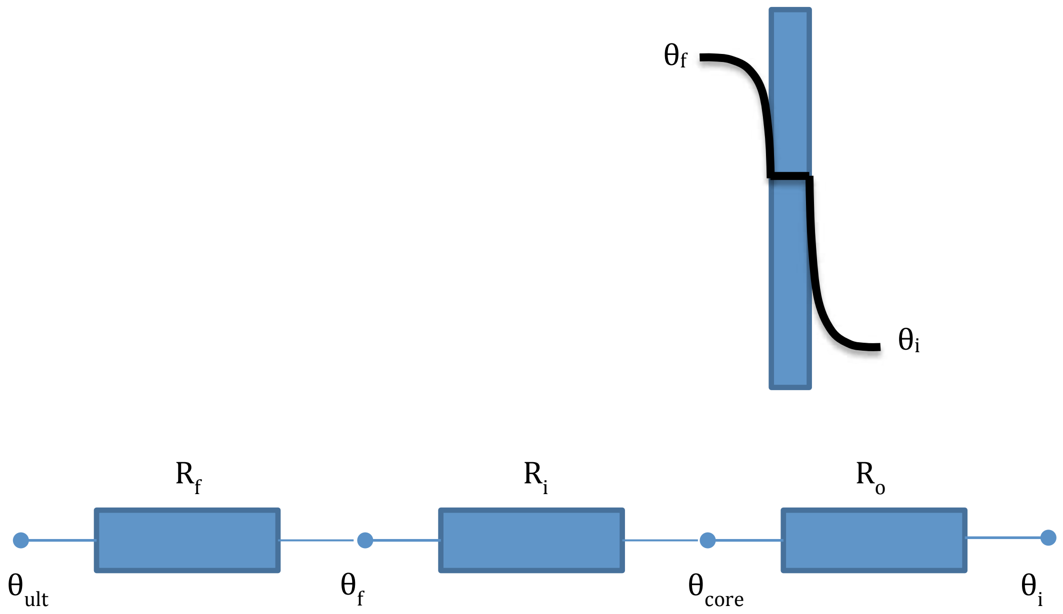

Figure 11 Temperature distribution within a thermally thin surrounding structure without insulation. The series below shows an electrical analogy with the resistances, heat capacity and the temperatures across the surrounding structures.

Thermally thin materials are characterized by that the majority of the total thermal resistance is the convection- and radiation heat transfer coefficients. The heat transfer resistance inside the material is relatively small compared to the heat transfer resistances to and from the material, by radiation and convection. (Society of Fire Protection Engineers 2002). Because of the relatively small thermal resistance in the core material, the temperature distribution across the core is negligible and lumped heat can be applied (Wickström, DRAFT - Heat transfer in fire technology 2012).

Equation (20) is the same as equation (12) and gives an expression for the maximal temperature that can occur in a compartment with thermally thin materials.

$$\Theta_{f,max} = \frac{\alpha_2}{c_p + \frac{1}{R_{tot}\alpha_1 O}} \quad (20)$$

Since lumped heat is applied, the total thermal resistance for thermally thin walls depend solely on the thermal resistance between the fire and the wall and between the wall and the outside air, which depend on the maximal fire temperature and the maximal core temperature. Initially, the convection- and radiation heat transfer resistances are treated as constant.

$$R_{tot} = R_i + R_o = R_{h,i} + R_{h,o} \tag{21}$$

After a long time, when steady state is reached, the energy flow through the wall is constant. The heat flow through the wall is consequently equal to the heat flow from the fire to the wall. The core is interpreted as the thermally thin material, see Figure 11. The expressions are simplified by the fact that $\Theta_i = \Theta_\infty = 0$

$$\dot{q}''_w = \frac{\Theta_{f,max}}{R_{tot}} = \frac{\Theta_{core,max}}{R_o} = \frac{\Theta_{f,max} - \Theta_{core,max}}{R_i} \tag{22}$$

The maximal core temperature can be expressed as a function of maximal fire temperature $\Theta_{f,max}$, initial temperature T_i and the relation between outside thermal resistance and total thermal resistance $\frac{R_o}{R_{tot}}$. Figure 12 shows how the maximal fire- and core temperatures depend on the opening factor.

$$\Theta_{core,max} = \frac{R_o}{R_{tot}} \Theta_{f,max} \tag{23}$$

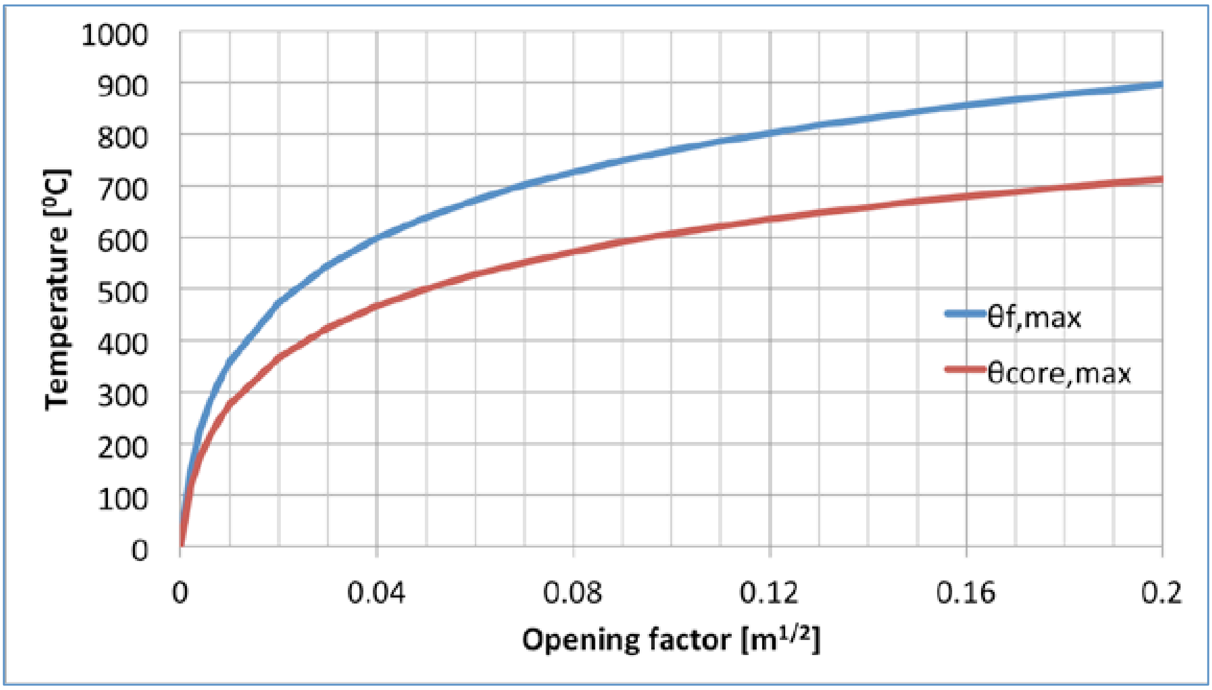

Figure 12 Maximal fire- and core temperature rise for a compartment with thermally thin surrounding structure for different opening factors. The heat transfer coefficients $h_{c,i}$ = 25 W/m^{2}K, $h_{c,0}$ = 4 W/m^{2}K, c_p = 1150 J/kgK, ε = 0.8. The thermal resistances $R_{h,i}$ and $R_{h,o}$ has been calculated as a function of temperature, described in chapter 4.6.

4.4.3 Thermally thin surrounding structures with insulation

The typical temperature distribution for thermally thin surrounding structures with insulation and the positioning of thermal resistances can be seen in Figure 13.

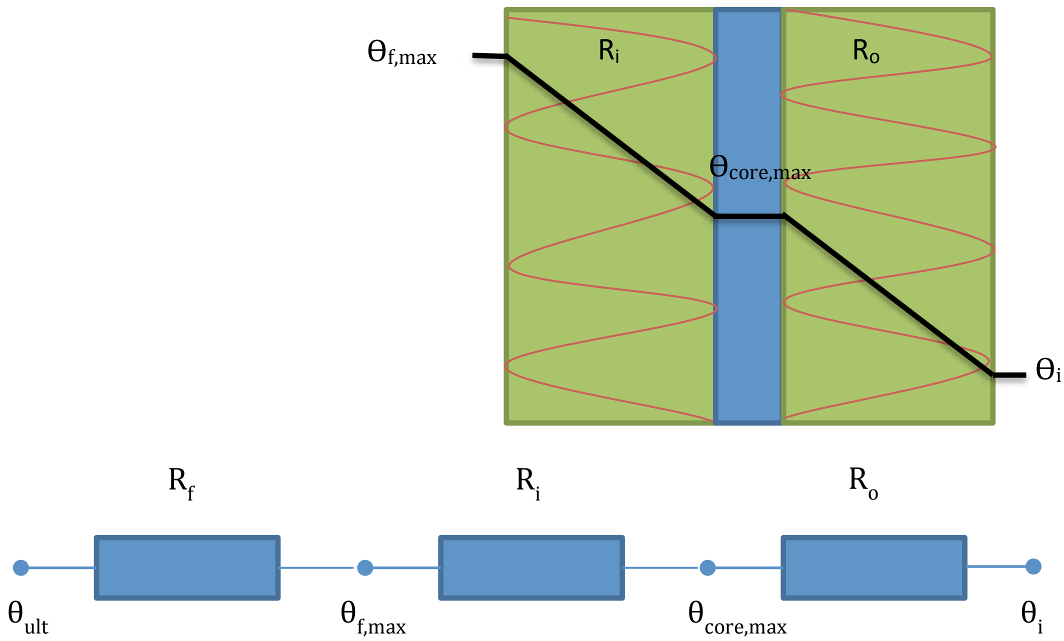

Figure 13 Temperature distribution within a thermally thin structure with insulation. The series below shows an electrical analogy with the resistances, heat capacity of the core and the temperatures across the wall. The heat transfer resistances between the air and the surrounding structures are included in R_i and R_o.

A thermally thin solid can be insulated, either on one side or on both sides of the core, the fire is assumed to expose the walls from the left.

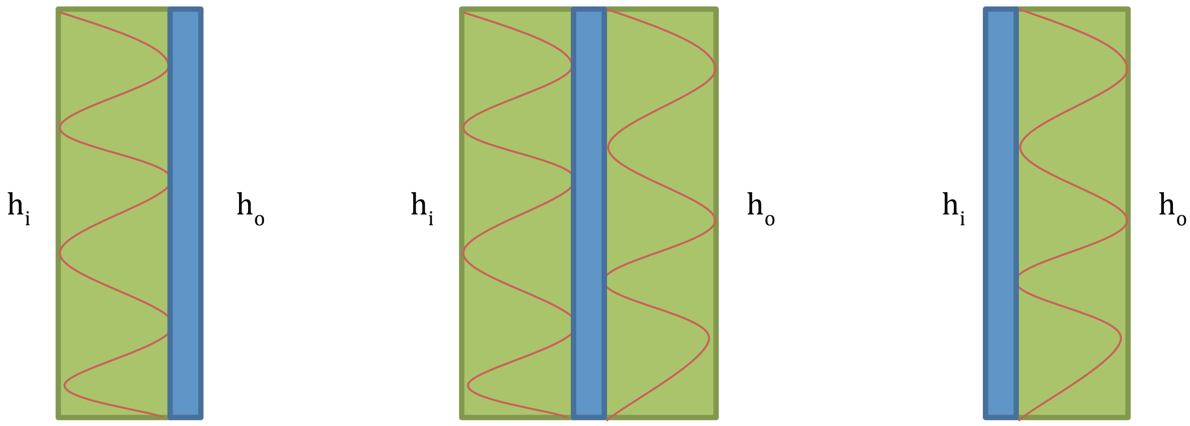

Figure 14 Thin solids with insulation on the fire-exposed side, on the non-fire exposed side and on both sides. h_i [W/m^{2}K] is the heat transfer coefficient on the fire exposed side and h_o [W/m^{2}K] is the heat transfer coefficient on the non-fire exposed side.

The maximal fire temperature can be expressed as in equation (12).

$$\Theta_{f,max} = \frac{\alpha_2}{c_p + \frac{1}{R_{tot}\alpha_1 O}} \qquad (24)$$

The total thermal resistance for thermally thin walls with insulation depends on the heat transfer coefficients, the thickness and conductivity of the insulations. The different thermal resistances in equation (25) can be chosen to represent any of the three cases in Figure 14.

Table 1 shows the thermal resistances of usual insulating building materials with the most convenient thicknesses to give a indication of what thermal resistance various types of insulations may correspond to. The insulation's impact on the maximal fire temperature for thin insulated walls is shown in Figure 15.

$$R_{tot} = R_i + R_o = R_{h,i} + R_{ins,i} + R_{ins,o} + R_{h,o} = constant \qquad (25)$$

Table 1 The thermal resistance, R_{ins} [m^2s/W] for different insulation products (Quintiere 1998).

Material	Thickness, d [m]	Conductivity, k [W/mK]	Thermal resistance, R_{ins} (d/k) [m^2s/W]
Gypsum plaster	0.009	0.50	0.018
Gypsum plaster	0.013	0.50	0.026
Gypsum plaster	0.026	0.50	0.052
Fibre insulating board	0.045	0.040	1.1
Fibre insulating board	0.070	0.040	1.8
Fibre insulating board	0.12	0.040	3.0
Polyurethane foam	0.10	0.030	3.3
Polyurethane foam	0.20	0.030	6.7

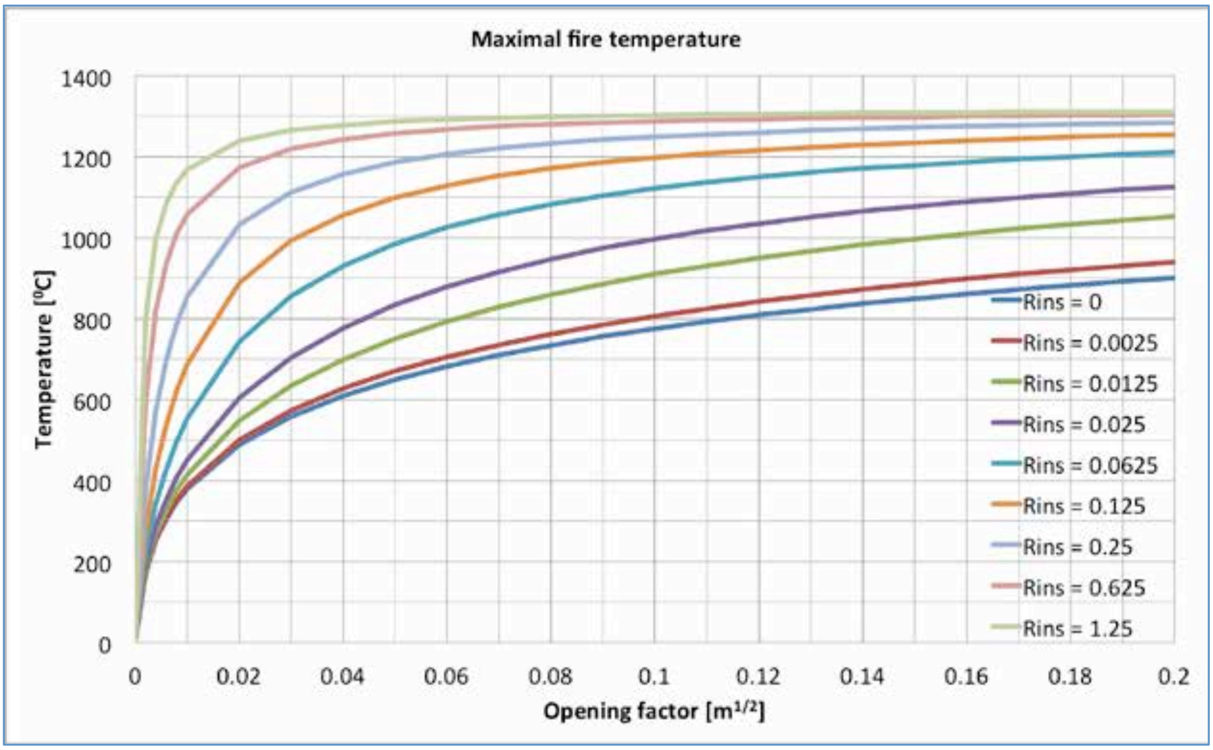

Figure 15 Maximal fire temperature rises for insulated thermally thin surrounding structure with different amount of insulation. The heat transfer coefficients are $h_{c,i}$ = 25 W/m^2K and $h_{c,o}$ = 4 W/m^2K and the specific heat is c_p = 1150 J/kgK. The thermal resistances $R_{h,i}$ and $R_{h,o}$ has been calculated as a function of temperature, described in chapter 4.6. The unit of the insulation is m^2K/W.

4.5 Time-temperature curves based on analytical solutions

To find an analytical fire temperature function of time, the energy balance for the compartment is analysed, see equation (1).

The heat exiting by radiation through the opening and the heat stored as hot gases are here neglected since they are considered relatively small for fully developed fire situations, see equation (14).

4.5.1 Semi-infinite surrounding structure

The heat absorbed by the walls is of great importance for the fire temperature. The heat flux transferred to surrounding surfaces is expressed by equation (14) and stored in the surrounding structure. According to Fourier´s law the heat flux to the surface can be written as in equation (26).

$$\dot{q}''_w = k\left(\frac{dT}{dx}\right)_{x=0} = \dot{q}_c - \dot{q}_l = \alpha_2\alpha_1 O - \Theta_f\alpha_1 O c_p \qquad (26)$$

The heat conducted through the wall depends on the heat created from the combustion subtracted by the heat loss by convection through the opening. Equation (26) can thus be rewritten as in equation (27) below by extracting $\alpha_1 O c_p$ from both terms.

$$k\left(\frac{dT}{dx}\right)_{x=0} = \alpha_1 O c_p\left(\frac{\alpha_2}{c_p} - \Theta_f\right) \qquad (27)$$

The expression $\frac{\alpha_2}{c_p}$ can be replaced with the ultimate fire temperature Θ_{ult} and $\alpha_1 O c_p$ can be replaced with h_f for semi-infinite solids according to equation (13) and (16).

$$k\left(\frac{dT}{dx}\right)_{x=0} = h_f\left(\Theta_{ult} - \Theta_f\right) \qquad (28)$$

To find a simple analytical model, the solution for the convection heat transfer to semi-infinite walls, the third kind of boundary condition, is examined (Holman 1986). The heat transfer coefficient and the gas temperature rise are assumed constant.

$$\dot{q}_0 = -k\left(\frac{dT_s}{dx}\right)_{x=0} = h\left(\Theta_g - \Theta_s\right) \tag{29}$$

The solution for the relative surface temperature rise for equation (29) is derived with Laplace transform technique and will not be discussed further in this report, but is available in various literatures such as "Heat Transfer" by J. P. Holman.

$$\frac{\Theta_s}{\Theta_g} = 1 - e^{\frac{t}{\tau}} erfc\left(\sqrt{\frac{t}{\tau}}\right) \tag{30}$$

where

$$\tau = \left(\frac{\sqrt{k\rho c}}{h}\right)^2 \tag{31}$$

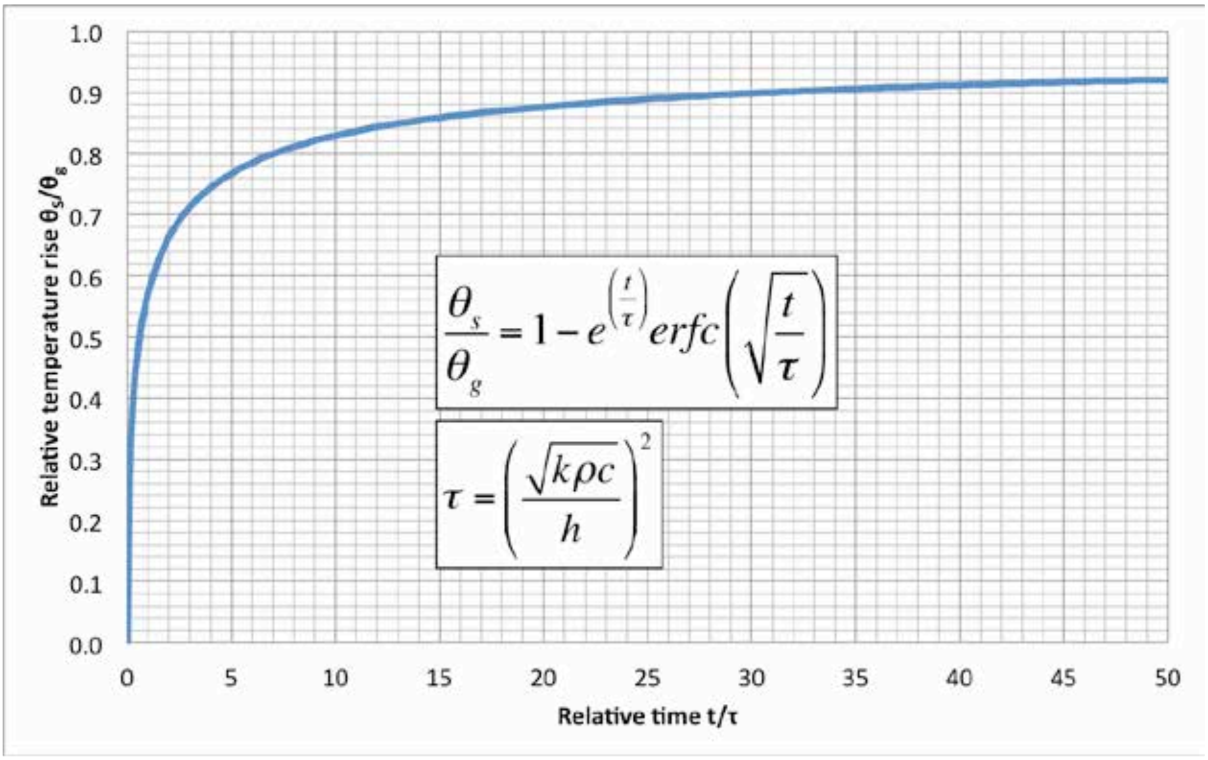

Figure 16 Laplace solution for heat transfer to semi-infinite solids.

To find a simple analytical solution for semi-infinite walls, equation (28) and (29) are compared to identify terms that represent each other, see Table 2. Noticeable is that the terms identified have the same unit. This identification is the fundamental idea in how the analytical solution is derived and how two similar equations for the heat transfer to semi-infinite walls have analogous solutions.

$$\alpha_1 O c_p \left(\Theta_{ult} - \Theta_f\right) \leftrightarrow h(\Theta_g - \Theta_s) \quad (32)$$

$$h \to h_f = \alpha_1 O c_p \quad (33)$$

$$\Theta_g \to \Theta_{ult} = \frac{\alpha_2}{c_p} \quad (34)$$

In analogy with the third kind of boundary condition above, the fire temperature, instead of the surface temperature, can now be written as a function of the maximal fire temperature and the parameters for the compartment.

$$\frac{\Theta_f}{\Theta_{ult}} = \left(1 - e^{\frac{t}{\tau_f}} erfc\left(\sqrt{\frac{t}{\tau_f}}\right)\right) \tag{35}$$

$$\tau_f = \left(\frac{\sqrt{k\rho c}}{\alpha_1 O c_p}\right)^2 \tag{36}$$

Table 2 Visualization of how identification is used to find an analytical solution. The top row shows an equation for heat transfer to a semi-infinite solid and the corresponding solution. The row below shows the equation derived from the energy balance in the room, which is similar to the one above, and the identified solution.

Initial equation	**Solution for semi-infinite surrounding structure**	**Definition of time constant**
$-k\left(\frac{dT_s}{dx}\right)_{x=0} = h(\Theta_g - \Theta_s)$	$\frac{\Theta_s}{\Theta_g} = \left(1 - e^{\frac{t}{\tau}} erfc\left(\sqrt{\frac{t}{\tau}}\right)\right)$	$\tau = \left(\frac{\sqrt{k\rho c}}{h}\right)^2$
$k\left(\frac{dT_s}{dx}\right)_{x=0} = \alpha_1 O c_p(\Theta_{ult} - \Theta_f)$	$\frac{\Theta_f}{\Theta_{ult}} = \left(1 - e^{\frac{t}{\tau_f}} erfc\left(\sqrt{\frac{t}{\tau_f}}\right)\right)$	$\tau_f = \left(\frac{\sqrt{k\rho c}}{\alpha_1 O c_p}\right)^2$

In Figure 17, the new model is plotted for constant values. The new model is analysed further in chapter 0.

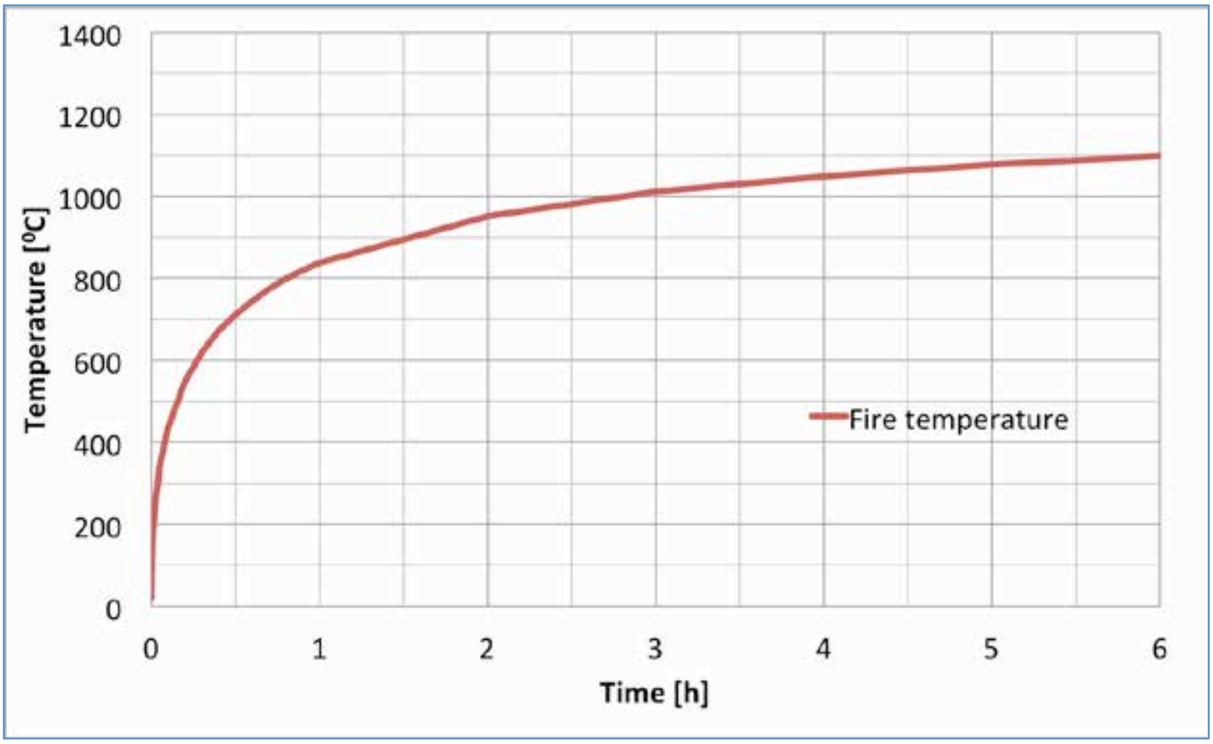

Figure 17 Calculated fire temperature for semi-infinite walls with constant parameters. O = 0.04 $m^{1/2}$, c_p = 1150 J/kgK, α_1 = 0.5 $kg_{air}/m^{5/2}s$, α_2 = 1518000, $\sqrt{k\rho c}$ = 1160 $Ws^{1/2}/m^2K$.

4.5.2 Thermally thin surrounding structures with/without insulation

Assuming that there is insulation on both sides of the walls, the thermal resistances/insulations are considered constant and the heat transfer coefficients are treated as a part of the insulation.

$$R_i = R_{h,i} + R_{ins,i} = constant \quad (37)$$

$$R_o = R_{h,o} + R_{ins,o} = constant \quad (38)$$

To make it easier to overlook when deriving an analytical solution for the maximal core- and fire temperature, a group of constants are expressed as ς.

$$\varsigma = \alpha_1 c_p O R_i \tag{39}$$

The energy balance for the compartment is used as a starting point, see equation (1). The energy loss as radiation through the opening and the energy bound as hot gas in the compartment is neglected since they are relatively small (Karlsson and Quintiere 2000), which gives equation (40).

$$\dot{q}_c = \dot{q}_w + \dot{q}_l \tag{40}$$

Equation (4), (6) and (9) is used in equation (40).

$$\alpha_1 \alpha_2 A_o \sqrt{H_o} = \alpha_1 c_p A_o \sqrt{H_o} \Theta_f + A_{tot} \dot{q}''_w \tag{41}$$

Equation (10) is used in equation (41) to introduce the opening factor. The heat losses to the walls are treated as the heat flux from the fire to the walls, which depend on the thermal resistance between the fire and the surrounding structure. Given that all the heat capacity and thermal capacity of the surrounding structure is assumed concentrated to the core, the flux from the fire Θ_f to the core Θ_{core} can be illustrated with Figure 11 and Figure 13.

$$\alpha_1 \alpha_2 O = \alpha_1 c_p O \Theta_f + \frac{\Theta_f - \Theta_{core}}{R_i} \tag{42}$$

Isolating the fire temperature rise from equation (42) gives an expression that depends on the core temperature rise.

$$\Theta_f = \frac{\Theta_{core}}{\alpha_1 c_p O R_i + 1} + \frac{\alpha_1 \alpha_2 O R_i}{\alpha_1 c_p O R_i + 1} = \frac{\Theta_{core}}{\varsigma + 1} + \frac{\alpha_1 \alpha_2 O R_i}{\varsigma + 1} \tag{43}$$

The dynamic core temperature balance depends on the core properties, the heat absorbed from the fire and the heat emitted to the outside air, see Figure 13. Equation (44) is used to simplify the expressions.

$$(d\rho c)_{core} = C_{core} \tag{44}$$

$$C_{core}\frac{d\Theta_{core}}{dt} = \frac{\Theta_f - \Theta_{core}}{R_i} - \frac{\Theta_{core}}{R_o} = \frac{\Theta_f - \Theta_{core}}{R_i} - \frac{\Theta_{core}}{R_o} \tag{45}$$

The fire temperature rise can be expressed as in equation (43), the core temperature rise can be isolated and the simplified expression in equation (39) can be used to make the calculation easier to overlook. After some rewritings the expression in equation (46) is achieved. The full derivation is found and described in Appendix D.

$$\frac{d\Theta_{core}}{dt} = \frac{1}{\left(\frac{C_{core}}{\frac{1}{R_i + R_f} + \frac{1}{R_o}}\right)}\left(\Theta_{core,max} - \Theta_{core}\right) \tag{46}$$

To find an analytical solution for thermally thin walls with constant thermal resistance on both sides of the wall, the expression for the core temperature rise as a function of a constant fire temperature and ideal insulation on the non-fire exposed side is examined i.e. equation (47) and (48), see Figure 18.

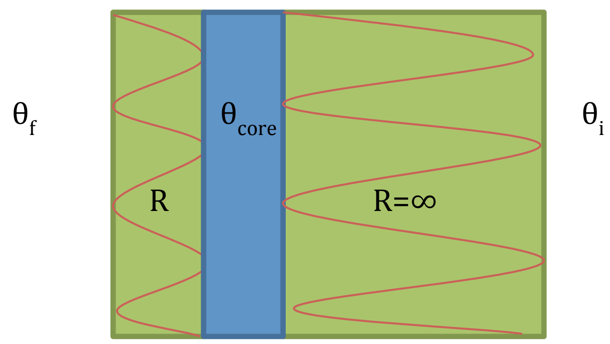

Figure 18 Thermally thin core that is completely insulated on the non-fire exposed side, a constant thermal resistant R on the fire-exposed side and a constant fire temperature $\boldsymbol{\theta_f}$.

$$\frac{d\Theta}{dt} = \frac{1}{dc\rho R}(\Theta_f - \Theta) \quad (47)$$

Equation (47) has the solution for the core temperature rise that depends on the constant fire temperature and the time constant (Wickström, DRAFT - Heat transfer in fire technology 2012).

$$\frac{\Theta}{\theta_f} = 1 - e^{-\frac{t}{\tau}} \quad (48)$$

where

$$\tau = dc\rho R \quad (49)$$

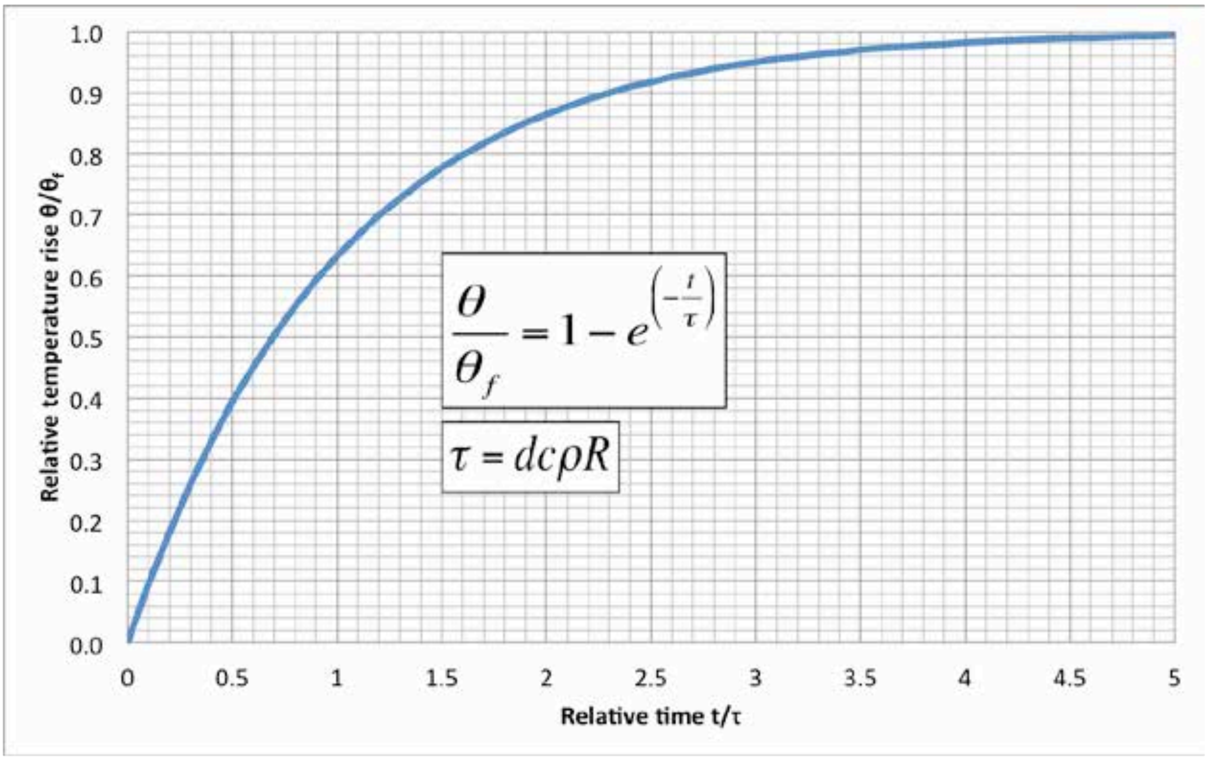

Figure 19 General solutions for both equation (46) and (47) with relative temperature rise and relative time.

To find an analytical solution for thermally thin surrounding structures, equation (46) and (47) are compared to identify terms that represent each other, see Table 3. Noticeable is that the terms identified have the same unit. This identification is the fundamental idea in how the analytical solution is derived and how two similar equations for the relative core temperature rise have analogous solutions.

$$\frac{1}{\left(\frac{C_{core}}{\frac{1}{R_i + R_f} + \frac{1}{R_o}}\right)}(\theta_{core,max} - \theta_{core}) \leftrightarrow \frac{1}{dc\rho R}(\theta_f - \theta) \quad (50)$$

$$\frac{\boldsymbol{\theta_{core}}}{\boldsymbol{\theta_{core,max}}} = \left(\mathbf{1} - \boldsymbol{e}^{-\frac{t}{\tau_{core}}}\right) \quad (51)$$

$$\boldsymbol{\tau_{core}} = \frac{\boldsymbol{C_{core}}}{\frac{\mathbf{1}}{\boldsymbol{R_i + R_f}} + \frac{\mathbf{1}}{\boldsymbol{R_o}}} \quad (52)$$

Table 3 Visualization of how identification is used to find an analytical solution. The top row shows an equation for the temperature increase for a thermally thin core and the corresponding solution. The row below shows the equation derived from the dynamic heat balance for the core, which is similar to the one above, and the identified solution.

Initial equation	**Solution for thermally thin surrounding structures**	**Definition of time constant**
$\frac{d\Theta}{dt} = \frac{1}{dc\rho R}(\theta_f - \Theta)$	$\frac{\Theta}{\theta_f} = \left(1 - e^{-\frac{t}{\tau}}\right)$	$\tau = dc\rho R$
$\frac{d\Theta_{core}}{dt} = \frac{1}{\left(\frac{C_{core}}{\frac{1}{R_i + R_f} + \frac{1}{R_o}}\right)}(\theta_{core,max} - \theta_{core})$	$\frac{\theta_{core}}{\theta_{core,max}} = \left(1 - e^{-\frac{t}{\tau_{core}}}\right)$	$\tau_{core} = \frac{C_{core}}{\frac{1}{R_i + R_f} + \frac{1}{R_o}}$

To find an analytical expression for the fire temperature rise, the core temperature rise in equation (51) is substituted into equation (43). The expression can be simplified with the expression in equation (39) analogy with the expression for the core temperature rise. After some rewritings the expression in equation (53) will come through, which identifies the fire temperature rise as a function of the maximal temperature rise and the time constant. The fully derivation is found in Appendix E.

$$\theta_f = \theta_{f,max}\left(1 - \left(\frac{\left(\frac{1}{R_i}\right)^2}{\left(\frac{1}{R_i}+\frac{1}{R_o}\right)\left(\frac{1}{R_f}+\frac{1}{R_i}\right)}\right)e^{-\frac{t}{\tau_{core}}}\right) \tag{53}$$

$$\tau_{core} = \frac{C_{core}}{\frac{1}{R_i + R_f}+\frac{1}{R_o}} \tag{54}$$

The fire temperature at t = 0 is therefore calculated as in equation (55) and is not equal to the initial temperature.

$$\theta_f = \theta_{f,max}\left(1 - \frac{\left(\frac{1}{R_i}\right)^2}{\left(\frac{1}{R_i}+\frac{1}{R_o}\right)\left(\frac{1}{R_f}+\frac{1}{R_i}\right)}\right) \tag{55}$$

Examples on how the equations in this chapter can be used are found in Appendix G.

4.6 Time-temperature curves based on numerical solutions

4.6.1 Thermally thin surrounding structures without insulation

To be able to perform a numerical calculation, which allows parameters to depend on the fire temperature, the dynamic heat balance for the core is used. The relatively small heat losses can be ignored, including the inertia of the air (Anthony, o.a. 2008). The isolated fire temperature from the heat balance is used from equation (43).

$$\theta_f = \frac{\theta_{core} + \alpha_1 \alpha_2 O R_i}{\alpha_1 c_p O R_i + 1} \tag{56}$$

$$C_{core} \frac{d\Theta_{core}}{dt} = \frac{\theta_f - \theta_{core}}{R_i} - \frac{\theta_{core}}{R_o} \tag{57}$$

The temperature rise for the fire is a function that depends on the temperature rise of the core. The temperature for the core has to be calculated in order to calculate the fire temperature.

$$\frac{d\Theta_{core}}{dt} = \frac{1}{C_{core}} \left(\frac{\theta_f - \theta_{core}}{R_i} - \frac{\theta_{core}}{R_o} \right) \tag{58}$$

The time derivate for the temperatures can then be approximated into small increments.

$$\frac{d\theta}{dt} \approx \frac{\theta^{j+1} - \theta^j}{\Delta t} \tag{59}$$

The temperature can then be calculated with a forward difference scheme with small time increments (Wickström, DRAFT - Heat transfer in fire technology 2012).

$$\theta^{j+1} \approx \Delta t \frac{d\theta^j}{dt} + \theta^j \tag{60}$$

The core- and fire temperature from equation (56) and (58) can then be calculated numerically, by replacing the temperature rise in equation (60) with the core temperature rise from equation (58), see equation (61) and (62).

$$\theta_{core}^{j+1} = \frac{\Delta t}{C^j{}_{core}} \left(\frac{\theta_f^j - \theta_{core}^j}{R_i^j} - \frac{\theta_{core}^j}{R_0^j} \right) + \theta_{core}^j \tag{61}$$

$$\theta_f^j = \frac{\theta_{core}^j + \alpha_1 \alpha_2 O R_i^j}{\alpha_1 c_p O R_i^j + 1} \tag{62}$$

Using the same input values for each parameters, including constant thermal resistance, gives the exact fire- and core temperature for different times as the analytical solution, for small time increments, see Figure 20. A rational step forward, when the numerical and analytical solutions give the same results with the same input values, is to let parameters vary with temperature for the numerical solution.

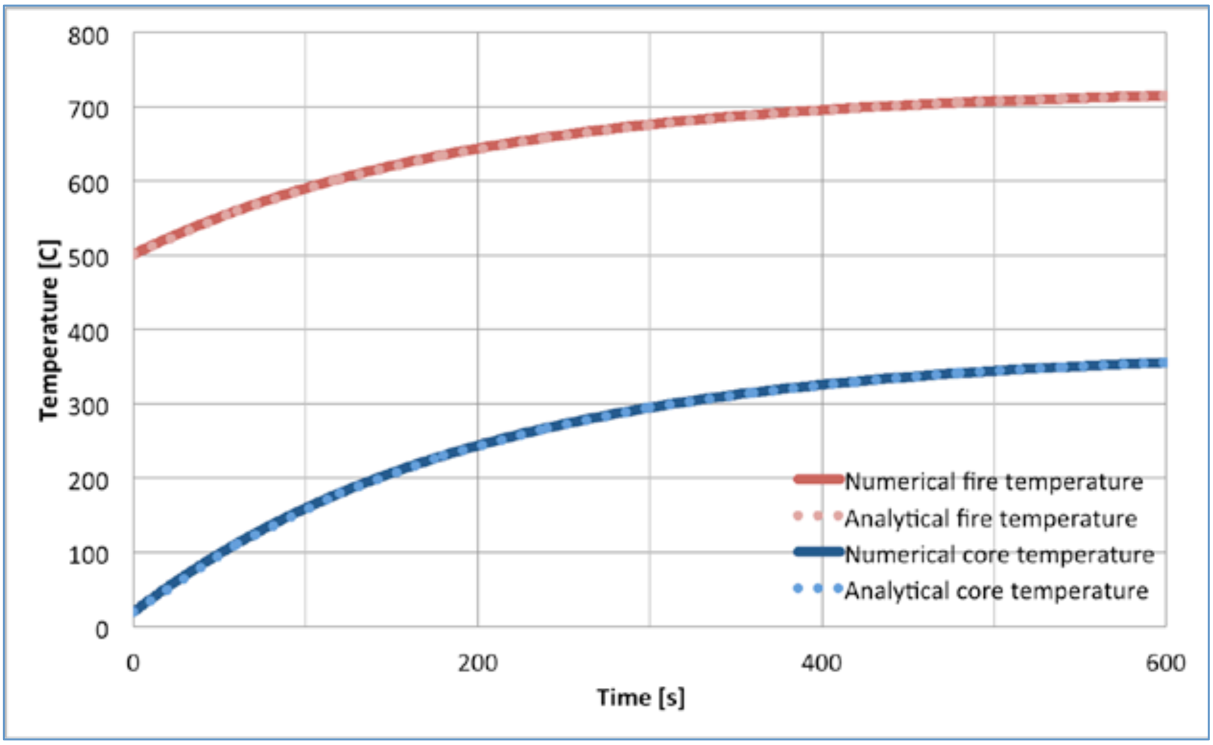

Figure 20 Calculated fire- and core temperatures by analytical and numerical solutions with the same parameters.

If the thermal resistances depend on the fire- and the core temperature, instead of being constant, the solution must either be iterated or equation (62) must be derived, for each time step, so that it is possible to use the described numerical method for the fire temperature.

$$R_i^j = \frac{1}{h_{c,i} + \varepsilon\sigma\left({T_f^j}^2 + {T_{core}^j}^2\right)\left(T_f^j + T_{core}^j\right)} \tag{63}$$

$$R_0^j = \frac{1}{h_{c,o} + \varepsilon\sigma\left({T_{core}^j}^2 + {T_i^j}^2\right)\left(T_{core}^j + T_i^j\right)} \tag{64}$$

4.6.2 Thermally thin surrounding structures with insulation

For thermally thin solids, which have insulation, the procedure to perform numerical calculations is the same as without insulation above. The difference, when adding insulation, is that the radiation heat transfer coefficients depend on the surface temperatures of the insulations instead of the core temperature.

$$\theta_f^j = \frac{\theta_{core}^j + \alpha_1\alpha_2 O R_i^j}{\alpha_1 c_p O R_i^j + 1} \tag{65}$$

$$\theta_{core}^{j+1} = \frac{\Delta t}{C^j{}_{core}}\left(\frac{\theta_f^j - \theta_{core}^j}{R_i^j} - \frac{\theta_{core}^j}{R_o^j}\right) + \theta_{core}^j \tag{66}$$

where

$$R_i^j = R_{h,i}^j + R_{ins,i}^j = \frac{1}{h_{c,i} + \varepsilon\sigma\left({T_{s,i}^j}^2 + {T_i^j}^2\right)\left(T_{s,i}^j + T_i^j\right)} + \frac{d_{ins,i}}{k_{ins,i}} \tag{67}$$

$$R_o^j = R_{h,o}^j + R_{ins,o}^j = \frac{1}{h_{c,o} + \varepsilon\sigma\left({T_f^j}^2 + {T_{s,o}^j}^2\right)\left(T_f^j + T_{s,o}^j\right)} + \frac{d_{ins,o}}{k_{ins,o}} \tag{68}$$

The insulations are treated as thermal resistances, without thermal inertia. The temperature distribution is therefore treated as linear through every part of the wall, see Figure 21. The surface temperatures can then be calculated as a momently relation between the fire-, core- and outside temperature, the heat transfer coefficients and the thermal resistances of the insulations, see equation (69) and (70) (Wickström, DRAFT - Heat transfer in fire technology 2012).

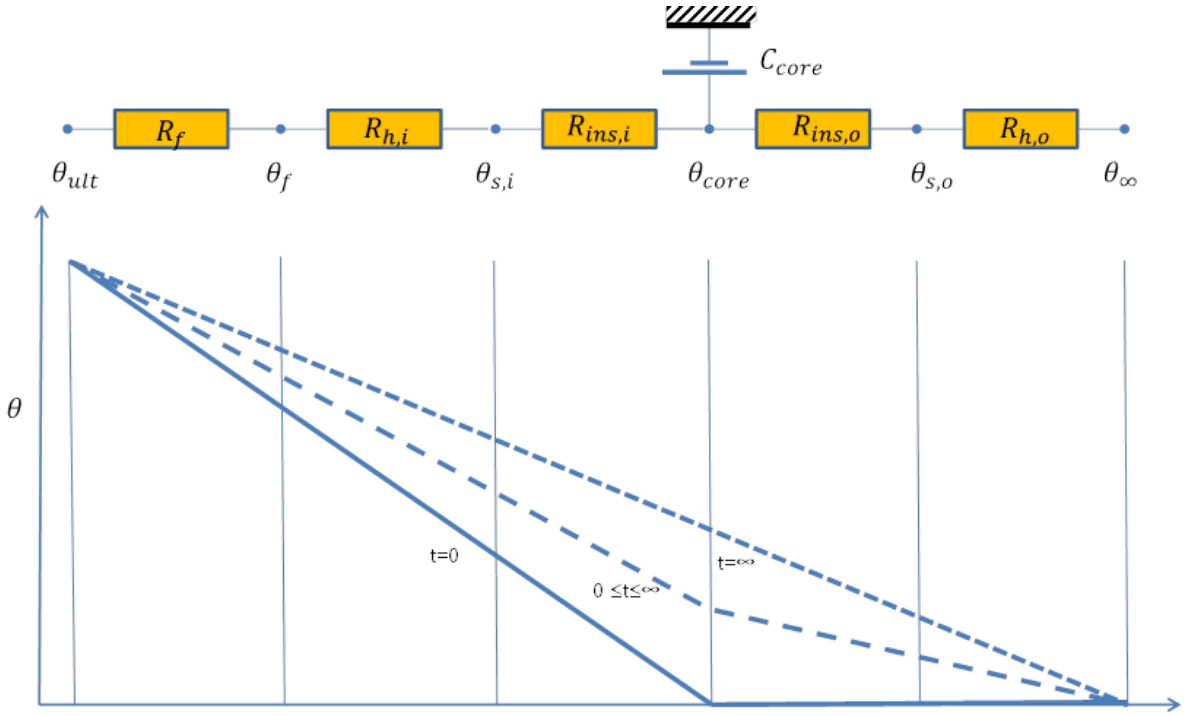

Figure 21 Schematic temperature distribution inside a thermally thin surrounding structure assuming lumped heat and an indication of the temperature in the beginning (t=0), after some time (0≤t≤∞) and after very long time (t=∞).

$$\frac{\theta_f - \theta_{s,i}}{R_{h,i}} = \frac{\theta_f - \theta_{core}}{R_i} \tag{69}$$

$$\frac{\theta_{core} - \theta_{s,o}}{R_{ins,o}} = \frac{\theta_{core}}{R_o} \tag{70}$$

The fire exposed insulation surface temperature can be expressed as the fire temperature minus the relation between the thermal resistances multiplied with the temperature difference between the fire and the core as in equation (71), derived from equation (69).

$$\theta_{s,i} = \theta_f - \frac{R_{h,i}}{R_i}(\theta_f - \theta_{core}) \tag{71}$$

The non-fire exposed insulation surface temperature can be expressed as the core temperature subtracted by the relation between the thermal resistances multiplied with the core temperature rise as in equation (72), derived from equation (70).

$$\theta_{s,o} = \theta_{core} - \frac{R_{ins,o}}{R_o}\Theta_{core} \tag{72}$$

Equation (71) and (72) can be used in equation (67) and (68) to calculate the heat transfer resistances at each time-step.

When using a numerical calculation technique to calculate the fire temperature, it is possible to let the parameters vary with temperature or time, for each time step.

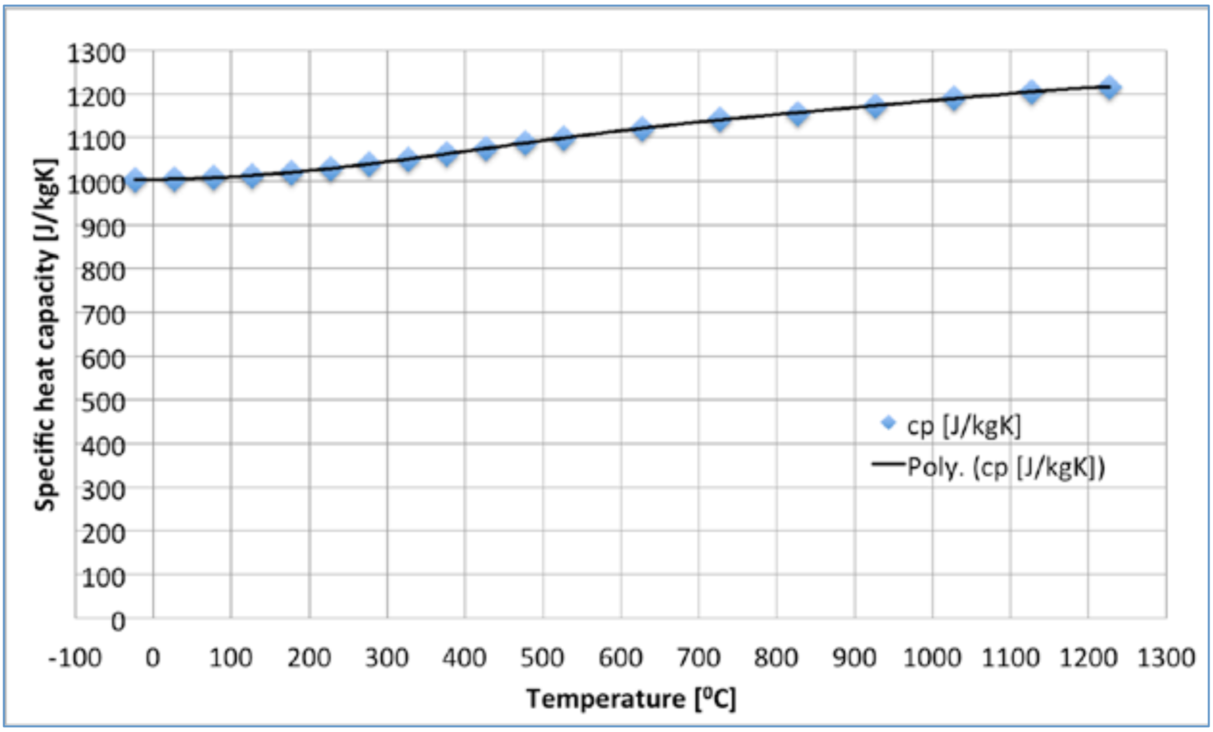

Figure 22 Specific heat capacity for air depending on temperature (Society of Fire Protection Engineers 2002) and a 6th order polynomial trend line.

Excel has been used, with the values for specific heat capacity for different temperatures (Society of Fire Protection Engineers 2002) to find a 6^{th} order polynomial trend line and its function, see Figure 22.

How the ultimate fire temperature is affected by if the specific heat capacity for air is chosen as a constant value or depending on temperature is illustrated in Figure 23.

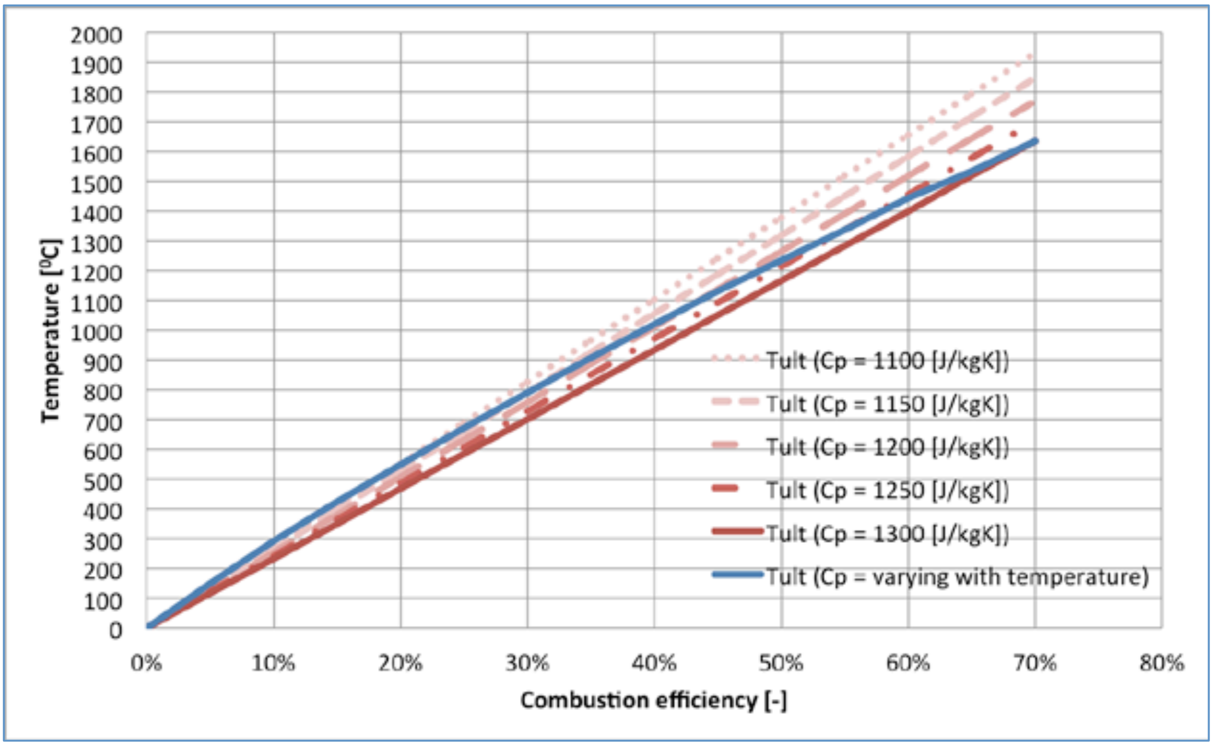

Figure 23 Impact on the ultimate fire temperature if the specific heat capacity of air is chosen as a constant value or as a function of temperature.

5 Summary of formulas

The equations for the new model are in this chapter summarised for each typical fire case.

5.1 Function to calculate maximum temperature

5.1.1 Semi- infinite surrounding structures

$$\theta_{f,max} = \theta^{ult} = \frac{\alpha_2}{c_p} \tag{73}$$

5.1.2 Thermally thin surrounding structures

$$\theta_{f,max} = \frac{\alpha_2}{\frac{1}{R_{tot}\alpha_1 O} + c_p} \tag{74}$$

$$\theta_{core,max} = \frac{R_o}{R_{tot}}\theta_{f,max} \tag{75}$$

$$\begin{aligned} R_{tot} &= R_{h,i} + R_{ins,i} + R_{ins,o} + R_{h,o} \\ &= \frac{1}{h_{c,i} + \varepsilon\sigma\left(T_{f,max}{}^2 + T_{s,i,max}{}^2\right)\left(T_{f,max} + T_{s,i,max}\right)} \\ &+ \sum_j^n \frac{d_{j,i}}{k_{j,i}} + \sum_j^n \frac{d_{j,o}}{k_{j,o}} \\ &+ \frac{1}{h_{c,o} + \varepsilon\sigma\left(T_{s,o,max}{}^2 + T_i{}^2\right)\left(T_{s,o,max} + T_i\right)} \end{aligned} \tag{76}$$

5.2 Functions to calculate time dependent fire temperature

5.2.1 Analytical semi-infinite surrounding structures

$$\theta_f = \theta_{ult}\left(1 - e^{\frac{t}{\tau_f}} erfc\left(\sqrt{\frac{t}{\tau_f}}\right)\right) \tag{77}$$

$$\tau_f = \left(\frac{\sqrt{k\rho c}}{\alpha_1 O c_p}\right)^2 \tag{78}$$

5.2.2 Analytical thermally thin surrounding structures

$$\theta_f = \theta_{f,max}\left(1 - \left(\frac{\left(\frac{1}{R_i}\right)^2}{\left(\frac{1}{R_i} + \frac{1}{R_o}\right)\left(\frac{1}{R_f} + \frac{1}{R_i}\right)}\right) e^{-\frac{t}{\tau_{core}}}\right) \tag{79}$$

$$\theta_{core} = \theta_{core,max}\left(1 - e^{-\frac{t}{\tau_{core}}}\right) \tag{80}$$

$$\tau_{core} = \frac{C_{core}}{\frac{1}{R_i + R_f} + \frac{1}{R_o}} \tag{81}$$

$$R_f = \frac{1}{\alpha_1 c_p O} \tag{82}$$

$$R_i = R_{h,i} + R_{ins,i} = \frac{1}{h_{c,i} + h_{r,i}} + \sum_j^n \frac{d_{j,i}}{k_{j,i}} \tag{83}$$

$$R_o = R_{h,o} + R_{ins,o} = \frac{1}{h_{c,o} + h_{r,o}} + \sum_j^n \frac{d_{j,o}}{k_{j,o}} \tag{84}$$

5.2.3 Numerical thermally thin surrounding structures with/without insulation

These equations can be solved with iteration for the varying parameters.

$$\theta_{core}^{j+1} = \frac{\Delta t}{(d\rho c^{j})_{core}}\left(\frac{\theta_f^j - \theta_{core}^j}{R_i^j} - \frac{\theta_{core}^j}{R_o^j}\right) + \theta_{core}^j \tag{85}$$

$$R_i^j = \frac{1}{h_{c,i} + \varepsilon\sigma\left({T_f^j}^2 + {T_{s,i}^j}^2\right)\left(T_f^j + T_{s,i}^j\right)} + \frac{d_{ins,i}}{k_{ins,i}} \tag{86}$$

$$R_o^j = \frac{1}{h_{c,o} + \varepsilon\sigma\left({T_{s,o}^j}^2 + {T_i^j}^2\right)\left(T_{s,o}^j + T_i^j\right)} + \frac{d_{ins,o}}{k_{ins,o}} \tag{87}$$

$$\theta_f^j = \frac{\theta_{core}^j + \alpha_1\alpha_2 O R_i^j}{\alpha_1 c_p O R_i^j + 1} \tag{88}$$

$$\theta_{s,i}^j = \theta_f^j - \frac{R_{h+r,i}^j}{R_i^j}\left(\theta_f^j - \theta_{core}^j\right) \tag{89}$$

$$\theta_{s,o}^j = \theta_{core}^j - \frac{R_{ins,o}^j}{R_o^j}\left(\theta_{core}^j\right) \tag{90}$$

5.3 Excel spread sheet

The Excel spread sheet was constructed with assistance of the excel program VBA (Visual Basic for Applications), which uses a programming language. The program enables the users to perform repetitive tasks in excel automatically instead of manually (Chinowsky 2009).

The equations that were used in the sheet are the equations used for numerical solutions of the fire temperature, represented in chapter 5.2 above and equation (91). The spread sheet also includes the analytical solutions for semi-infinite walls and thermally thin walls with or without insulation.

To solve the numerical solution in chapter 5.2 the dynamic heat balance for the hot gases in the compartment was introduced and a numerical forward scheme technique was used with equation (91) instead of equation (88). This is only a method to perform the calculations and the affect the results are negligible.

$$\theta_f^{j+1} = \frac{\Delta t}{c_p^j \rho_{air}^j V_c}\left(\alpha_1 \alpha_2 A_o \sqrt{H_o} - \alpha_1 c_p^j A_o \sqrt{H_o}\theta_f^j - A_{tot}\frac{\theta_f^j - \theta_{core}^j}{R_i^j}\right) + \theta_f^j \quad (91)$$

Numerical calculations in excel, with assistance from VBA, makes it possible to let parameters vary with temperature. The only parameters that are forced to vary with temperature in the numerical solutions in the spread sheet are the convection- and radiation heat transfer coefficients.

The design of the Excel spread sheet and a short manual is presented in Appendix F.

6 Analysis

The equations that have been derived for the new model have been analysed in this chapter. They are analysed in two ways; first the solution for the time-temperature curve will be analysed to see the difference if the parameters are held constant in the analytical solution or if the parameters are varying in the numerical solution. Then the new method is compared with older, more accepted, methods, which have been described in chapter 5 i.e. the MQH-method and the EUROCODE method.

Examples of how the analytical solutions can be applied on practical problems can be seen in Appendix G.

If not specified otherwise, the following input values have been used as the constant parameters in chapter 0 and 6.2.

Table 4 Input values for parameters used when comparing analytical- and numerical solutions.

Parameter	Variable	Value	Unit
Opening factor	O	0.04	$m^{1/2}$
Flow factor	α_1	0.5	$kg/m^{5/2}s$
Combustion yield	α_2	1518000	J/kg
Convection heat transfer coefficient fire exposed side	$h_{c,i}$	25	W/m^2K
Convection heat transfer coefficient non-fire exposed side	$h_{c,o}$	4	W/m^2K
Specific heat for air	c_p	1150	J/kgK
Core thickness	d	0.003	m
Core specific heat capacity	c	460	J/kgK
Core density	ρ	7850	kg/m^3

6.1 Analysis of analytical solution for semi-infinite surrounding structures

The new model for semi-infinite solids has a curve that is very similar to the ISO 834 curve and the parametric fire curve from EUROCODE 1. If the same input for every parameter is used, the new model result in roughly 100 ^{0}C lower temperatures, see Figure 17. The fire temperature from the new model is actually the wall surface temperature, see chapter 4.4.1, since the heat transfer resistance between the wall and the fire is neglected. If the heat transfer resistance is taken into account, the fire temperature will increase. The ISO 834 fire curve includes the heat transfer resistance and will therefore receive a higher temperature than the new model. The impact from the heat transfer resistance is not evaluated in this report.

If the time constant, τ is altered and set to 1270 seconds, the shape of the curve from the new model is very similar to the ones in EUROCODE, see Figure 24. The new model is also sensitive for surrounding structures with different thermal inertia and different opening factors, like the parametric fire curves according to EUROCODE 1.

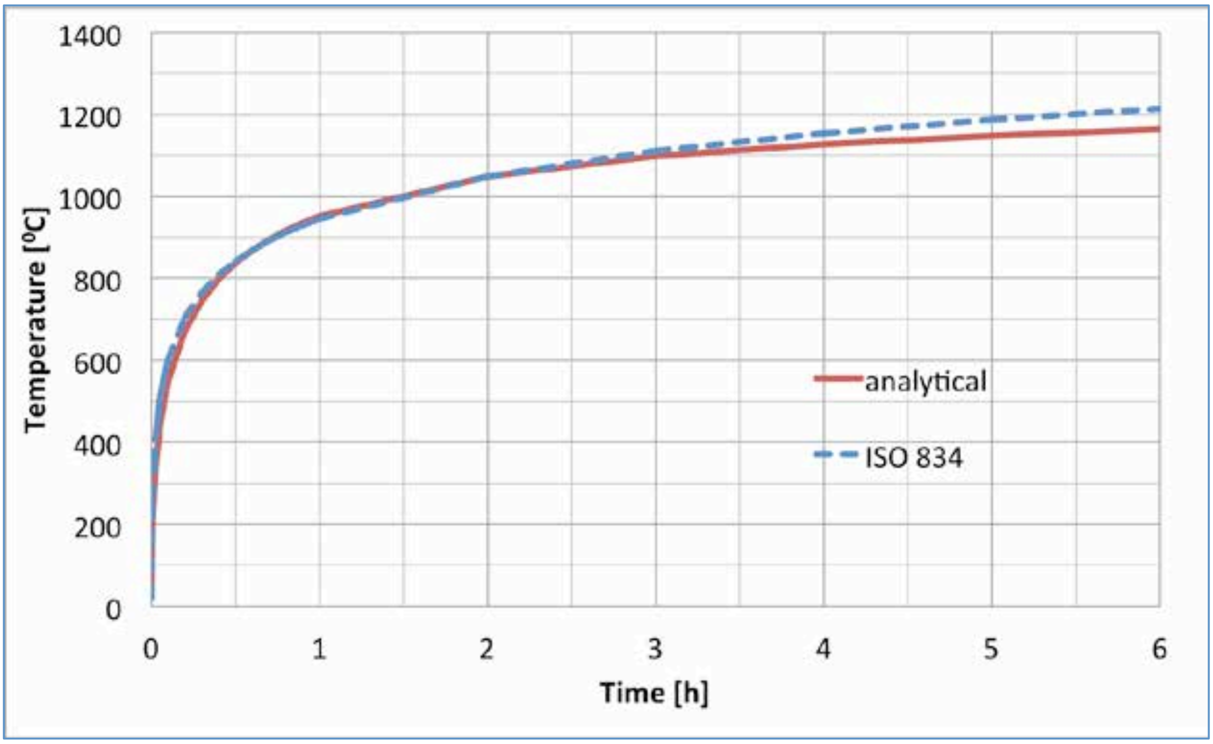

Figure 24 Calculated fire temperatures for semi-infinite walls with constant parameters. O = 0.04 $m^{1/2}$, c_p = 1150 J/kgK, α_1 = 0.5 $kg_{air}/m^{5/2}s$, α_2 = 1518000 J/kg, $\sqrt{k\rho c}$ = 1160 $Ws^{1/2}/m^2K$ and $\boldsymbol{\tau}$ =1270 s.

6.2 Analysis of constant vs. varying heat transfer resistances for thermally thin surrounding structures

The inside and outside convection- and radiation heat transfer resistances $R_{h,i}$ and $R_{h,o}$ can either be chosen constant and the analytical solution can be applied, or the convection and radiation heat transfer resistances can be calculated as functions of temperature and a numerical solution must be used. How sensitive the calculated fire temperature is for choosing different constant values, compared to calculate it as in equation (86) and (87), is analysed in this chapter for different amounts of insulation.

For steady state conditions after long time the value for the inside and outside convection and radiation heat transfer resistances can be calculated with equation (71), (72), (74), (75) and (76). Higher amount of insulation give higher maximal fire temperature, which results in lower heat transfer resistance on the fire-exposed side $R_{h,i}$. Higher amount of insulation do also give lower outside surface temperature, which results in higher heat transfer resistance on the non-fire exposed side $R_{h,o}$. These phenomena are illustrated in Figure 25. This figure gives an indication of what values that should be used as constant values for the convection- and radiation heat transfer resistances when using the analytical solution.

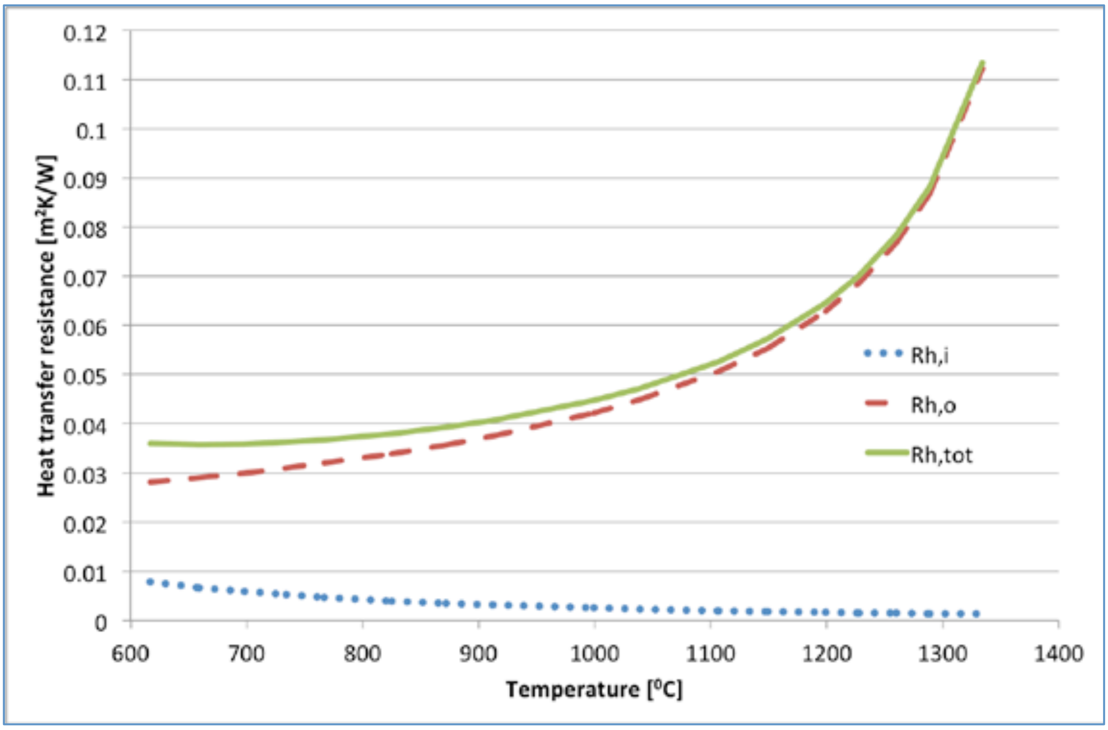

Figure 25 Convection- and radiation heat transfer resistance for the fire exposed side and the non-fire exposed side at steady state conditions for different maximal fire temperature caused by higher amount of insulation.

6.2.1 Moderate insulation on both sides

The core is insulated on both sides with 26 mm thick gypsum plaster; see Table 1, and the impact on the fire temperature for different convection and radiation heat transfer resistances are examined.

Figure 26 describes how the fire temperature changes with time if it is solved analytically with constant $h_c + h_r$ or numerically where $h_c + h_r$ are varying with temperature. The insulations $R_{ins,i}$ and $R_{ins,o}$ are both set to 0.052 m^2K/W for 26 mm gypsum plaster, and the thermal resistances from the air to the surface are added. The heat transfer resistances from the air to the surfaces vary for different temperatures and it is therefore hard to designate a universal constant for these resistances.

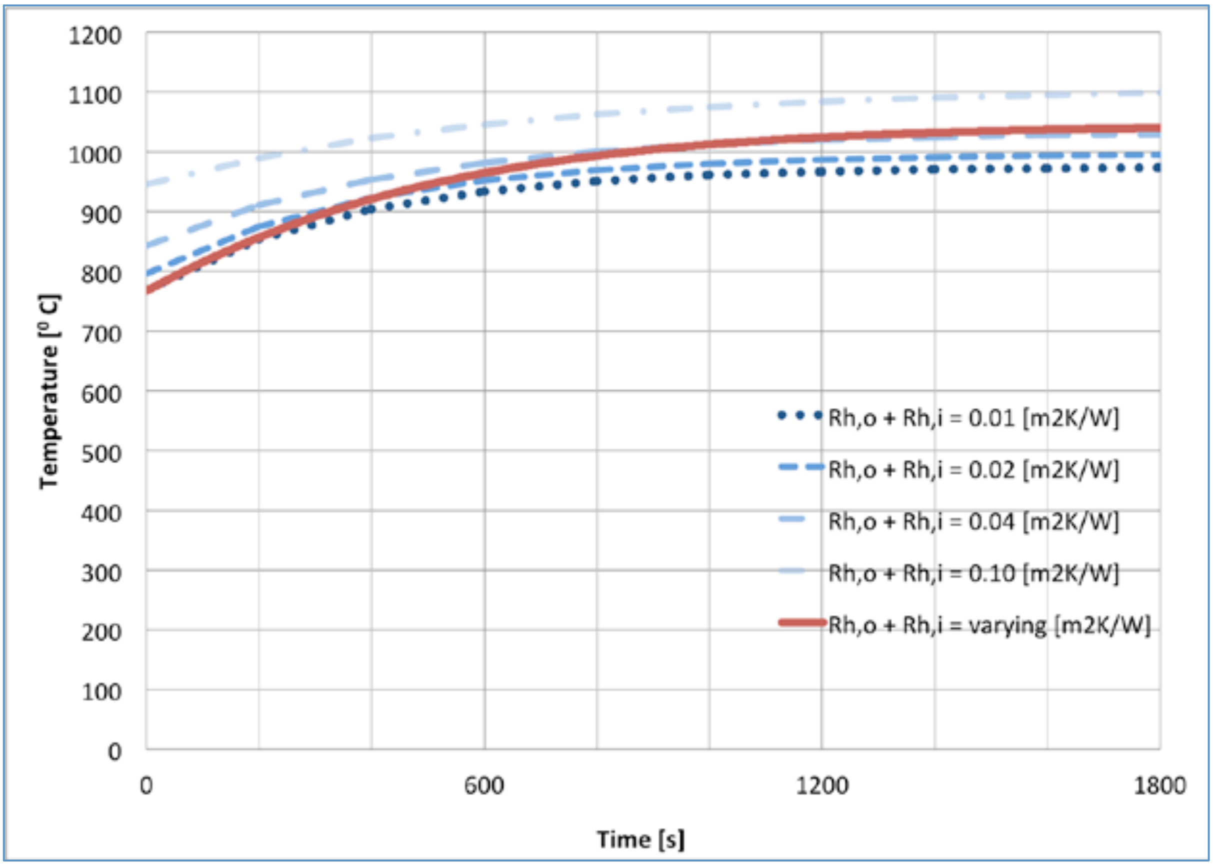

Figure 26 Fire temperature with constant- and varying convection and radiation heat transfer resistances. $R_{ins,i} = R_{ins,o} = 0.052$ m^2K/W. $R_{h,i}$ and $R_{h,o}$ are varying as in equation (67) and (68).

Constant- and varying heat transfer resistances give similar fire temperature curves and the difference between them is solely depending on the difference in heat transfer resistance, see Figure 26. When the insulations are reduced, see Figure 27, the heat transfers resistances have more influence, and are more important, for an accurate fire temperature. Figure 26 and Figure 27 both show how difficult it is to assign appropriate constant values for the convection- and radiation heat transfer resistances instead of calculating them as in equation (86) and (87).

6.2.2 No insulation on either side

The core is non-insulated on both sides and the impact on the fire temperature for different convection- and radiation heat transfer resistances are examined.

For non-insulated thermally thin walls it becomes more important to take into account the heat transfer resistance between the air and the surface, see Figure 27. The constant heat transfer resistance results in a wide spread of temperatures, which illustrates that it is harder to assign a correct constant value for less insulation.

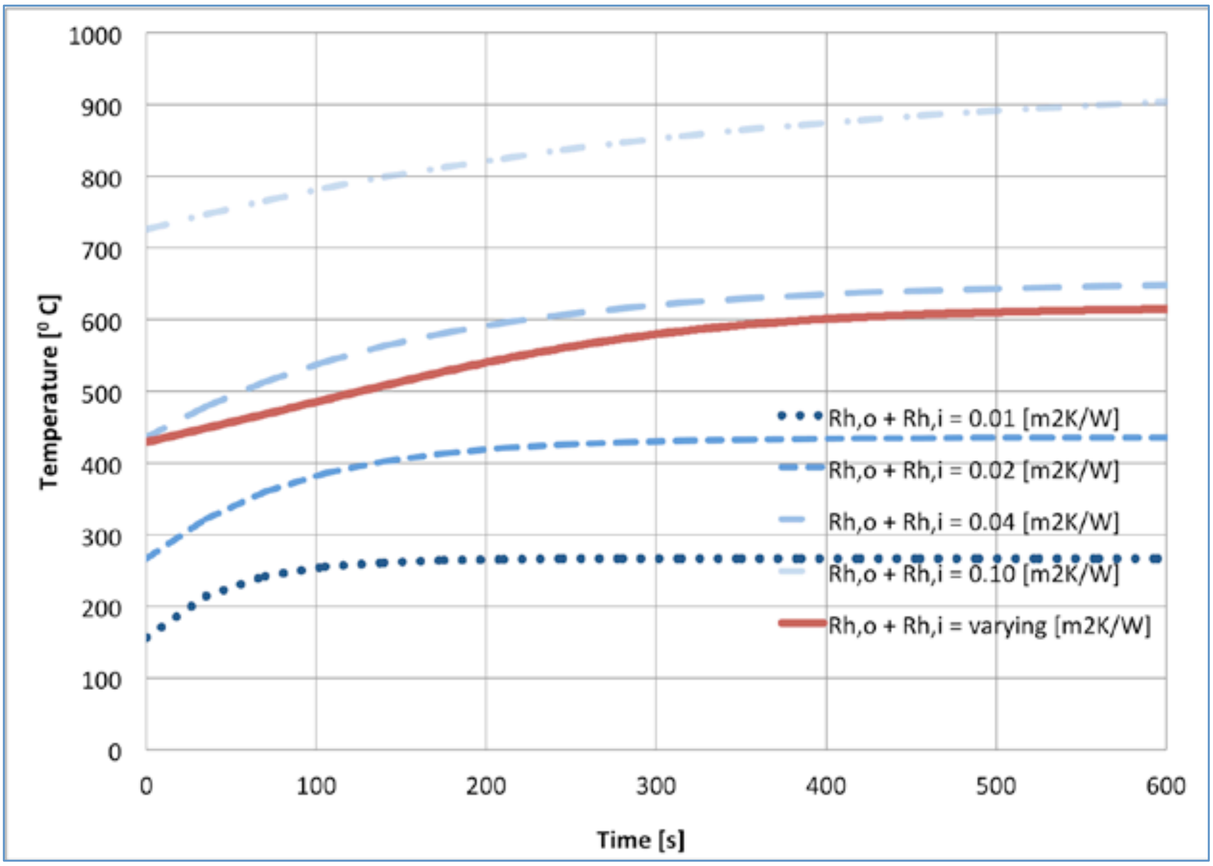

Figure 27 Fire temperature with constant- and varying convection and radiation heat transfer resistances. $R_{ins,i} = R_{ins,o} = 0$ m^2K/W. $R_{h,i}$ and $R_{h,o}$ are varying as in equation (67) and (68).

6.2.3 Well insulated on the non-fire exposed side

The core is only insulated on the non-fire exposed side with 45 mm fibre insulation board; see Table 1, and the impact on the fire temperature for different convection- and radiation heat transfer resistances are examined.

The fire temperature will also be affected by where the insulation is placed. This is displayed in Figure 28 and Figure 30. In Figure 28, $R_{ins,i}$ = 0 m^2K/W and $R_{ins,o}$ = 1.1 m^2K/W, which means that the insulation is placed on the non-fire exposed side of the wall. In Figure 30, the insulation is placed on the fire exposed side of the wall since $R_{ins,i}$ = 1.1 m^2K/W and $R_{ins,o}$ = 0 m^2K/W. These figures indicate that when the walls are greatly insulated on the fire-exposed side, the fire temperature will rise very fast and reach the maximal fire temperature for the compartment quickly. When the walls are greatly insulated on the non-fire exposed side, the thickness and specific heat capacity of the core will determine how the fire temperature will develop. If the core is directly exposed by the fire, it will receive a higher temperature, which makes it more vulnerable.

The difference between the results is because of the difference between the constant- and varying heat transfer resistances. When the convection- and radiation heat transfer resistances are relatively small for higher temperature, i.e. when the core is greatly insulated on either side, the maximal fire temperature is not affected considerable; see Figure 28 and Figure 30.

If more thermal resistance is added to the fire-exposed side, to compensate for the heat transfer resistance, the fire curve will become straighter. It will thus have a higher fire temperature in the beginning in comparison to if it has less thermal resistance. However, it will thereafter straighten out and all curves will thereby receive the same fire temperature after some time i.e. independent of what thermal resistance that is added to the fire-exposed side, see Figure 28. The reason for this behaviour is because of how the analytical solution is derived and how it is defined, see equation (79) and (81). Figure 28 also indicates the difficulties for choosing an appropriate value to correspond to the convective and radiation heat transfer resistances. A higher thermal resistance does not necessary mean more conservative temperatures for all times, even though that is the most instinctive analysis.

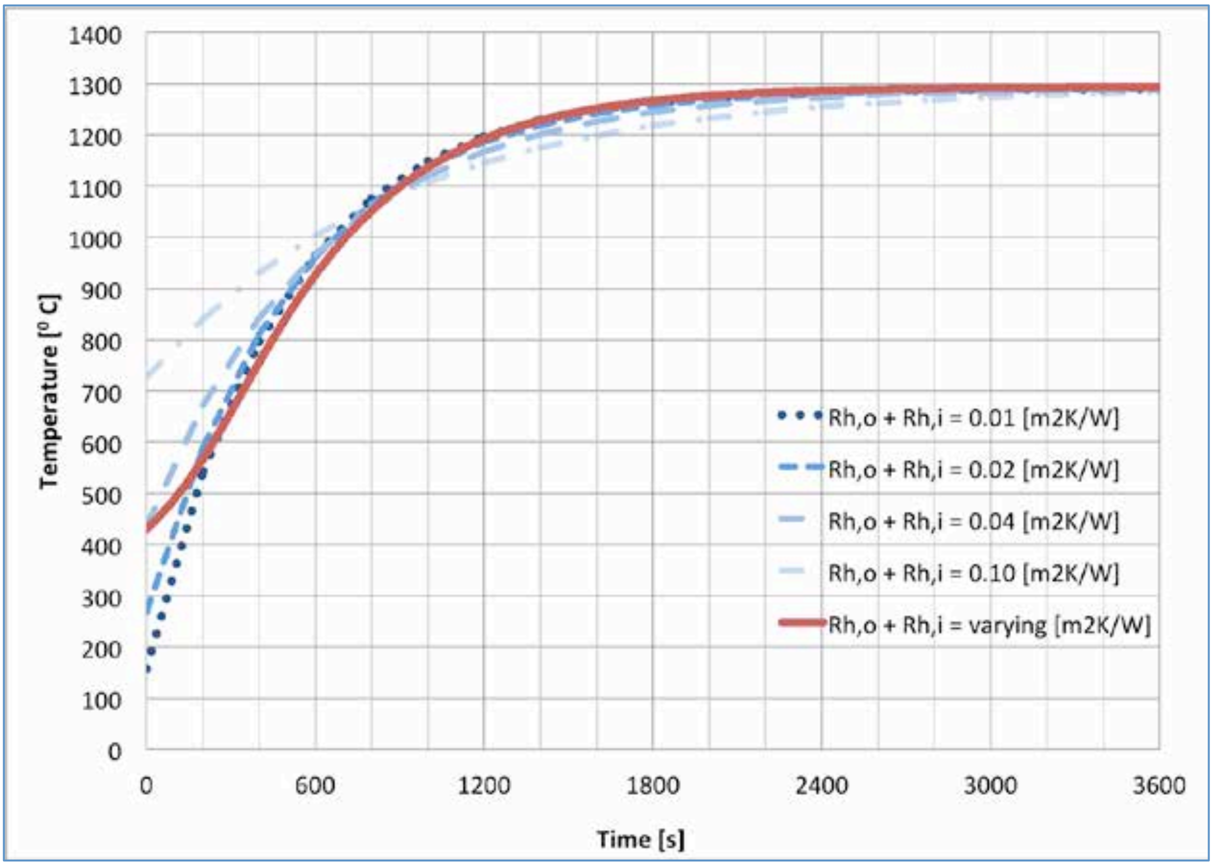

Figure 28 Fire temperature with constant- and varying convection and radiation heat transfer resistances. $R_{ins,i}$ = 0 m^2K/W and $R_{ins,o}$ = 1.1 m^2K/W. $R_{h,i}$ and $R_{h,o}$ are varying as in equation (67) and (68).

A consequence for adding a large thermal resistance, to achieve a safer result with higher fire temperature, is that the corresponding core temperature will decrease with higher resistance. Decreasing core temperatures means that the results actually become less safe for the core, when adding extra resistance, see Figure 29. It is important to keep this in mind when e.g. dimensioning fire protection.

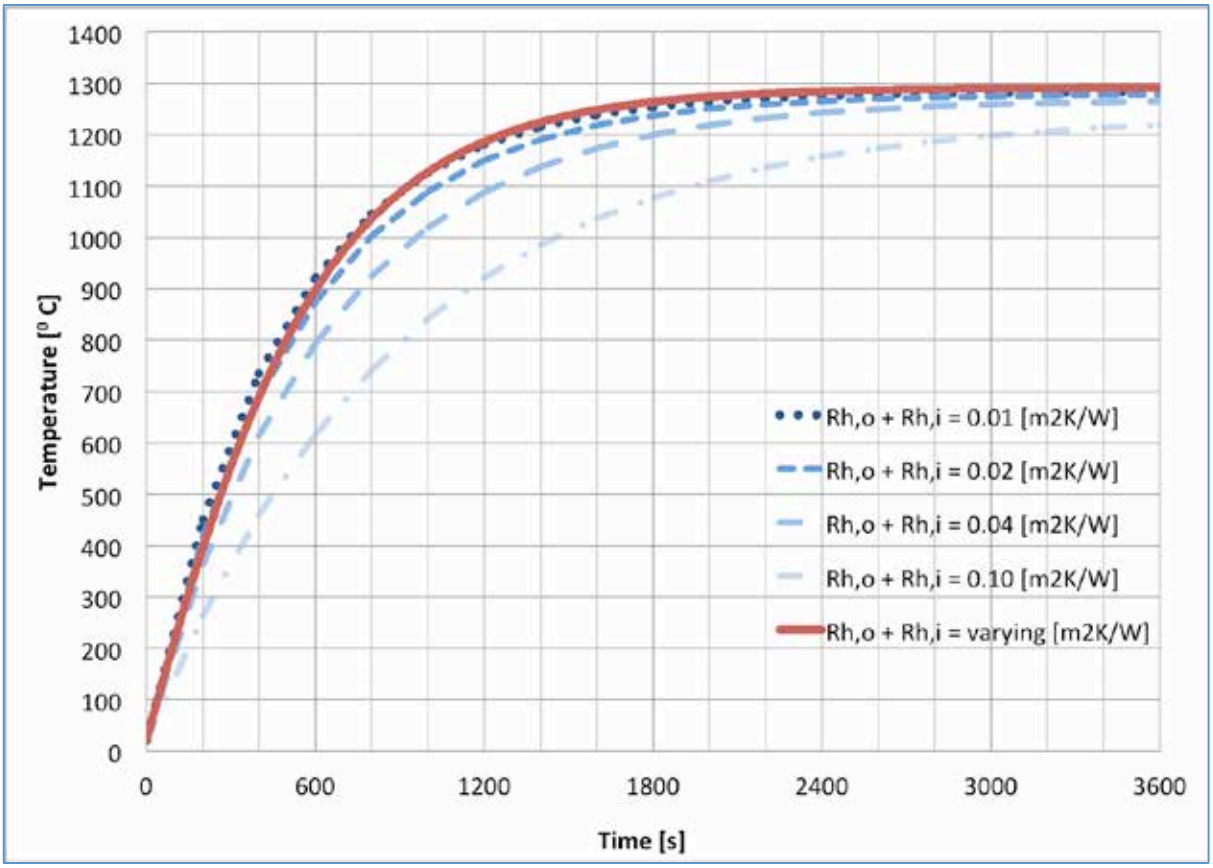

Figure 29 Core temperature with constant- and varying convection and radiation heat transfer resistances. $R_{ins,i}$ = 0 m^2K/W and $R_{ins,o}$ = 1.1 m^2K/W. $R_{h,i}$ and $R_{h,o}$ are varying as in equation (67) and (68).

6.2.4 Heavily insulated on the fire exposed side

The core is only insulated on the fire exposed side with 45 mm fibre insulation board; see Table 1, and the impact on the fire temperature for different convection- and radiation heat transfer resistances are examined.

As stated before, when the fire-exposed side is greatly insulated, neither the fire temperature nor the core temperature is significantly affected by whether the convection- and radiation heat transfer resistances are taken into consideration or not, see Figure 30. The figure below shows that the convection- and radiation thermal resistance have little impact since it is relatively small in comparison to the insulation.

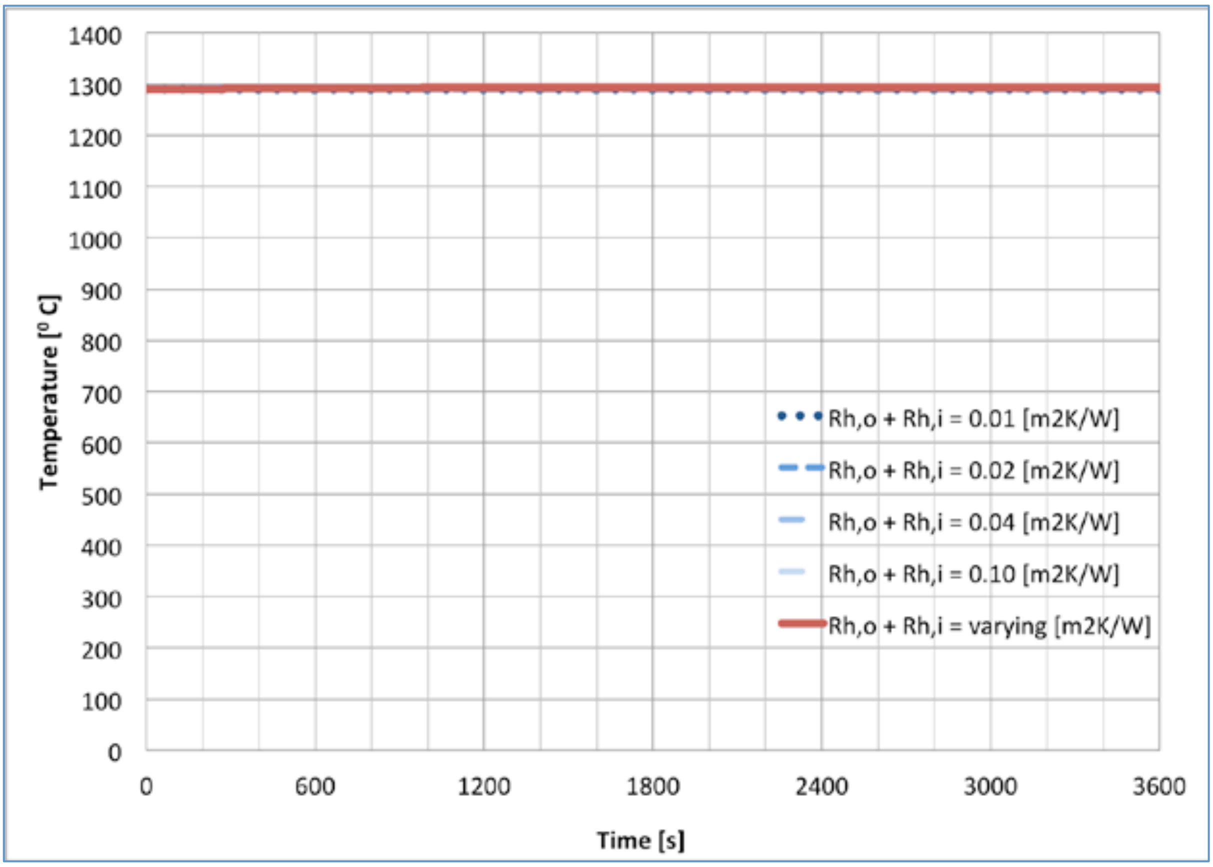

Figure 30 Fire temperature with constant- and varying convection and radiation heat transfer resistances. $R_{ins,i}$ = 1.1 m^2K/W and $R_{ins,o}$ = 0 m^2K/W. $R_{h,i}$ and $R_{h,o}$ are varying as in equation (67) and (68).

6.3 Comparison between new model and other models for different cases

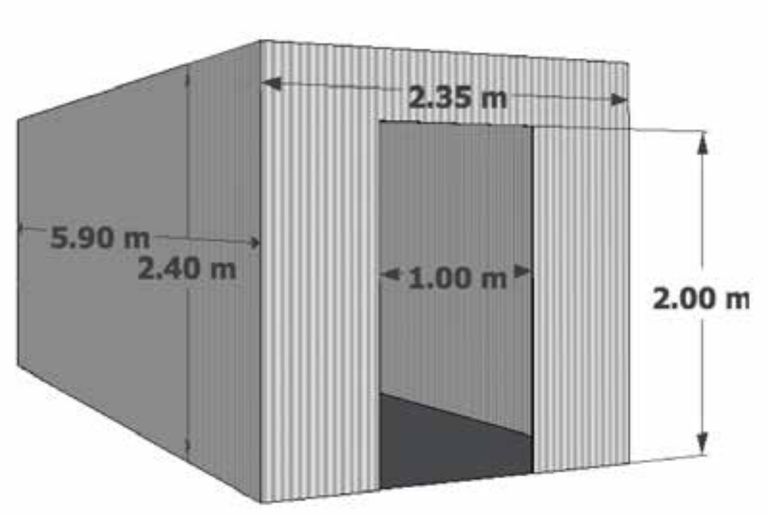

Figure 31 Compartment geometry used in case 1,2 and 3 (Back 2012).

6.3.1 Case 1 – Concrete bunker (representing semi-infinite thick surrounding structures)

The compartment geometry is based on the experiments performed by Anna Back, and matches the geometry in case 2 and case 3 (Back 2012). Despite from the compartment geometry, the properties of the walls and the results are not related to Back's work.

Table 5 Parameter values used in case 1.

Parameter	Variable	Value	Unit
Width	W	2.35	m
Length	L	5.90	m
Height	H	2.40	m
Opening area	A_o	2	m^2
Opening height	H_o	2	m
Opening ratio	$A_o\sqrt{H_o}$	2.82	$m^{3/2}$
Total enclosure area	A_{tot}	67.33	m^2
Opening factor	$A_o\sqrt{H_o}/A_{tot}$	0.042	$m^{1/2}$
Concrete conductivity	k	1.7	W/mK
Concrete density	ρ	2300	kg/m^3
Concrete specific heat	c	900	J/kgK
Concrete thermal inertia	$\sqrt{k\rho c}$	1876	W^2s/m^4K^2

The parametric fire model according to EUROCODE 1 has been calculated with the equations (2) and (3) in Appendix C, with the values from Table 5. The analytical curve is based on the new curve for semi-infinite solids introduced in this report and calculated with equations from chapter 5.2.

Comparing the analytical model with the parametric fire model in Figure 32 shows that the new analytical model is at least 100^0C colder than the parametric fire curve according to EUROCODE 1. This can partially depend on the fact that the fire temperature is assumed equal to the surface temperature. The lower fire temperature in the new model indicates that it needs further investigation.

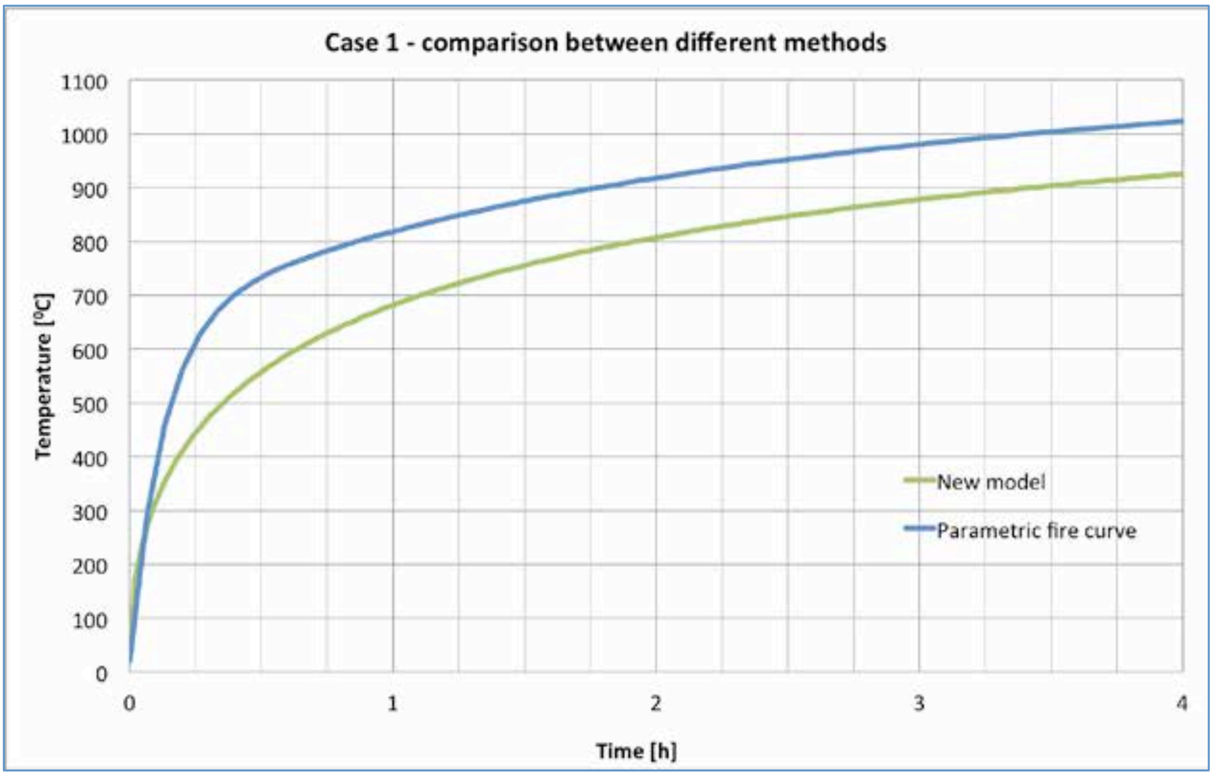

Figure 32 Comparison between different calculation methods for a concrete bunker (case 1).

6.3.2 Case 2 –Steel container (without insulation)

Case 2 is based on experiments made by Anna Back, who made experiments in a container. The experiments are described so detailed that they are easy to use as input parameter references and to compare the results with calculations by different models. Since the experiments with heptane fuel had a more constant heat release rate, those experiments are used for comparison (Back 2012).

Table 6 Parameter values used in case 2.

Parameter	Variable	Value	Unit
Width	W	2.35	m
Length	L	5.90	m
Height	H	2.40	m
Opening area	A_o	2	m^2
Opening height	H_o	2	m
Opening ratio	$A_o\sqrt{H_o}$	2.82	$m^{3/2}$
Total enclosure area	A_{tot}	67.33	m^2
Opening factor	$A_o\sqrt{H_o}/A_{tot}$	0.042	$m^{1/2}$
Steel thickness	d	0.003	m
Steel conductivity	k	45	W/mK
Steel density	ρ	7850	kg/m^3
Steel specific heat	c	460	J/kgK
Steel thermal inertia	$\sqrt{k\rho c}$	3300	W^2s/m^4K^2

The MQH curve is based on the values in Table 6 and the measured heat release rate from the experiments (Back 2012), and is calculated according to equations in Appendix A. The new model curve, with varying parameters is based on the numerical solution for thermally thin solids introduced in this report and calculated with the equations in chapter 5.2.

Since the experiments resulted in a two-zone scenario with one hot- and one cold zone, it is not optimal to compare the post-flashover model, which has been introduced in this report. Despite from this fact, it is interesting to see how well this experimentally registered hot layer temperature compare to this new one-zone model´s temperature.

The MQH method for thermally thin models does not match the experiments. This can likely be explained by the fact that the MQH method does not take into consideration the heat transfer coefficients, which have great impact when the thermal resistance inside the wall is small.

The new model, where parameters are varying in the numerical solution, shows realistic fire temperatures but the maximal fire temperature is slightly lower than the experimentally registered fire temperatures. Even though the new model only depends on the compartment properties, it shows temperatures comparable with the experimental results. One possible reason to this difference could be that the model do not take into consideration how the temperature is distributed, since it is approximated as evenly distributed in the compartment.

The difference could also be a result from parameters that have been used, which do not vary with temperature in the model, as they do in reality.

Even though the results are not completely accurate, the new model indicates very well the fire temperature development. It should also be taken into account that the model is a one-zone model, created for post-flashover scenarios, and that it estimate the fire temperature for this case very good. In Figure 33 it appears as if the experimentally measured fire temperature is very precise, this is not the case. The measured values fluctuate up and down with roughly estimated 10 %, and the measured values do not show the exact temperature, since it is an average temperature taken from a number of measure points.

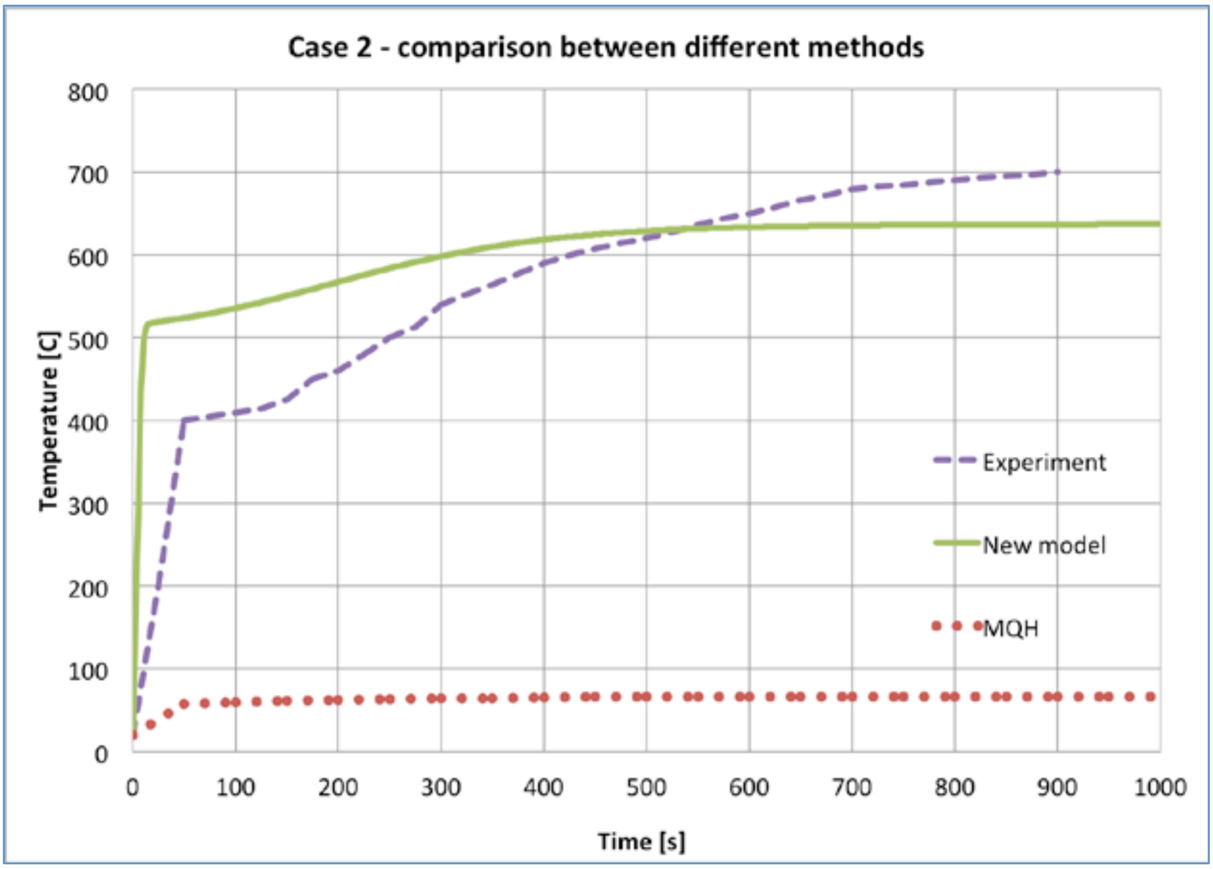

Figure 33 Comparison between different calculation methods for a steel container without insulation (case 2) and the experimental result (Back 2012).

6.3.3 Case 3 – Steel container (with insulation)

Case 3 is based on same experiments, made by Anna Back, which was mentioned in section 6.3.2. (Back 2012).

Table 7 Parameter values used in case 3.

Parameter	Variable	Value	Unit
Width	W	2.35	m
Length	L	5.90	m
Height	H	2.40	m
Opening area	A_o	2	m^2
Opening height	H_o	2	m
Opening ratio	$A_o\sqrt{H_o}$	2.82	$m^{3/2}$
Total enclosure area	A_{tot}	67.33	m^2
Opening factor	$A_o\sqrt{H_o}/A_{tot}$	0.042	$m^{1/2}$
Steel thickness	d	0.003	m
Steel conductivity	k	45	W/mK
Steel density	ρ	7850	kg/m^3
Steel specific heat	c	460	J/kgK
Insulation thickness	d_{ins}	0.095	m
Insulation conductivity	k_{ins}	0.037	W/mK
Insulation density	ρ_{ins}	30	kg/m^3
Insulation thermal inertia	$\sqrt{k\rho c}$	57.45	W^2s/m^4K^2

The new model curve is calculated by the numerical solution for thermally thin solids, introduces in this report, and calculated with equations from chapter 5.2.3. Flashover is assumed to happen after 200 s. when the measured fire temperature from the experiments has reached a temperature of 550 ^{0}C. The new model is valid when flashover has occurred. The EUROCODE- and MQH models are not valid for this case.

The new model, calculated with the numerical solution, where parameters are varying, show good accuracy for the fire temperature measured from the experiments, even though it is a one-zone model created for post-flashover scenarios, see Figure 34. As in case 2, it appears as if the measured fire temperature from the experiment is very precise, but this is not the case in this scenario either. The measured fire temperature fluctuate with approximate 10 % up and down, which still might be slightly inaccurate since the fire temperature is an average temperature from a number of measure points.

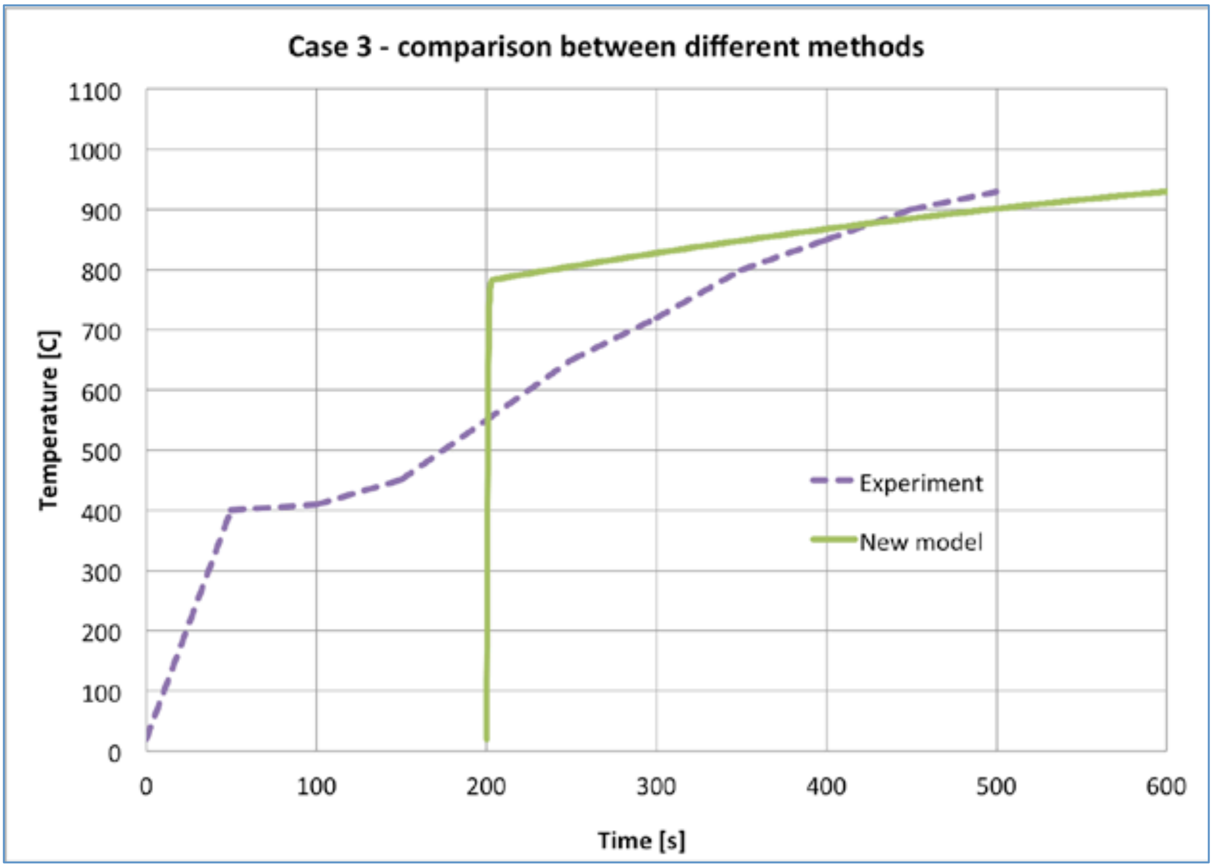

Figure 34 Comparison between different calculation methods for a steel container with insulation (case 3).

7 Discussion

This chapter will discuss the result and the analysis of the new model that has been derived, where the focus is on the reliability and sensitivity of the new model. Finally, some suggestions for further researches are listed.

7.1 Model for semi-infinite surrounding structures

The new model for semi-infinite walls results in a fire temperature lower than the parametric fire curves according to EUROCODE 1 and the ISO 834 fire curve, see Figure 17 and Figure 32. If the heat transfer resistance between the fire and the wall is taken into consideration, the fire temperature will be higher for the new model.

The new model starts after flashover has occurred and therefore the heat transferred to the surrounding structure before flashover is not taken into consideration. In reality, the surrounding structures absorb heat before flashover and if that is taken into consideration the surrounding structure will become insulating faster and the fire temperature will increase. The fact that the fire temperature actually is the surface temperature, in the new model, also motivates that the fire temperature should be higher. A further development of the model should include the heat transfer effects.

7.2 Model for thermally thin surrounding structures with/without insulation

7.2.1 New model VS other models

In the analysis, the new model was compared with mostly post-flashover scenarios but also one pre-flashover scenario. The reason to why the new calculation model is compared with a pre-flashover case, in chapter 6.3.2, is to see how well it corresponds to the gas temperature received from experimental trials. It is generally not valid to compare the new model to pre-flashover scenarios but it indicates how bad the MQH method is for thermally thin surroundings because it does not take into account the heat transfer resistances, which the new model does, see Figure 33. The new model is a one-zone model and it is fairer to compare this model to e.g. the method of Magnusson and Thelandersson and the parametric fire model according to EUROCODE 1. Even if the fire does not become fully developed and is within the restricted lines for the model, the MQH model gives bad results, mainly since it does not consider the convection and radiation heat transfer resistances. This is one of the reasons why the new model was constructed, to make a model, which works better for fires within thin surrounding structures. The MQH- method was thereby compared with the new model, to be able to conclude if the new model was better adjusted to these kinds of fire scenarios.

In case 2, where the container fire is investigated, it is clear that the new model has better accuracy compared to the experiments than the MQH-method. Similar conclusion is found in case 3, where an insulated steel container was studied, where the new model gives good indications of the fire temperature after flashover has occurred.

The new model is in the realistic range of the experimental curve for all of the cases, which indicates that it can be trustworthy.

Something else that is working for the new models advantage is that it does not depend on experimental results like the other methods do. When a method is constructed from experiments, the method will be restricted to scenarios that have the same look as the tested enclosures. The new model on the other hand has been built analytical and later on compared with experiments, which makes the model less limited. This can be a reason why the model has such a good agreement with the experimental results in case 2 and 3 in comparison to the other methods, which not are valid for the scenarios that are described.

7.2.2 Analytical VS Numerical solution

Conformity between the different solutions

The analytical solution, where parameters are held constant and the numerical solution, where parameters are varying, give the same results, since they are based on the exact same assumptions and approximations. The main difference between them is that the numerical solution calculates the appropriate convection and radiation heat transfer resistances, depending on temperature, for the fire development. For the analytical solution a constant value for this parameter must be chosen. The heat transfer resistances R_{h+r} are varying and are higher for lower temperatures and decreases rapidly as the temperatures increase.

The maximal fire temperature for the analytical solution for thin surrounding structures can alternatively be chosen from Figure 12 and Figure 15. The analytical solution will then approach a maximal temperature that, by iteration, takes the heat transfer resistance for convection and radiation into account by calculation.

One advantage the numerical calculation has is that it can let parameters vary with temperature or time. Even though this can be made possible for some parameters, it might not be the best option. If many parameters are varying and depending on the temperature, the result might give the impression that they are more accurate. However, as mentioned earlier, a fire is very complex and many assumptions and approximations have already been made about the fire development in general and in the model, which makes the result uncertain. For example, the specific heat capacity for the hot gases is approximated as specific heat capacity for air at constant pressure, even though many other products than air exist in the hot gases for fire situations. It may, for example, not be reasonable to let the specific heat capacity vary as if it were air under normal circumstances, since it is much more complicated than that.

The Excel-sheet application

There are two different numerical solutions possible for the new model, one that is used in the report that requires iteration, and one that is used in the Excel-sheet based on forward scheme calculations. The difference between the results are approximately zero, since the calculation method used in the Excel spread sheet is based on the dynamic heat balance for the air in the compartment, which is very small. The main difference is the way the calculations are performed.

The application that was made is very fast and does also give only the most important information about the fire. This is the main difference between this application and other computer-programs like FDS, described in chapter 3.6. FDS has very long simulation time and do often give more information about the fire than needed. Results from an FDS-simulation are however easy to understand and overlook when represented in the program Smokeview. Sometimes a result is wanted that can be delivered quickly and gives a direction of how the fire is going to develop, which the Excel application can offer. Another major advantage of using an Excel application is that it is easy to understand and it is easy to alter parameters such as; compartment geometry, amount of insulation properties for the walls and air to give a quick hint of what impact different input values have on the fire temperature.

7.3 Future research

There are still various things that are unsure in the new model and it is necessary for more studies to be able to use the model unrestricted. A few suggestions are listed below.

- More fully developed fire- experiments are needed for enclosures with thin surrounding structures, i.e. the container fire. Today, these cases are hard to find, however they are needed to make the assumptions more valid and bring out the insecurities of the model.
- The new model needs to be compared with more experiments to see how well it adjusts to different kinds of scenarios. Then it will be easier to identify what limitations the model has.
- Compare the new calculation model with computer models for calculations on room fire scenarios, e.g. FDS, to see if the models correspond to each other.
- The impact of the different parameters in an enclosure fire needs further investigation e.g. the combustion efficiency, which is included in α_2. It is set to 50 % and has a great impact on the fire temperature and might be higher or lower than 50 %.
- Improve and investigate the model for semi-infinite surrounding structures e.g. take into consideration the heat transfer resistance between the fire and the surface and the heat loss as radiation through the openings.

8 Conclusions

This work had a purpose to find a simple model for calculating the fire temperature for different fire scenarios. The objective was to make the model trustworthy and also to construct a user-friendly Excel- application for calculations on different fire scenarios. A few questions were asked in the beginning of the work, chapter 1.2.2, and they are answered in this chapter.

- **What are the main uncertainties in the calculation methods used today?**

Almost all of the calculation methods that are used today are based and validated on experimental research. The experiments have been executed in an environment to simulate a room fire. First of all, the experimental basis makes the methods restricted to be valid for only the scenarios that the method has been tested for. Second of all, since the methods have only been tested for room fire scenarios with rather thick walls, there is a lack of models that fits the fire scenario within thin surrounding structures.

The methods are most often used for all kinds of fire scenarios since the users are not aware of their limits and sometimes the creators of the methods may not be aware of all the limits of the method either. If the method is well known, the users are more likely to trust the results even though it gives strange results.

- **Is there a need for a new calculation model?**

As pointed out in the previous question, there are some uncertainties in the methods that are used today. Even though most of the methods work within their limits, there is not one model that has been brought up in this work that is adjusted to fire within thin surrounding structures. There is therefore a need for a new model which is less limited and that can be used for calculating the fire temperature within both semi-infinite- and thin surrounding structures. If the model is less restricted, it will be easier to use, which in turn makes the results more likely to come out correctly.

- **What parameters are of significance in a fire scenario?**

All of the parameters in a fire scenario have, more or less impact in how a fire is going to develop. The material properties in the compartment, i.e. the thermal inertia, have a significant part in fire scenarios within semi-infinite surrounding structures. However it is hard to find out how the material properties changes with temperature. They are often only known for specific states, e.g. very precise temperatures. The fire gets affected of these changed properties but there is hard to tell how much and if it is even worth to take into account.

For the final temperature in a compartment, it seems like the combustion efficiency and the specific heat capacity of the hot gases in the compartment have most importance. However, for the fire development with time, the compartment geometry and the thermal properties of the surrounding structure have most importance.

It seems like different parameters have more or less significance on different parts in a fire scenario. More research is thereby needed to make sure how all the depending parameters should be taken care of.

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