Fire development in passive houses: qualitative description and design of full-scale fire tests

David Vanhaverbeke

Promotor: Prof. Stephen Welch

Co-promotor: Prof. Bart Merci

Mentor: Ir. Karel Lambert

International Master of Science in Fire Safety Engineering

The University of Edinburgh

2015

This thesis is submitted in partial fulfilment of the requirements for the degree of The International Master of Science in Fire Safety Engineering (IMFSE). This thesis has never been submitted for any degree or examination to any other University/programme. The author(s) declare(s) that this thesis is original work except where stated. This declaration constitutes an assertion that full and accurate references and citations have been included for all material, directly included and indirectly contributing to the thesis. The author(s) gives (give) permission to make this master thesis available for consultation and to copy parts of this master thesis for personal use. In the case of any other use, the limitations of the copyright have to be respected, in particular with regard to the obligation to state expressly the source when quoting results from this master thesis. The thesis supervisor must be informed when data or results are used.

April 29, 2015

read and approved

David Vanhaverbeke

"If anyone builds on this foundation
using gold, silver, costly stones,
wood, hay or straw, their work will
be shown for what it is, because the
day will bring it to light. It will be
revealed with fire, and the fire will
test the quality of each person's
work. If what has been built survives,
the builder will receive a reward."

1 Cor. 3. 12-14

Apostle Paul mentions in his First Epistle to the Corinthians a key feature in the fire safety scene: we build further upon work of others. It is thus very important that each and every one of us is aware of his or her responsibility. We make buildings fire safe. Everyone has to rely on the quality of the work of others, but has also the responsibility of working in a professional and ethical way. One day, fires will strike buildings that are made fire safe by one of us. On that day, our measures taken will show what they are made of: gold, silver, costly stones, wood, hay or straw.

David Vanhaverbeke

Table of contents

List of figures

List of tables

List of symbols

Symbol	Unit	Property
A_{leak}	m^2	Leakage area from a passive house to the outside
A_L	m^2	Leakage area in between two pressure zone in FDS
α	m^2/s	Thermal diffusivity
β	/	A nondimensional ration that expresses the susceptibility of a gas to give a backdraft upon sudden ventilation
c_s	J/kgK	Specific heat of a solid material in FDS
c_p	$kJ/kg\,K$	Specific heat constant
d_{la}	m	Lever arm of a force around a hinge
d_{tp}	m	Thermal penetration depth
δ	/	Nondimensional pressure peak predicting value
F_h	N	Force applied by occupants on the handle of a door
F_p	N	Force applied by gauge pressure on a door
G	%	Solar radiation permeability
ΔH_c	J/kg	Heat of combustion
K	/	Expresses the overall insulation grade. The lower the K-value, the better the insulation
k	/	Correction factor of dampers (Depends on setting value of the damper)
k_s	W/mK	Conductive heat coefficient in FDS
λ (or k)	W/mK	Thermal conductivity
M_d	Nm	Moment of force around the hinges of a door

Symbol	Unit	Property
$\boldsymbol{m}$	kg	Mass
$\boldsymbol{n_{50}}$	h^{-1}	Fraction of the total air volume of the house that leaks out of the house in one hour if the volume is kept at 50Pa overpressure
$\boldsymbol{P}$	Pa	Pressure
$\boldsymbol{\Delta p_m}$	Pa	Pressure difference over a damper
$\boldsymbol{\dot{Q}}$	kW	Heat release rate
$\boldsymbol{\dot{Q}''}$	kW/m^2	Heat release rate per unit area
$\boldsymbol{Q}$	J	Heat
$\boldsymbol{\rho}$	kg/m^3	Density
$\boldsymbol{\rho_s}$	kg/m^3	Density of a solid material in FDS
$\boldsymbol{\rho_\infty}$	kg/m^3	Density of the ambient conditions.
$\boldsymbol{\rho\lambda c_p}$	W^2s/m^4K^2	Thermal inertia
$\boldsymbol{T}$	°C or K	Temperature
$\boldsymbol{U}$	W/m^2K	Value that expresses the heat lost through this object, depending on the temperature difference
$\boldsymbol{\dot{V}_{leak}}$	m^3/s	Leak volume flow rate in between two pressure zones in FDS
$\boldsymbol{V}$	m^3	Volume
$\boldsymbol{V_{pressure\ rise}}$	m^3	Volume available for the pressure to expand
$\boldsymbol{V_{air}}$	m^3	Volume available for the fire to use the oxygen from
$\boldsymbol{\dot{V}}$	m^3/s	Volume flow rate
$\boldsymbol{T_s}$	K	Temperature of a solid material in FDS

Symbol	Unit	Property
$\dot{q}_c''$	$\mathrm{W/m^2}$	Convective heat flux absorbed by a wall in FDS
$\dot{q}_r''$	$\mathrm{W/m^2}$	Radiative heat flux absorbed by a wall in FDS
$\dot{q}_s'''$	$\mathrm{W/m^3}$	Specific heat release rate inside a solid material in FDS
ψ	$\mathrm{W/mK}$	Linear heat transfer coefficient (property of a thermal bridge)
x	m	Distance
y	m	Distance
z	m	Distance

List of acronyms

Acronym	Meaning
AIT	Auto ignition temperature
CFBT	Compartment fire behaviour training
CFAST	Consolidated model of fire and smoke transport
CFD	Computational fluid dynamics
FC/VC	Fuel-controlled/ventilation-controlled
FDS	Fire dynamics simulator
FSE	Fire safety engineering
HRR	Heat release rate
HRRPUA	Heat release rate per unit area
IMFSE	International Master of Science in Fire Safety Engineering
LES	Large eddie simulation
LFL	Lower flammability limit
MFR	Mass flow rate
MLR	Mass loss rate
NIST	National Institute for Standards and Technology
OECD	Organisation for Economic Cooperation and Development
PHP	Passiefhuis platform (passive house platform)
PSA	Probability safety assessment
SCBA	Self-contained breathing apparatus
VEA	Vlaams Energie Agentschap (Flemish Energy Agency)
VIBE	Vlaams Instituut voor Bio- Ecologisch Bouwen en Wonen

Abstract

The growing awareness of the need for sustainability and a smaller ecological footprint results in the construction of more passive and low-energy houses. These houses are better insulated, well-confined and mechanically ventilated. This influences the fire development and turns the gauge pressure created by fire into an important parameter. The forces needed in order to open a door due to this gauge pressure were quantified in this thesis. However, there is no such thing as a passive house that is representative for all other passive houses. Ventilation conditions, materials, volume and fuel load can significantly change. Keeping those arguments in mind, thoughts are given on the pressure built-up for different scenarios.

The temperature and possible forms of rapid fire progress are of interest too. This thesis investigated qualitatively several fire phenomena that could possibly occur: backdraft, pulsing fire behaviour, smoke explosions and ventilation-induced flashover.

Full-scale tests were designed and presented in this thesis. A sensitivity analysis was performed to investigate the influence of lining material, heat release rate, location of the fire and thermal properties of the plaster board. It is investigated which construction type, ventilation system and fire is representative for a passive house. This resulted in the construction of a forty foot shipping container sized building. The concrete block building is insulated and made well-confined so it resembles a passive house. The tests that are designed and presented in thesis, investigate the influence of heat release rate, fuel, room volume and ventilation on pressure and temperature development.

Abstract (Dutch)

Door het groeiende besef dat duurzaamheid en een kleinere ecologische voetafdruk noodzakelijk zijn, worden meer passiefwoningen en lage energie woningen gebouwd. Deze huizen zijn beter geïsoleerd, luchtdicht gemaakt en mechanisch geventileerd. Dit beïnvloedt het brandverloop en maakt van de overdruk, gecreëerd door de brand, een belangrijke parameter. De krachten die nodig zijn om een deur te openen bij deze overdruk worden becijferd in deze thesis. Een passiefhuis dat representatief is voor alle passiefhuizen bestaat niet. Ventilatieomstandigheden, brandlast, materialen en volume kunnen zeer sterk variëren. Dit resulteert in een verschil in opgebouwde druk. Verschillende scenario's worden in deze thesis besproken.

Naast de overdruk zijn ook de temperatuur en alle mogelijke vormen van rapid fire progress heel belangrijk. Deze thesis onderzoekt en bespreekt verschillende brandfenomenen die kunnen voorkomen: backdraft, pulserend brandgedrag, rookexplosies en ventilatie geïnduceerde flashover.

Testen op ware grote zijn ontworpen en voorbereid. Een sensitiviteitsstudie is gemaakt om de invloed van de bekleding, heat release rate, locatie van de brand en de thermische eigenschappen van de pleisterborden te onderzoeken. Er is onderzocht welke constructie, ventilatiesysteem en brand representatief is voor een passiefhuis. Dit leidde tot de bouw van een constructie met dezelfde geometrie als een scheepscontainer van 12 meter lang. Dit gebouw is opgetrokken uit betonblokken, geïsoleerd en luchtdicht gemaakt zodat het de eigenschappen van een passiefhuis heeft. Verschillende testen die de invloed van heat release rate, volume, ventilatie en brandstof op het temperatuur- en drukverloop onderzoeken worden voorgesteld.

1 Introduction and objectives

1.1 Problem description

Different ways of building results in different fires. Different fire developments result in different risks for people and fire fighters. These latter need adapted tactics and techniques for each fire scenario. This is in a nutshell the reason why a good understanding of the possible fire scenarios in a passive house is of key importance.

The evolution towards more insulation and well confined constructions is going on for decades and keeps going (see section 2.2.) The fire risk in these houses has been questioned. Architects, fire brigades and the legislator were not sure about the fire risks and posed questions about the fire safety. Although [1] and [2] answered these questions, there are still some questions and uncertainties about how a passive house will influence a traditional fire curve as is to be expected in a traditional house fire. No full-scale tests have been conducted on this matter, so the questions about this fire development can only be answered nowadays by numerical simulations and reduced-scale experiments. The questions to be answered by the tests designed in this thesis are:

- What will the pressure development look like during a fire?
- What will the maximum temperature be?
- Does the fuel have a significant influence?
- Will the ventilation help the smoke to spread faster?
- Could the ventilation system prevent the smoke from leaving the fire room?

There are, however, answers available to these questions. A literature review and a description of the working principles of fires in passive houses are presented in the next chapters.

This different way of constructing has implications for the evacuation procedure. Since passive houses are expensive to build and the need for opening windows in a passive house is smaller, people could opt to install windows that cannot be opened. This reduces the number of escape routes in case of fire [2]. However, this problem should be limited since by far not all passive houses are equipped with windows that cannot open. Another problem arises with the higher pressure. A gauge pressure between two different rooms results in the need for a higher force to open a door between these two rooms. Elderly people could possibly have problems with opening doors that swing open the wrong side [1].

It is not clear if more rapid fire progress phenomena will be observed in passive house fires. By giving an overview and a description of these rapid fire progress phenomena, this thesis tries to get an idea if these different phenomena are more likely to happen in a passive house.

1.2 Objectives

The main objective of this thesis is to design and prepare full-scale tests to confirm or counter research about fires in passive houses. These tests should give an answer to the questions formulated here. A first important research question is: What is the temperature in the fire room if the fire turns under-ventilated? A second main research question is: What is the pressure evolution during these fires?

Besides these main questions, some additional research questions emerge. When is the temperature low enough so the fire cannot regain strength if a door is opened? Does the fuel have a significant influence on the results? What is the influence of the volume? What is the influence of the ventilation system switched on or off on the pressure development? What is the influence of the heat release rate? Is it possible that ventilation systems can be turned out and off in a smart way depending on where the fire is detected?

These research questions will be answered by the tests designed and presented in this thesis. In addition to the design of these tests, this thesis will discuss the role of rapid fire progress and pulsing fire behaviour in passive house fires: which forms of rapid fire progress could occur and are they more likely to happen in passive house fires? It is also the goal of this thesis to get a better understanding of the working principles of a pulsing fire and describe the possible occurrence of this phenomenon in passive houses.

2 Literature review

2.1 Definition and requirement of passive houses.

The requirements for a passive house in Belgium are agreed upon and set by a non-profit organization called *passiefhuisplatform* (PHP). This organization is sustained by several leading actors and institutions in the building industry. When a house is certified as a passive house by a recognised organisation, one can get a financial compensation in the Brussels Capital Region and the Walloon Region. The exact definitions applied by these governments for approving compensations might slightly differ.

According to PHP [3], a passive house is a very low-energy house that aims at a comfortable environment both during winter and summer, and aims at only using a heating system in extreme winter conditions. During the year, the house is heated by body heat, electrical appliances and sunlight. A passive house uses 75 % less energy than an average new house in Flanders, and 85% less energy than the average Flemish dwelling. The label “passive house” can thus be considered a benchmark for low-energy houses.

There are three main requirements for a dwelling to be certified as a passive house [4]:

- The annual energy demand for cooling and heating should not exceed 15 kWh/m^2.
- The airtightness value n_{50} should be smaller than 0.6. (This value reflects the airtightness and is explained in the next paragraph.)
- The probability of overheating should be smaller than or equal to 5%. (This value is calculated using software approved by the government in Annex V of [5].)

To reach these severe requirements while still providing a comfortable living environment, PHP advises to focus on six main points. These points are taken from [3]. All the calculation procedures are provided in [4].

- A very good overall insulation is a key factor in a passive house. This is obtained by the extensive use of insulation material, prevention of thermal bridges and the use of special-designed windows and doors.. The heat lost through a wall or surface is called the U-value. It tells us which heat is lost through 1 m² of that wall, depending on the temperature difference over the wall. The ψ is the linear thermal transfer coefficient and expresses the heat lost per meter length of a thermal bridge, depending on the temperature difference over the thermal bridge, see [6]. The required values for floor, walls, roofs, carpentry, glass and thermal bridges are given here. These are needed to meet the primary requirement of 15 kWh/m².
    - U-value$_{\text{floors, walls, roofs}}$ <0.15 W/m²K
    - U-value$_{\text{carpentry, glass}}$ <0.8 W/m²K
    - $\psi_{\text{thermal bridges}}$<0.01 W/mK
- Airtightness is of key importance in a passive house. The air that flows in and out is an important source of heat losses. The airtightness of a house is expressed by the n_{50}-value. This value is measured by a blower door test and is a primary requirement for the certification. The n_{50}-value is the normalized renewal rate of the total air volume during one hour at 50 Pa gauge pressure. The n_{50}-value should be smaller than 0.6. This can only be reached by evaluating all the surfaces and connections of the volume in the design phase of the building. Special airtight films are used, and different objects are taped to each other. The construction work needs to be done very carefully, since one mistake can ruin the overall n_{50}-value.
- By smart use of sunlight, the energy provided by the sun can be caught inside the house and partly substitute the heating system. Windows with a high U-value, that still allow a large part of the sunlight energy to pass through the glass, are needed. In wintertime, these windows can harvest more energy than the energy that is lost by conduction. However, this raises the need for external solar blinds, to prevent the house from overheating in the summer. The g value of glass is the solar radiation permeability, expressed in percentages. The g-value should at least be 50% in a passive house, to reach the primary requirement of 15 kWh/m².

- Air quality needs to be guaranteed with a mechanical ventilation system. A ventilation system A refers to natural ventilation. Ventilation system B and C refer respectively to mechanical air supply and mechanical air extraction. In a passive house, system D is needed. In this system, supply and extraction fans are installed. This enables designers to control the air supply and install a heat recuperation system. In the winter, the cold supply air is heated by the hotter extracted air. For passive houses, this heat recuperation system needs an efficiency of minimum 75 % at design flow rate. The fans can have a maximum energy usage, which needs to be calculated with methods given in [4]. These units refer to the design value of the flow rate that is expressed in m^3h. This energy usage can also be expressed per m^3 transported air. This would be 162 J/m^3.
- The combination of renewable energy and a passive house can possibly result in a zero-energy house. Since the energy demand of a passive house is extremely low, it is more interesting to install renewable energy than in a normal dwelling.
- Not only the house is important. The way of living and the appliances in the house are of importance as well. Emphasis is put on buying appliances with good energy efficiency labels.

Reduction measures for the probability of overheating are not included in these six points of good workmanship. Overheating is defined as the temperature overshooting 25 °C. This can be prevented by having a high thermal inertia. By having enough material with a high thermal inertia (see 2.4), the temperatures will be stabilized. During the day, heat from the sun can be stored in this thermal inertia, whereas during the night, it can prevent the dropping of temperatures. A high thermal inertia will also make the house less sensible to the short opening and closing of doors and windows. This thermal inertia works as a heat buffer.

Criteria for the certification of low-energy houses, very low-energy houses and zero-energy houses can also be found in [4].

2.2 Legal requirements for new houses

Besides these criteria for the certification of a passive house, there are demands for every newly built dwelling stated by law. These demands will be become stricter in the next decade.

Low-energy housing is the future. Europe published a directive in 2002 [7], obliging all member states to introduce a framework of requirements and certification by recognised bodies for all new and renovated buildings. Member states had to make regulations and administrative provisions to comply with this directive. These provisions had to be brought into force at the latest on January 4th 2006 at the latest. Flanders introduced this framework by publishing a decree called "*Energiebesluit van 19 november 2010*" (or "Energy decree of November 19th 2010.") This decree has been altered many times since its publication date, the last time on December 19th 2014. The consolidated document can be consulted online, see [5]. In May 2010, the European Parliament published a new version of the directive published in 2002, [7]. The consolidated version of this new directive can be found in [8].

The decree contains more than is of interest to this thesis. It contains rules for recognition of certification bodies, social regulations, renewable energy, inspections and penalties. In this thesis, the focus lies on the actual requirements for newly built houses. These requirements are mentioned here. Requirements for other types of buildings and for major renovations can also be found in this same document.

- Demands are made on thermal insulation. Annex VII of [5] gives all the different required U-values for building elements. A maximum K-value for the building is stated as well. The K-value is a nondimensional value that tells us something about the heat losses to the outside. A better insulation will result in a lower K-value. From January 1st 2012, all new residential buildings can have a maximum K-value of 40. This K-value has to be calculated according to methods approved by the government.
- The demands for ventilation are mainly based on the standard NBN D 50-001. The requirements that are different from the standard are stated in Annex IX of [5].
- The E-value is a nondimensional number that reflects the energy efficiency of a building. It takes into account how much energy will be used to heat the building, to power the fans, to heat up water… The method to calculate the E-value is given in Article 9.1.8. and Annex V of [5]. The required E-values are given in table TABLE 2.1.
- The probability of overheating is limited and has to be calculated with the method given in Annex V of [5].
- The required calculated heating power cannot be higher than 70 kWh/m² per year. The calculation method is described in Annex V of [5].
- Every building with a building permit that is requested after January 1st 2014, needs to have a renewable energy system installed. Options are: solar panels (photovoltaic or thermal), a biomass system, a heat exchange system for geothermal energy, connection to a public heating system that is fed with renewable energy or participation in a wind turbine project.

TABLE 2.1 Required E-values for new residential buildings in Flanders (article 9.1.11. from [5])

Date building permit requested	Required E-value
Before January 1st 2010	E100
From January 1st 2010 onwards	E80
From January 1st 2012 onwards	E70
From January 1st 2014 onwards	E60
From January 1st 2016 onwards	E50
From January 1st 2018 onwards	E40
From January 1st 2020 onwards	E35
From January 1st 2021 onwards	E30

It is difficult to compare the legally required E-values with the criteria of passive houses. E-values take into account the energy that one produces locally, while the criteria for a passive house only take into account the energy required to heat a building, regardless of the source of that energy. In other words: the E-value tells us something about the net energy requirement of the building, while a passive house is certified by looking at the energy usage for heating and ventilating the building.

2.3 Appearance and probability of fires in passive houses.

S. Brohez investigated in [2] the appearance of fires in passive houses. Only one fire has been found. It was a fire in the German city called Pleinfeld. Cellulose insulation started burning during construction works. This was not a passive house fire that is of interest to this thesis. However, it should be mentioned that fires in passive houses probably have happened before, but are not reported as such.

We have not found any literature on the likeliness to have a fire in a passive house compared to a traditional dwelling. Installations will be installed by professionals and all the systems will be new. In that way, we could expect a lower probability on fires in passive houses compared to the average dwelling that is.

However, by comparing passive houses to other newly built houses, one could expect a higher probability for fire in a passive house since more appliances are available. A ventilation, heat exchange and home automation system are systems typical for passive houses. These installations could cause a fire. Therefore, they raise the probability on fire. In addition to these systems, there is more insulation placed. Lights, transformers or switches that are poorly placed in insulation will reach a higher temperature upon electric failure. A timber structure will also raise the probability for fires. All these arguments discussed here will probably result in a higher overall probability for fire in passive houses.

2.4 Thermal behavior of common materials in passive houses

The inner shell of a building is of key importance in fires. Locally near the fire source, it will have an influence on the heat losses during the development stage of a fire. A combustible material will contribute to the fire, while other lining materials will act more like a heat sink.

Besides this local importance, lining materials are also important for the overall temperatures reached in a fire. Higher heat losses result in lower temperatures, less radiative feedback to the fire source and slower fire development. A short overview of the thermal properties and important combinations of these thermal properties is therefore given here. The information is taken from [9].

Thermal conductivity k or λ

The thermal conductivity k or λ expresses how much heat will be transferred per unit temperature difference over one unit of length. This value will determine whether a material will be an insulator rather than a conductor. Both the k and λ are widely used for thermal conductivity. In this thesis λ will be used, since k will later on be used as the correction factor for the adjustable orifice plate in the ventilation system.

Specific heat c_p

The specific heat expresses the energy needed to raise one unit of weight unit with one unit of temperature. In other words: this value expresses if a material contains a lot of heat at a given temperature.

Thermal diffusivity α

The thermal diffusivity is of importance in non-steady state conductive heat transfer. It expresses how much heat will be transferred and how much will be stored in the material. α is a combination of density ρ, specific heat c_p and thermal conductivity λ.

$$\alpha = {}^{\lambda}/_{\rho c} \tag{1}$$

Thermal inertia $\rho\lambda c_p$

Thermal inertia expresses how fast a material will heat up. A low thermal inertia results in higher surface temperatures. This stimulates a fire to grow quickly in the beginning and to reach higher temperatures in the fully-developed fire stage. Since a high thermal inertia will have a lower surface temperature, there will be a higher heat transfer rate. The material will thus absorb higher amounts of energy and thus act as a higher heat sink. The thermal inertia of a material is the multiplication of density ρ, specific heat c_p and thermal conductivity λ.

Thermal penetration depth d_{tp}

The thermal penetration depth d_{tp} is the depth inside a material that is influenced by the temperature difference. This depth depends on time. If the material is thicker than the thermal penetration depth, semi-infinite behavior can be assumed. It is not dependent on the temperature rise that is imposed. The existence of this thermal penetration time is a windfall for fire safety in well insulated structures. Let us compare two similar constructions. The only difference between these constructions is the insulation thickness. The first one has 5 cm insulation on the inside, the second one has 10 cm on the inside. As long as the thermal penetration time does not exceed 5 cm, the heat sink to the wall will exactly be the same for both buildings.

The penetration time obviously depends on the definition of "not being affected by the temperature rise." In [10], this "not being affected" is arbitrarily set to 0.5 % of the temperature difference between the original temperature of the material and the temperature that is imposed on the material. Using that definition, the thermal penetration depth is calculated as:

$$\mathrm{d}_{tp} = 4\sqrt{\alpha t} \quad (2)$$

TABLE 2.2 Thermal properties of some important materials. Most data taken from [10].

	λ (W/mK)	c_p (J/kgK)	ρ (kg/m^3)	α (m^2/s)	$\rho\lambda c_p$ (W^2s/m^4K^2)
Concrete	0.8-1.4	880	1900-2300	5.7×10^{-7}	2×10^{6}
Structural lightweight concrete	0.68[e]	900[e]	1590[e]	4.8×10^{-7}	9.7×10^{5}
Gypsum plaster	0.48	840	1440	4.1×10^{-7}	5.8×10^{5}
Brick	0.69	840	1600	5.2×10^{-7}	5.3×10^{5}
Oak[a]	0.17	2380	800	8.9×10^{-8}	3.2×10^{5}
Yellow pine[a]	0.14	2850	640	8.3×10^{-8}	2.5×10^{5}
Fibre insulating board	0.041	2090	229	$8.6\text{x}10^{-8}$	$2.0\text{x}10^{4}$
Polyurethane	0.23-0.32[b]	1200[b]	30-60[d]	$3.2\text{-}8.9\times10^{-6}$	$8.3\text{-}23.0\times10^{3}$
Cellulose	0.038[c]	±2000[c]	20-55[c]	$3.5\text{-}9.7\times10^{-7}$	$1.5\text{-}4.2\times10^{3}$

	λ (W/mK)	c_p (J/kgK)	ρ (kg/m^3)	α (m^2/s)	$\rho\lambda c_p$ (W^2s/m^4K^2)
Mineral wool	0.035-0.040[b]	800b	35-150[f]	2.9-14.3×10^{-7}	9.8-48.0×10^2
EPS	0.033-0.042[b]	1450[b]	15-40[d]	5.7-19.3×10^{-7}	7.2-24.4 ×10^2

[a] Measured perpendicular to the grain.

[b] Data taken from the documentation of the Flemish institute for bio and ecological living (VIBE). [11]

[c] Data taken from a manufacturer's technical sheet [12].

[d] Data taken from *Handboek Gevelisolatie* [13].

[e] Data taken from a conference paper of the First International Conference on Concrete Sustainability [14].

[f] Data taken from manufacturer's technical sheet [15].

2.5 Fires in passive houses

Since the Second World War, synthetic materials found their way into our living rooms. These materials have a higher heat of combustion and will result in a higher growth rate. This results in shorter times to flashover, as described by the National Institute for Standards and Technology (NIST) in [16]. In addition to the higher energy content of the rooms, houses nowadays are also very airtight. Since the seventies, due to the oil crisis, our new buildings started to be more confined. Under-ventilated fires will appear more often due to this airtightness.

These arguments have consequences and result in different fire scenarios. If a window or door is open, flashover will be reached around eight times faster [16]. If, on the other hand, no doors or windows are open or break, the fire will suffer faster from lack of oxygen. This process is driven to the limit in a passive house. Almost no leaks are available, and the ventilation flow is not strong enough to keep the fire developing, as described in [1]. These two arguments also result in a higher risk for rapid fire progress. These phenomena are discussed in sections 2.11, 2.12, 2.13 and 2.14.

The influence of better insulation in houses nowadays is not significant in the ignition, development and flashover stage of the fire. Typically, this first layer consists of bricks, gypsum board, concrete or plaster. These are the same materials as in traditional Belgian houses. Since fires are not a steady state heat transfer phenomena, the fire will only be influenced by the first layer of material in the beginning. The inner shell of the building acts as a heat sink in the beginning of the fire, as described in [1]. In the fully-developed stage, the thicker insulation will play a role eventually. The thermal penetration depth needs to be larger than the layer in front of the insulation and the original reference insulation thickness to have an influence.

The difference between materials like bricks, gypsum board, concrete or plaster is not that big, since the thermal inertia of those materials is in the same order of magnitude. (see TABLE 2.2)

It would have an important influence if the insulation were to be placed immediately as the first layer. This material would have a lower thermal inertia and would absorb less heat. This leads to higher temperatures and shorter times to flashover. This problem will only appear in poorly renovated houses, since a high thermal inertia is needed to prevent overheating as described in section 2.5.

2.6 Reduced-scale experiments of a fire in low-energy housing [1]

The IMFSE master thesis of B. Debrouwere [1] discussed the fire safety in low-energy or passive houses both theoretically and experimentally. The thesis was presented in 2012. The evolution of building towards low-energy buildings is discussed very well. The E-cube is a solar powered building designed as a do-it-yourself building kit. It was designed at University Ghent to compete in the Solar Decathlon. The E cube has 8 m sides and fulfills the demands discussed in 2.1.

A reduced-scale experiment was conducted. The dimensions of the E-cube were scaled down eight times. The box of 1 m^3 was made out of plaster board. The set-up was scaled down in such a way that the temperatures were not of reduced-scale. The scaling factors of the other parameters were calculated by dimensional analysis. The scaling factor of pressure, for example, was eight, which means that a measured gauge pressure of 10 Pa in the reduced-scale experiment represents a gauge pressure of 80 Pa in reality. The scaling factor of the time was $\sqrt{8}$. The fire used in the test, representing a sofa fire of 2 MW, was a 12.5 kW methanol fire.

TABLE 2.3 Results from reduced-scale experiments of a fire in a passive house. Data taken from [1].

Test set-up	Max T at 75 cm (°C)	Max T at 25 cm (head height) (°C)	Max P (experiment) (Pa)	Max P (scaled) (Pa)	t combustion stopped (experiment) (min)	t combustion stopped (scaled) (min)
Uninterrupted cube interior, with ventilation	±190	±150	±140	±1120	7.5	21
Uninterrupted cube interior, without ventilation	±190	±150	±140	±1120	5.5	16
Compartmented with false ceiling, with ventilation	±200	±125	±115	±920	6	17
Compartmented with false ceiling, without ventilation	±205	±125	±130	±1040	5	14

The oxygen concentration dropped in all the tests to 10.5 % before the fire died. The exact spot where the oxygen is measured is very important.

A one-zone model with a cut off linear regression combustion efficiency approach was developed. This models the efficiency of the combustion process only depending on de average oxygen mass concentration. This zone model somehow overestimates the temperature in this case, but pressure and oxygen level is predicted very accurately.

2.7 Two-zone model research on fires in low-energy houses [2]

A research project conducted in 2009 and 2010 discussed the danger of fires in passive houses. This research project was funded by the ministry of internal affairs of Belgium. The main results are presented in [17], the main report is written in French and presented in [2]. A dwelling for one family is modeled in CFAST. CFAST is a two-zone model developed by NIST. The room where the fire takes place is the living room. This living room has a volume of 111 m³. This volume is connected to a neighboring volume through a ventilation opening of 104 cm². The volume flow rate through the room of fire origin is 150 m³/h. The lining material of the walls and ceiling is plaster board. The floor is modeled as screed. The fire modeled in the living room is an αt^2 design fire with a maximum HRR of 3.45 MW, reached at 500 s.

The most important results of the most interesting simulations are shown in TABLE 2.4. This table can be compared to the results of the reduced-scale experiments in TABLE 2.3.

TABLE 2.4 Results from the CFAST calculation of a fire in a passive house. Data taken from [2].

Simulation set-up	**Max T in upper layer (°C)**	**Max P (Pa)**	**t combustion stopped (min)**
Reference Passive house (CFAST)	560	730	5
Lining material plaster.	350	500	5.5
Conventional house	400	65	7
Reference Passive house (FDS)	±550	/	±5

Both the pressure peak value and the time when the fire smothers are similar for the reduced-scale experiments and the time that the combustion stops. A significant difference can be seen in the temperatures. One can see there is still a big uncertainty about the temperatures reached in under-ventilated passive house fires. The reduced-scale experiments predict a temperature of about 200 °C, whereas these simulations predict a maximum temperature of about 550 °C.

2.8 Description of fire safety in passive buildings [18]

In a master thesis in order to obtain the degree "master of science in the industrial sciences: construction," a good overview is given on passive houses. Especially the descriptive parts on passive houses in general, possible types of construction and insulating materials are interesting. The types of constructions are described from the point of fire safety in a clear and comprehensive way. The part on insulating material lists, many material properties and their reaction to fire.

In a second part, simulations were performed with zone models and FDS. The part on simulations is not that interesting since the main focus was on the wall construction and not on the pressure development in the fire compartment. No attention was paid to the confinement of the room.

2.9 Influence of insulation on temperatures in a fire [19]

As mentioned in 2.4, the thermal properties of walls are of great importance. In a passive house, the insulation is significantly larger than in a conventional house. It has already been explained that for the development stage of a fire, only the first layer of material is of importance.

If a fire is provided with enough oxygen to develop into flashover and fully-developed stage, the insulation will have an influence. This was investigated experimentally by SP Fire Technics in Sweden and reported by A. Back in [19]. Four scenarios were investigated in a 20 foot shipping container. The container was insulated with mineral wool sheets of 9.5 cm. These were attached from the outside to the container. Two different fire sources were used: a heptane pool fire and wood cribs. The difference can be more than 100 °C. This results in a higher heat release rate.

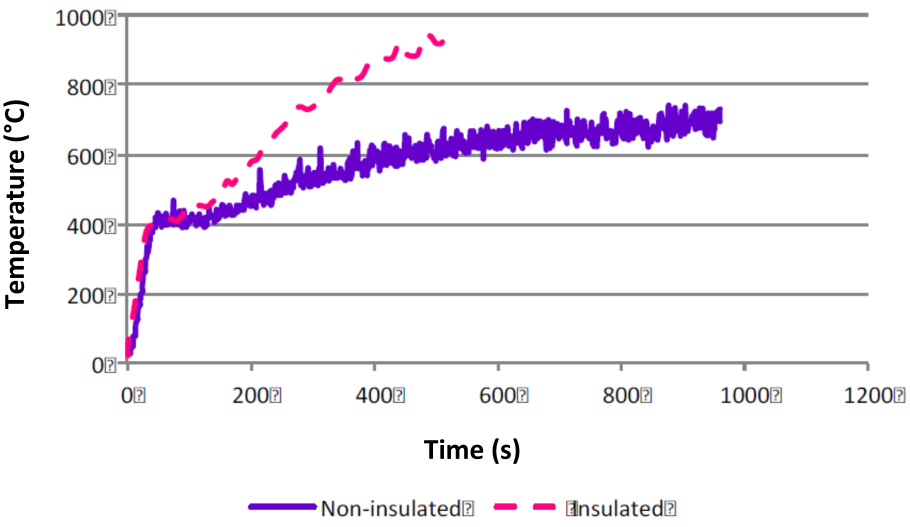


Fig. 2.1 Temperatures reached at 2,1 m height between fire source and ventilation opening for heptane fires. Taken from [19].

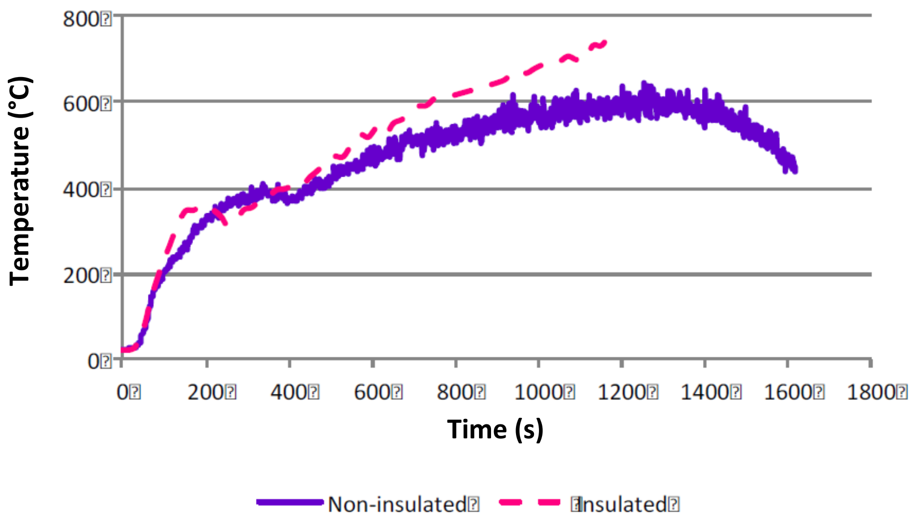


Fig. 2.2 Temperatures reached at 2,1 m height between fire source and ventilation opening for wood crib fires. Taken from [19].

One can see that the insulated and non-insulated case are similar in the beginning of the tests, because the insulation only plays a role when the penetration depth is equal to the thickness of the steel sheet from the container.

2.10 Fires in mechanically ventilated rooms.

Fires in mechanically ventilated rooms are of importance in the nuclear sector too. Nuclear facilities are well-confined and mechanically ventilated. Typically, they are kept at an under pressure. If nuclear particles are released, they will be kept inside. This under pressure is called the dynamic confinement. Fires in this area are thus investigated to get more insight in the pressure development of the fire, since this can ruin the dynamic confinement. This is exactly what is interesting for this thesis.

A state of the art document on probability safety assessment (PSA) for fires in nuclear environments was published by the Organisation for Economic Co-operation and Development (OECD) [20] in 2000. This document showed that there were significant uncertainties on these fires. This triggered the OECD member countries to start the International Fire Data Exchange Project: [21].The statistics of fires in nuclear facilities in all these countries were gathered. These statistics showed the need for more tests on mechanically ventilated confined rooms. In this regard, the PRISME project was started. This PRISME project is well described in [22]. PRISME conducted research on fires in multicompartment, mechanically ventilated and well-confined structures. The 35 full-scale tests were performed from 2006 until 2011.

TABLE 2.5 Overview of the PRISME program. (information from [22])

	Set-up	Connection between rooms	Abbreviation
PRISME Source	1 room	/	PRS-SI
PRISME Door	2 or 3 rooms	Door(s)	PRS-D
PRISME Leak	2 or 3 rooms	Openings Narrow vertical slot Firebreak door Crossing duct	PRS-LK
PRISME Integral	4 rooms	doors	PRS-INT

The most interesting findings here come from the PRS-D tests. These are performed in two rooms connected through an open door:

$$2 \times 5m \times 6m \times 4m = 240m^3$$

From the moment the renewal time (measured before the fire) reaches a value of 8.6, the fire behaves as if it was taking place a free atmosphere. Since the Tr value depends on the volume, this is calculated backwards in order to be able to interpret this in the scope of this thesis.

An estimation from the values given in [22] (through the heat of combustion,) shows that these tests used a fire of around 588 kW in free air conditions.

$$0.014\, kg/s \times 42 \times 10^3 kJ/kg = 588\ kW$$

In [22], normalized mass loss rates are given, from which the peak HRR and the steady burning HRR were deduced here. This gives an idea of the order of magnitude of air flow rate needed to sustain a fire of this size.

Therefore, we can conclude that a fire of 588 kW is not influenced at all by the oxygen depletion at a flow rate of 2016 m^3/h. The flow rate that will be used in the tests designed in this thesis (see section 3.2.2,) is 80 m^3/h and thus an order of magnitude smaller, while the fire is of comparable size. This clearly shows that the ventilation provided in a passive house will not be enough to sustain the fire at a significant HRR.

TABLE 2.6 Backwards calculated Tr values for PRS-D tests. Adapted from [22].

Project	**Tr (h^{-1})**	**Flow (m^3/h)**	**Peak HRR (kW)**	**Steady burning HRR (kW)**
PRS-D1	0	0	380	No steady burning occurred
PRS-D4	1.5	360	380	147
PRS-D2	4.7	1128	440	235
PRS-D3	8.6	2016	588	470

In [23], two test series are described: the F-400 and the PS-120 tests. The PS-120 tests are of most interest here. The volume in those tests is 120 m², which is comparable to the 70 m² volume that will be used in this thesis. The PS-120 tests were performed in the DIVA facility of the IRSN Fire Test Laboratory. It consists of a room of 6 m long, 5 m wide and 4 m high. It is equipped with an exhaust and supply fan. This paper discusses the theoretical model that gives us the possibility to get more insight of why the pressure development has it's typical shape. The model and the typical shape of the pressure development is also mentioned later in this thesis. The main parameters that influence this pressure peak are HRR, the characteristics of the ventilation network, the thermal losses and the geometry. The characteristics of the fan itself are not touched upon. Maybe this is because they assume a theoretical fan with quadratic characteristics in their model. But even if a quadratic characteristic is assumed, one needs a second point. Very important, in my opinion, is the maximum pressure the fan can deliver if there is no flow. This point is called the static pressure and will be of importance when it comes to possible reverse flow in the supply duct.

2.11 Ventilation-induced flashover

If a fire turns under-ventilated before flashover strikes, but when enough heat is created, the fire can start its development again when oxygen is available. The heat development is shown in Fig. 2.3, taken from [24]. The dotted red line shows a traditional fire development where enough ventilation is provided to develop a flashover. One can see that the ventilation-induced flashover can be seen as a delayed flashover. The reached temperature is the same as one could expect in a normal flashover.

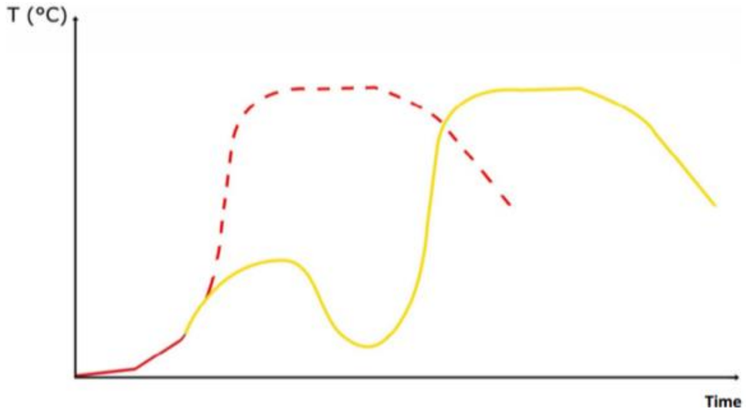


Fig. 2.3 Typical temperature development in a ventilation induced flashover. Taken from[24].

2.12 Backdraft

What is a backdraft?

A great deal has been written about backdrafts. Backdraft is defined in a quite comprehensive definition by Karlsson and Quintiere in [9]:

"Limited ventilation during an enclosure fire can lead to the production of large amounts of unburnt gases. When an opening is suddenly introduced, the inflowing air may mix with these, creating a combustible mixture of gases in some part of the enclosure. Any ignition sources, such as a glowing ember, can ignite this flammable mixture, resulting in an extremely rapid burning of the gases. Expansion due to the heat created by the combustion will expel the burning gases out through the opening and cause a fireball outside the enclosure. The phenomenon can be extremely hazardous."

According to K. Lambert in [25], backdrafts rarely occur on the fire scene. This is because the conditions for a backdraft are quite hard to reach in a normal fire. The room needs to be filled with combustible gases. These gases consist of pyrolyzates and products released during incomplete combustion like CO. In order to produce this huge amount of unburned pyrolyzates, the fire room needs to be very hot. The air flow that rushes in the room upon opening a door or window is often called "the gravity current."

A typical temperature development of a backdraft in a fire can be seen in Fig. 2.4, taken from [26]. One can see that higher temperatures are reached in comparison to a traditional compartment fire development.

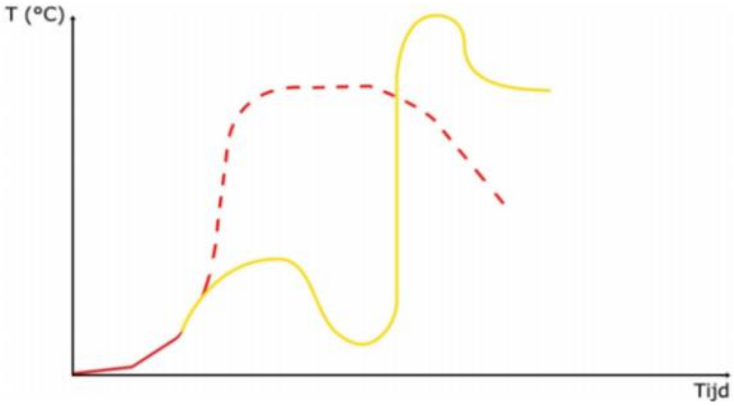


Fig. 2.4 Typical temperature development for a backdraft. Taken from [26].

Which tests have been conducted?

Two remarks need to be made about the tests that are conducted in order to get more insight in the backdraft phenomena. Firstly, most of the tests are conducted with liquid or gaseous fuel. These fuels are more controllable. But on the other hand, they do not represent reality, since most fires have solid fuels. Secondly, in almost all the tests that are conducted, investigators let the fire burn for a while with enough ventilation. When they close the room, the fire has produced enough heat to produce a massive amount of pyrolyzates which do not burn because of a lack of oxygen. This is how they reach the right conditions for flashover in a test setting, but this is an unlikely scenario to happen in reality. These two remarks are also formulated in [25].

For a review of all done tests, I refer to the comprehensive literature review on backdrafts made by K. Lambert [25]. In this thesis, I will explain the two set of tests that have been done with solid fuel, since these are the newest and closest to reality.

A first set of tests with solid material is performed in [27]. The box used for these tests measured 0.62 m x 0.42 m x 0.42 m. The solid fuel used was wood. First they let the fire burn for a while with enough ventilation. Then they closed the door, and opened it later again. If a backdraft occurred it was around 6 seconds after opening the door again. Temperatures in the box are shown in Fig. 2.5. The concentrations of NOx, CO, CO_2 and O_2 and CH are also measured. The ratio β was presented in this paper and shown in (3).

$$\beta = \frac{combustible\ gas\ volume\ fraction}{lower\ flammability\ limit} \quad (3)$$

Previous research always mentioned the mass fraction of the unburned fuel. This was easy because the fuel was exactly known in the projects with gas or liquid fuel. The fraction of CO and CH was used to calculate the combined gas mixture fraction and the lower flammable limit (LFL.) From that mixture the theoretical flammability limit was calculated.

This ratio indicates if a backdraft will occur or not. The critical value of β for wood fires is 1,42. This means that if ventilation and an ignition source is suddenly available to this mixture, a backdraft is possible. This β criterion, should also be dependent on the temperature. It is plausible that a mixture with β equal to 1.45 will not result in a backdraft if its temperature is 150 °C, but will do so at a temperature of 300 °C.

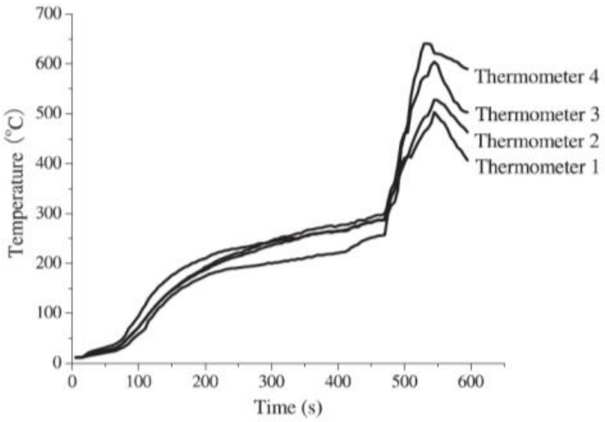


Fig. 2.5 Temperatures in the hot gas layer in one of the tests. Taken from [27].

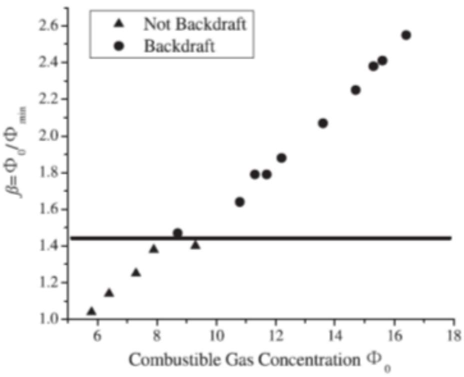


Fig. 2.6 β values for the different tests. Taken from [27].

A second set of experiments with solid materials is performed by L.C. Tsai and C.W. Chiu, reported in [28]. This set consisted of three tests. All of them were performed at full size in the same room, which measured 5.9 x 2.35 x 2.4 m. The fire was three times a sofa fire. It mainly consisted out of polyurethane. In this test, the investigators did not let the fire burn without limited ventilation at first. The room was closed from the very first moment, except from the leaks. This test represents reality very well.

In the first test, there was no decoration at all in the room. After the HRR dropped because of lack of oxygen, they waited for 600 s before opening the door. No backdraft occurred. Part of the explanation for not having a backdraft occurring is there were too much heat losses through the wall. The heat that was lost through the wall was not used to create pyrolysis gases. Another reason was that the temperature was too low at the moment that ventilation was provided.

In the second test, there was decoration in place. The walls were lined with combustible plywood. Part of the heat that is lost through the wall goes to the pyrolysis process of the plywood. In this test, the door was opened at the moment the temperature started to decrease due to a reduction in the heat release rate caused by the lack of oxygen. 48 seconds after the door was opened, flames rushed out of the front door. These are fuel rich gases that burn out of the door, and can work as an ignition source for the a flammable mixture that is formed between the gravity current and the fuel rich layer on top. This flammable mixture is probably ignited, because 8 seconds later, a fire ball was formed. The temperatures, central in the room during this test are shown in Fig. 2.7 and taken from [28]. When the door was opened, the temperature of the smoke was in approximately 300 °C. This will be of importance to judge if a backdraft is likely to occur in a passive house. The third test showed similar results to the second test.

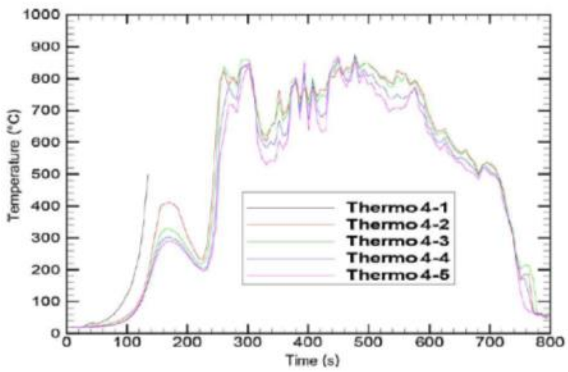


Fig. 2.7 Temperatures central in the room during successful backdraft test. Taken from [28].

2.13 Smoke explosion

A smoke explosion differs from a backdraft. A smoke explosion is defined by [29] as

"A closed compartment that suddenly erupts in flames breaking glass and even causing structural damage without a vent ever being open."

The big difference with a backdraft is that it is not triggered by a sudden ventilation. For a smoke explosion, a flammable mixture there needs to be in the compartment. This flammable mixture will be formed by an under-ventilated fire. According to the literature, there are two main groups of smoke explosions. K. Lambert [25] cited E. Hartin a US chief fire officer. In his definition he mentions that a smoke explosion generally occurs remote from the fire room. In this case, an under-ventilated fire produces pyrolizates and CO. Due to the buoyancy or due to the pressure, these gases flow towards other rooms. In these rooms, there is plenty of oxygen available. If the flammable gases mix with the oxygen, a flammable mixtures is waiting for an ignition source.

In [29], they mention that there several scenarios that can be thought of to reach the right conditions for a smoke explosion. A difficult ventilation flow path can be one of them. A fire located in a high place in a volume is another one. A fire could also develop in a smouldering fire. During the smouldering stage, the oxygen percentage could rise again due to oxygen entrainment through leaks, and cause the right conditions for a smoke explosion.

In the case of a passive house, the risk for an under-ventilated fire is bigger than in a normal house. A smoke explosion could possibly occur with the help of the ventilation system. The fans are very weak ones. Only low flow rates are installed. Imagine a room with a fire that turns under-ventilated, since the fans are not strong enough to provide enough oxygen to keep the fire developing. Nevertheless, the fans may be strong enough to help the transport of CO and pyrolyzates towards an adjacent room. There the gases can mix with the oxygen and form a flammable mixture. An ignition source could for example be the fire that burns a hole through a door or a wall penetration, or the fire brigade opening the door to the fire room. Another possibility are hot fuel rich gases that come through the leaks and mix locally with oxygen resulting in local flaming combustion can act as an ignition source.

2.14 Pulsing fire

Scientific papers on pulsing fires could not be found. But it is a phenomenon observed on the fireground. K. Lambert describes the phenomena in [30]. Consider a fire that has limited ventilation. Due to the heating of the gases inside the fire room, they expand and cause a pressure rise. The limited ventilation openings are thus used to push out hot smoke gases. At a certain point before flashover, the fire turns under-ventilated. The HRR decreases and the temperature drops. The gauge pressure becomes negative due to the cooling of the gases through heat losses to the wall. Fresh air is thus sucked in the compartment. This allows the fire to grow. This is described more in detail in the section 3.2.3 and in Fig. 4.16.

Since not too much research has been done in this area, some thoughts are given on this phenomena. (see 3.2.3 and Fig. 4.16)

2.15 Flame extinction at low oxygen concentrations

A fire only turns under-ventilated due to lack of oxygen. The 21% volumetric (or 23% mass percentage) oxygen content of air drops significantly in fire. The percentage where no flaming combustion can no longer occur, depends on the local temperature. Nevertheless, it is still useful to measure the oxygen content in a room where a fire turns under-ventilated.

The oxygen concentration in an under-ventilated compartment with a heptane pool fire is investigated in [31]. The test set-up consisted of a one cubic meter fire room made out of steel plates. The inside was lined with refractory ceramic tiles. Different ventilation procedures were followed. Test 1 and 2 were ventilated naturally, whereas test 3 and 4 were ventilated mechanically. The oxygen concentration did not differ too much. Fig. 2.8 shows the oxygen concentrations at floor and ceiling level during the tests. The oxygen at flame extinction varies from 11.6 % to 14.3%. This big difference between these values is because the oxygen is measured at ceiling and bottom height. Not the overall O_2 percentage, but the local O_2 and temperature really matter.

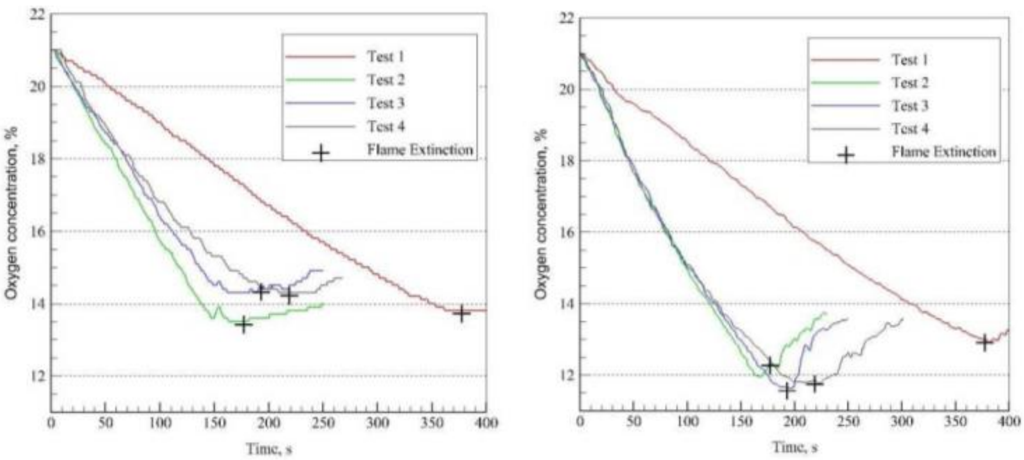


Fig. 2.8 Oxygen concentrations in an under-ventilated heptane pool fire in a 1m³ heptane pool fire. Left: near the floor. Right: at the ceiling. Taken from [31].

A similar set of experiments is presented in [32]. Also a heptane pool fire was placed in a 40 cm cubic box with limited ventilation at the floor and ceiling. The oxygen concentrations volumetric percentage are given in Fig. 2.9. Oxygen concentration at flame extinction is generally in the range of 10% to 12%.

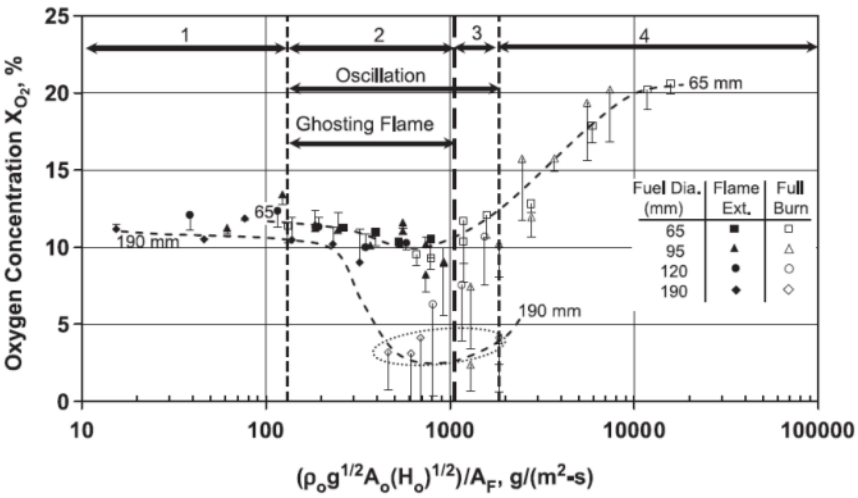


Fig. 2.9 Oxygen concentrations in an under-ventilated heptane a 40 cm cubic pool fire for different ventilation factors. Taken from [32].

In the full-scale, solid fuel backdraft tests performed by Tsai and Chiu in [28], the oxygen depletion is also measured. The fuel in these tests were sofas, mainly consisting of polyurethane foam. A comparison between the other graphs in the paper with the graph shown in Fig. 2.10 shows that the fire turns under-ventilated at the first extremity in the graph after 150, at around 18% of O_2 concentration. After this, the oxygen concentration increases until around 19% where the backdraft occurs. We see that the backdraft consumes almost all the oxygen until around 14.5 %. After the backdraft, the fire turned fully-developed. This leads to a higher temperature. This higher temperature and the fact that a fully-developed fire is ventilation-controlled, leads towards the low oxygen concentrations as 14 % to 15 %. These values are higher than to the tests previously mentioned and described in [31] and [32].

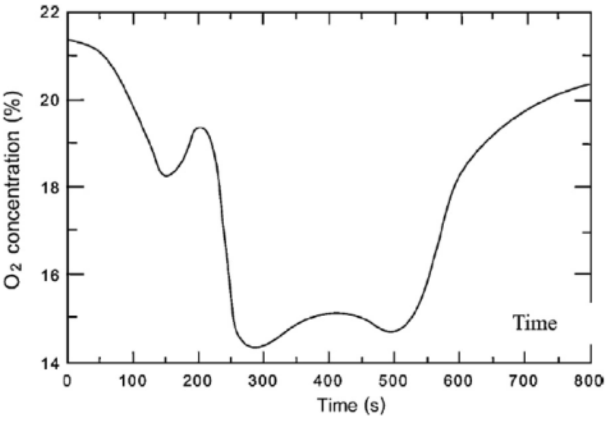


Fig. 2.10 Oxygen concentration during an under-ventilated room fire and backdraft. Taken from [32].

3 Methodology

3.1 Visit passive houses

To get a better understanding of what a passive house looks like, two passive houses were visited. These houses are both passive, but still completely different. It is not the goal to cover all kinds of passive houses, but to get a grasp of what passive housing looks like. One is a row house that is currently being renovated by the owners themselves. The other house is a new standalone, built by a company. It has a concrete structure and is larger. It is a myth that windows cannot be opened in passive houses: in both houses it is possible to open several windows. This counters the argument of an additional threat in case of fire, since evacuation through windows would not be possible. However, there are passive houses where windows cannot open, and where evacuation possibilities are fewer. Most important parameters of these houses are described after this part and compared in TABLE 3.1.

TABLE 3.1 Comparison of two visited passive houses

	Renovated	**Newly built**
Total volume (m^3)	+-550	724 (+-5%)
n_{50}-value	Estimation: 0.2-0.3	0.31
Thermal inertia	Mainly screed (+plaster boards and cellulose)	Concrete
Maximum flow fan (m^3/h)	300	450
Coupling fire detection and ventilation possible?	Yes	Yes
Main insulation material	Cellulose	Polyurethane

3.1.1 Renovated passive house

This row house is not yet finished. With a lot of patience, it is being renovated by the passionate owners. It used to be a typical construction with bricks, but during the renovation process, parts of the former structural walls are replaced by a timber structure. The airtightness is assured by foils, plaster and OSB-plates that are correctly taped off. The heat exchange system is not the conventional system where the cold air runs over hot tubes. In this house, it consists of a wheel. In the longitudinal direction, the wheel consists of tubes. The hot air runs through these tubes. Since the wheel is made out of metal, the wheel absorbs the heat quickly. It turns very slowly, the tubes that are heated turn towards the cold air flow. The cold air flows through the hot tubes, which heats up the air. The advantage of this system is a higher efficiency at different flow rates. A disadvantage is that it brings in another moving part that can break.

3.1.2 Newly built passive house

This building is a standalone house. Structural elements are all made out of concrete. The construction work for this type of construction building is less intense. The concrete also provides the airtightness of the building. Since fire is not a steady-state phenomenon, the inner layer will be most important in the first stages of the fire. As described in paragraph 2.4, the inner shell will act as a heat sink. The material here is concrete. This has a high thermal inertia and will thus result in a lower temperature than the house described in 3.1.1 in case of a fire that dies from lack of oxygen. A few months after the visit, there happened to be a small fire in the house. It had nothing to do with the fact that it was a passive house. The box with fuses heated up and started to smoulder. A lot of smoke was the result, without any damage to the building.

3.2 Test set-up design requirements

In this paragraph, thoughts are given to what the boundary conditions are, which materials and parameters to choose and how the tests can be made as comparable to the reality as possible. In the next chapter, the practical implementation of these ideas is given.

3.2.1 Construction

The construction will be used for other tests too, which has the implication that the geometry and size are fixed. The inner dimensions of the construction are the same as the inner dimensions of a 40 foot shipping container: 12.03 m long, 2.35 m wide and 2.39 m high.

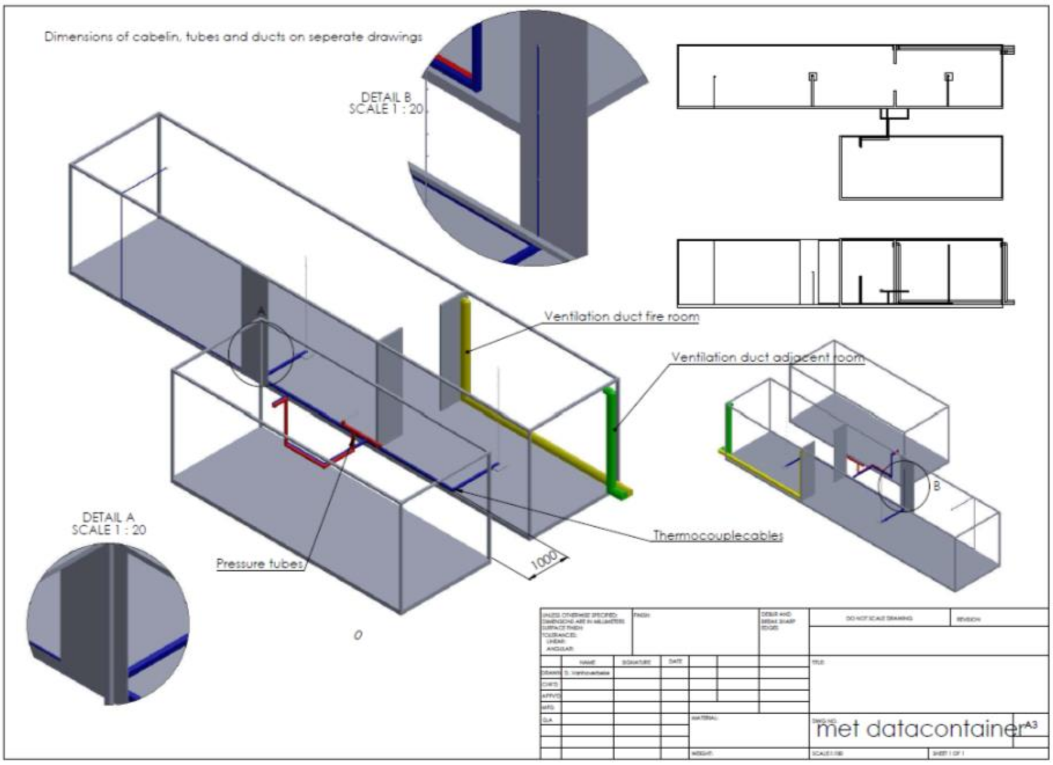


Fig. 3.1 Set up of construction.

In the growth phase and development phase, only the inner shell of the wall will be important. A typical material for the inner shell is plaster board. Behind the plasterboard there is insulation. This will often be a frame of steel studs with mineral wool in between. The outer shell is made of bricks. For this test we opted for a wall construction that consists of two plasterboards of 9 mm. Behind this, a steel stud frame filled with mineral wool of 5 cm is placed. The outer shell consists of 20 cm concrete blocks for durability reasons. The concrete blocks are finished with plaster on the inside to ensure the airtightness. The insulation does not need the thickness it should have in a real passive house, since the heat front will not travel through this layer of 5 cm insulation during the time that is of interest for these tests, and it is not a steady state heat transfer problem as described in section 2.4.

It is important that the door that is placed in the construction is a passive house door. If leaks appear around this door, all the other effort to turn the construction airtight is in vain.

3.2.2 Ventilation

The volume is divided into two rooms, which simulate two different rooms of a passive house. In one room there will be air extracted, in the other one there will be fresh air supply. The fire room will cover two thirds of the overall volume, while the adjacent room will cover one third of the overall volume. In between these rooms, there is need for a ventilation opening. Under the door in this separation wall, the ventilation opening is provided. We assume that the large room (18.8 m^2) is a living room, and the small room (9.4 m^2) a bathroom. In Fig. 3.2 and Fig. 3.3, one can see the minimal and maximal nominal flows required by the Belgian government. [33] is a guidance document on NBN D50-001:1991 and NBN EN 13779:2004. These standards are obligatory referred to in the Flemish Decree "*Het energiebesluit van 19 November 2010*", see [5].

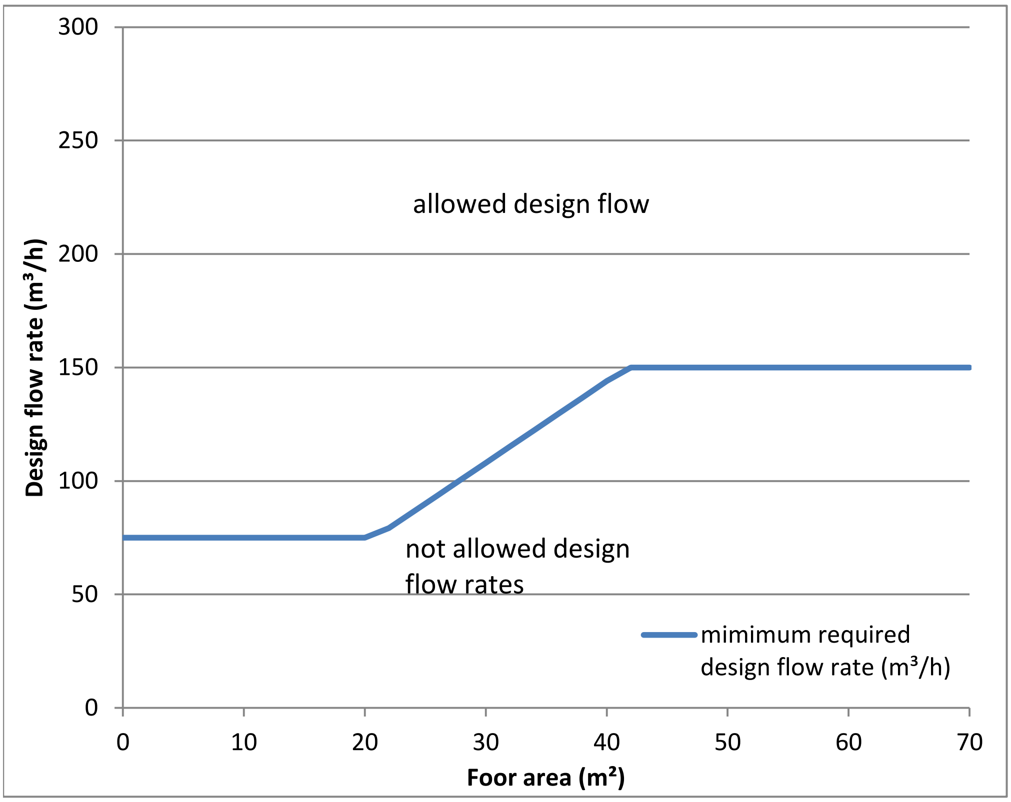


Fig. 3.2 Allowed design flow rates for living rooms. Data taken from [33].

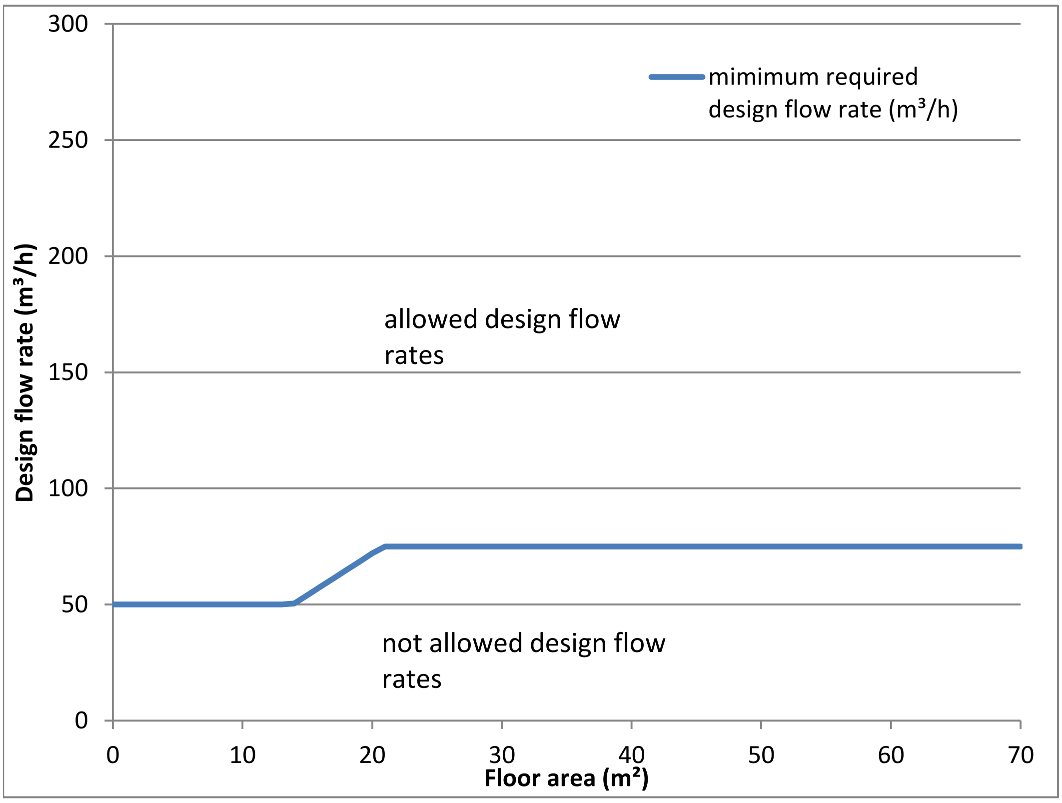


Fig. 3.3 Allowed design flow rates for closed kitchens, washing rooms and drying rooms. Data taken from [33].

TABLE 3.2 Minimal required, maximal allowed and installed nominal flow rates. Data taken from [33].

	Living (large room)	Kitchen (small room)	Installed value
Minimal flow rate (m^3/h)	75	50	80
Maximal flow rate (m^3/h)	∞	∞	

Since the flow rate will be 80 m^3/h we can calculate the area needed under the door, since the value of maximum 0.357 m^3/h per cm^2 in the ventilation document [33]. $80\, {}^{m^3}/_{h} / 0.357\, {}^{m^3}/_{h\, cm^2} = 224\, cm^2$. Since the door is 80 cm wide, this gives a minimum height for the ventilation opening of 2.8 cm. The design value for this ventilation opening will be 3 cm.

Overpressures as high as 1200 Pa can occur. This was one of the outcomes of the research ordered by the Belgian government, and performed by UMons in [1]. The IMFSE thesis of Brecht Debrouwere [1] shows too that pressure plays a major role in passive house fires. It is worth giving some thoughts to the parameters influencing the pressure development. It is not straightforward, since the different parameters influence each other. This could, with some reasonable assumptions, result in a zone model. This zonemodel would be a set of differential equations, where the characteristics of the fans, the ventilation ducts, the leakage area, the fire growth rate… would be input values. A zone model as described here is developed at UGent and described in [34]. This zone model is able to predict the pressure development for a well-confined and mechanically-ventilated one room compartment in the case of fire. This zone model could be developed further for a two room configuration. The development of this zone model is not within the scope of this thesis. Nevertheless, important parameters will be discussed here.

According to [23], the HRR, the characteristics of the ventilation network, the thermal losses and the geometry are of importance. Computational fluid dynamics (CFD) calculations can only be used if it is kept in mind that these simulations are not well validated for under-ventilated fires. The results are thus not reliable. CFD calculations are used for a sensitivity analysis later on in this document.

To get some insight in the important parameters, we take a look at the model presented in [23]. It is a heat balance, that would be one of the major equations in the zone model that is described in this paragraph.

$$\frac{\mathrm{d}(\mathrm{m}C_v T)}{\mathrm{dt}} + \rho_e \dot{v}_e C_{p_g} T_e - \rho_i \dot{v}_i C_{p_g} T_i - \rho_l \dot{v}_l C_{p_g} T_l - \dot{m}_f C_{p_f} T_f = \dot{Q}_f - \dot{Q}_w \quad (4)$$

The parameters of importance are logically the terms in this heat balance for open systems. This heat balance has to be understood like this: If the heat in the compartment (first term) rises, the gas expands and the pressure increases. In [23], this formula is elaborated further. A qualitative description of the different terms is given here.

1. Supply fan and duct characteristics

This parameter represents the third term in (4). A passive house is very airtight. (n_{50}<0.6) A supply and extraction fan are provided and connected to the corresponding ventilation duct networks. The need for different flow rates in different rooms is reached by adapting the duct diameters, nozzles and fans. In case of a fire, this system is drawn out of its design range. The fire will raise the temperature. The pressure will rise throughout the whole building since there are always balance-ventilation openings in between ventilation compartments. The flow rate out of the building will increase. The flow rate into the building will decrease, or even become negative. Since the HRR depends on how much oxygen is provided to the fire, the pressure rise depends on the air entering the building and the total volume. There will thus be a dynamic equilibrium influenced by all these parameters.

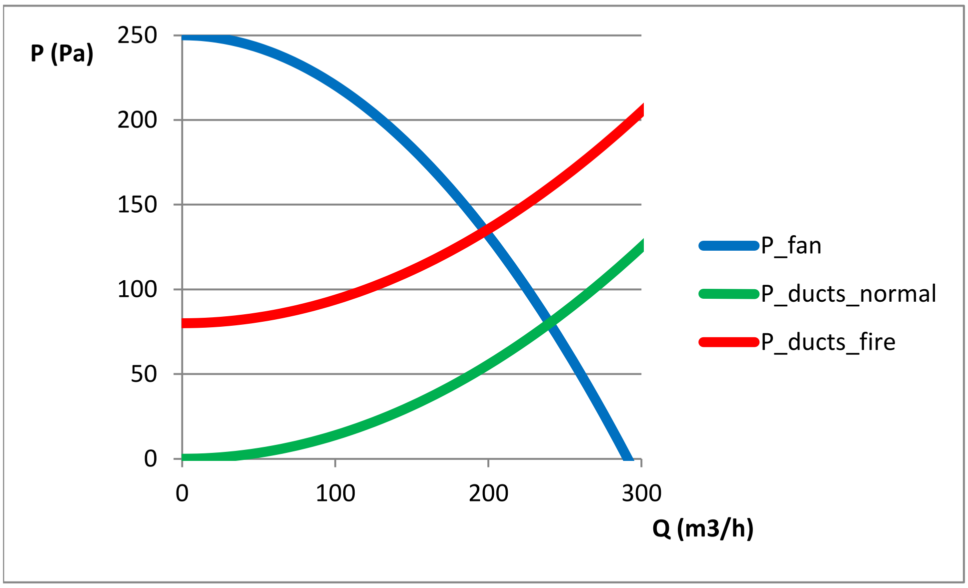


Fig. 3.4 Supply Fan and supply duct characteristics in case of fire.

This is a thought experiment to gain some insight in the phenomenon, so the numbers in the figures only have explanatory purposes. The blue line in Fig. 3.4 represents the fan characteristics, and the green line represents the duct characteristics. In the design phase of a building, if the duct characteristics are known, the fan is chosen to provide the nominal design flow rate, [35]. In case of fire, the pressure inside the building will rise, which can be represented by shifting the duct characteristics upward. If the fire builds up a pressure ΔP, the duct characteristic moves upward with ΔP. The intersection of the fan and duct characteristics shows that the fan encounters a higher pressure and gives a lower flow rate because of this.

2. Fire

This fire is represented by the fifth and the sixth term in (4). In the beginning, the fire will behave like any other fire. But during the development phase, the fire will reach its fuel-controlled/ventilation-controlled point (FC/VC) before it has the chance to develop towards flashover. The heat release rate will thus stabilise and lower from the moment the oxygen in the room is used. Possibly the pulsing phenomena (see 4.3) could occur. This term is the source term in the equation.

3. Extraction fan and duct characteristics

The extraction fan and duct characteristics are represented by the second term in (4). The same reasoning as described in the supply ducts holds for the extraction ducts. The pressure built up by the fire will 'help' the hot gases to flow out. This gauge pressure ΔP will raise the extraction flow rate.

We see in Fig. 3.4 that the gauge pressure ΔP, caused by the fire, will shift the duct characteristics downward. The performance point will shift to the right. The exhaust fan will thus extract a bigger volume.

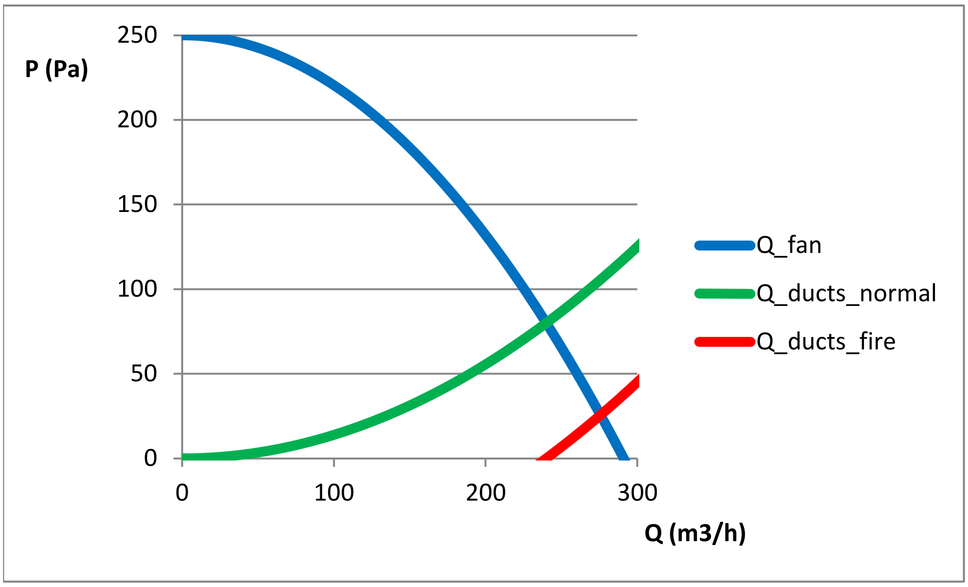


Fig. 3.5 Extraction fan and duct characteristics in case of fire.

Both the supply and extraction flow tend to stabilize the situation. The lower supply flow rate and higher extraction flow rate will both cause the pressure to drop. An equilibrium will thus be reached.

It needs to be kept in mind that the extraction flow from the fire room will be less efficient in terms of mass flow. Since the gases will be hot and thus have a smaller mass flow rate (MFR).

4. Thermal losses

The thermal losses are represented by the fourth and last term in (4). This is the heat that is lost through the gases that leak out of the compartment, and the heat losses to and through the walls.

As described in section 2.4 on lining materials, the walls will act as a heat sink. Since these test will only last a few minutes, only the first layers will be affected.

This first layer of all our side walls is plasterboard. Plasterboard is a common material and will for this reason also be used in these tests as well. The thermal behaviour of plasterboard is somehow special. Plasterboard consists mainly of $CaSO_4.2H_2O$. It contains ±21% of chemically bound water and 3% of free water according to [36]. Between 80°C and 250°C, this water is released. A lot of heat of the fire is taken by the latent heat of the vaporisation process. This process can be modelled by using temperature dependent specific heat constants. These are given in Fig. 3.6.

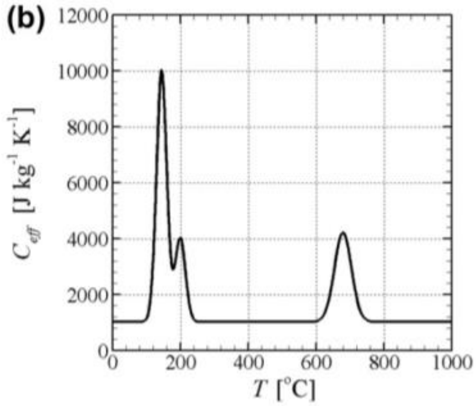


Fig. 3.6 Temperature dependent specific heats for plasterboard. Taken from [36].

Another way of tackling this problem is by using a system of latent heat, that quantifies the heat that is used for the different chemical decompositions. This is described in [36].

The first chemical decomposition (5) takes place at 145°C. The heat taken by this decomposition reaction is 338 kJ/kg. The second decomposition reaction (6) takes place at 200°C. The heat taken here is 115 kJ/kg. A final reaction (7) takes place at 800 °. The heat taken by this reaction is 200 kJ/kg.

$$CaSO_4.2H_2O \rightarrow {}^{3}/_{2}\,H_2O + CaSO_4.{}^{1}/_{2}\,H_2O \tag{5}$$

$$CaSO_4.{}^{1}/_{2}\,H_2O \rightarrow {}^{1}/_{2}\,H_2O + CaSO_4 \tag{6}$$

$$CaCO_3 \rightarrow CaO + CO_2 \tag{7}$$

This has implications for these tests. The thermal properties of the plaster boards change if they reach temperatures higher than 80°C according to [36]. This means the plasterboards have to be replaced every single test.

A similar problem arises with the concrete. The floor and part of the ceiling are bare concrete. Thermal properties of concrete are temperature dependent. Since this concrete cannot be replaced like the plasterboards, there will be an error introduced due to the different thermal behaviour of the concrete in the different tests. An advantage is that the thermal inertia of concrete is three times the thermal inertia of the plaster boards. This means that the temperature of the concrete will not be that high as plaster boards. The concrete will thus have had lower temperatures, which causes less change in thermal properties. The thermal properties concrete are given in EN 1992-1-2:2004 (E) [37]. The specific heat, thermal conductivity and density is respectively shown in Fig. 3.7, Fig. 3.8 and Fig. 3.9.

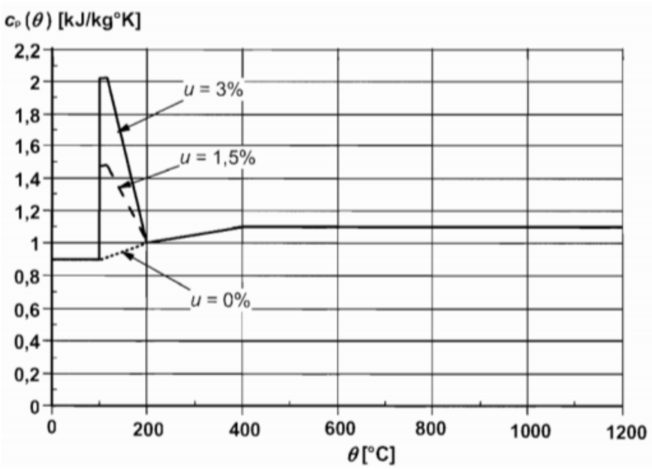


Fig. 3.7 Specific heat for siliceous concrete with moisture contents by weight of u=0 %, u=1,5 % and u=3,5 %, as function of temperature. Taken from [37].

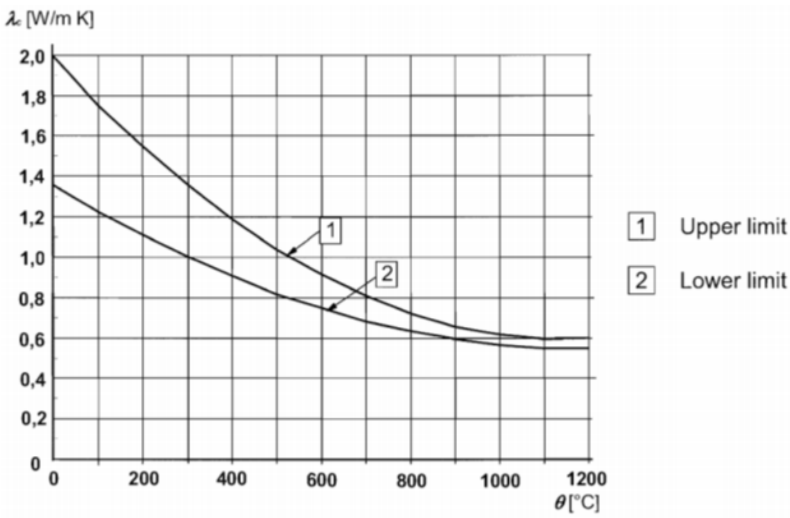


Fig. 3.8 Thermal conductivity of concrete as function of temperature. Taken from [37].

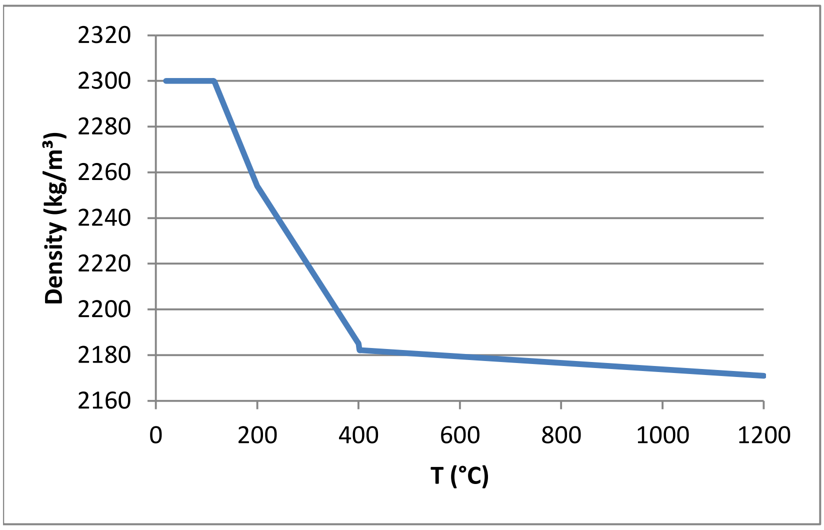


Fig. 3.9 Density of concrete as function of temperature (given a density of 2300 kg/m³ at 20 °C). Data taken from [37].

3.2.3 Fire

The fire in the test case should represent a real house fire. There is no such thing as "one representative real passive house fire." We should not choose the fires that occur the most: small kitchen fires or an electrical fires without big consequences will occur at a higher frequency than large fires with large consequences. But since we want to investigate and prevent fires with large consequences we have to take into account the worst credible fires [38]. After this part, several fires are discussed that could be used as worst credible fires in the modelling and testing.

Fast growing αt^2 fire from [9]

The fire in a passive house should be fast growing. A slow growing fire does not represent the worst credible fire possible in a house. A fast growing αt^2 fire is more representative. This is easy to model. Since [9] also gives growth rates for different object on fire, we could use one of the objects labelled as fast growing.

A sofa fire is fast growing. It is also a realistic fuel for a house fire. But a problem arises with sofa fires. If six tests are performed, we need six identical sofas. It should also be made sure that the sofas would burn. This is not that straightforward, since sofas cannot be sold in Europe if they do not meet certain fire safety requirements. Even if we could light the sofas it is not sure that they would burn in the same way each time.

Pallet Fire modelled from data taken from [39].

Another option is a pallet fire. This is also a fast growing fire according to [9], and was used in the tests performed by S. Svensson on tactical patterns on the fire ground [39]. This is a tempting option since pallets are freely available. Since different pallets will have differences (thickness, kind of wood, moisture, chemical pollution…), one can never be sure that the pallets will burn in the same way every time. However, if these parameters are monitored and looked upon, it can be a good option. This option is further investigated with data from [39].

A stack of 5 pallets is considered as fire in the tests designed. This is done because it has several benefits:

- It represents the start of a realistic dwelling fire well. Since it has a fast growth rate according to [9].
- The same fire can be repeated, within an acceptable margin of deviation. [39]
- It is cheap or even freely available.
- It can smolder, which is an important phenomena12 for under-ventilated fires.

There are some drawbacks too:

- It is not very well described what the HRR is. Since we do not measure the HRR, this is an important shortcoming.
- There will be variations, due to moisture content, way of stacking, different wood, different thickness, way of construction…
- It does yield less soot than more representative hyrdrocarbon fires like polyurethane fires.

To predict the HRR of a stack of pallets, data form [39] is used. A stack of 5 pallets was used. This stack was burning 9 times in the same setting. The standardized weight is given in Fig. 3.10. The average of these test results is taken at five different times. This gives an average burning rate, which is given in Fig. 3.11. From this curve, a quadratic trend line is fitted. This trend line has an R^2 value of 0.9859. The derivative of the trend line of the burned mass gives the mass loss rate at a given time. Under the assumptions of 25 kg/pallet and a heat of combustion of $\Delta H_{c,wood}$= 20 MJ/kg, this derivative was converted to the HRR and gives us HRR[kW]=4t. This HRR is shown in Fig. 3.15. The slow, medium, fast and ultra-fast growing αt^2 fire is shown for comparison.

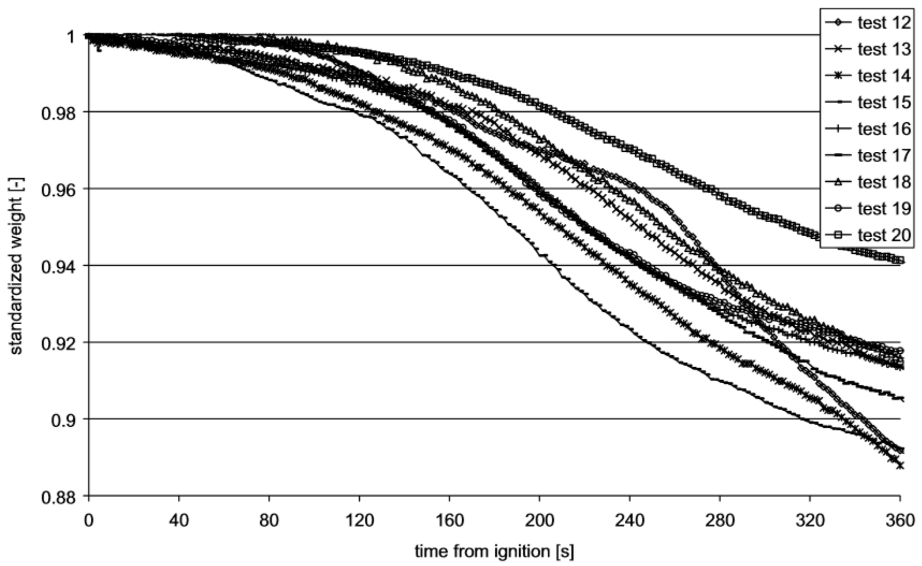


Fig. 3.10 Standardized weight of pallets during burning. Taken from [39].

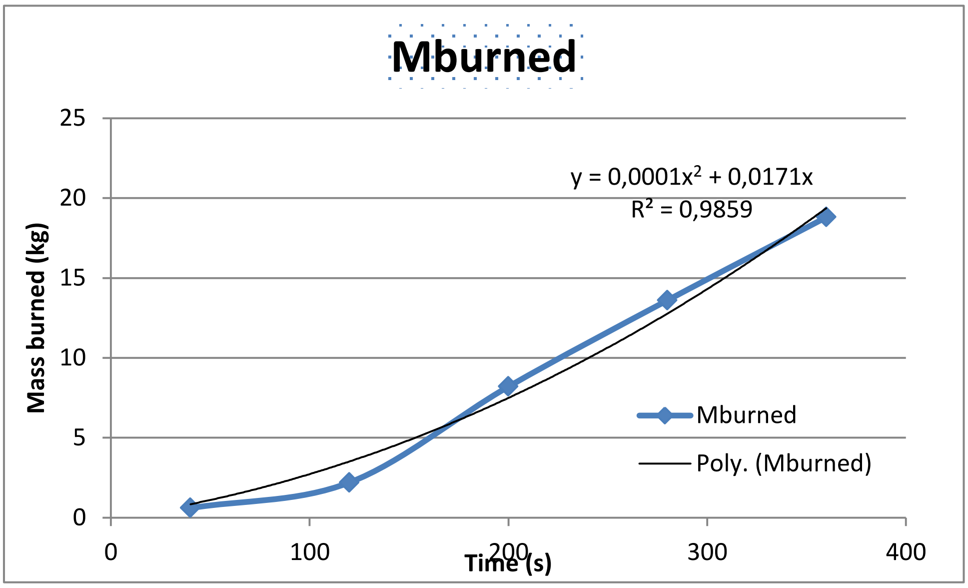


Fig. 3.11 Mass of the pallets burned vs time. Data taken from [39].

The available air in the room is 67.5 m^3. Using the maximum energy that can thus be used (3 kJ/g air [10] and 1200 g/m^3) gives 270 MJ that can maximally be released. This is reached after 367 s or 6 minutes. This is substantially smaller than the 14 – 21 minutes predicted in [1] and described in 2.6.

CFBT fire

Firemen all over the world learn how a fire in a compartment develops by training sessions in shipping containers. 40 foot shipping containers are a basic training cell. There is a lot of practical experience out there with the fire behavior in these cells. The fire that is used during these burns is a wood fire. Some boards are placed parallel with the walls in the corner. Boards are also placed parallel with the roof. Not too much research is done on the HRR during these fires. The University of Adelaine in Australia conducted research on this topic [40].

A typical fuel load for a CFBT exercise is shown in Fig. 3.12.

Fig. 3.12 Typical fuel load for a CFBT exercise. Taken from [40].

They defined three different types of burns. Although having the same fuel load, the arrangement is different. This is shown in TABLE 3.3. The tests are conducted at the CFBT facility of Brukunga. The facility is equipped with smoke extraction ducts. This enables the researchers of measuring the flow rate, carbon dioxide concentration and carbon monoxide concentration. From those measured parameters, it is possible to calculate the HRR through the approximated heat released per mole oxygen used in the combustion process.

TABLE 3.3 Definitions of CFBT fire types

Burn type	Fuel Load	Fuel Arrangement	Rear doors
1	Standard	• 2 particle boards on walls • 3 particle boards on roof • Particle board pieces in corner	Open for duration of burn
2	Standard	• 2 particle boards on walls • 3 particle boards on roof • Particle board pieces in corner	Closed once fire has developed Reopened after anti-ventilation is demonstrated
3	Standard	• 2 particle boards on walls • 2 particle boards on roof • 1 particle board suspended at lower level on chains • Particle board pieces in corner	Open for duration of burn

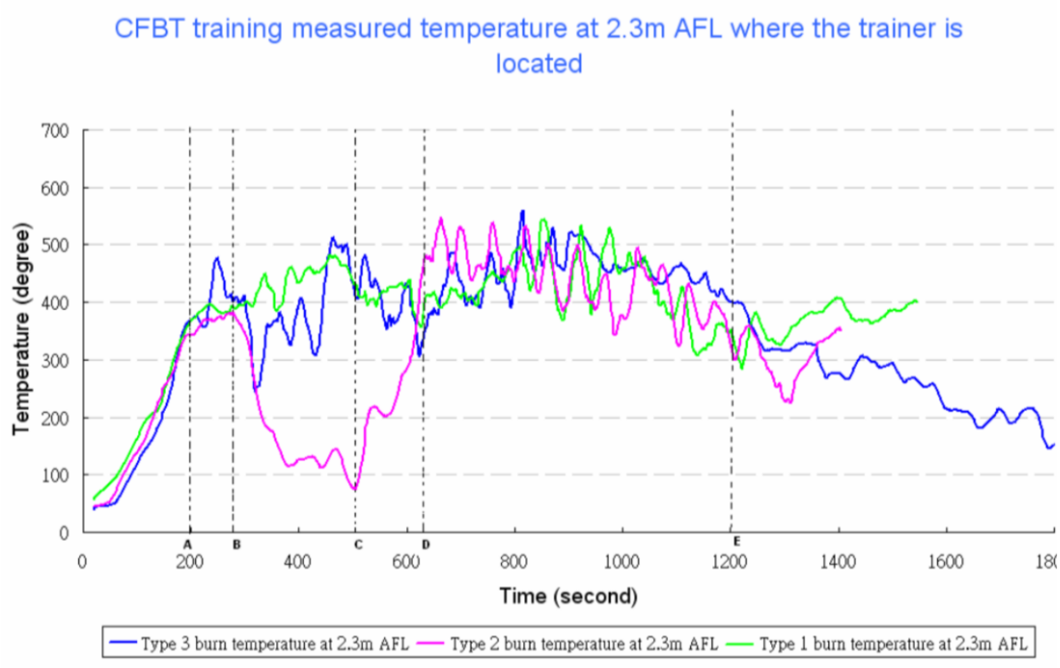


Fig. 3.13 Temperatures measured during CFBT container burns of type 1, 2 and 3. Taken from [40].

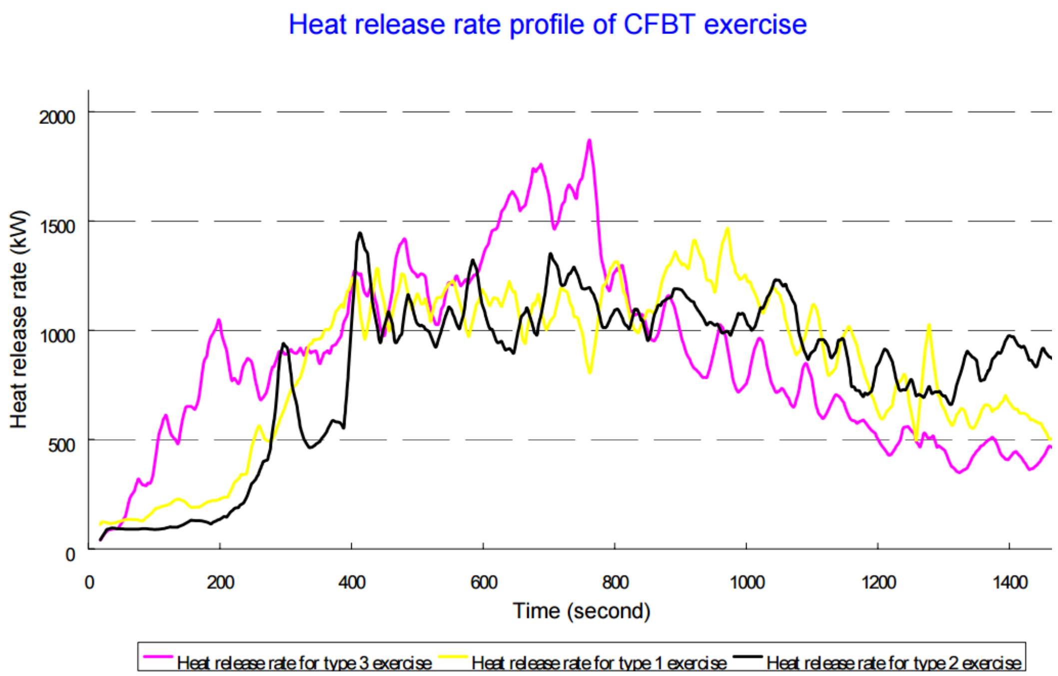


Fig. 3.14 Heat release rates measured during CFBT container burns of type 1, 2 and 3. Taken from [40].

Comparison

Several fires have been looked upon now. These fires are all compared in Fig. 3.15. The HRR curves for a slow, medium, fast and ultrafast growing fire are given for comparison. We see that a type 3 CFBT fire and a stack of pallets have approximately the same growth rate. This is similar to a fast growing fire. The growth rate of the type 3 fire slows down since the fire runs out of fuel or becomes ventilation-controlled. This will be the same in our test set-up. So a type 3 CFBT fire is convenient for our set-up. However, we should take care the fire develops fast enough in the first minutes. (It should not look like the type 1 and 2 CFBT fires) These first minutes are of key importance in the tests presented in thesis.

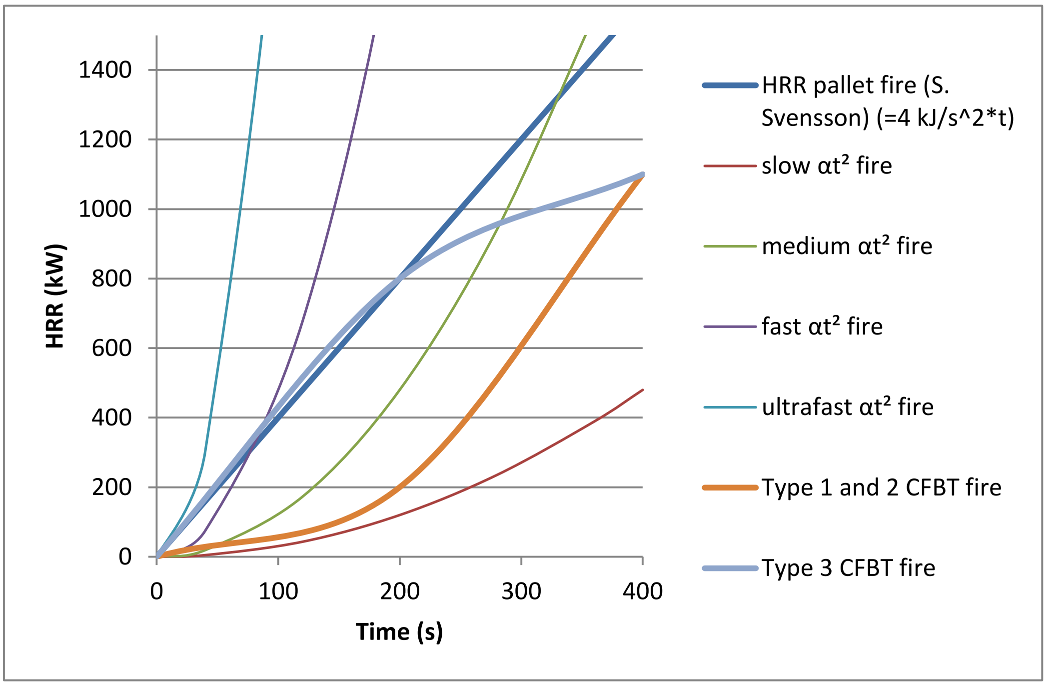


Fig. 3.15 Comparison of different discussed heat releases. Data taken from[9],[40][39] and [40].

3.2.4 Measurements

What is interesting to measure? The simple answer to this question is: everything. However, the practical feasibility and the utility of the measurements do play a role. The different quantities that could be measured are discussed here.

Temperature

As usual, temperature is a key parameter in fire tests. Temperature rise is the cause of the pressure rise and it plays an important role in the evacuation process, pyrolization process, fire spread and the likelihood on backdrafts or smoke explosions. Therefore it is no surprise that temperature is in one of the main hypothesis questions of this thesis. Temperature has to be measured both both in the fire and in the adjacent room from floor to ceiling. Measurements of wall temperatures are of interest too. Thermocouples will do a good job here, since the room will be filled with smoke, and thus block radiation from the fire that could influence the measured thermocouple temperature.

Pressure

The pressure is a key parameter too. As mentioned earlier, this is the main difference between a passive house fire and a traditional fire. It can prevent people from escaping. The gauge pressure between the fire room and the ambient, and the gauge pressure between the fire room and adjacent room is both of interest. Gauge pressure apparatuses exist and have an acceptable accuracy for this application.

Flow in supply and extraction duct

It is important at least to know what the flow rate is before the fire to compare to real passive houses. During the fire, it is also interesting to measure. It will show when backflow in the supply duct will occur. This is practically feasible by measuring the pressure difference over an orifice plate in the ventilation ducts where laminar flow appears. (away from corners and fans) If enough gauge pressure apparatuses are available, the flow can be monitored during the tests.

HRR

The HRR is very important for the pressure development. It is thus very interesting to measure. But since there is no smoke hood available, it is not that straightforward to measure the HRR. A possible method is to measure the mass loss rate (MLR.) The MLR can be converted to the HRR through the heat of combustion of the fuel. Measuring the MLR turned out not to be possible with the apparatuses available for these tests.

O_2 and CO concentration

Measuring O_2 is interesting since we would be able to see at which overall percentage of oxygen this particular fire smothers due to lack of oxygen. CO concentration is interesting to measure and to investigate when the fire turns under-ventilated. The comparison between the test with the gasoline fire, the sofa fire and the reference wood fire can be interesting. Unfortunately, a mobile gas analysing system was not available for these tests.

Explosive range

Does the smoke in the fire and adjacent room form an explosive mixture at some point or upon opening the door? Is the mixture too lean or too rich? This could be answered by using a catalytic explosion cell. This cell continually checks if the mixture is flammable. It was decided not to use this apparatus since this was not available, and it would probably show a too lean mixture.

Smoke detectors

How fast would sleeping people be alerted in case of a fire? And what is the influence of the ventilation on this time? By placing a smoke detector in the fire room and the adjacent room, we could get an idea of the answers on this question.

4 Discussion on test set-up

4.1 Comparison tests with reality

The goal of this paragraph is to make an abstract representation of a passive house fire. By doing so, we get a clear view on parameters that are taken into account. It allows us to compare tests, simulations and reality. In a test, one could neglect or take into account the rest of the ventilation duct network to other parts of the house. One could neglect the rooms besides the fire room. One could assume the pressure equally distributed over all the rooms in the building. One could consider the ventilation system switched on or off. The goal of this abstract representation is to list the different assumptions made. This will be helpful to get some insight in the problem.

4.1.1 Simplified abstract representation of passive house

A comparison is made between cases with different assumptions. It shows what should be taken into account to come as close as possible to reality. The cases refer to TABLE 4.1 and TABLE 4.2.

Case A: no ventilation installed, one room.

In this representation, no ventilation is installed. Assuming that the building has an n_{50}-value of 0.6, the gauge overpressure has to escape through these leaks. Simulations showed that the overpressure here reaches values in the range of 0.12 bar, which could break windows. (The static pressure that a 2 m x 2 m x 7 mm glass window can resist is around 3830 Pa according to [41].) The leak that was modelled is calculated with (12). The input file for these simulations can be found in Annex 9.14. More information on these simulations is given in section 4.2.1. This representation is certainly not like reality, since mechanical ventilation will always be installed in passive houses.

Case B: ventilation switched off, one ventilation compartment

Only one "ventilation compartment" is considered. If the volume of the set-up is large enough, it could look like reality. This could for example be the E-cube, where the fire is investigated by [1]. Unfortunately the volume in the test set-up designed in this thesis is only 70 m^3, too small to be comparable to the 510 m^3 sized E-cube.

Case C: ventilation switched off, multiple ventilation compartments with small ventilation openings in between the rooms

Multiple rooms are considered in this case. The assumption made in this case is that the pressure rise due to the fire is able to spread all over the volume. The pressure rise will be lower. However, the oxygen in the other rooms cannot be consumed by the fire, since the ventilation openings in between the compartments are too small to provide a supply of fresh air and an extraction of exhaust gases. This starts to look like reality. It could represent a passive house where all the doors are closed.

Case D: ventilation switched off, multiple ventilation compartments with large ventilation openings in between the rooms

Just as in case C, multiple rooms are considered. The pressure rise due to the expansion of the gas will take place over all the volume. The openings between the rooms are large. All the oxygen in the volume is now available for the fire. The fire will thus grow bigger than in case B and C, but also has to heat up a larger volume. This would mean that the pressure rise would be comparable to case B, since the volume where the oxygen can be used and the volume where the air can expand is equal in both cases. But since it takes longer to heat up all the air than in case B, the expanded gas has more time to escape through the ventilation ducts, so the pressure peak will not be as high as in B. There will also be more heat losses, since it takes longer for all the oxygen being used, and thus energy being released. The total pressure rise will thus be higher than in case C, but lower than in case B.

Case E, F and G

Cases E, F and G respectively have the same properties as B, C and D, except for the fact that the ventilation system will be kept up and running throughout the fire. This means that, as described before, a dynamic equilibrium will be achieved. The ventilation flow is not enough to sustain the reached HRR. However, there will be a higher HRR after the fire smothered compared to case E, F and F.

Overview

The discussed comparisons in pressure peak and HRR are bought together in TABLE 4.1**.**

TABLE 4.1 Relative pressure and HRR estimation compared to $V_{pressure}/V_{air}$ ratio

Case	Pressure	HRR	$V_{pressure\ rise}/V_{\mathrm{air}}$
A	+++++++++	+	/
B	++++	+	1
C	++	+	>1
D	+++	+++	1
E	++++	++	1
F	++	++	>1
G	+++	++++	1

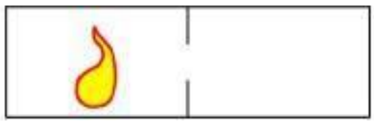
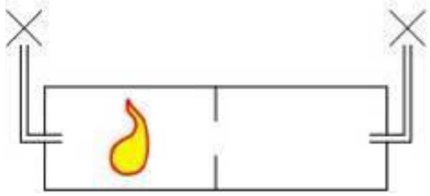
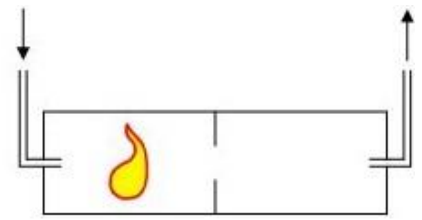
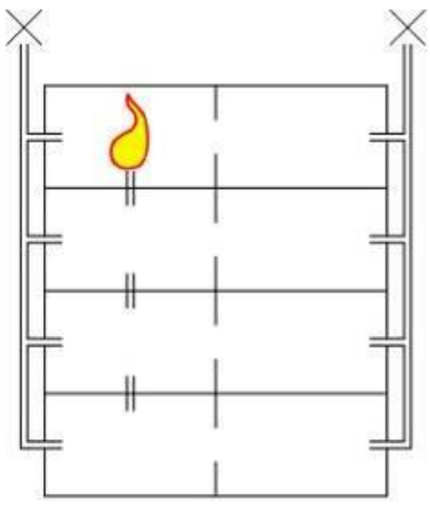
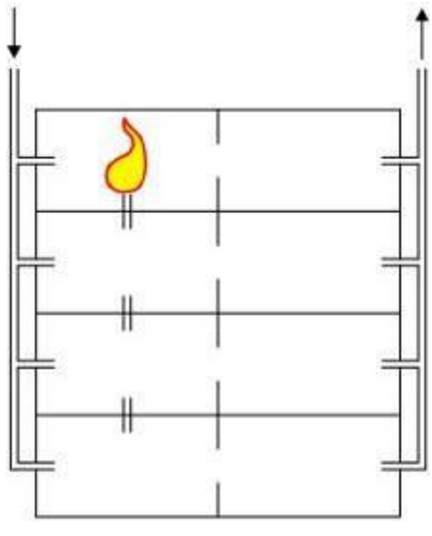
Reality

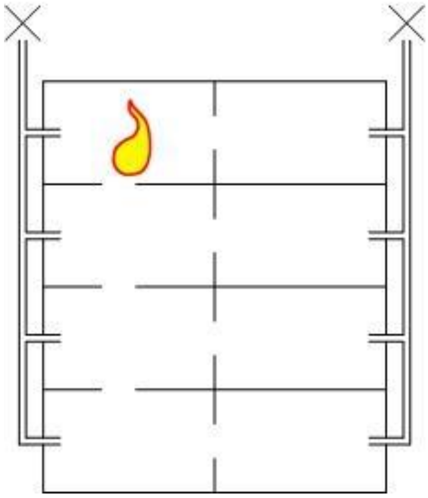
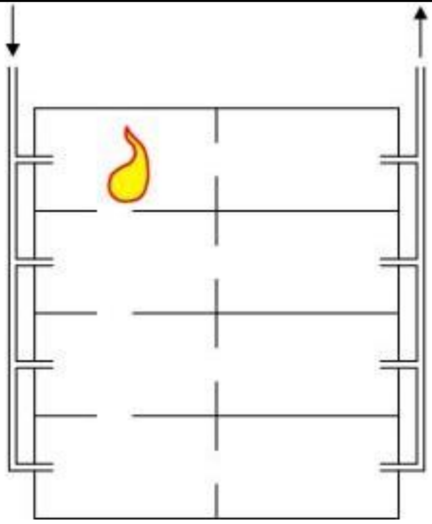
In reality, a real fire in a passive house will probably be situated in between case F and case G. Since passive houses often have an open structure, they are likely to resemble case G. But in the case that many doors are closed, or the fire is at the upper , the fire will more resemble case F. In the case that the ventilation is shut down, due to a fire detection, it resembles not case F and F, but respectively case C and D.

Test set-up

For this thesis, it was impossible to build a complete passive house. The dimensions of the construction were given at forehand. The construction presented resembles case B and E. How can we bring the test set-up as close as possible to reality? In other words: how can we bring case B and E closer to case C, D, F and G? Adding a big airtight volume is impossible. For cases F and G: one could work with a special fan, that has the characteristics that a fire room would face at the nozzle. This is discussed in the next paragraph.

TABLE 4.2 Different ventilation cases

Case	Ventilation switched off	Case	Ventilation switched on
A			
B		E	
C		F	

Case	Ventilation switched off	Case	Ventilation switched on
D		G	

4.1.2 Existence of pressure peak predicting value δ.

The ratio $V_{pressure\ rise}/V_{air}$ is important to predict the pressure peak. $V_{pressure\ rise}$ is the volume where the gases being heated can expand. V_{air} is the volume filled with air that can be consumed by the fire. If $V_{pressure\ rise}$ is larger than V_{air}, the pressure rise cannot be that big. If the ratio is one, the pressure rise will be higher since the gases can only expand in the volume that provides oxygen to the fire.

Hereby we suggest the existence of a nondimensional value, that could predict the pressure peak in a passive house. The ratio $V_{pressure\ rise}/V_{air}$ will, besides several other parameters, play an important role in this nondimensional value.

The actual value of V_{air} is important too. A compare is made between case B and case D. Consider case B, where there is only a small room full of air available to the fire. In case D, a whole house is available to the fire. The fire burns until all the oxygen available is consumed. In case D, the fire will take longer to heat all the gases. If there were no leaks, nor heat losses, the pressure peak would reach in both cases the same level. This can be seen in (8): the ratio m_{air}/V_{air} will be the same for case B and D. The temperature rise in this ideal case with no heat losses will be the same too. This can be seen in (9): the ratio $Q_{released}/m_{air}$ will be the same, since m_{air} will decide how much material will be burned, and thus how much heat will be released through (10).

$$\Delta P = \frac{m_{air} R_{air} \Delta T}{V_{air}} \tag{8}$$

$$\Delta T = \frac{Q_{released}}{c_p m_{air}} \tag{9}$$

$$Q_{released} = m_{burned} \Delta H_c \tag{10}$$

Back to reality, where leaks and heat losses exist. The heating process takes longer in case D, so the built pressure has more time to escape through the leaks and ventilation ducts. If the volume is bigger, there will also be more heat losses to the walls since there is a larger area where the convective heat transfer can take place. These two arguments show that V_{air} is an important parameter for the height of the pressure peak.

Another important parameter is the resistance of the leaks. This can be expressed by the leak area A_{leak}. A high leak area will result in lower pressure peaks and vice versa.

The lining material can also play an important role. This could be represented by the average thermal inertia $\rho\lambda c_p$ of the lining materials.

Combining all these factors, I suggest this could result in a pressure peak predicting value δ.

$$\delta = f(V_{pressure\ rise}, V_{air}, A_{leak}, \rho k c_{p,average}) \tag{11}$$

4.1.3 Consequence for fan characteristics and flow rate control

There is a problem arising if this test set-up is compared to a real situation. This problem is caused by the fact that a fan for a real house will serve to ventilate all the house. Its flow will provide different ventilation compartments from fresh air.

Since in the test set-up designed in this thesis, a fan will be installed only to ventilate this compartment, it will be a smaller fan than the one that would be installed in a house. A bigger fan will have a higher static pressure. This static pressure is important in fire, because it will determine at what point the flow will be reversed in the supply ducts.

In a real situation, a more extensive duct network will be installed compared to the one in the test set-up presented in this thesis.

Is there a way to install one single fan and a simple duct system in our test set-up that will act as a fan and duct network in a real house? In other words: how can we resemble a real passive house the most with only one fan and a one supply and extraction duct?

We can approximate it by installing a fan that has a realistic static pressure. We can run the fan at maximum speed and smother the ducts to obtain the desired flow rate. By doing this, we obtain a higher static pressure which resembles more a real fan installed in a house.

This theoretical explanation is made clear with some numbers. Keep in mind that these number are only for explanatory purposes.

Let's consider a passive house with three ventilation compartments. In this house, a flow rate of 80 m^3/h is needed in every ventilation compartment. This makes 240 m^3 in total. A fan with flow characteristics that intersects the duct characteristic at 240 m^3/h is selected for this imaginary house. This fan is represented by the dark blue line in Fig. 4.1. The duct characteristics are shown in dark green. This 240 m^3 would be distributed over the three ventilation compartments. In our test case, we only built one ventilation compartment that accounts for 80 m^3/h. By smothering the duct network, we can obtain the desired flow rate. This is shown in pale green in Fig. 4.1 by the pale green line. The other option would be to run the fan not at top speed and not smother the duct. This would result in a lower static pressure. Backflow in the supply duct would occur too fast in comparison with the real situation. This line of the fan at lower speed is shown in Fig. 4.1 by the pale blue line.

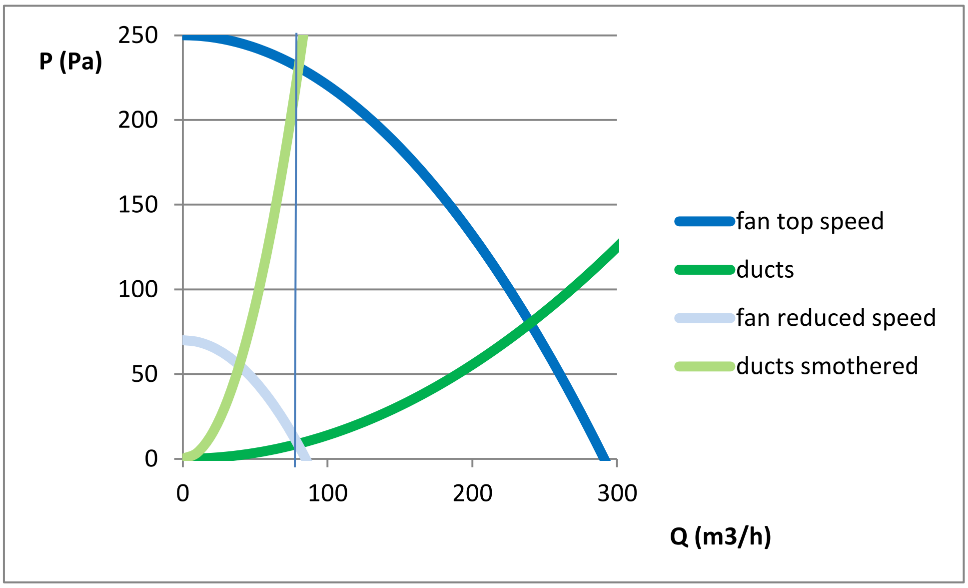


Fig. 4.1 Comparison test set up and real dwelling.

4.2 Sensitivity analysis

4.2.1 Fire Dynamics Simulator (FDS)

The simulations presented here are calculated by the finite volume program FDS. FDS uses the principles of Large Eddie Simulation (LES.) The program solves a finite form of mass, enthalpy, species and momentum transport. Since low Mach numbers are used, FDS is not able to simulate an explosion. A grey gas model is implemented. For detailed information on the sub models or equations reference is made to [42].

Combustion model

In this paragraph, we dig a little deeper in the combustion model since this is very important to understand how the program will behave in under-ventilated conditions. FDS uses a lumped species, mixed limited infinitely fast reaction model. To reduce the number of transport equations for chemical species, these species are considered lumped species. Instead of calculating the transport equation for CH_4, H_2O, O_2, N_2 and CO_2, transport equations for air, fuel and products is calculated. The heat release rate is calculated through the heat of combustion of the fuel. The amount of fuel that reacts in a certain volume during a certain time step is calculated by a model that predicts how much of the fuel and air will be mixed. This is done though the Eddy Dissipation Concept. The time scale τ_{mix} is modelled depending on the volume element size. This time scale determines how much of the fuel and air will be mixed and thus burned. This model is adequate for diffusion flames.

The reaction will always take place whenever fuel and air are available, unless one of the two extinction criteria are met. One extinction criteria is the temperature in the volume being lower than the auto ignition temperature (AIT), there will be no reaction. It is difficult to calculate the AIT of smoke. By default, the AIT is set to 0 °C. The other extinction criteria is gases that are too much diluted with fuel or another agent.

Leakages and pressure zones

Both the leakages to the ambient and the ventilation openings in between the fire room and the adjacent room are modelled by using the feature pressure zones in FDS. Pressure zones are volumes that are completely sealed besides the leakages connecting them to each other and the ambient. The volume flow rate through these leaks is calculated using (12), taken from [43].

$$\dot{V}_{leak} = A_L sign(\Delta p) \sqrt{2 \frac{|\Delta p|}{\rho_\infty}} \tag{12}$$

Solid phase heat transfer model

According to the technical reference guide of FDS, [43], the heat transfer through a wall is calculated by FDS using (13).

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left(k_s \frac{\partial T_s}{\partial x}\right) + \dot{q}_s''' \tag{13}$$

ρ_s, c_s, T_s and k_s are respectively the density, temperature and conductive heat coefficient of the solid material. The first term represents the accumulation of energy in the material, the second term gives the energy transferred and the last term represents the energy released inside the material. This one dimensional heat transfer formula is used by FDS in walls. The thickness of the wall is divided in a finite number of volumes, for which the formula is solved. For the first and the last volume in the wall, FDS uses boundary conditions. The boundary condition on the inside of the volume is presented in (14).

$$k_s \frac{\partial T_s}{\partial x}(0,t) = \dot{q}_c'' + \dot{q}_r'' \tag{14}$$

Where $\dot{q}_c''$ represents the convective heat transfer to the wall, and $\dot{q}_r''$ represents the radiative heat transfer to the wall. The boundary condition at the back of the wall depends on which boundary condition that is chosen by the user. It can be insulated or not.

Convective heat transfer to the wall

Convective heat transfer in FDS to the wall is modelled through the convective heat transfer coefficient h [43]. This heat transfer coefficient is not straightforward to calculate. FDS tackled this problem by using an empirical model for h. This is empirical natural/forced convection model is the default model. There is an optional near wall model available in FDS.

4.2.2 Model Set-up

All the FDS input files of simulations discussed here can be seen in the annexes. In TABLE 4.3, one can find the grid sizes used. The grid was uniformly distributed over the volume. Defining different meshes with a finer grid in places with more turbulence leaded to instable pressures. The reason for that is a coding error in FDS 6.1.2 and all versions prior to that. This coding error will be discussed in the next section. This will be solved in newer versions. The fuel used is propane. The HRR curve used is the pallet fire shown in Fig. 3.15. The wall used in the model is a plaster board layer of 18 mm, mineral wool insulation material of 4.5 cm and concrete bricks of 20 cm. The ventilation opening between the fire room and the adjacent room is taken as 100 cm². Fig. 4.2 shows the output of FDS, visualised with the program Smokeview.

It needs to be noted that one cannot use the calculated values of the pressures. It is difficult to know what the leakage area was. We took a leakage area to the outside (representing the leaks and the ventilation channels) of 0.35 m², because this gave realistic values for the pressure. So the absolute values of the pressure don't have an meaning, since the leakage area was modelled in that way they became typical values. However, the pressures can be compared to each other.

The pallet fire, described in 3.2.3 is used as reference case. The fire is modelled as a rectangle measuring 0.8 m x 1.2 m, since that is the standard size of a pallet.

The material properties for different materials used in the simulations are given in TABLE 4.3. The origin of these values is described in section 2.4.

The FDS input files of all the results shown here are given in annex 9.7 to 9.14.

TABLE 4.3 FDS grid cell sizes

Mesh	Cell size (cm)
Extremely fine	5
Very fine	7.5
Fine	10
Medium	15
Coarse	20

TABLE 4.4 Material properties for simulations

Product	Conductive heat transfer coefficient $(\mathbf{W/mK})$	Density $(\mathbf{kg/m^3})$	Specific heat $(\mathbf{kJ/kgK})$
Concrete	1.2	2200	0.88
Fibre insulating board	0.041	229	2.09
Plasterboard	0.48	1440	0.84
Brick	0.69	1600	0.84
Polyurethane	0.034	20	1.4

4.2.3 Coding errors in FDS

During the simulations for this thesis, two coding were discovered in FDS 6.1.2. Pressure rose logarithmic, while there was no physical reason to do so. The exact cause of the coding errors was eventually found together with FDS programmers. These problems will be solved in the new releases of FDS.

Defining different meshes upon each other creates troubles if one works with pressure zones. This was done to have a better resolution of the flow at places with more turbulence. This leaded to instable pressures. The problem was that the pressure solver counted the pressures from both meshes, which resulted in unstable pressures. Defining the different grids not upon each other, but next to each other is an option, but this was eventually not done in this thesis.

Another problem was the leaks modelled between two pressure zones. The FDS handles this leak in the wrong way if the obstruction between the two pressure zones is not at least one cell size thick. This is a problem because FDS tackles the leaks by modelling this leak as a duct in between the two pressure zones. In new FDS releases, an error will be created instead of calculating on with unrealistic values.

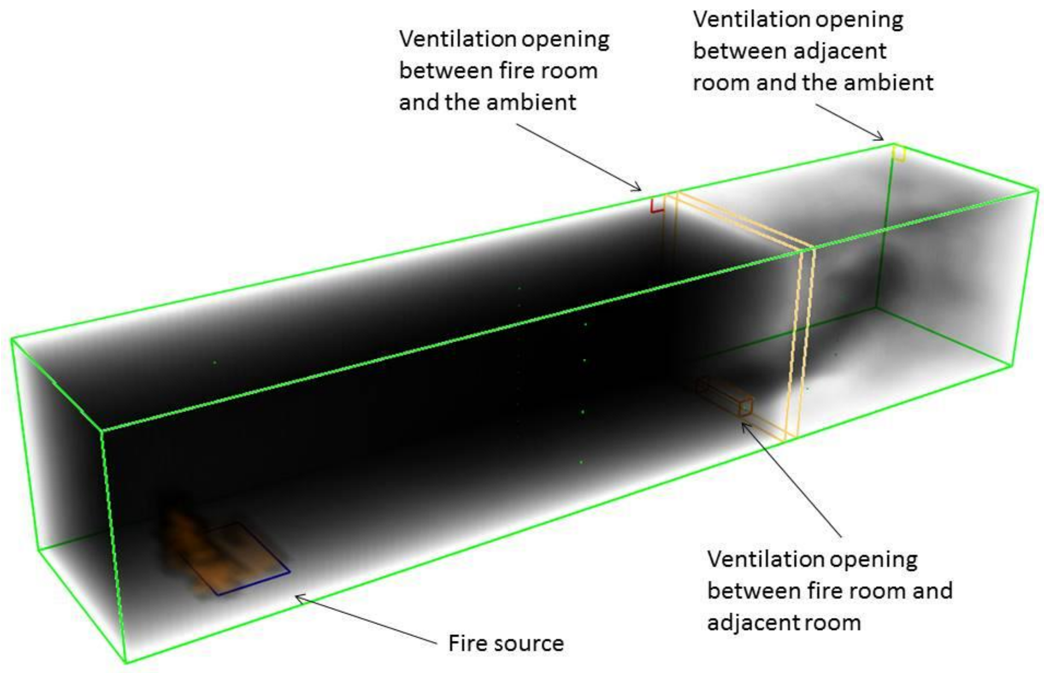


Fig. 4.2 FDS simulation model set-up.

4.2.4 Sensitivity to grid cell size

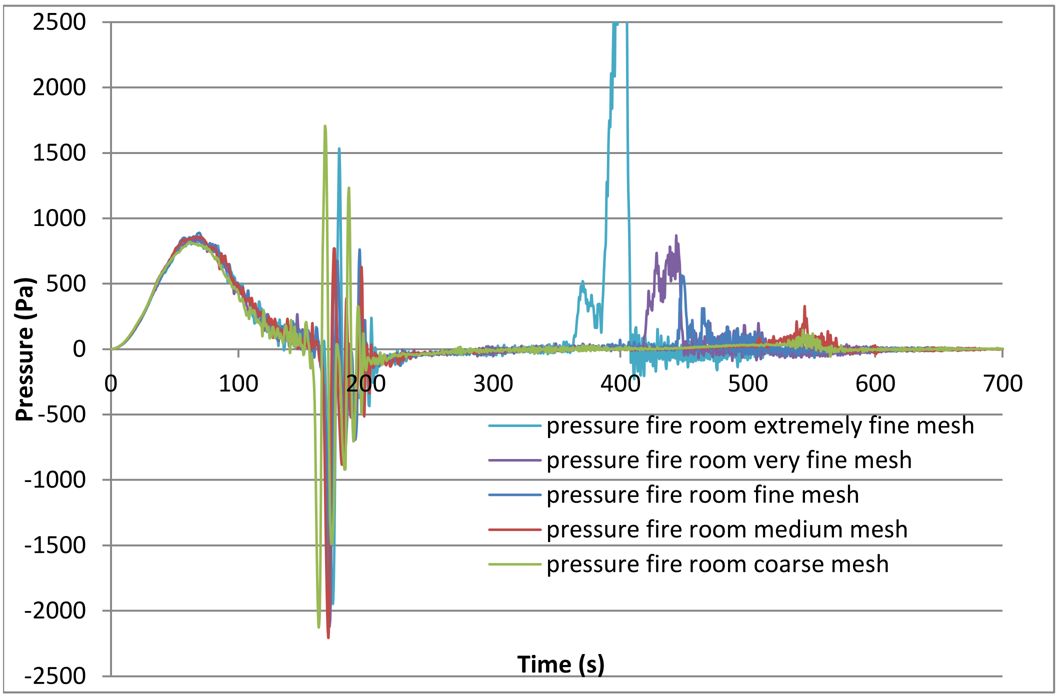


Fig. 4.3 Sensitivity of pressure development in the fire compartment to different cell sizes.

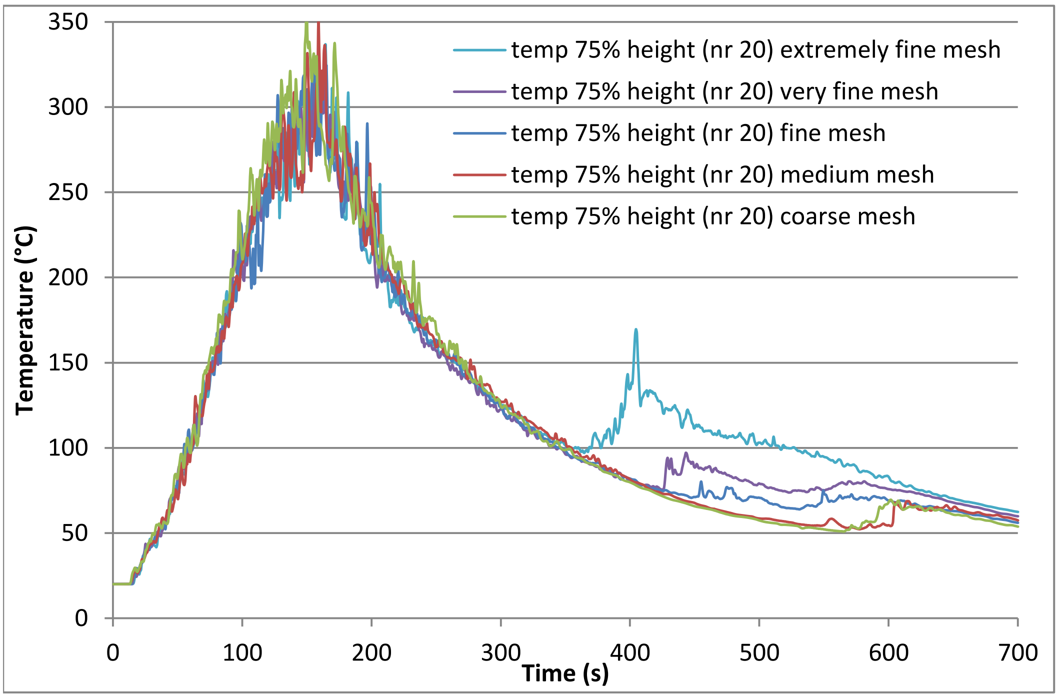


Fig. 4.4 Sensitivity of temperature development in the fire compartment to different cell sizes.

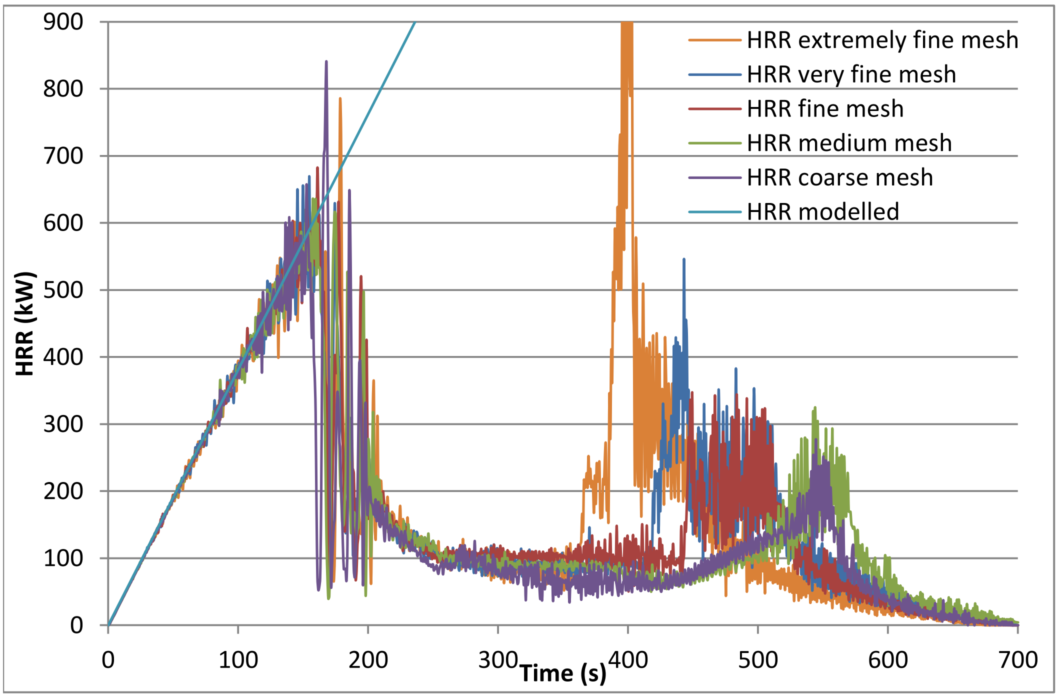


Fig. 4.5 Sensitivity of HRR for different cell sizes.

One can see in Fig. 4.3 that the first pressure peak does not really depends on the cell size. The pressure is unstable between seconds 150 to 210. Visualizing the output in the program Smokeview shows that this is caused by gases that are suddenly ignited. This would not happen in reality and is a result of the combustion model that does not need an ignition source. In reality there will not be an ignition source present everywhere in the room to ignite a mixture from the moment it turns flammable at a certain small spot. The unstableness of the pressure after the pressure peak has lowered is not realistic. The phenomenon is neither described in literature.

We do not observe the pulsing phenomena. Instead, there is some kind of steady burning at the ventilations openings. If there would be an ignition source or if the cases are hot enough, this seems like a realistic phenomenon. The cell size does not seem to have a major influence on this phenomena. However, the cell size does have an important influence on the second peak in pressure. This peak appears earlier and reaches higher values with finer grids. This second peak in the HRR occurs because of the oxygen that enters the building between seconds 200 until the peak occurs. It is the same principle as the pulsing fire behaviour described in section 4.3. It is difficult to tell if this is a realistic phenomenon. In the case where cells of 5 cm are used, the pressure reached a value of 5800 Pa. This is unlikely to happen and seems to be a result of the numerical instability.

Cell size does not seem to have a large influence on the temperatures reached. The HRR is neither influenced much by the cell size in the first 400 s. However the second peak of HRR comes earlier and sharper.

We conclude that for the pressure peak and temperatures during the first stages of the fire, the grid independency is reached quite fast. In order to be on the safe side, most simulations in this thesis have been performed with a fine grid of 10 cm.

4.2.5 Sensitivity to HRR

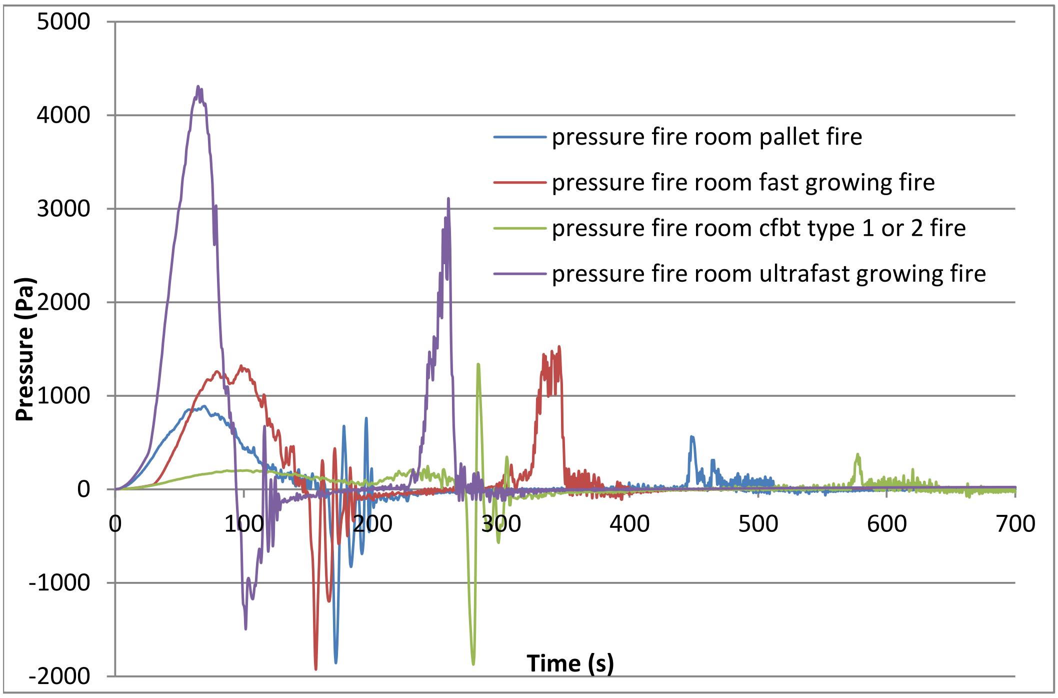


Fig. 4.6 Sensitivity of pressure development in the fire compartment for different heat release rates.

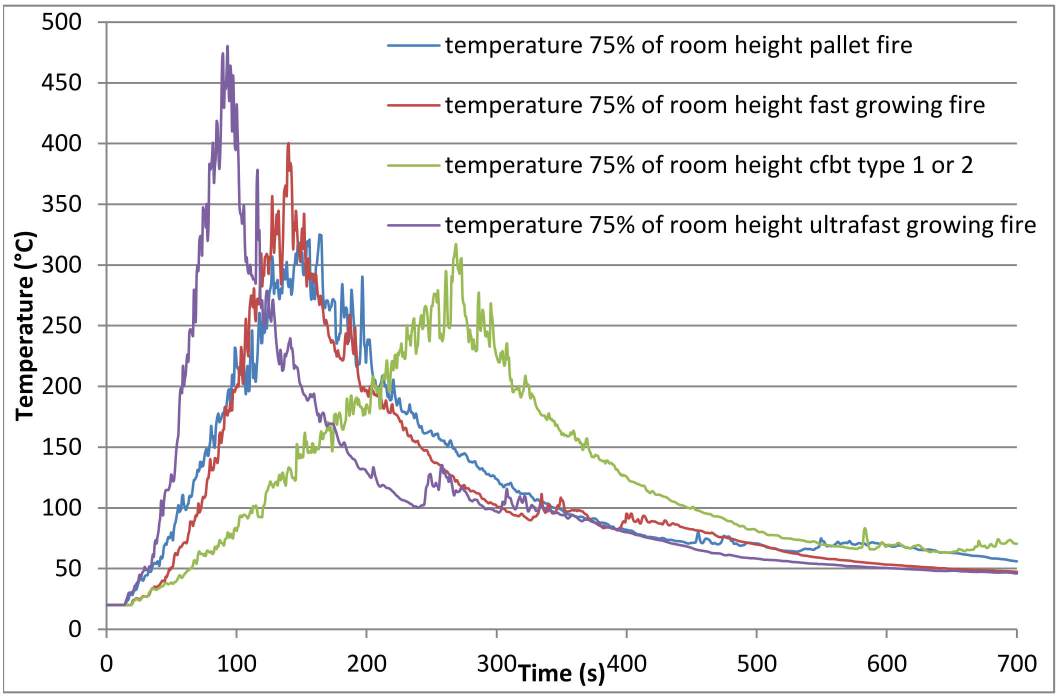


Fig. 4.7 Sensitivity of temperature development in the fire compartment to different heat release rates.

The influence of the HRR on the pressure development is very high. All the HRR curves modelled can possibly occur in a passive house fire. Gauge pressures reached vary from 200 Pa to 4350 Pa.

We possibly observe the pulsing phenomenon here. In the case of the ultrafast fire, there is a negative pressure present. This sucks in fresh air. This fresh oxygen induces a second peak in HRR and pressure. This is logical since the pressure is four times higher than in the pallet fire case. More smoke will be pushed out, which enables to pressure to drop lower if the gases cool down. A fire with a step shaped HRR was modelled too, but is not shown here. This fire burns from the very first second at full power of 2850 MW. This was done to see if a pulsing fire could be observed. The pressure in the step-shaped fire case rose to 47500 Pa, which is unreasonably high. Windows will fail with pressures this high. The pulsing phenomenon was neither observed clearly in that case. Since the result is not realistic, it is not shown here.

The influence on the temperature is smaller, but still significant: temperatures vary from 310 °C to 475 °C.

4.2.6 Sensitivity to lining material

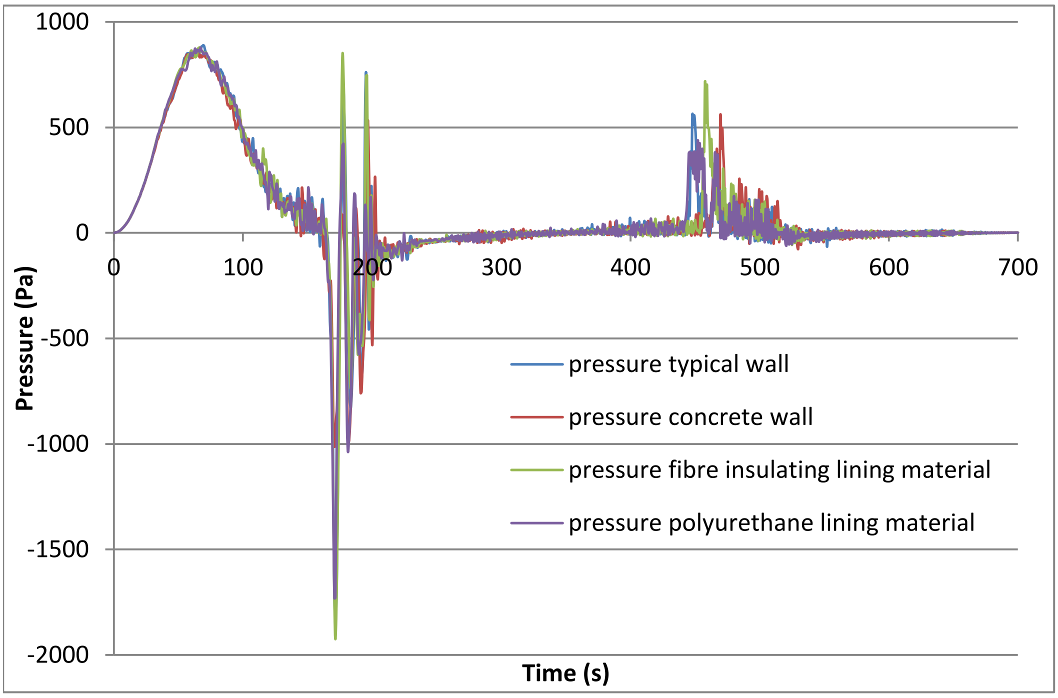


Fig. 4.8 Sensitivity of pressure development in the fire compartment to different lining materials.

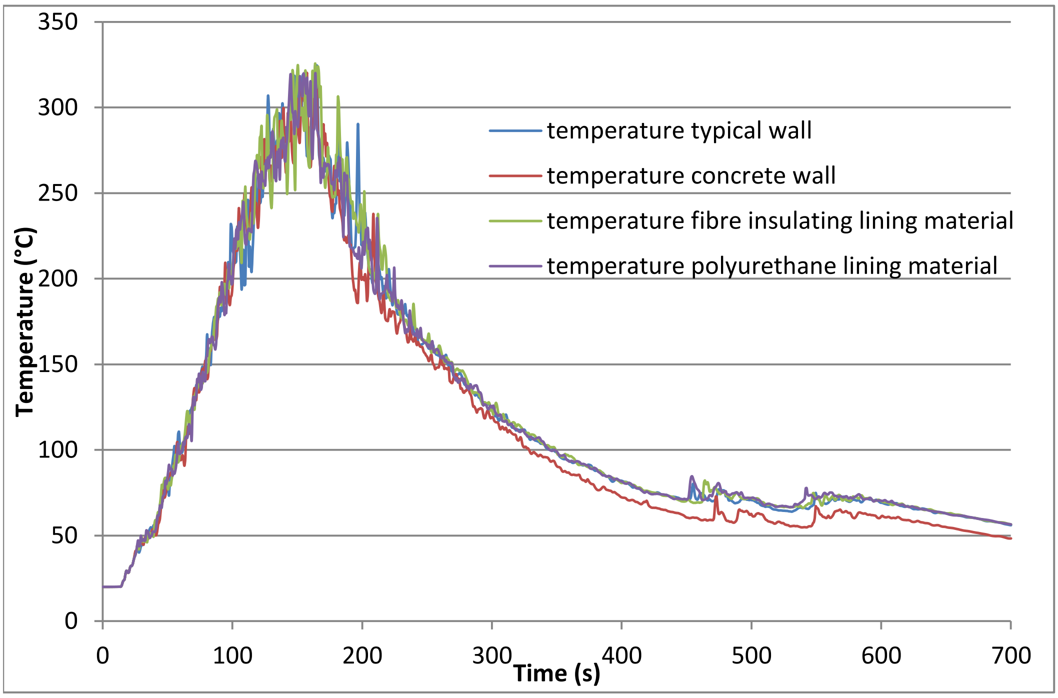


Fig. 4.9 Sensitivity of temperature development in the fire compartment to different lining materials

The simulation shows almost no influence of the lining material. These results are unexpected. As described in section 2.9 with experimental results from [19], insulation plays a major role in temperatures. The experimental results are measured in a container that had an opening, which is not the case here. In our case, there is no ventilation opening which means that there are neither convective heat losses. That is why one could expect the influence of the insulation to be even higher here. This is not the case. Maybe coding errors in FDS are responsible for this strange behaviour? To investigate this, a cube of 1m³ was modelled in FDS. The initial temperature of the air inside the cube is 1000 °C. The wall material is modelled changed in each simulation. Four simulations were ran: plasterboard, polyurethane, concrete and a quasi-perfect insulator were modelled. The quasi perfect insulator was modelled with a conductivity of 10^{-7} W/mK, the density was modelled as 10^{-7} kg/m³ and the specific heat was modelled as 10^{-7} kJ/kgK. The result of this simulation is shown in Fig. 4.10. The only heat losses possible in this case are the heat losses to the wall. One would expect the temperature for a quasi-perfect insulator remain their initial temperature of 1000 °C. The polyurethane seems even to be a better insulator than the quasi-perfect insulator. Plasterboard and concrete have almost the same behaviour. It is clear that there has to be a coding error or in the program or in the input files. Simulations where the cube is modelled without pressure zones and leaks, but completely sealed show the same results. The input files for these simulations discussed here is presented in annex 9.15.

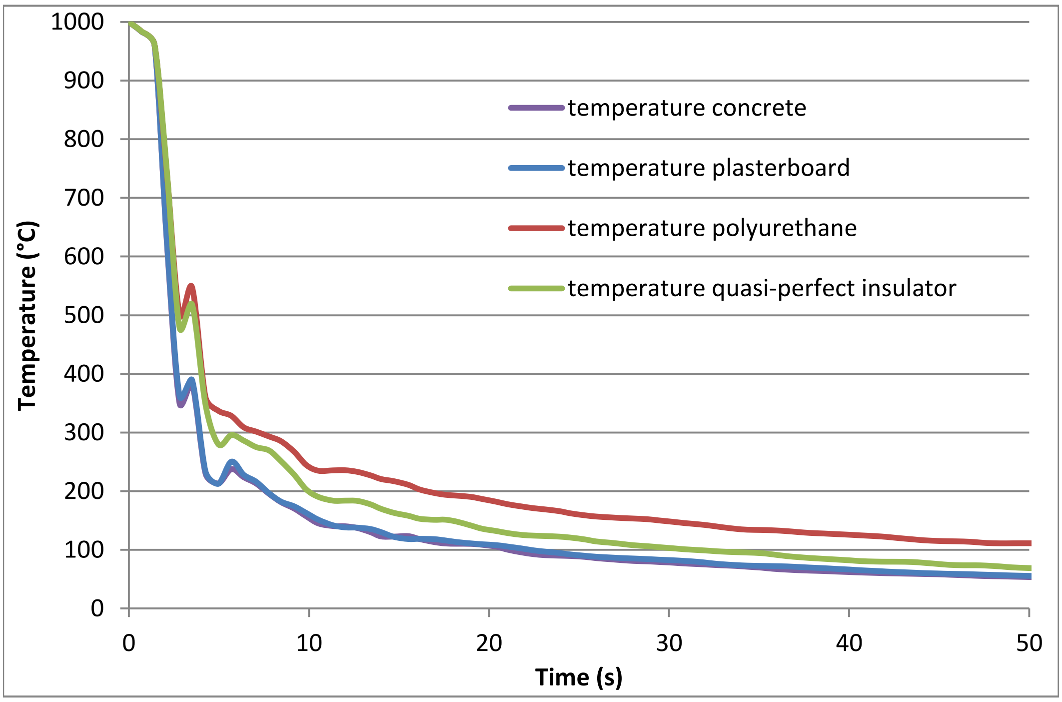


Fig. 4.10 Influence of lining material in FDS in a 1m³ cube filled with air of 1000 °C.

4.2.7 Sensitivity to location of the fire

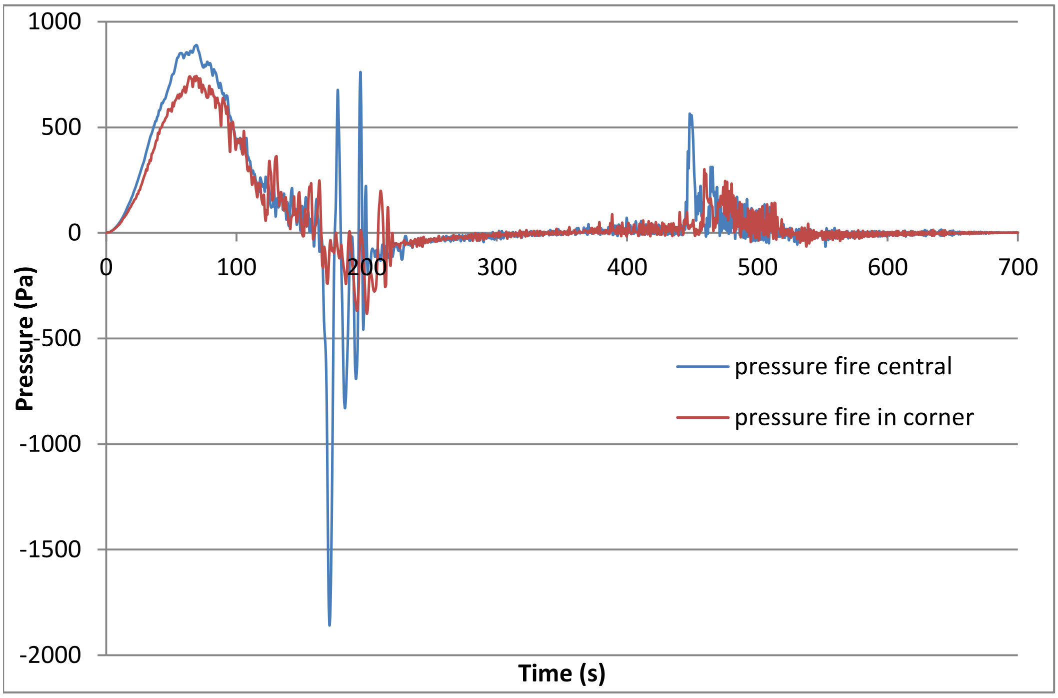


Fig. 4.11 Sensitivity of pressure development in the fire compartment to different locations of the fire.

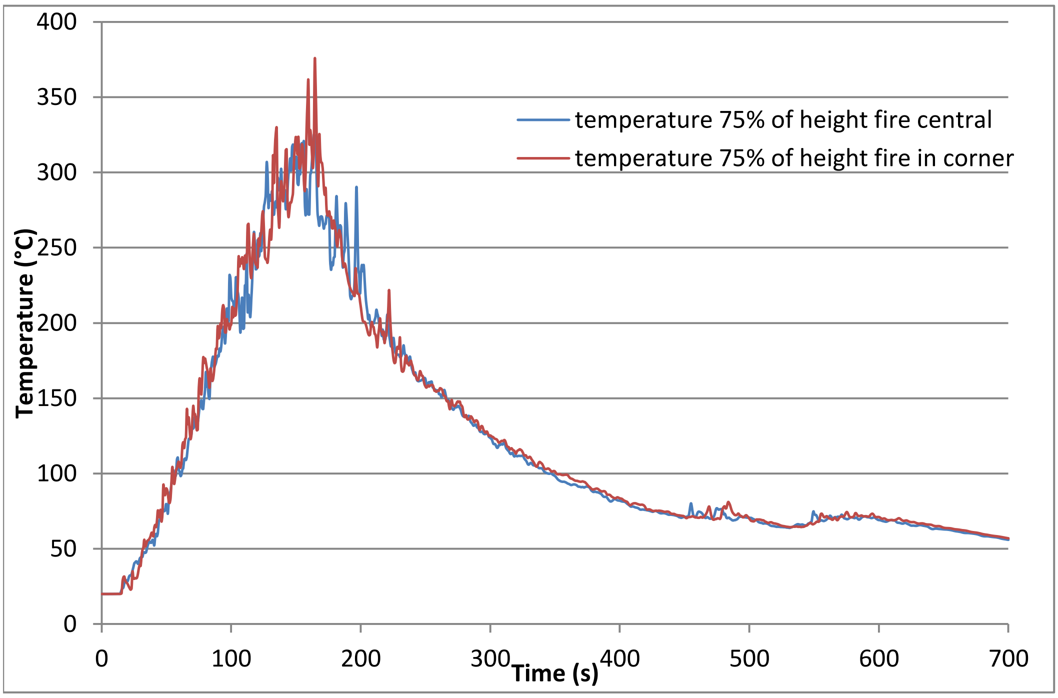


Fig. 4.12 Sensitivity of temperature development in the fire compartment to different locations of the fire.

The location of the fire does not have a significant influence on temperature. However, it makes a difference for the pressure reached. This is possibly because more heat is absorbed by the wall if the fire is located against the wall. This heat absorbed by the wall does not contribute to the heating and expanding gases. However it is strange that this is not observed in the temperature graph. The flow path of the buoyant gases will change, which could explain small differences in temperature. It is not clear why the pressure is unstable after the pressure dropped in the case with the fire central in the room, while it the pressure is much more stable in the case with the fire located against the walls.

4.2.8 Sensitivity to thermal parameters and application of plaster board.

In all the simulations shown here, plaster board and insulation was placed on the ceiling. This will not be the case in the tests. For practical reasons, there will only be plaster board installed above the fire, and not all over the container. The plasterboard can also be modelled with the changing specific heat constant presented in Fig. 3.6. The results of the simulations investigating this influence are shown in Fig. 4.13 and Fig. 4.14.

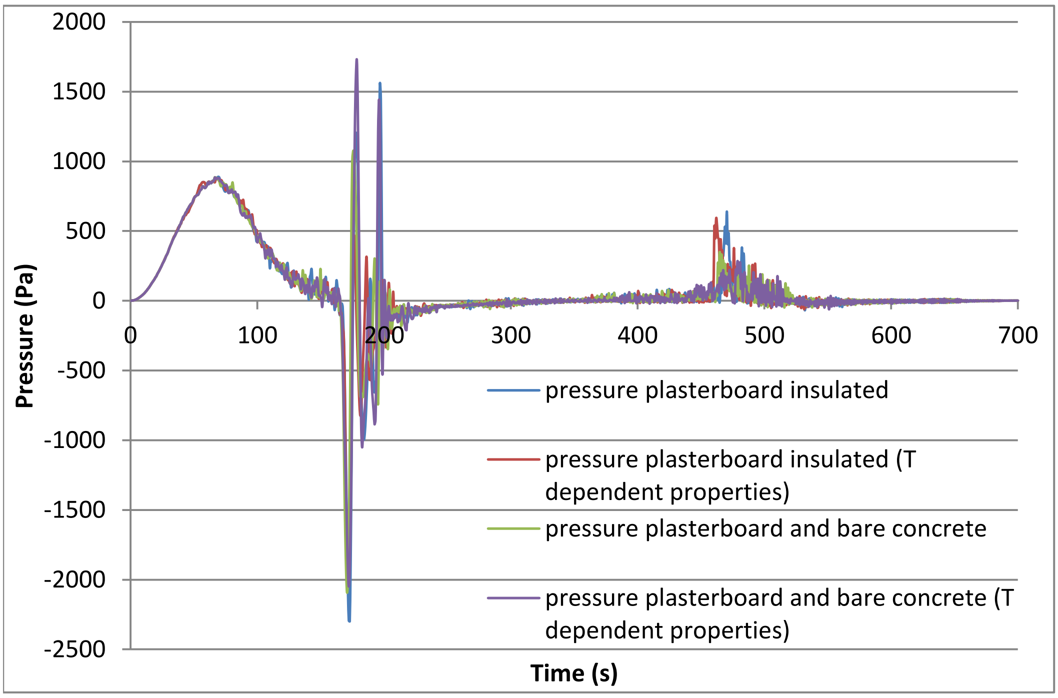


Fig. 4.13 Sensitivity of pressure development in the fire compartment to placement and thermal properties of plasterboard.

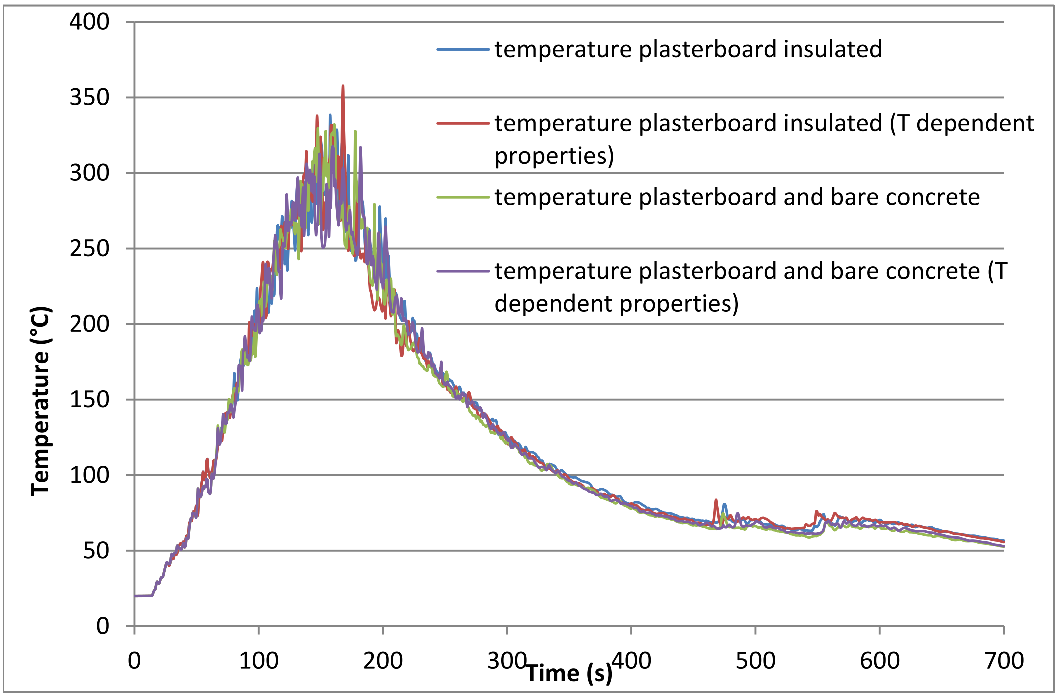


Fig. 4.14 Sensitivity of temperature development in the fire compartment to placement and thermal properties of plasterboard.

From Fig. 4.13 and Fig. 4.14, it is clear that the placement and temperature dependant properties of plaster board is not important. If one looks close at Fig. 4.13, one can see a small difference of a few degrees between the insulated case and the not insulated case.

However, one should take care with these results since it is not clear if FDS treats the thermal properties of the wall in the correct way, as described in section 4.2.6.

4.3 Pulsing fire: a qualitative description

The pulsing phenomena as described in 2.14 will happen in fires with limited ventilation openings. A fire starts and the air provided to the fire is not vitiated yet. Slowly, al the oxygen available to the fire will be used. The HRR will first stabilize and eventually drop. During this growth rate, the temperature in the room increases significantly. The gases in the room thus expand and escape through the limited ventilation openings. Since the HRR drops, temperatures will lower too. The pressure will thus consequently drop too. If the ventilation opening is not too small, the fire could possibly gain strength again, but remain ventilation-controlled. The pressure will thus rise again, preventing fresh air to enter. This is a cycle that can go on and on. It is represented by the flowchart represented in Fig. 4.16.

This could be the case in a room of a passive house that has ventilation openings to the other rooms in the house. Another possibility is that this pulsing phenomena occurs between the fire room and the outside instead of in between the fire room and an adjacent room.

In the case the ventilation openings are too small to have the pulsing phenomena, the start of the fire is the same. FC/VC point will be reached before flashover, at this point there will be an overpressure due to the expanding hot gas inside. The HRR will thus stabilize and decrease after reaching the FC/VC point. Temperatures will lower too. This causes the pressure to drop, which causes an under pressure. But in this case, there will be not enough air supply to raise the HRR. This scenario could possibly occur in a passive house where all the volumes are connected through open doors for examples. This cycle is represented by Fig. 4.15.

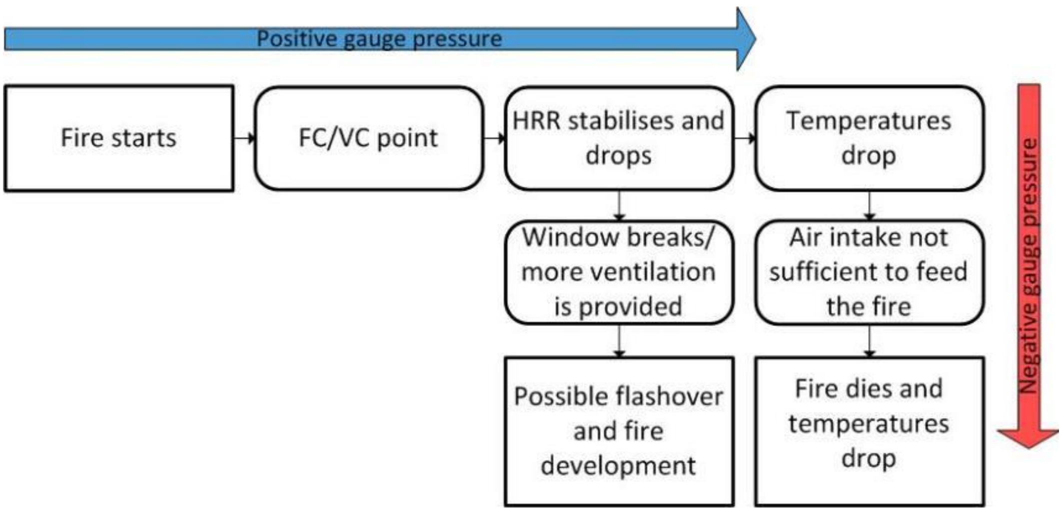


Fig. 4.15 No pulsing occurring in the under-ventilated fire development.

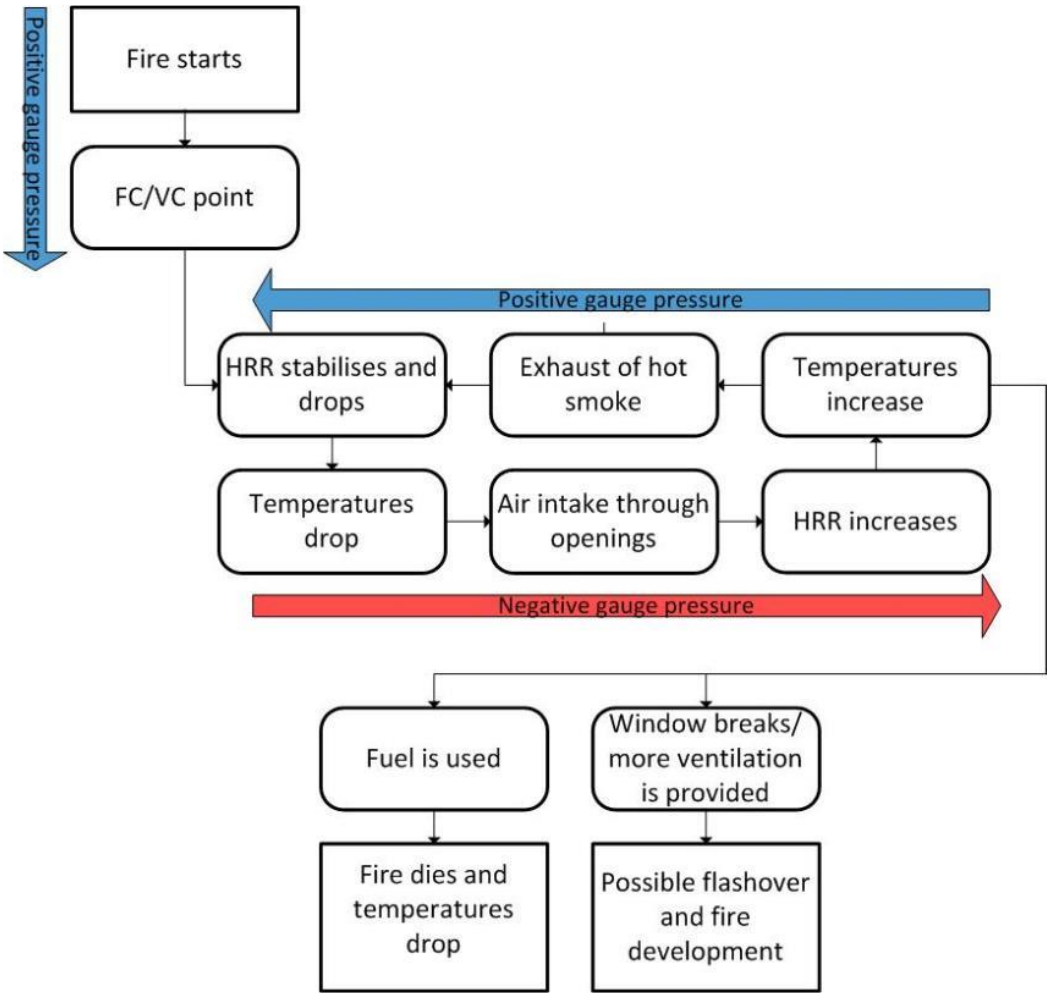


Fig. 4.16 Pulsing occurs in the under-ventilated fire development.

Both scenarios could possibly occur in passive houses. The pulsing scenario can occur if the fire room is closed but connected to other volumes in the house through ventilation openings. If the same fire happened in the same house, but with an open door (large ventilation opening), the fire will be able to grow bigger compared to the pulsing fire scenario. But it will not have the pulsing effect. This effect is qualitatively shown in Fig. 4.17. Which scenario will take place depends on a lot of factors: the shape and size of ventilation openings, if doors are open or closed, fire-induced leakages…

In the case a pulsing fire occurs, it is important to define the gauge pressure. It is possible that the fire room has a negative gauge pressure towards the rest of the house, but a positive gauge pressure compared to the outside. The gauge pressure in Fig. 4.16 is thus relative to the adjacent rooms. The gauge pressure in Fig. 4.15 is relative to the outside.

Pulsing could also occur towards the outside. In that case the ventilation opening is not to an adjacent volume, but to the atmosphere.

It also has to be pointed out that it is possible that the fire does not follow one of these scenarios. A fire can develop towards a ventilation-induced flashover and fully-developed fire if a window breaks due to the high temperatures, or if a door is opened. Fire-induced leakages (e.g. seals, vapour barriers or airtight insulation that burns away or melt) can provide the fire with oxygen. This could be enough to keep the fire alive. Since these leakages are caused by the fire, it is likely that they will grow bigger. So the HRR can increase too.

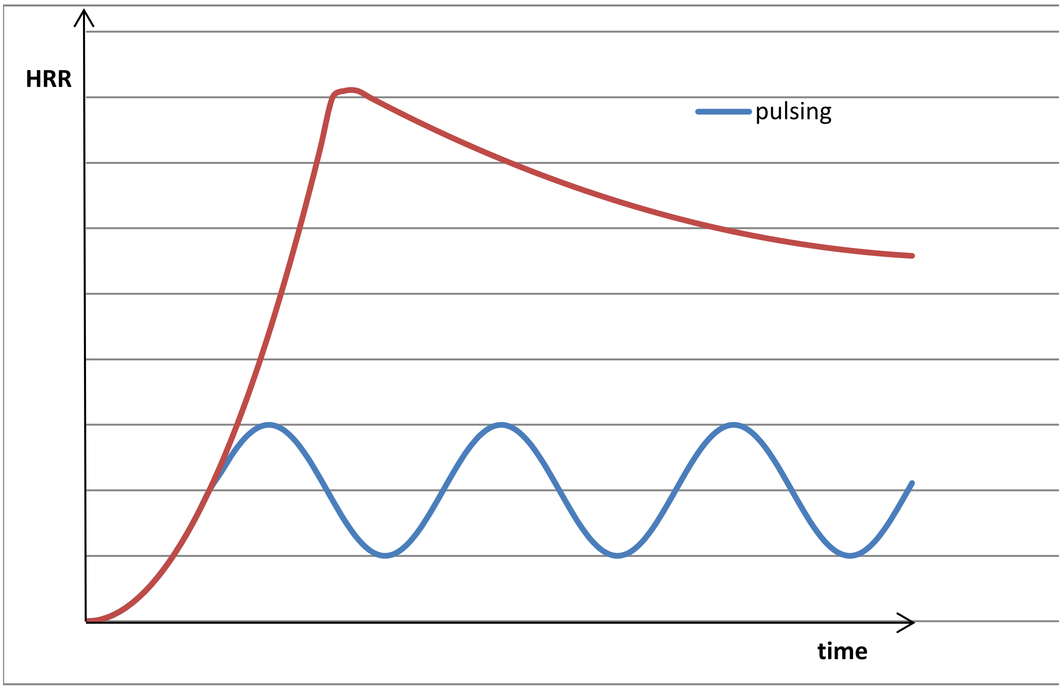


Fig. 4.17 Comparison of HRR expected of a pulsing vs. non pulsing fire in a passive house.

Simulations were performed on the occurring of the pulsing behaviour with a ventilation opening between the two rooms, depending on the size of that opening. The opening area changed from 100 cm^2 to 500 cm^2. The FDS input file can be found in annex 9.13. The results of these simulations is shown in Fig. 4.18, Fig. 4.19 and Fig. 4.20. No obvious results of the pulsing phenomena could be observed. This could be because FDS is not able to simulate a smouldering fire. However, one can distinguish two phenomena that can reveal a possible pulsing fire.

The first phenomenon is the unstable HRR and pressure occurring after the fire smothered because of lack of oxygen. In Fig. 4.20, one can see that the mass flow rate (MFR) turns positive and negative during a time scale of about 10 s. This is thus a very small time scale for a pulsing phenomenon in a fire of this size. This probably is not realistic but appearing because of the combustion model where mixed is burned.

A second phenomenon can be observed over a larger time scale. The MFR from the fire room to the adjacent room first is positive since there is a positive gauge pressure in the fire room. Later the HRR becomes unstable for about 50 seconds, so the pressure and the MFR logically copies this behaviour. After the HRR stabilizes, the MFR is slightly negative during around 400 seconds. In this time, the temperature drops, so gases shrink and air from the adjacent room enters the fire room. This air will probably cause the raised HRR that occurs after around 550 seconds. Again the combustion model stands in the way of a good simulation of this phenomena.

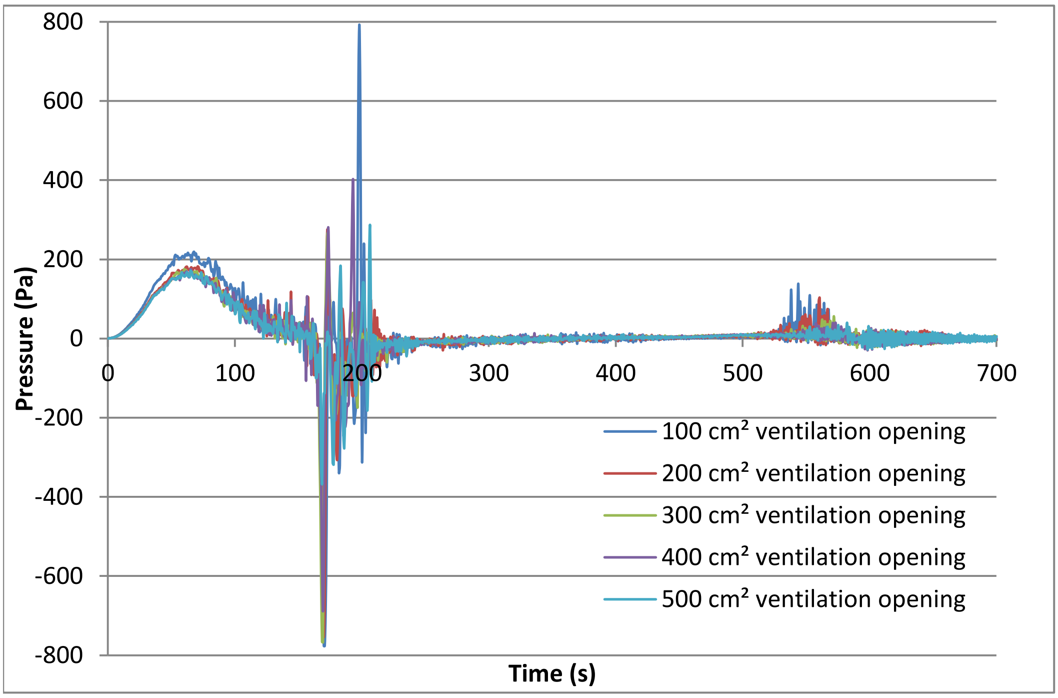


Fig. 4.18 Pressure in fire room for different ventilation openings between fire and adjacent room.

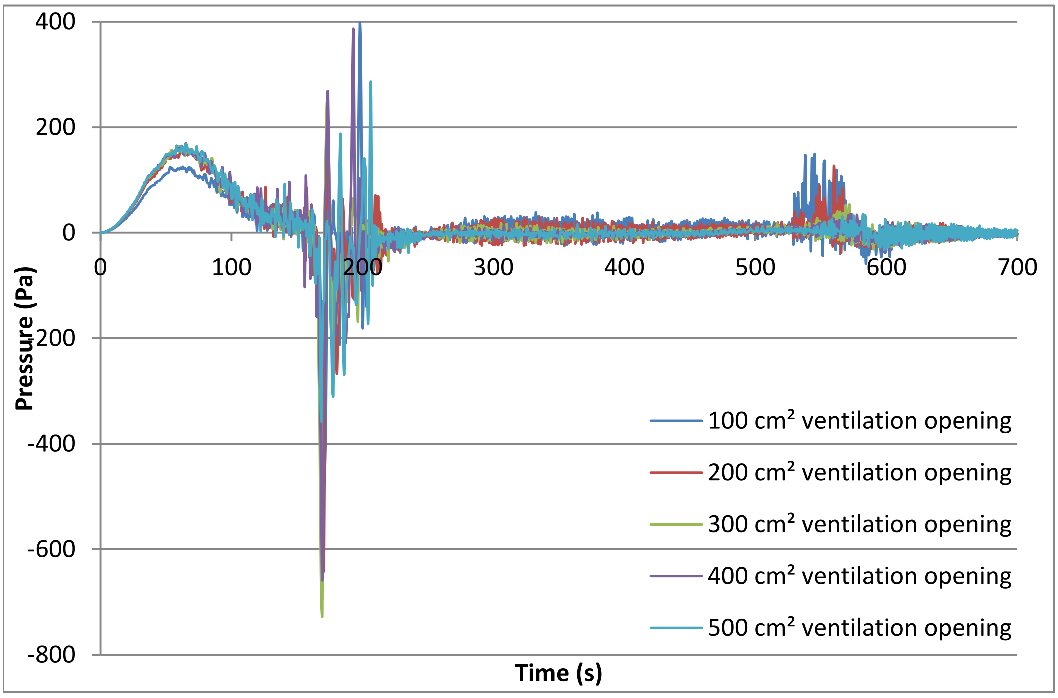


Fig. 4.19 Pressure in adjacent room for different ventilation openings between fire and adjacent room.

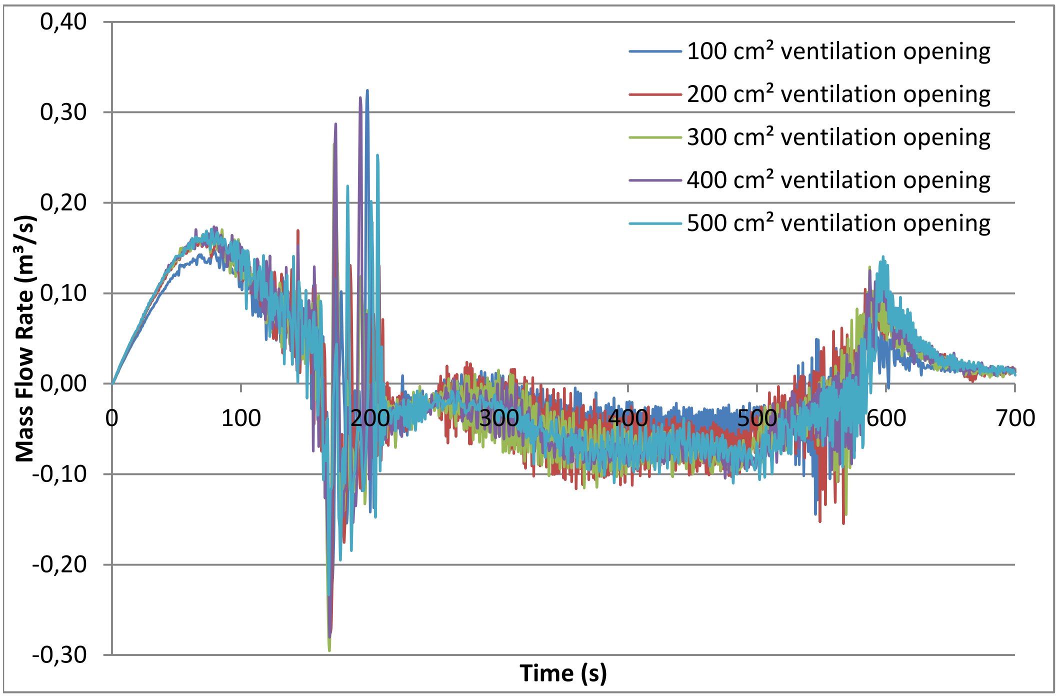


Fig. 4.20 Mass flow rate between fire and adjacent room for different ventilation openings between fire and adjacent room.

4.4 Door forces quantified

Consider a typical door of 2 m height and 0.9 m width. A typical value for the peak gauge pressure in the fire room is 1000 Pa. This is in the order of magnitude of values given in [1] and [2]. Using (15) shows that this results in a force (F_p) of 1800 N. This force is exerted in the middle of the door. People open doors by pushing or pulling at the door handle, which is at another lever arm (d_{la}) from the hinges than the resultant force exerted by the gauge pressure. To open the door, the moment (M_d) around the hinges should equal zero. The force exerted by people on the door is called F_h.

$$F_p = \Delta P \times A \tag{15}$$

$$M_d = \sum F \times d_{la} \tag{16}$$

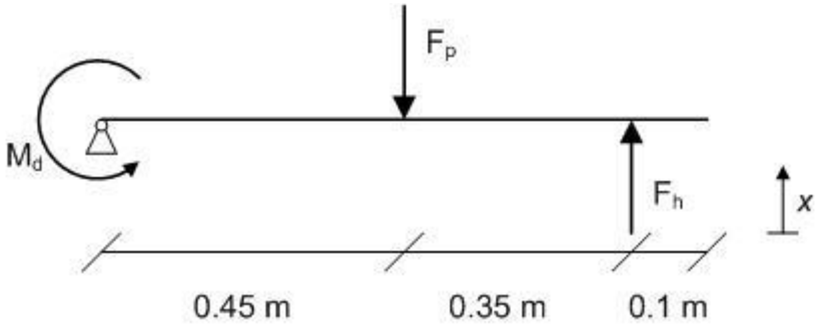


Fig. 4.21 Forces acting on the door

Fig. 4.21 shows the forces acting on a door. If F_p is1800 N and the typical door values shown in Fig. 4.21 are used, (16) shows that F_h needs to be 1013 N in order to open the door. This is a huge force.

Forces that can be applied, dependent on the age and sex of people is investigated by A.I.M. Voorbij and L.P.A. Steenbekkers and reported in [44]. Graphs representing this information are shown in Fig. 4.22. In total 750 subjects took part in these tests. The force measured was gradually built up, and maintained for 3 s. Subjects were encouraged during the tests.

One can see that the results strongly depend on the age and sex. Only pulling forces are of importance since people want to run away from the fire. From the age of 50 years, one loses strength. One can see that 150 N is a value that can be exerted by most people. It would thus be necessary for the fire safety that one never should exert a force higher than 150 N. With the typical door measurements discussed earlier in this parameters, this means a maximum pressure of 148 Pa. Typical peak values in passive house fires are an order of magnitude higher.

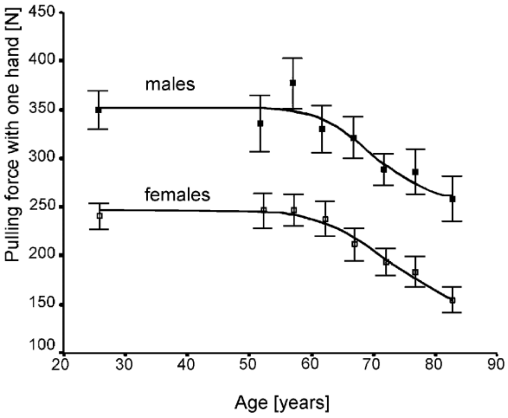


Fig. 4.22 Push and pull forces depending on age and sex. Taken from [44].

5 Results: practical design of test results

Since the tests will be performed by another student, no test results are available yet. The construction is erected. Hereby the final test design is given in a concise way.

5.1 Test set-up: implementation

5.1.1 Construction

As already mentioned the inner dimensions of the construction are 12.03 m long, 2.35 m wide and 2.39 m high. Technical drawings and dimensions are given in annex 9.1 and 9.2.

The construction is freestanding on a concrete slab foundation. The construction is made from concrete blocks that are 20 cm wide. On top of these blocks, a concrete slab is poured as ceiling. Those concrete blocks are not airtight. Therefore, plaster is applied on the inside of the blocks. The concrete slabs are airtight. In front of this wall, there will be placed metal studs of 4.5 cm wide. The cavities between these metal studs will be filled with mineral wool. In front of this metal studs, two plaster boards of 9 mm will be placed. The first plasterboard will always have to be replaced in between two tests. The ceiling of the fire room will be covered over a length of 3 meter with insulation and plaster board. This to prevent spalling, and too high heat losses to the concrete. The reason why not all the ceiling will be covered with plaster board and insulation is for practical issues: this needs to be replaced, and this is not that straightforward at the ceiling.

Fig. 5.1 Picture of the skeleton of the construction with concrete bricks.

5.1.2 Ventilation

The selected fans are common residential fans. The model chosen for both supply and extraction was Soler & Palau TD-350/125. The pressure flow curves of this tube fans are given in the data sheet of the fan [45] and shown in Fig. 5.3. Technical drawings of the ventilation ducts and their location can be found in annex 9.1 and 9.4.

The selected ventilation system is shown in Fig. 5.2. The tubes are stiff zinc coated steel tubes with a diameter of 100 mm. All the connections and tubes are made by the company Lindab and featured with the click function from Lindab. This function allows simply to click the duct in the connection. As mentioned in 3.2.2 it is important to use the fan at top speed, and smother the duct system to achieve 80 m³/h. This way, the duct system will have a higher static pressure and resembles more a real passive house ventilation system.

During the tests, the fans will be placed in a semi closed space next to the test construction. This will prevent the wind from having a big influence. This space will not be completely sealed, so the pressure in that space is not influenced by the supply and extraction flow.

Fig. 5.2 Curves, connections, plate orifices and nozzles of the ventilation system.

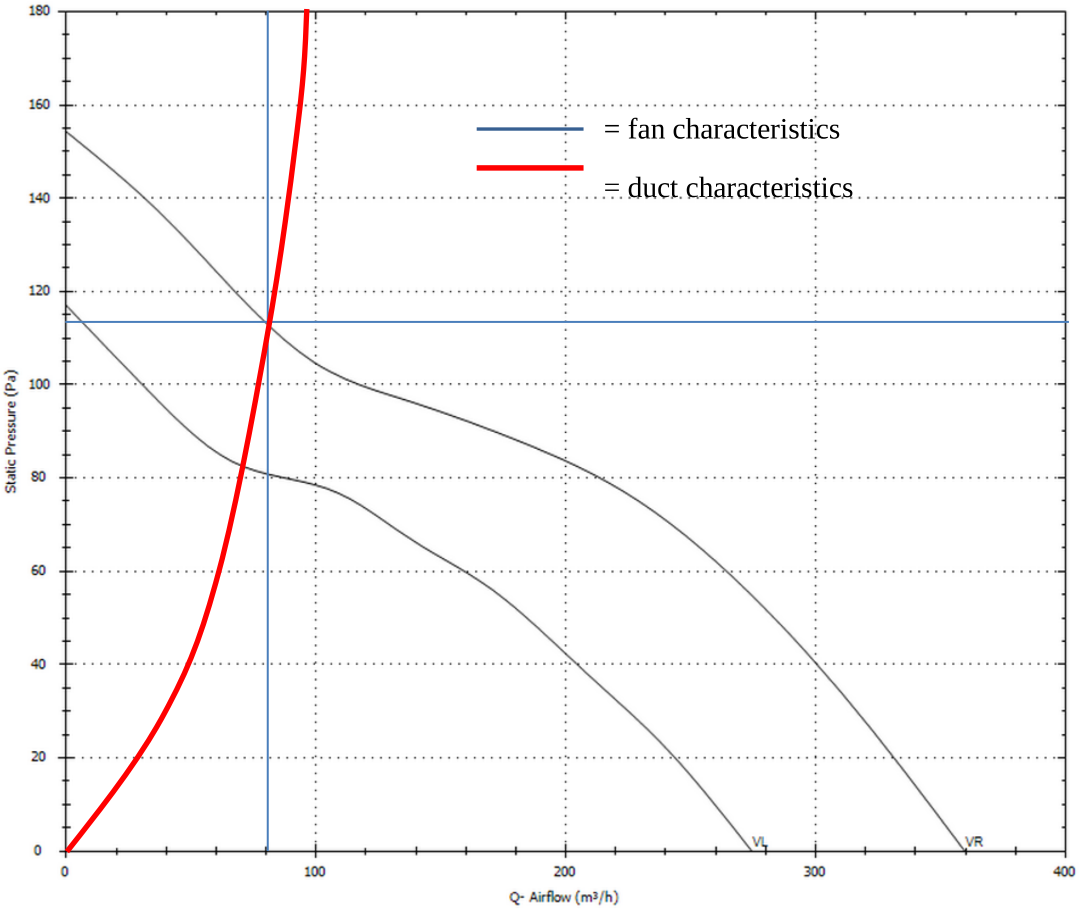


Fig. 5.3 Curves of S&P TD350/125 fans and duct characteristics. Adapted from [45].

Fig. 5.4 Picture of one S&P TD350/125 fan.

5.1.3 Fire

In Fig. 3.15, one can see the different heat release rates. As already mentioned, a fast growing fire is assumed representative for a fire in a passive house. One can see that the HRR of a type 3 CFBT fire represents quite well the fast growing fire curve. Therefore, the type 3 CFBT fire is selected as the best option for these tests.

5.1.4 Measurements

From the measurements discussed in 3.2.4, only temperature, pressure and flow rates measurement will be done. Smoke alarms will be installed too. Other measurements were not possible because the equipment was not available or too expensive. The exact location of all the measurement equipment can be found in annex 9.2, 9.5 and 9.6.

Temperature

Temperature will be measured with 27 thermocouples. All thermocouples used are from the K-type and have a thickness of 0.5 mm. Two trees with 11 thermocouples are used to measure the temperature over the height of the two rooms. Every 20 cm, a thermocouple is located. Three thermocouples are use every 60 cm on the wall, to know the wall temperature of the plaster board. One thermocouple is located at the back of the plasterboard. Two thermocouples are used in the supply and extraction ducts. These should be placed next to the orifice plates, since it is an interesting parameter to calculate the flow rate at these orifice plates. A last thermocouple is placed above the fire source, to see if the fire develops every test in the same way. An overview is given in TABLE 5.1.

TABLE 5.1 Overview of thermocouples in test set-up.

Thermocouple	location	remarks
1-11	Thermocouple tree in adjacent room	Measurement of gas temperature. Rising numbers bottom to top.
12-22	Thermocouple tree in fire room	Measurement of gas temperature. Rising bottom to top.
23	At plasterboard 60 cm height	
24	At plasterboard 120 cm height	
25	At plasterboard 180 cm height	
26	Back of plasterboard 120 cm height	
27	On top of fire	To check the repeatability of the fires.
28	In tube to adjacent room, next to orifice plate	To know the temperature of the gases in the duct, in order to calculate the flow with (18).
29	In tube to fire room, next to orifice plate	To know the temperature of the gases in the duct, in order to calculate the flow with (18).

Fig. 5.5 Picture of one thermocouple with the plug at one end and the weld at the other end.

Pressure

The gauge pressure is measured both between the fire room and the ambient, and between the fire room and the adjacent room. The apparatuses used are produced by Halstrup Walcher. The range of the apparatus used for the gauge pressure between the fire and the ambient is 0-2000 Pa, with an accuracy of +/- 0.2%. The range of the apparatus used for the gauge pressure between the fire and the adjacent room is 0-250 Pa, with an accuracy of 0.5%. Both apparatuses look the same as the one shown in Fig. 5.4

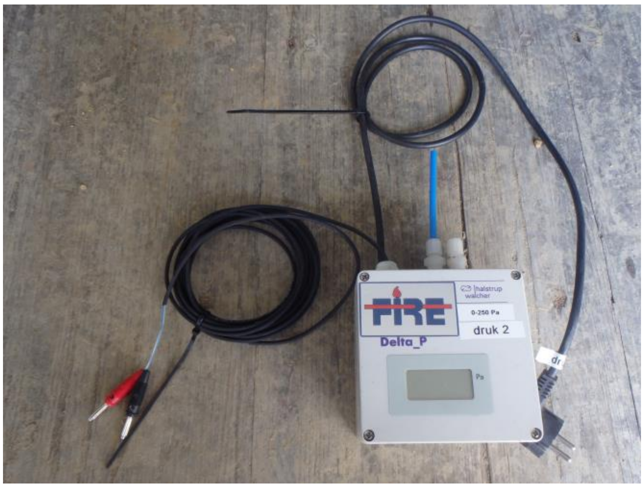


Fig. 5.6 Picture of a gauge pressure difference apparatus.

Flow in supply and extraction ducts

As already mentioned, both in the supply and extraction duct an adjustable orifice plate will be installed. A picture of this adjustable orifice plate is shown in Fig. 5.7. It is a Lindab product called DIRU 100. Since the fans should work at top speed to have the highest static pressure, the right flow rate of 80 m³/h or 22 l/s is obtained by smothering the flow with this adjustable orifice plate.

The changing of the opening in the orifice plate is called the setting value, this setting value results in a k factor. The k factor needs to be adjusted such that a pressure drop that resembles a flow of 22 l/s is reached. This relation is found in [46] and shown in Fig. 5.8. The graph holds for air at standard temperatures, where (17) holds for elevated temperatures, taken from [47]. Δp_m is the gauge pressure measured at the nozzles provided at the damper, q is the flow through the duct. A validity range for this equation is not given. (18) is adapted from (17) in order to calculate immediately the flow in the duct from the measured temperature and gauge pressure.

$$q = k\sqrt{\frac{\Delta p_m \times 1.2}{\rho}} \quad (17)$$

$$q = k\sqrt{\frac{\Delta p_m \times T}{293}} \quad (18)$$

The damper needs to be set in an iterative way:

- A setting value for the damper and thus a k-value is guessed.
- $\Delta p_m$is measured.
- q is calculated using (17) or obtained using Fig. 5.8
- q is compared to the required flow.
- Setting value (and thus k) is adjusted and the setting sequence starts again until q equals the derived flow of 22 l/s.

Fig. 5.7 Picture of the adjustable orifice plate: DIRU 100.

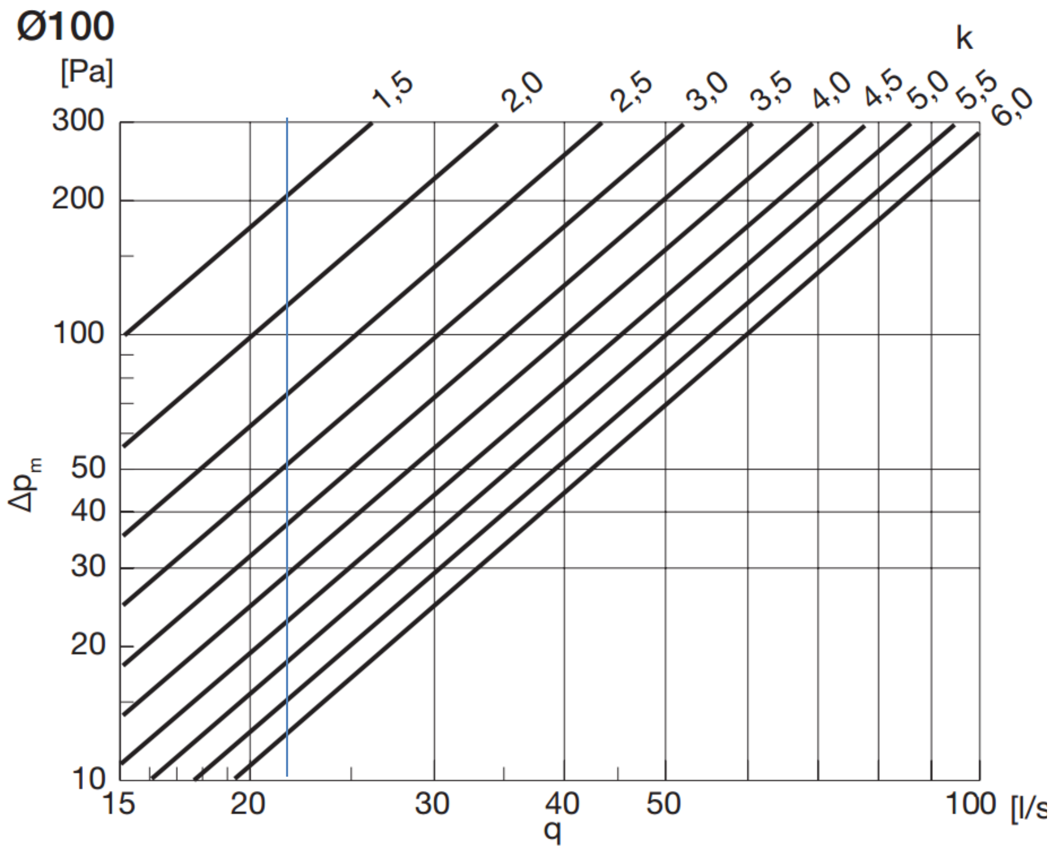


Fig. 5.8 Relation between pressure drop over the orifice plate and flow rate. Adapted from [46].

Smoke alarms

The smoke alarms that will be placed in the construction is an optical smoke detector, which is certified by a recognized body and fulfils to requirements set by the European standard EN 14604.

5.2 Test outlines

5.2.1 Overview

Six tests are designed to investigate the most important parameters. The different tests are presented here. An example of a script on how to actually conduct the tests is given for test 1 in annex 9.16. Information on which materials that are needed, how many people are needed, what to check, who is responsible for what, which are the tasks and rules during an experiment and more practical information is given in that script. The procedure to ignite the fire and to close the door is also described in the document.

TABLE 5.2 Overview different test settings

	Fire load	Door (between two rooms)	Ventilation
Test 1	Wood	Closed	Off
Test 2	Wood	Opened	Off
Test 3	Sofa	Closed	Off
Test 4	Gasoline	Closed	Off
Test 5	Wood	Closed	Air supply in fire room
Test 6	Wood	Closed	Extraction in fire room

5.2.2 Test 1: reference case

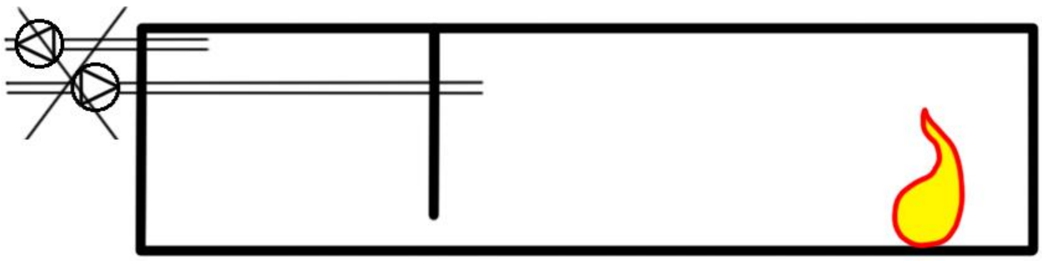


Fig. 5.9 Test 1: reference case.

This is the reference test, the other tests will be compared to this one. The basic research questions will be answered here: What is the temperature at the moment that the fire turns under-ventilated? and "What will the pressure development look like?" In addition hereto, both the door to the outside and the door between the two rooms will be opened after 12 minutes. This will show us if the fire will recover strength and could turn into flashover if the fuel load allows it. And, if yes, how fast will it do so?

According to [48], the average time of arrival of a Belgian fire service is 9min 50 sec after the phone call. This makes 12 minutes a good time to open the door and see what happens, since it is a realistic time compared reality. Two minutes for the people to discover the fire and call the fire brigade and 10 minutes for the fire brigade to arrive on the fireground.

5.2.3 Test 2: influence of volume

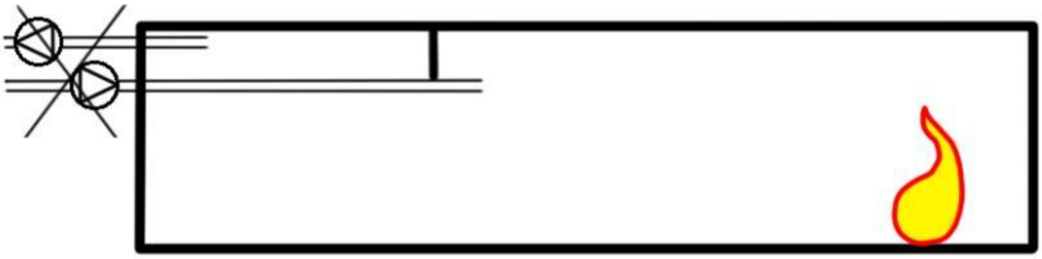


Fig. 5.10 Test 2: influence of volume.

Will the volume have an influence on the maximum temperature or pressure? After 12 minutes, the door will be opened and it will be checked if the fire can regain strength and turn into flashover if the fuel load would allow it to do so.

5.2.4 Test 3: influence of fire load: sofa

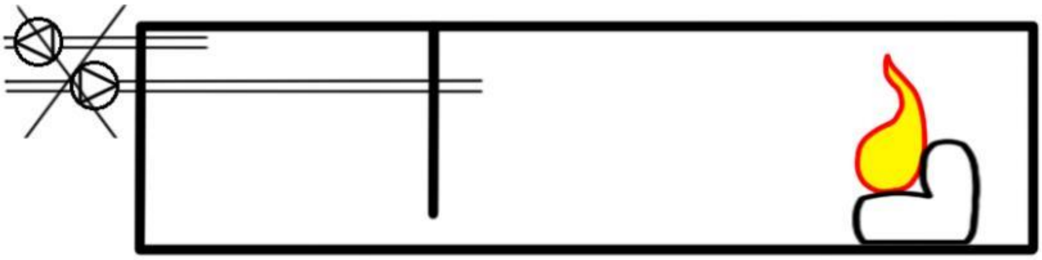


Fig. 5.11 Test 3: Influence of fire load: sofa fire.

Does the fire load have a significant influence on the maximum temperature and pressure? The HRR curve will have a big influence on this, but since the reference wood fire and the sofa should have both a fast developing fire [9] this influence should be limited. If it turns out that the fire load has a big influence, this could lead to recommendations for future work. Like in test 1 and test 2, the door will be opened after 12 minutes too.

5.2.5 Test 4: Influence of fire load: gasoline

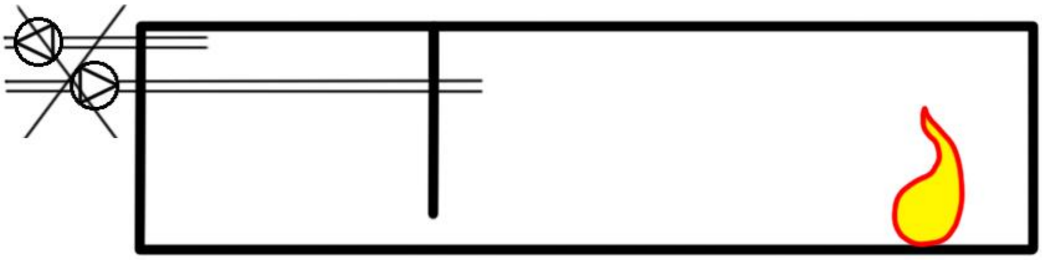


Fig. 5.12 Test 4: Influence of fire load: gasoline fire.

It could be possible that the difference between the wood fire and the sofa was just by coincidence not too big. That is the reason why a gasoline fire is used to compare. This will show the importance of the HRR, since a gasoline fire grows by approximation almost instantly to its steady state HRR. A downside here of a pool fire is the fact that it cannot smoulder. This will be interesting to see how representative a non-smouldering fire is for under-ventilated fires. The door will be opened after 12 minutes to see if the fire can restart, which will probably not be the case it here is no smouldering and the gasoline does not have its AIT.

5.2.6 Test 5: Air supply in the fire room

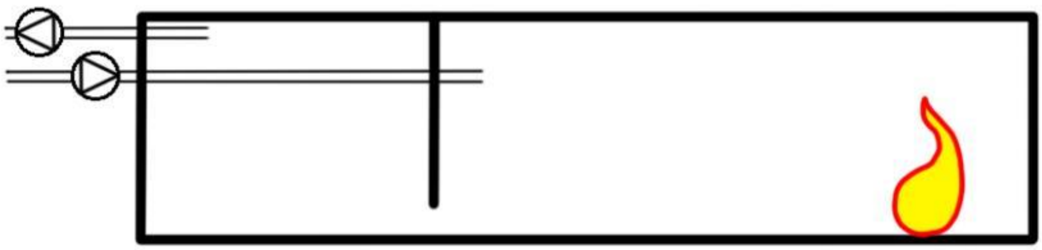


Fig. 5.13 Test 5: Influence of ventilation: air supply in the fire room

Does the ventilation have a significant influence? Will the fire be able to reverse the flow in the supply duct?

After 15 minutes, both doors will be opened, to see if the fire can regain strength. If the influence of the ventilation system is not significant, these 15 minutes can be compared to the 12 minutes of the first tests.

5.2.7 Test 6: Air extraction form the fire room

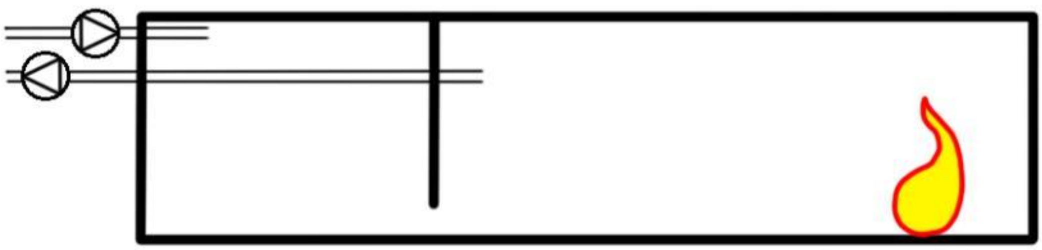


Fig. 5.14 Test 5: Influence of ventilation: extraction from the fire compartment.

Will the ventilation system have a big influence? Is the ventilation system strong enough to prevent smoke from going to the adjacent room for a while?

After 20 minutes, both doors will be opened, to investigate if the fire can regain strength. If the influence of the ventilation system is not too significant, these 20 minutes can be compared to the 22 and 15 minutes of the other tests.

6 Conclusions

There is a higher risk on rapid fire progress in passive house fires. That is clear from the literature review and the qualitative description of these phenomena. Since more passive houses are built and the requirements for new constructions are becoming more severe, we will face more fires with a risk on rapid fire progress. Backdraft, smoke explosion and ventilation-induced flashover will thus be observed more on the fire ground in the future. These fire developments bring more risks along with them, so a good understanding of these phenomena will only become more important.

There is no such thing as one representative passive house. Although all passive houses have several properties in common, they can differ quite a lot. The visits to passive houses clearly showed this. We visited a concrete structure, stand-alone passive house and a row house with partly timber structure and natural insulation. But not only structure, lining material and insulation can differ. Volume and ventilation openings to other rooms can vary too.

The sensitivity analysis showed little dependence of temperature and pressure on the lining material. It seems that FDS did not solve the heat losses to the wall in a correct way. However, the HRR has a major influence. It is important to note that no conclusions can be drawn on the absolute value of the pressures reached in this sensitivity study, since the size of the leaks was modelled in such a way that the pressure reached a value in the range as predicted by reduced-scale experiments and zone model simulations.

Almost no research had been done on pulsing fires until now. The right conditions are possibly available in a passive house for a fire to turn into a pulsing fire. Simulations, however, did not reveal the occurrence of this phenomenon.

If the ventilation flow would have been high enough to prevent the smoke from spreading to other rooms, the home automation system could command the fans to run at full speed if the fire was detected in a room where air was extracted from. Unfortunately, the fans are not powerful enough to overcome the pressure built up by the fire, so it is always the best option to switch off the ventilation system in case of fire.

The quantification of the required force to open doors upon evacuation showed that this force is huge at the moment of the pressure peak. This shows the importance of a good understanding of the pressure development during passive house fires.

The full-scale tests designed throughout this thesis should confirm and refine the results obtained by reduced-scale experiments and two-zone models. Most important here is the maximum pressure reached, the shape of this pressure curve and the maximum temperature reached.

Future work

As already mentioned, the literature review revealed that pulsing fires are not well researched yet. This is an important topic since it is a serious threat for fire fighters. The phenomenon does not occur often, so firefighters are not used to it. In a pulsing fire, it is possible that no smoke is coming out from a small ventilation opening. Firemen could possibly draw wrong conclusions as “This fire did already die because of lack of oxygen.” Upon entering the building or fire room they could be surprised by the under-ventilated fire conditions. At that moment, they face the risk that these under-ventilated fire conditions develop through a form of rapid fire progress into a fully-developed fire. They could be surprised by this evolution because they expected a fire that was completely smothered. Hereby, a recommendation is made for a more thorough investigation and better understanding of the conditions needed for a pulsing fire.

Another topic that deserves more interest is the probability of fire starting in passive or low-energy houses. More appliances in houses mean more possible fire scenarios. Is the probability of a fire starting in a new house with more insulation, ventilation system, heat exchange system, solar panels and home control system in place higher than in a traditional house? If a fire results from a badly installed system, it will probably happen in the period just after finishing the construction. Is a fire in new passive or low-energy houses thus more likely to happen in the first days, weeks or months after finishing the construction?

7 Acknowledgements

In the very beginning of this thesis, I mentioned apostle Paul. He told us we have to work together and rely on each other to achieve something. Saying this, I mean that I could never have done this thesis all by myself. As you could expect, several stakeholders [38] helped with this project.

People who know me a bit know that words as: perfect, great, super, really cool and thank you a lot frequently occur in my daily vocabulary. In that way, superlatives might lose their meaning. I would like to point out that comparatives and superlatives mentioned in this paragraph have the meaning that they actually should have.

First of all I would like to thank the firefighting school IPF Hainaut for the corporation. The sponsoring of the construction is highly appreciated. I definitely hope this could lead to a larger connection between the firefighting world and the fire safety worlds. Claude, thank you very much for your practical insight and down to earth analysis of everything. You were always available for another phone call!

My promotor Prof. Stephen Welch gave me the opportunity to prepare these tests in Belgium. A once (or hopefully twice) in a lifetime opportunity. Thank you for that possibility! Prof. Bart Merci, co-promotor, respect for what you do and achieve in your job. You had to manage lots of things in this semester, but you still immediately answered to emails and gave feedback. Thank you for that! I really would like thank my mentor Karel Lambert a lot for the freedom, feedback, input and clear opinion that you always gave me during the months I worked on this thesis. You do a great job by bringing knowledge from the fire safety world to the firemen in Belgium! Prof. Sylvain Brohez, thank you for the helpful information, useful references and the lunch in that day cold day during wintertime.

I visited two passive houses: thank you Bruno and Ruben for the ‘warm’ but still eco-friendly welcome and information. It triggered me to do it the same way later: when I’m grown up and maybe have some real estate.

Thanks to my grandparents from for using their car and trailer to transport the ventilation system, thermocouple trees and other stuff. Same holds for my uncle and aunt in Ghent, who acted as a five star rated B&B as well as my personal drivers with their van. Couchsurfing and Uber could not do better!

My fellow students: you changed who I am. Since more than a year now, it sometimes happens that I show an emotion. One might, on very rare occasions, even hear me talking about them. Thank you for everything. See you somewhere in the world. As my French teacher in high school told: “Il n’y a que les arbres qui ne se rencontrent jamais”-“It are only the trees that don’t come across each other.” See you somewhere on this interesting planet!

Although this is already the second page of the acknowledgments section (thanks to the Edinbugh 1.5 spacing rule), there are still three sets of people that I would like to thank:

A first set of people are the people that did not ask how my thesis was going because I didn't like to explain another time that we were running out of time with the tests. Now you can read exactly what I was doing at that time. By approximation this set of people is equal to my simpatico friends (or homies, as they call themselves) in Ieper and my parents: thank you!

A second set of people are the people that helped thinking on this thesis, offered there help with the construction or helped me with proof reading. This set of people is by approximation equal to sum of the members of the fire brigade in Ieper and my inspiring friends from BIZON: thank you! (Remember me to set a date for that dinner I promised!)

A third set of people that I want to thank are the people with whom I could camp and sit around a campfire sometimes throughout this wonderful program. I would reply the meta campfire discussion/question: "Are useless campfire discussions useful?" with a convinced "yes!"

To each and every one of you: take care, stay cool, thank you and see you around.

8 References

[1] B. Debrouwere, "A study of initial fire behaviour in low-energy houses," M.S. thesis, Department of Flow, Heat and Combustion, Ghent University, Belgium, 2012.

[2] S. Brohez, N. Cornil, C. Fourneau, H. Breulet and S. Desmet, 2011, February, "Passive House and fire = Inferno?," [ONLINE] available: www.besafe.be/kennisdatabank/brandveiligheid-passiefhuizen, consulted on 2015, February 27.

[3] Passiehuis Platform vzw, "Wat is een passiefhuis?," [ONLINE], available: http://www.passiefhuisplatform.be/artikel/wat-een-passiefhuis, consulted on 2015 February 26.

[4] Passiefhuis Platform vzw/Plate-forme Maison Passive asbl, "Vademecum residentieel," supported by Government Brussels Captital Region and Walloon Region, Belgium, 2014.

[5] Flemish parlement, 2014, December 30, "Het Energiebesluit van 19 november 2010," [ONLINE] available: codex.vlaanderen.be/Zoeken/Document.aspx?DID=1019755&para m=inhoud, consulted on 2015, December 27.

[6] C. Boonstra, R. Clocquet, L. Joosten, "Passiefhuizen in Nederland," 1st ed., Boxtel, the Netherlands: Æneas BV, 2013.

[7] European parliament, Directive 2002/91/EC of the European Parliament and the Council of 2002, December 16 on the energy performance of buildings, Official Journal of the European Communities (2003) L 1/65.

[8] European parliament, Directive 2010/31/EU of the European Parliament and the Council of 19 May 2010 on the energy performance of buildings, Official Journal of the European Communities (2010) L 153/13.

[9] B. Karlsson, J.G. Quintiere, "Enclosure Fire Dynamics," 1st ed. Boca Raton, CRC Press, 2000.

[10] D. Drysdale, "An Introduction to Fire Dynamics," 3rd ed. City of New York: Wiley, 2011.

[11] Vlaams Instituut voor bio en ecologisch bouwen en wonen, "Isolatie, Gezonde en milieuverantwoorde woningen, technische fiche," [ONLINE] available: http://www.vibe.be/downloads/1.Technische_documentatie/Technische%20fiches/Isolatie/Tf-Isolatie.pdf, consulted on 2015, March 4.

[12] Isoproc Solutions, "Technische fiche Cellulose," [ONLINE] available: https://www.isoproc.be/images/uploads/products/Cellulose/i3-cellulose-technische-fiche-102013-NL.pdf, consulted 2015, march 4.

[13] R. Van Boxtel, "Handboek Gevelisolatie," 1st ed., The Netherlands: Landelijke Specialisten Gevelisolatie, 1995.

[14] M. G. Vangeem, T. A. Holm and J. P. Ries, "Optimal Thermal Mass and R-value in Concrete," First International Conference on Concrete Sustainability, Tokyo, Japan, 2013.

[15] Rockwool, "Frequently asked questions," [ONLINE] available: http://www.nl.rockwool.be/services/veelgestelde+vragen, consulted on 2015 March 4.

[16]S. Kerber, “Analysis of Changing Residential Fire Dynamics and Its Implications on Firefighter Operational Timeframes,” Underwriters Laboratories, 2012.

[17]S. Brohez, N. Cornil, C. Fourneau, H. Breulet and S. Desmet, “Brandveiligheid in passiefhuisen,” FOD binnenlandse zaken, published summary of research project “brand in een passiefhuis = een inferno?”, 2010.

[18]F. Verleyen, “Brandveiligheid in passiefgebouwen,” M.S. thesis, Department of Industrial Sciences, KaHo Sint-Lieven, Belgium, 2014.

[19]A. Back, “Fire development in insulated compartments: Effects from improved thermal insulation,” M.S. thesis, Department of Fire Safety Engineering and Systems Safety, Lund University, Lund, Sweden, 2012.

[20]OECD, “Fire risk analysis, fire simulation, fire spreading and impact of smoke and heat on instrumentation electronics,” state of the art-document, Nuclear Energy Agency, Paris, France, Rep. NEA/CSNI/R(99)27, 2000.

[21]OECD, “Fire Project Report: Collection and Analysis of Fire Events,” statistical data document, Nuclear Energy Agency, Paris, France, rep. NEA/CSNI/R(2009)6, 2009.

[22]L. Audouin, L. Rigollet, H. Prétrel, W. Le Saux and M. Röwekamp, “OECD PRISME project: fires in confined and ventilated nuclear-type multi-compartments – Overview and main experimental results,” Fire Safety Journal, vol. 62, pp. 80-101, 2013.

[23]H. Prétrel, W. Le Saux and L. Audouin, “Pressure variations induced by a pool fire in a well-confined and force-ventilated compartment,” Fire Safety Journal, vol. 52, pp. 11-24, 2012.

[24] K. Lambert, (2011, February 5) “The most familiar form of rapid fire progress: flashover,” [ONLINE] available: http://www.cfbt-be.com/images/artikelen/art_06_ENG.pdf, downloaded on 2015, February 13.

[25]K. Lambert, (2014, January 18) “Backdraft: fire science and firefighting, a literature review,” [ONLINE]. Available: http://www.cfbt-be.com/index.php/publicaties/papers, downloaded on 2015, February 15.

[26]K. Lambert, (2010, September 3) “Backdraft,” [ONLINE] available: http://www.cfbt-be.com/images/artikelen/artikel_04%20ENG.pdf, downloaded on 2015, February 13.

[27]A. Chen, L. Zhou, B. Liu and W. Chen, “Theoretical analysis and experimental study on critical conditions of backdraft,” Journal of Loss Prevention in the Process Industries, vol. 24, no. 5, pp. 632-637, 2011.

[28]L.C. Tsai and C.W. Chiu, “Full-scale experimental studies for backdraft using solid materials,” Process Safety and Environmental Protection vol. 91, pp. 202-212, 2013.

[29]Fleischmann, Charles M., and ZhiJian Chen, “Defining the Difference between Backdraft and Smoke Explosions,” Procedia Engineering, vol.62, pp 324-330, 2013.

[30]K. Lambert, S. Baaij, “Brandverloop Technisch bekeken, tactisch toegepast,” 1st ed. Den Haag, The Netherlands: Sdu Uitgevers, 2011.

[31]Loo, A. Si-Xian, A. Coppalle and P. Aîné, “Flame Extinction in a Ventilation-controlled Compartment,” Procedia Engineering, vol. 62, pp. 301-308, 2013.

[32]Y. Utiskul, J. G. Quintiere, A. S. Rangwala, B. A. Ringwelski, K. Wakatskuki and T. Naruse, “Compartment fire phenomena under limited ventilation,” Fire Safety Journal, vol. 40, no. 4, pp. 367-390, 2005.

[33]Vlaams Energie Agentschap, “Ventilatiedocument: residentieel,” Flemish Government, Brussels, Belgium, 2014.

[34]T. Beji and B. Merci, Numerical Simulations of Pool Fires in Well-Confined and Force-Ventilated Fires, private communication, 2013, December.

[35]Lindab, “De Ventilatiegids,” Lindab Belgium, Gent, Belgium, 2015.

[36]D. Kontogeorgos, K. Ghazi Wakili, E. Hugi and M. Founti, “Heat and moisture transfer through a steel stud gypsum board assembly exposed to fire,” Construction and Building Materials, vol. 26, pp. 746-754, 2012.

[37]EN 1992-1-2 (2004) (English): Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design, The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC

[38]E. R. Rosenbaum et al, “SFPE Engineering Guide to Performance-Based Fire Protection,” 2nd ed. Bethesda, 2007.

[39]S. Svensson, “A study of tactical patterns during firefighting operations,” Fire safety journal, vol. 37, no. 7, pp. 673-695, 2002.

[40]D. Moore, P. Chan, G. Nathan and R. Marchant, “Measurement and Modelling of Compartment Fire Behaviour Training,” Final Report of Research Project, Univeristy of Adelaide, Adelaine, Australia, 2006.

[41]Building research institute, “Windows and glass in the exterior of buildings,” Wahsington, publication 478, 1957.

[42]K. McGrattan, R. McDermott, C. Weinschenk and K. Overholt, “Fire Dynamics Simulator Technical Reference Guide Volume1: Mathematical Model,” NIST, Gaithersburg, Maryland, Rep. 19894, 2014.

[43]J. Floyd, F. Forney, S. Hostikka, T. Korhonene, R. McDermott and K. McGrattan, “Fire Dynamics Simulator User’s Guide,” NIST, Gaithersburg, Maryland, NIST Special Publication 1019, Rep. 11828, 2012.

[44]A.I.M. Voorbij and L.P.A. Steenbekkers, “The composition of a graph on the decline of total body strength with age based on pushing, pulling, twisting and gripping force,” Applied Ergonomics, vol. 32, pp. 287-292, 2001.

[45]Solar Palau, (2015, april 7). Technical sheet TD 350/125 [ONLINE]. Available http://www.solerpalau.com/td-350-125-230v-50.html

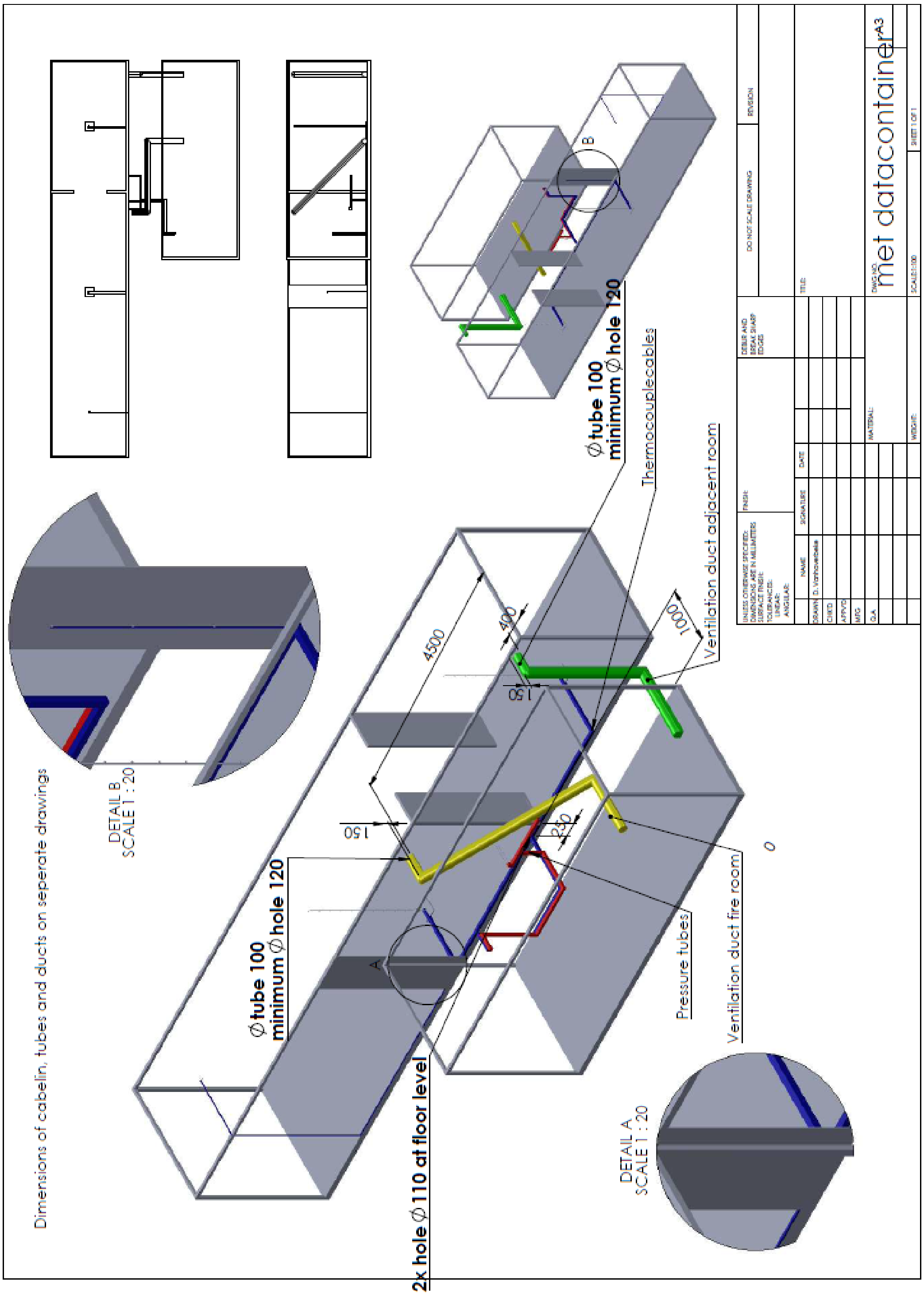
[46]Lindab, (2015, april 8). Technical sheet DIVU [ONLINE]. Available http://itsolution.lindab.com/lindabwebproductsdoc/pdf/documentation/ads/lindab/technical/diru.pdf

[47]Lindab, (2015, april 9). Mounting instructions dampers [ONLINE]. Available http://itsolution.lindab.com/lindabwebproductsdoc/pdf/documentation/ads/lindab/mounting/ai-dampers-en-1046.pdf

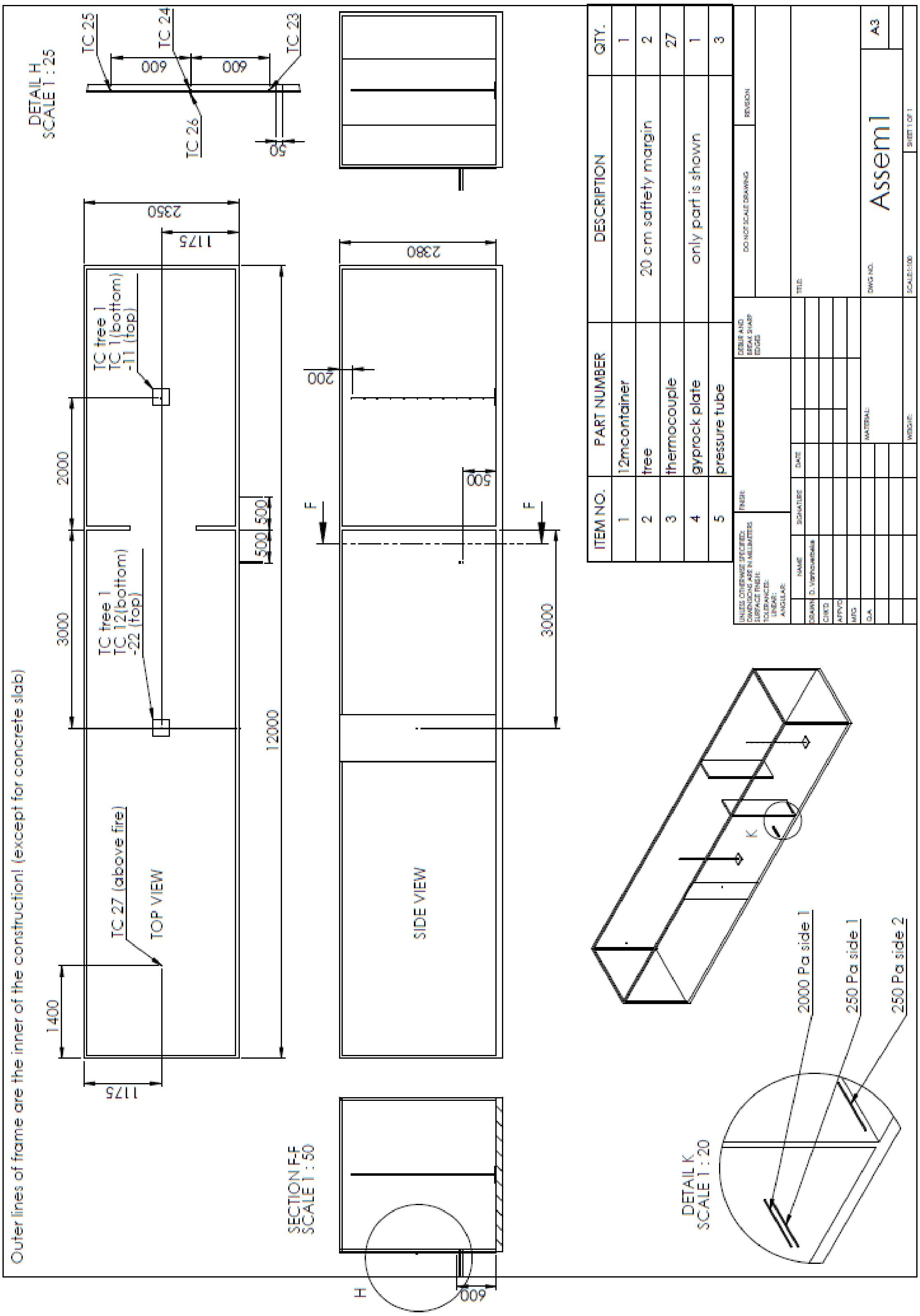
[48]FOD binnenlandse zaken, “Statistieken Belgische brandweer,” dienst algemene directive civiele veiligheid, statistical data document, 2012.

9 Appendixes

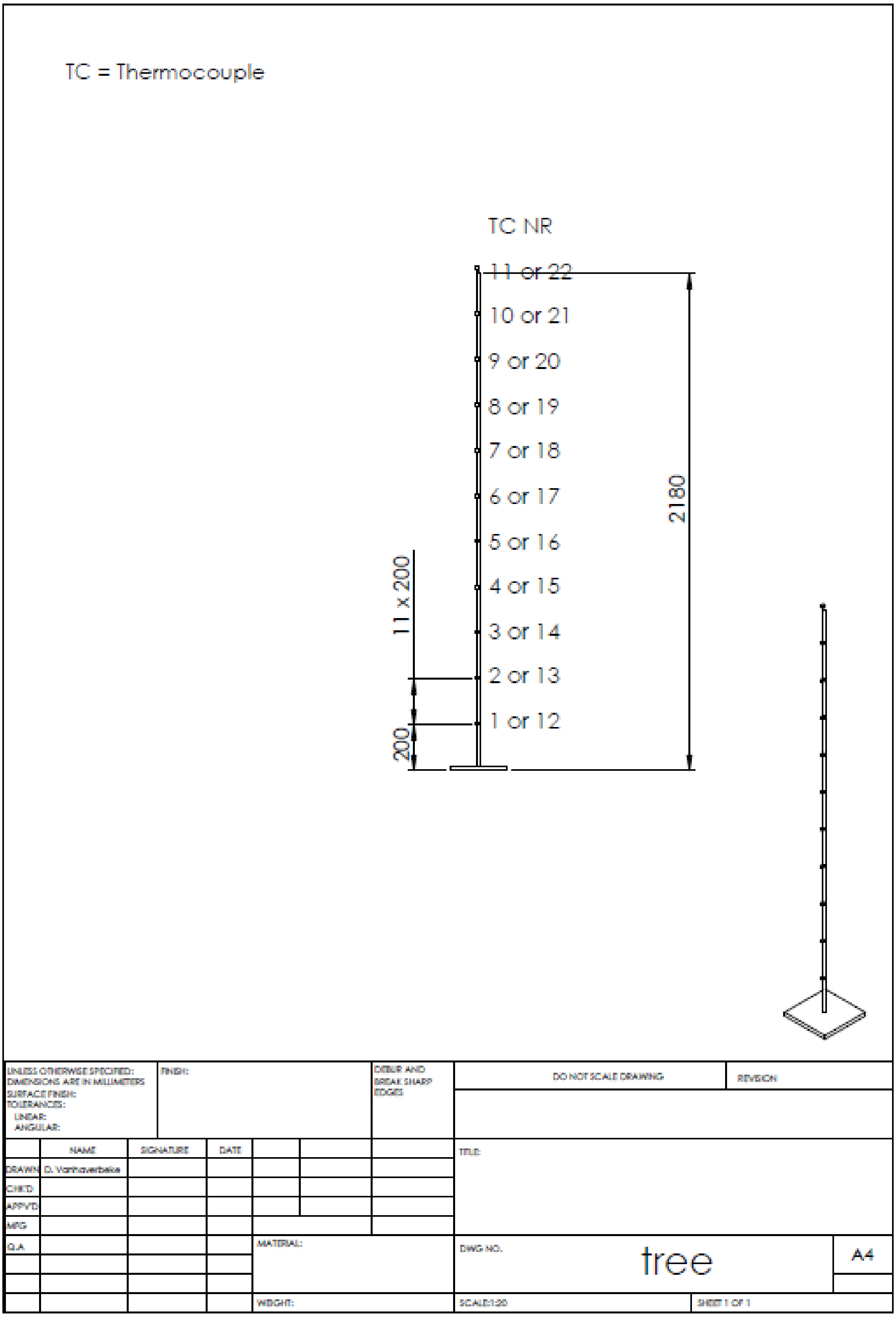
9.1 Drawing of container



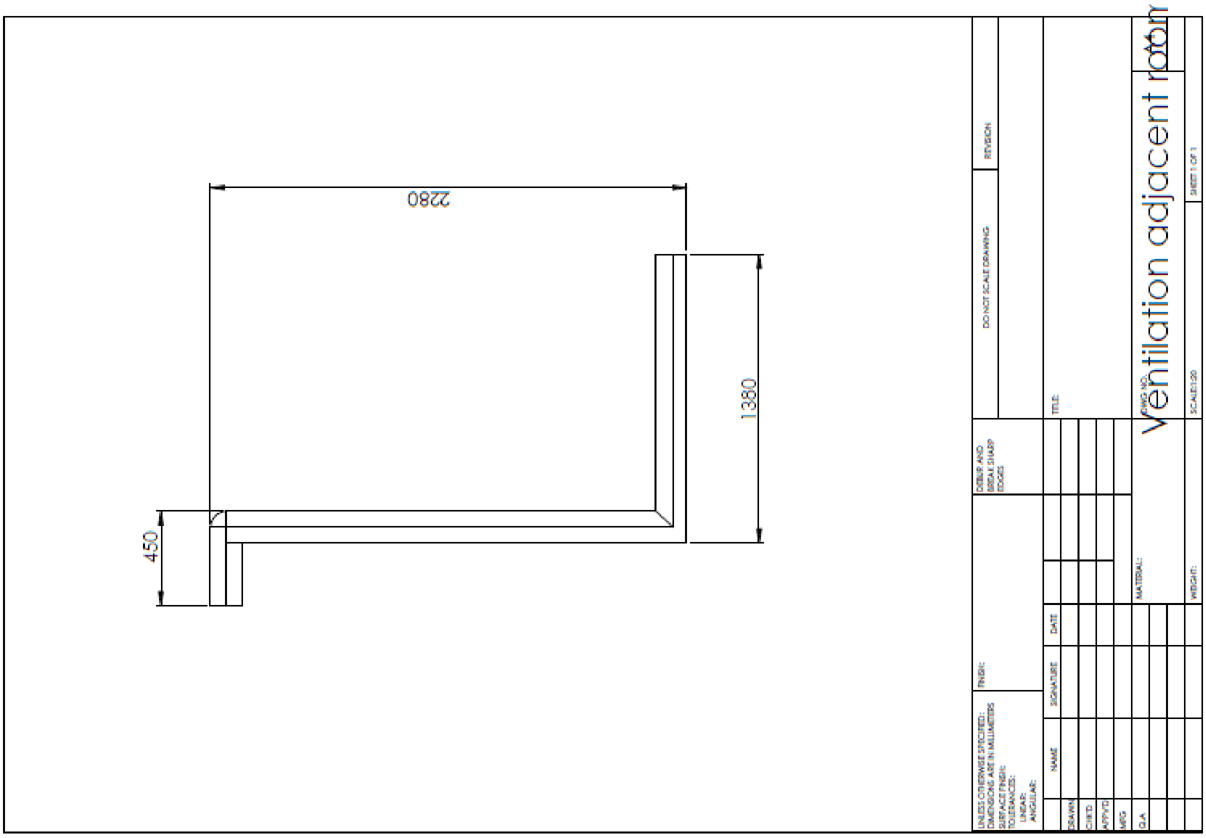
9.2 Technical drawing of container construction and measurement locations

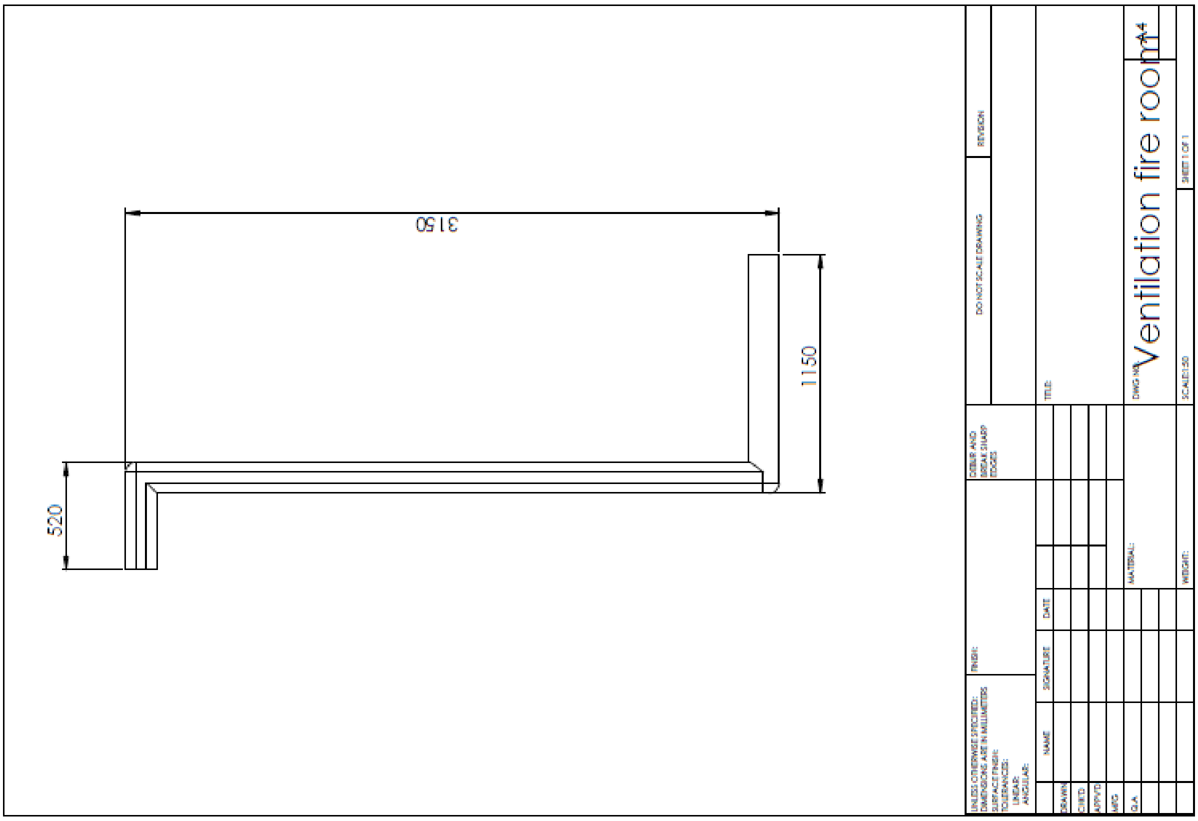


9.3 Technical drawing of thermocouple tree

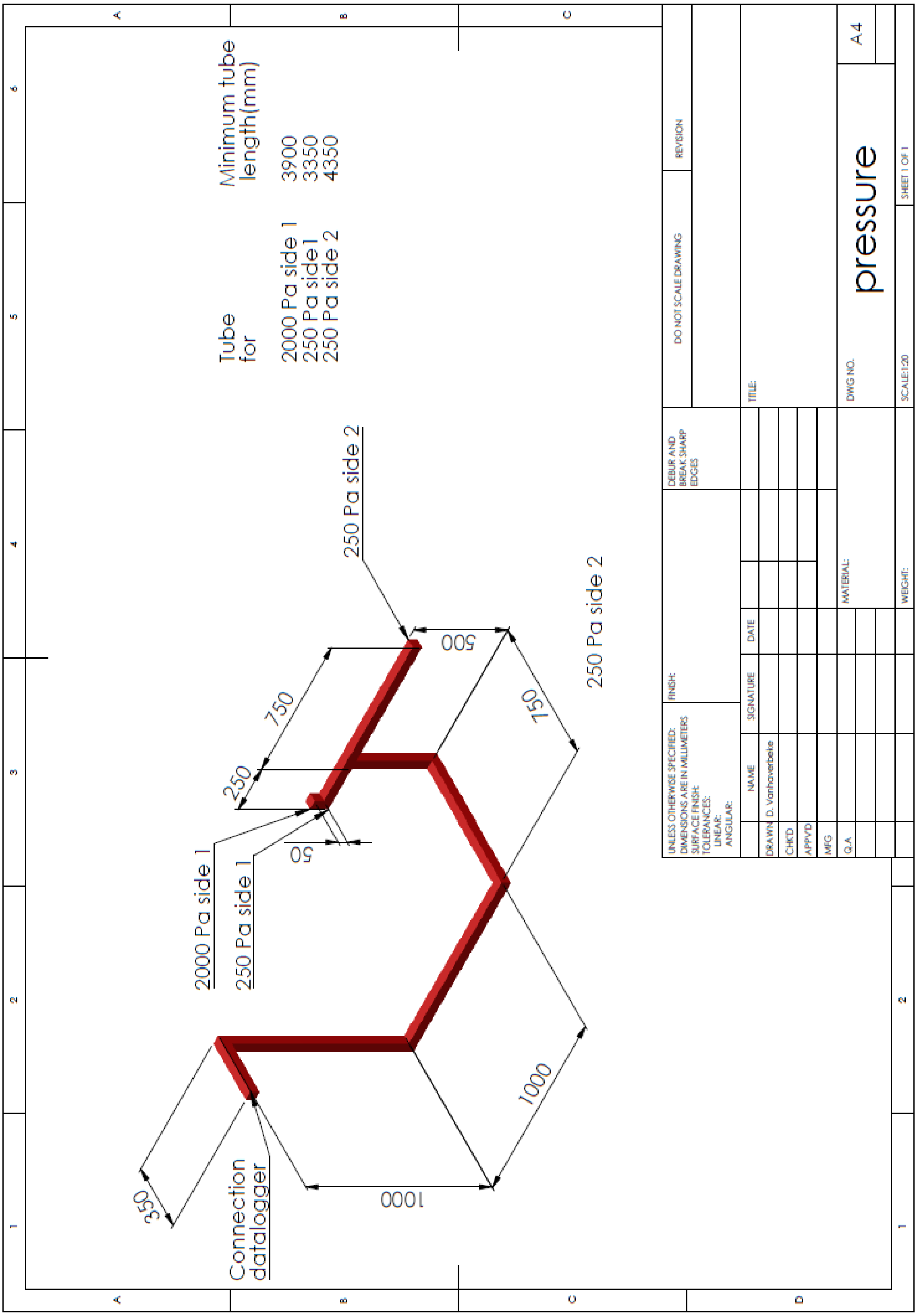


9.4 Technical drawing of ventilation ducts

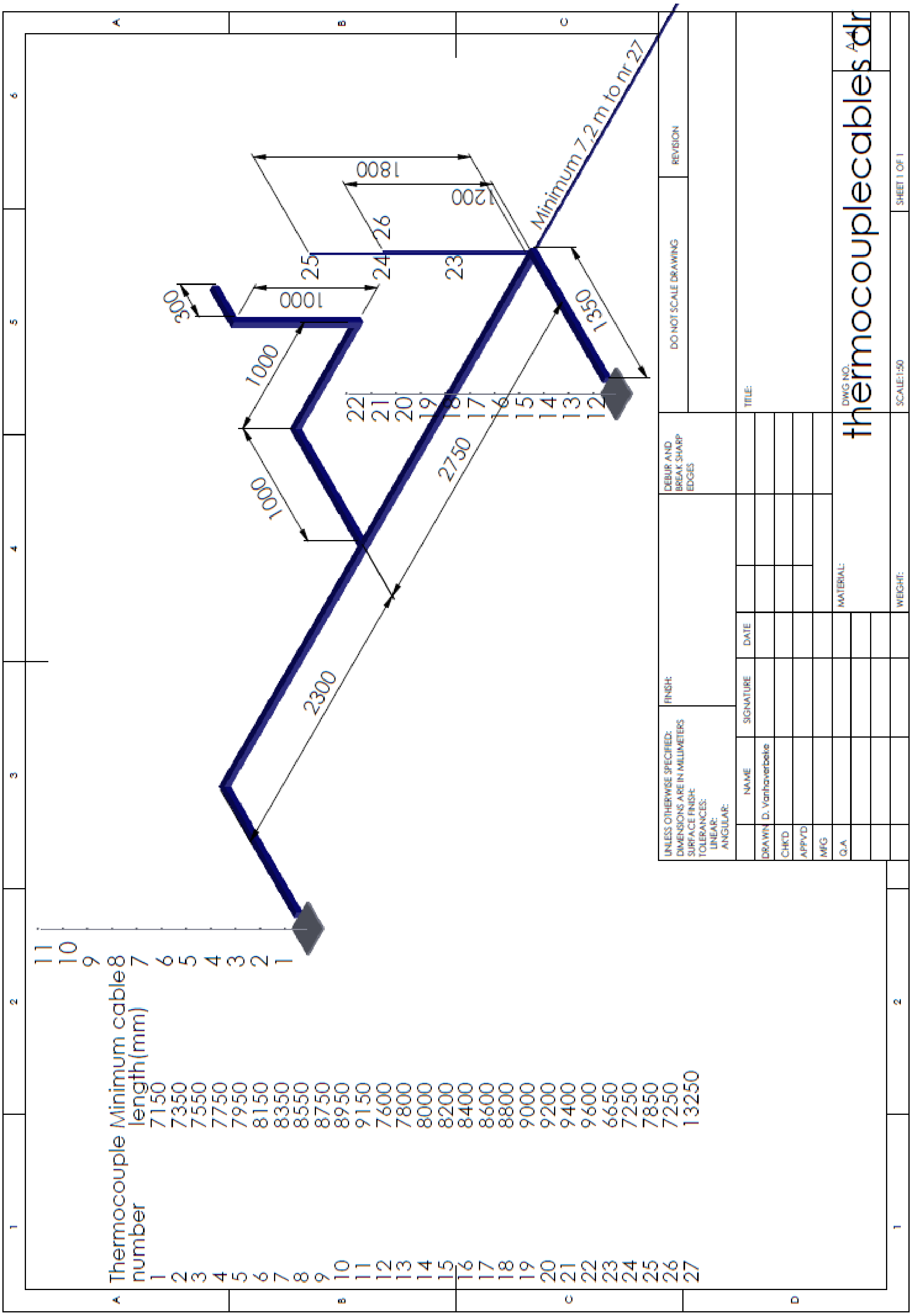




9.5 Drawing of pressure tubes



9.6 Drawing of thermocouple wires



Thermocouple number	Minimum cable length(mm)
1	7150
2	7350
3	7550
4	7750
5	7950
6	8150
7	8350
8	8550
9	8750
10	8950
11	9150
12	7600
13	7800
14	8000
15	8200
16	8400
17	8600
18	8800
19	9000
20	9200
21	9400
22	9600
23	6650
24	7250
25	7850
26	7250
27	13250

9.7 FDS input file reference simulation

This first input file is the reference case, the base input file. All the other input files are equal to this file, besides some specific changes. Only these variations are given as annexes.

```
&HEAD CHID='Standardtest, ventilation off', TITLE='Fast growing fire standardtest, leak 100'/
&MESH IJK=24,122,24, XB=0.0,2.4,   0.0,12.2,     0.0,2.4/
&TIME T_END=700/
&MISC SURF_DEFAULT='INERT', RADIATION=.TRUE. /
&SURF ID='FIRE', HRRPUA=3970, COLOR='BLUE', RAMP_Q='fireramp'/ FYI: HRRPUA from
stefan svensson (see motivation pallet fire)
&RAMP ID='fireramp', T=0.0, F=0.0/
&RAMP ID='fireramp', T=1000.0, F=1.0/
&REAC ID = 'PROPANE'
SOOT_YIELD = 0.01
C = 3.
H = 8./
==============================SURFACES=================================
&SURF ID='WALL'
MATL_ID(3,1)='GYPSUM'
MATL_ID(2,1)='INSULATOR'
MATL_ID(1,1)='BRICK'
THICKNESS=0.2,0.45,0.018
BACKING= 'EXPOSED'
COLOR='GREEN'/

&SURF ID='CONCRETE'
MATL_ID='CONCRETE'
THICKNESS=0.2
BACKING='EXPOSED'
COLOR='GRAY'/

&SURF ID='GYPROCK'
MATL_ID='GYPSUM'
THICKNESS=0.012
BACKING='EXPOSED'/

&SURF ID='LEAK10', LEAK_PATH=1,0,COLOR='RED'/
&SURF ID='LEAK20', LEAK_PATH=2,0,COLOR='YELLOW'/
&SURF ID='LEAK21', LEAK_PATH=2,1,COLOR='ORANGE'/
============================PROPERTIES=================================
&MATL ID = 'BRICK'
CONDUCTIVITY = 0.69
SPECIFIC_HEAT = 0.84
DENSITY = 1600. /

&MATL ID = 'INSULATOR'
CONDUCTIVITY = 0.041
SPECIFIC_HEAT = 2.09
DENSITY = 229. /

&MATL ID = 'GYPSUM'
CONDUCTIVITY = 0.48
SPECIFIC_HEAT = 0.840
DENSITY = 1440. /

&MATL ID = 'CONCRETE'
DENSITY = 2200.
CONDUCTIVITY = 1.2
SPECIFIC_HEAT = 0.88 /
============================CONSTRUCTION===============================
```

```
&OBST XB=0.0,0.0,   0.0,12.2,    0.0,2.4, SURF_ID='WALL'/ B-side
&OBST XB=2.4,2.4,   0.0,12.2,    0.0,2.4, SURF_ID='WALL'/ D-side

&OBST XB=0.0,2.4,   0.0,0.0,     0.0,2.4, SURF_ID='WALL'/ A-side
&OBST XB=0.0,2.4,   12.2,12.2,   0.0,2.4, SURF_ID='WALL'/ C-side

&OBST XB=0.0,2.4,   0.0,12.2,   0.0,0.0, SURF_ID='CONCRETE'/ floor
&OBST XB=0.0,2.4,   0.0,12.2,   2.4,2.4, SURF_ID='WALL'/ ceiling

&OBST XB=0.0,2.4,   3.8,4.0,     0.0,2.4, SURF_ID='GYPROCK'/ separation wall

&OBST XB= 0.6,1.8,   10.2,11.0   0.0,0.0, SURF_ID='FIRE'/
===============================LEAKAGE==================================
&OBST XB=2.2,2.4,   0.0,0.0,      2.2,2.4, SURF_ID='LEAK20'/
&OBST XB=2.4,2.4,   4.0,4.2,      2.2,2.4, SURF_ID='LEAK10'/
&OBST XB=0.8,1.6,   3.8,4.0,     0.0,0.2, SURF_ID='LEAK21'/

&ZONE XB=0.0,2.4,   4.0,12.2,    0.0,2.4, LEAK_AREA(0)=0.0035/ 2 x diameter 1000 mm
&ZONE  XB=0.0,2.4,     0.0,4.0,       0.0,2.4,  LEAK_AREA(1)=0.01,  LEAK_AREA(0)=0.0035/  2  x
diameter 1000 mm
===============================DEVICES==================================
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,2.0,0.2, ID='1'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,2.0,0.4, ID='2'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,2.0,0.2, ID='3'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,2.0,0.2, ID='4'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,2.0,1.0, ID='5'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,2.0,1.0, ID='6'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,2.0,1.0, ID='7'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,2.0,1.0, ID='8'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,2.0,1.0, ID='9'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,2.0,1.0, ID='10'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,2.0,1.0, ID='11'/

&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,7.0,0.2, ID='12'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,7.0,0.4, ID='13'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,7.0,0.6, ID='14'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,7.0,0.8, ID='15'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,7.0,1.0, ID='16'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,7.0,1.2, ID='17'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,7.0,1.4, ID='18'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,7.0,1.6, ID='19'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,7.0,1.8, ID='20'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,7.0,2.0, ID='21'/
&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,7.0,2.2, ID='22'/

&DEVC                 XYZ=0.0,7.0,0.6,                QUANTITY='INSIDE_WALL_TEMPERATURE',
DEPTH=0.00,IOR=1,ID='23' /
&DEVC                 XYZ=0.0,7.0,1.2,                QUANTITY='INSIDE_WALL_TEMPERATURE',
DEPTH=0.00,IOR=1,ID='24' /
&DEVC                 XYZ=0.0,7.0,1.8,                QUANTITY='INSIDE_WALL_TEMPERATURE',
DEPTH=0.00,IOR=1,ID='25' /
&DEVC                 XYZ=0.0,7.0,0.6,                QUANTITY='INSIDE_WALL_TEMPERATURE',
DEPTH=0.012,IOR=1,ID='26' /

&DEVC QUANTITY='TEMPERATURE', XYZ=1.2,10.6,2.2, ID='27'/

&DEVC                 XYZ=0.0,7.0,2.2,                QUANTITY='INSIDE_WALL_TEMPERATURE',
DEPTH=0.00,IOR=1,ID='@2.2m 0 deep' /
&DEVC                 XYZ=0.0,7.0,2.2,                QUANTITY='INSIDE_WALL_TEMPERATURE',
DEPTH=0.001,IOR=1,ID='@2.2m 1 deep' /
```

```
&DEVC XYZ=0.0,7.0,2.2, QUANTITY='INSIDE_WALL_TEMPERATURE', DEPTH=0.002,IOR=1,ID='@2.2m 2 deep' /
&DEVC XYZ=0.0,7.0,2.2, QUANTITY='INSIDE_WALL_TEMPERATURE', DEPTH=0.003,IOR=1,ID='@2.2m 3 deep' /
&DEVC XYZ=0.0,7.0,2.2, QUANTITY='INSIDE_WALL_TEMPERATURE', DEPTH=0.004,IOR=1,ID='@2.2m 4 deep' /
&DEVC XYZ=0.0,7.0,2.2, QUANTITY='INSIDE_WALL_TEMPERATURE', DEPTH=0.005,IOR=1,ID='@2.2m 5 deep' /
&DEVC XYZ=0.0,7.0,2.2, QUANTITY='INSIDE_WALL_TEMPERATURE', DEPTH=0.006,IOR=1,ID='@2.2m 6 deep' /
&DEVC XYZ=0.0,7.0,2.2, QUANTITY='INSIDE_WALL_TEMPERATURE', DEPTH=0.007,IOR=1,ID='@2.2m 7 deep' /
&DEVC XYZ=0.0,7.0,2.2, QUANTITY='INSIDE_WALL_TEMPERATURE', DEPTH=0.008,IOR=1,ID='@2.2m 8 deep' /
&DEVC XYZ=0.0,7.0,2.2, QUANTITY='INSIDE_WALL_TEMPERATURE', DEPTH=0.009,IOR=1,ID='@2.2m 9 deep' /
&DEVC XYZ=0.0,7.0,2.2, QUANTITY='INSIDE_WALL_TEMPERATURE', DEPTH=0.010,IOR=1,ID='@2.2m 10 deep' /
&DEVC XYZ=0.0,7.0,2.2, QUANTITY='INSIDE_WALL_TEMPERATURE', DEPTH=0.011,IOR=1,ID='@2.2m 11 deep' /
&DEVC XYZ=0.0,7.0,2.2, QUANTITY='INSIDE_WALL_TEMPERATURE', DEPTH=0.012,IOR=1,ID='@2.2m 12 deep' /

&DEVC QUANTITY='PRESSURE', XYZ=1.2,7.0,0.2, ID='p12'/
&DEVC QUANTITY='PRESSURE', XYZ=1.2,7.0,0.4, ID='p13'/
&DEVC QUANTITY='PRESSURE', XYZ=1.2,7.0,0.6, ID='p14'/
&DEVC QUANTITY='PRESSURE', XYZ=1.2,7.0,0.8, ID='p15'/
&DEVC QUANTITY='PRESSURE', XYZ=1.2,7.0,1.0, ID='p16'/
&DEVC QUANTITY='PRESSURE', XYZ=1.2,7.0,1.2, ID='p17'/
&DEVC QUANTITY='PRESSURE', XYZ=1.2,7.0,1.4, ID='p18'/
&DEVC QUANTITY='PRESSURE', XYZ=1.2,7.0,1.6, ID='p19'/
&DEVC QUANTITY='PRESSURE', XYZ=1.2,7.0,1.8, ID='p20'/
&DEVC QUANTITY='PRESSURE', XYZ=1.2,7.0,2.0, ID='p21'/
&DEVC QUANTITY='PRESSURE', XYZ=1.2,7.0,2.2, ID='p22'/

&DEVC QUANTITY='DUCT VOLUME FLOW',DUCT_ID='LEAK 0 1',ID='0 1'/
&DEVC QUANTITY='DUCT VOLUME FLOW',DUCT_ID='LEAK 0 2',ID='0 2'/
&DEVC QUANTITY='DUCT VOLUME FLOW',DUCT_ID='LEAK 1 2',ID='1 2'/

&DEVC QUANTITY='PRESSURE', XYZ=0.2,4.5,0.5, ID='side 1 2000 Pa'/
&DEVC QUANTITY='PRESSURE', XYZ=0.2,3.5,0.5, ID='side 2 250 Pa'/

&SLCF QUANTITY='TEMPERATURE', PBX=1.2, FYI='Temperature slice mid plane'
&SLCF QUANTITY='VELOCITY', PBX=1.2, FYI='Temperature slice mid plane'
&SLCF QUANTITY='VELOCITY', PBX=2.2, FYI='Temperature slice x= 2,2 m plane'
&SLCF QUANTITY='VELOCITY', PBY=4.2, FYI='Temperature slice y= 4,2 m plane'

&BNDF QUANTITY='RADIOMETER'/

&TAIL/
```

9.8 FDS input files Grid dependency

Coarse grid: SIM_39

```
&MESH IJK=12,61,12, XB=0.0,2.4,   0.0,12.2,     0.0,2.4/
```

Medium grid: SIM_38

```
&MESH IJK=16,81,16, XB=0.0,2.4,   0.0,12.15,     0.0,2.4/
```

Reference case: fine grid (SIM_40)

&MESH IJK=24,122,24, XB=0.0,2.4,   0.0,12.2,   0.0,2.4/

Very fine grid: (SIM_41)

&MESH IJK=32,162,32, XB=0.0,2.4,   0.0,12.15,   0.0,2.4/

Extremely fine grid (SIM_48)

&MESH IJK=48,244,48, XB=0.0,2.4,   0.0,12.2,   0.0,2.4/

9.9 FDS input files on HRR sensitivity

Reference case: pallet fire (SIM_40)

&SURF ID='FIRE', HRRPUA=3970, COLOR='BLUE', RAMP_Q='fireramp'/ FYI: HRRPUA from stefan svensson (see motivation pallet fire)
&RAMP ID='fireramp', T=0.0, F=0.0/
&RAMP ID='fireramp', T=1000.0, F=1.0/
&REAC ID = 'PROPANE'
SOOT_YIELD = 0.01
C = 3.
H = 8./

Fast growing fire (SIM_42)

&SURF ID='FIRE', HRRPUA=3970, COLOR='BLUE', RAMP_Q='fireramp'/ FYI: HRRPUA from karlsson and quinterie page 42
&RAMP ID='fireramp', T=0.0, F=0.0/
&RAMP ID='fireramp', T=29.0, F=0.01/
&RAMP ID='fireramp', T=87.0, F=0.09/
&RAMP ID='fireramp', T=145.0, F=0.24/
&RAMP ID='fireramp', T=200.0, F=0.47/
&RAMP ID='fireramp', T=261.0, F=0.810/
&RAMP ID='fireramp', T=291.0, F=1/
&REAC ID = 'PROPANE'
SOOT_YIELD = 0.01
C = 3.
H = 8./

CFBT type 1 or 2 (SIM_43)

&SURF ID='FIRE', HRRPUA=1250, COLOR='BLUE', RAMP_Q='fireramp'/ FYI: type 1 or 2 burn in cfbt container. From australian researchpaper.
&RAMP ID='fireramp', T=0.0, F=0.0/
&RAMP ID='fireramp', T=200.0, F=0.208/
&RAMP ID='fireramp', T=400.0, F=1.0/
&REAC ID = 'PROPANE'
SOOT_YIELD = 0.01
C = 3.
H = 8./

Ultrafast growing fire (SIM_44)

&SURF ID='FIRE', HRRPUA=3970, COLOR='BLUE', RAMP_Q='fireramp'/ FYI: HRRPUA from stefan svensson (see motivation pallet fire, but ultrafast growing)
&RAMP ID='fireramp', T=0.0, F=0.0/
&RAMP ID='fireramp', T=25.0, F=0.03/
&RAMP ID='fireramp', T=50.0, F=0.12/
&RAMP ID='fireramp', T=75.0, F=0.27/
&RAMP ID='fireramp', T=100.0, F=0.48/
&RAMP ID='fireramp', T=125.0, F=0.75/
&RAMP ID='fireramp', T=144.0, F=1.0/
&REAC ID = 'PROPANE'

SOOT_YIELD = 0.01
C = 3.
H = 8./

9.10 FDS input files on lining material sensitivity

Reference case: plasterboard, insulation and concrete blocks (SIM_40)

```
&SURF ID='WALL'
MATL_ID(3,1)='GYPSUM'
MATL_ID(2,1)='INSULATOR'
MATL_ID(1,1)='BRICK'
THICKNESS=0.2,0.045,0.018
BACKING= 'EXPOSED'
COLOR='GREEN'/
```

Concrete wall (SIM_46)

```
&SURF ID='CONCRETE'
MATL_ID='CONCRETE'
THICKNESS=0.2
BACKING='EXPOSED'
COLOR='GRAY'/
```

Fibre insulation board (SIM_45)

```
&SURF ID='WALL'
MATL_ID(2,1)='INSULATOR'
MATL_ID(1,1)='BRICK'
THICKNESS=0.2,0.2
BACKING= 'EXPOSED'
COLOR='GREEN'/
&MATL ID = 'INSULATOR'
CONDUCTIVITY = 0.041
SPECIFIC_HEAT = 2.09
DENSITY = 229. /
```

Polyurethane (SIM_59)

```
&SURF ID='WALL'
MATL_ID(2,1)='INSULATOR'
MATL_ID(1,1)='BRICK'
THICKNESS=0.2,0.2
BACKING= 'EXPOSED'
COLOR='GREEN'/
&MATL ID = 'INSULATOR'
CONDUCTIVITY = 0.034
SPECIFIC_HEAT = 1.040
DENSITY = 20. /
```

9.11 FDS input files on location of the fire sensitivity

Reference case (SIM_40)

```
&OBST XB= 0.6,1.8,   10.2,11.0   0.0,0.0, SURF_ID='FIRE'/
```

Fire in corner (SIM_47)

```
&OBST XB= 1.2,2.4,   11.4,12.2   0.0,0.0, SURF_ID='FIRE'/
```

9.12 FDS input files on thermal parameters and placement of plaster board

Reference case: thermal properties of plaster board not dependant of temperature. (SIM_40)

```
&SURF ID='WALL'
MATL_ID(3,1)='GYPSUM'
MATL_ID(2,1)='INSULATOR'
MATL_ID(1,1)='BRICK'
THICKNESS=0.2,0.045,0.018
BACKING= 'EXPOSED'
COLOR='GREEN'/

&SURF ID='CONCRETE'
MATL_ID='CONCRETE'
THICKNESS=0.2
BACKING='EXPOSED'
COLOR='GRAY'/

&SURF ID='GYPROCK'
MATL_ID='GYPSUM'
THICKNESS=0.012
BACKING='EXPOSED'/

&MATL ID = 'BRICK'
CONDUCTIVITY = 0.69
SPECIFIC_HEAT = 0.84
DENSITY = 1600. /

&MATL ID = 'INSULATOR'
CONDUCTIVITY = 0.041
SPECIFIC_HEAT = 2.09
DENSITY = 229. /

&MATL ID = 'GYPSUM'
CONDUCTIVITY = 0.48
SPECIFIC_HEAT = 0.840
DENSITY = 1440. /

&MATL ID = 'CONCRETE'
DENSITY = 2200.
CONDUCTIVITY = 1.2
SPECIFIC_HEAT = 0.88 /
&OBST XB=0.0,0.0,   0.0,12.2,   0.0,2.4, SURF_ID='WALL'/ B-side
&OBST XB=2.4,2.4,   0.0,12.2,   0.0,2.4, SURF_ID='WALL'/ D-side

&OBST XB=0.0,2.4,   0.0,0.0,    0.0,2.4, SURF_ID='WALL'/ A-side
&OBST XB=0.0,2.4,   12.2,12.2,  0.0,2.4, SURF_ID='WALL'/ C-side

&OBST XB=0.0,2.4,   0.0,12.2,   0.0,0.0, SURF_ID='CONCRETE'/ floor
&OBST XB=0.0,2.4,   0.0,12.2,   2.4,2.4, SURF_ID='WALL'/ ceiling

&OBST XB=0.0,2.4,   3.8,4.0,    0.0,2.4, SURF_ID='GYPROCK'/ separation wall
```

Thermal properties of plasterboard dependant on temperature. (SIM_57)

```
&SURF ID='WALL'
MATL_ID(3,1)='GYPSUM'
MATL_ID(2,1)='INSULATOR'
MATL_ID(1,1)='BRICK'
THICKNESS=0.2,0.045,0.018
```

```
BACKING= 'EXPOSED'
COLOR='GREEN'/

&SURF ID='CONCRETE'
MATL_ID='CONCRETE'
THICKNESS=0.2
BACKING='EXPOSED'
COLOR='GRAY'/

&SURF ID='GYPROCK'
MATL_ID='GYPSUM'
THICKNESS=0.012
BACKING='EXPOSED'/

&MATL ID = 'BRICK'
CONDUCTIVITY = 0.69
SPECIFIC_HEAT = 0.84
DENSITY = 1600. /

&MATL ID = 'INSULATOR'
CONDUCTIVITY = 0.041
SPECIFIC_HEAT = 2.09
DENSITY = 229. /

&MATL ID = 'GYPSUM'
CONDUCTIVITY = 0.48
SPECIFIC_HEAT_RAMP = 'c_ramp'
DENSITY = 1440. /

&RAMP ID='c_ramp', T= 0.0, F=0.840 /
&RAMP ID='c_ramp', T= 100.0, F=0.840 /
&RAMP ID='c_ramp', T= 140.0, F=10.0 /
&RAMP ID='c_ramp', T= 160.0, F=3.0 /
&RAMP ID='c_ramp', T= 200.0, F=4.0 /
&RAMP ID='c_ramp', T= 240.0, F=0.840 /
&RAMP ID='c_ramp', T= 640.0, F=0.840 /
&RAMP ID='c_ramp', T= 700.0, F=4.40 /
&RAMP ID='c_ramp', T= 760.0, F=0.840 /
&RAMP ID='c_ramp', T= 1000.0, F=0.840 /

&MATL ID = 'CONCRETE'
DENSITY = 2200.
CONDUCTIVITY = 1.2
SPECIFIC_HEAT = 0.88 /

&OBST XB=0.0,0.0,   0.0,12.2,    0.0,2.4, SURF_ID='WALL'/ B-side
&OBST XB=2.4,2.4,   0.0,12.2,    0.0,2.4, SURF_ID='WALL'/ D-side

&OBST XB=0.0,2.4,   0.0,0.0,     0.0,2.4, SURF_ID='WALL'/ A-side
&OBST XB=0.0,2.4,   12.2,12.2,   0.0,2.4, SURF_ID='WALL'/ C-side

&OBST XB=0.0,2.4,   0.0,12.2,   0.0,0.0, SURF_ID='CONCRETE'/ floor
&OBST XB=0.0,2.4,   0.0,12.2,   2.4,2.4, SURF_ID='WALL'/ ceiling

&OBST XB=0.0,2.4,   3.8,4.0,     0.0,2.4, SURF_ID='GYPROCK'/ separation wall
```

Both plaster board and bare concrete: thermal properties not dependant on temperature. (SIM_55)

```
&SURF ID='WALL'
```

```
MATL_ID(3,1)='GYPSUM'
MATL_ID(2,1)='INSULATOR'
MATL_ID(1,1)='BRICK'
THICKNESS=0.2,0.045,0.018
BACKING= 'EXPOSED'
COLOR='GREEN'/

&SURF ID='CEILINGFIRE'
MATL_ID(2,1)='GYPSUM'
MATL_ID(1,1)='CONCRETE'
THICKNESS=0.2,0.018
BACKING= 'EXPOSED'
COLOR='GREEN'/

&SURF ID='CONCRETE'
MATL_ID='CONCRETE'
THICKNESS=0.2
BACKING='EXPOSED'
COLOR='GRAY'/

&SURF ID='GYPROCK'
MATL_ID='GYPSUM'
THICKNESS=0.012
BACKING='EXPOSED'/

&MATL ID = 'BRICK'
CONDUCTIVITY = 0.69
SPECIFIC_HEAT = 0.84
DENSITY = 1600. /

&MATL ID = 'INSULATOR'
CONDUCTIVITY = 0.041
SPECIFIC_HEAT = 2.09
DENSITY = 229. /

&MATL ID = 'GYPSUM'
CONDUCTIVITY = 0.48
SPECIFIC_HEAT = 0.840
DENSITY = 1440. /

&MATL ID = 'CONCRETE'
DENSITY = 2200.
CONDUCTIVITY = 1.2
SPECIFIC_HEAT = 0.88 /
&OBST XB=0.0,0.0,   0.0,12.2,    0.0,2.4, SURF_ID='WALL'/ B-side
&OBST XB=2.4,2.4,   0.0,12.2,    0.0,2.4, SURF_ID='WALL'/ D-side

&OBST XB=0.0,2.4,   0.0,0.0,     0.0,2.4, SURF_ID='WALL'/ A-side
&OBST XB=0.0,2.4,   12.2,12.2,   0.0,2.4, SURF_ID='WALL'/ C-side

&OBST XB=0.0,2.4,   0.0,12.2,   0.0,0.0, SURF_ID='CONCRETE'/ floor

&OBST XB=0.0,2.4,   0.0,9.2,   2.4,2.4, SURF_ID='CONCRETE'/ ceiling
&OBST XB=0.0,2.4,   9.2,12.2,   2.4,2.4, SURF_ID='CEILINGFIRE'/ ceiling

&OBST XB=0.0,2.4,   3.8,4.0,     0.0,2.4, SURF_ID='GYPROCK'/ separation wall
```

Both plaster board and bare concrete: thermal properties dependant on temperature. (SIM_56)

```
&SURF ID='WALL'
MATL_ID(3,1)='GYPSUM'
MATL_ID(2,1)='INSULATOR'
```

```
MATL_ID(1,1)='BRICK'
THICKNESS=0.2,0.045,0.018
BACKING= 'EXPOSED'
COLOR='GREEN'/

&SURF ID='CEILINGFIRE'
MATL_ID(2,1)='GYPSUM'
MATL_ID(1,1)='CONCRETE'
THICKNESS=0.2,0.018
BACKING= 'EXPOSED'
COLOR='GREEN'/

&SURF ID='CONCRETE'
MATL_ID='CONCRETE'
THICKNESS=0.2
BACKING='EXPOSED'
COLOR='GRAY'/

&SURF ID='GYPROCK'
MATL_ID='GYPSUM'
THICKNESS=0.012
BACKING='EXPOSED'/

&MATL ID = 'BRICK'
CONDUCTIVITY = 0.69
SPECIFIC_HEAT = 0.84
DENSITY = 1600. /

&MATL ID = 'INSULATOR'
CONDUCTIVITY = 0.041
SPECIFIC_HEAT = 2.09
DENSITY = 229. /

&MATL ID = 'GYPSUM'
CONDUCTIVITY = 0.48
SPECIFIC_HEAT_RAMP = 'c_ramp'
DENSITY = 1440. /

&RAMP ID='c_ramp', T= 0.0, F=0.840 /
&RAMP ID='c_ramp', T= 100.0, F=0.840 /
&RAMP ID='c_ramp', T= 140.0, F=10.0 /
&RAMP ID='c_ramp', T= 160.0, F=3.0 /
&RAMP ID='c_ramp', T= 200.0, F=4.0 /
&RAMP ID='c_ramp', T= 240.0, F=0.840 /
&RAMP ID='c_ramp', T= 640.0, F=0.840 /
&RAMP ID='c_ramp', T= 700.0, F=4.40 /
&RAMP ID='c_ramp', T= 760.0, F=0.840 /
&RAMP ID='c_ramp', T= 1000.0, F=0.840 /
&MATL ID = 'CONCRETE'
DENSITY = 2200.
CONDUCTIVITY = 1.2
SPECIFIC_HEAT = 0.88 /

&OBST XB=0.0,0.0,   0.0,12.2,    0.0,2.4, SURF_ID='WALL'/ B-side
&OBST XB=2.4,2.4,   0.0,12.2,    0.0,2.4, SURF_ID='WALL'/ D-side

&OBST XB=0.0,2.4,   0.0,0.0,     0.0,2.4, SURF_ID='WALL'/ A-side
&OBST XB=0.0,2.4,   12.2,12.2,   0.0,2.4, SURF_ID='WALL'/ C-side

&OBST XB=0.0,2.4,   0.0,12.2,   0.0,0.0, SURF_ID='CONCRETE'/ floor
```

&OBST XB=0.0,2.4, 0.0,9.2, 2.4,2.4, SURF_ID='CONCRETE'/ ceiling
&OBST XB=0.0,2.4, 9.2,12.2, 2.4,2.4, SURF_ID='CEILINGFIRE'/ ceiling

&OBST XB=0.0,2.4, 3.8,4.0, 0.0,2.4, SURF_ID='GYPROCK'/ separation wall

&OBST XB= 0.6,1.8, 10.2,11.0 0.0,0.0, SURF_ID='FIRE'/

9.13 FDS input files on pulsing fire behaviour

Simulations conducted with a medium grid:

&MESH IJK=16,81,16, XB=0.0,2.4,0.0,12.15,0.0,2.4/

100 cm² (SIM_33)

&ZONE XB=0.0,2.4, 4.05,12.15, 0.0,2.4, LEAK_AREA(0)=0.00785/ 2 x diameter 1000 mm
&ZONE XB=0.0,2.4, 0.0,3.9, 0.0,2.4, LEAK_AREA(1)=0.01, LEAK_AREA(0)=0.00785/ 2 x diameter 1000 mm

200 cm²(SIM_34)

&ZONE XB=0.0,2.4, 4.05,12.15, 0.0,2.4, LEAK_AREA(0)=0.00785/ 2 x diameter 1000 mm
&ZONE XB=0.0,2.4, 0.0,3.9, 0.0,2.4, LEAK_AREA(1)=0.02, LEAK_AREA(0)=0.00785/ 2 x diameter 1000 mm

300 cm²(SIM_35)

&ZONE XB=0.0,2.4, 4.05,12.15, 0.0,2.4, LEAK_AREA(0)=0.00785/ 2 x diameter 1000 mm
&ZONE XB=0.0,2.4, 0.0,3.9, 0.0,2.4, LEAK_AREA(1)=0.03, LEAK_AREA(0)=0.00785/ 2 x diameter 1000 mm

400 cm²(SIM_36)

&ZONE XB=0.0,2.4, 4.05,12.15, 0.0,2.4, LEAK_AREA(0)=0.00785/ 2 x diameter 1000 mm
&ZONE XB=0.0,2.4, 0.0,3.9, 0.0,2.4, LEAK_AREA(1)=0.04, LEAK_AREA(0)=0.00785/ 2 x diameter 1000 mm

500 cm²(SIM_37)

&ZONE XB=0.0,2.4, 4.05,12.15, 0.0,2.4, LEAK_AREA(0)=0.00785/ 2 x diameter 1000 mm
&ZONE XB=0.0,2.4, 0.0,3.9, 0.0,2.4, LEAK_AREA(1)=0.05, LEAK_AREA(0)=0.00785/ 2 x diameter 1000 mm

9.14 FDS input file without ventilation installed/ducts completely sealed and n_{50}-value of 0,6.

Only leaks available to the ambient are the leaks representing a n_{50}-value of 0,6 (SIM_60)

&ZONE XB=0.0,2.4, 4.0,12.2, 0.0,2.4, LEAK_AREA(0)=0.00065/ leak according n50 = 0,6
&ZONE XB=0.0,2.4, 0.0,4.0, 0.0,2.4, LEAK_AREA(1)=0.01, LEAK_AREA(0)=0.00065/ leak according n50 = 0,6

9.15 FDS input file of 1m³ cube to investigate lining material.

Plaster board (SIM_61)

&HEAD CHID='check wall influence', TITLE='start temperature 1000 C'/
&MESH IJK=10,10,10, XB=0.0,1.0, 0.0,1.0, 0.0,1.0/

&TIME T_END=700/

&MISC SURF_DEFAULT='INERT', RADIATION=.TRUE. /
&INIT XB=0.0,1.0,0.0,1.0,0.0,1.0, TEMPERATURE=1000.0 /

==============================SURFACES=================================
&SURF ID='PLASTERBOARD'
MATL_ID='GYPSUM'
THICKNESS=0.2
BACKING='EXPOSED'/

```
&SURF ID='LEAK10', LEAK_PATH=1,0,COLOR='RED'/
==============================PROPERTIES==================================
&MATL ID = 'BRICK'
CONDUCTIVITY = 0.69
SPECIFIC_HEAT = 0.84
DENSITY = 1600. /

&MATL ID = 'INSULATOR'
CONDUCTIVITY = 0.041
SPECIFIC_HEAT = 2.09
DENSITY = 229. /

&MATL ID = 'GYPSUM'
CONDUCTIVITY = 0.48
SPECIFIC_HEAT = 0.840
DENSITY = 1440. /

&MATL ID = 'CONCRETE'
DENSITY = 2200.
CONDUCTIVITY = 1.2
SPECIFIC_HEAT = 0.88 /
==============================CONSTRUCTION================================
&OBST XB=0.0,0.0,   0.0,1.0,    0.0,1.0, SURF_ID='PLASTERBOARD'/ B-side
&OBST XB=1.0,1.0,   0.0,10.0,    0.0,1.0, SURF_ID='PLASTERBOARD'/ D-side
&OBST XB=0.0,1.0,   0.0,0.0,     0.0,1.0, SURF_ID='PLASTERBOARD'/ A-side
&OBST XB=0.0,1.0,   1.0,1.0,   0.0,1.0, SURF_ID='PLASTERBOARD'/ C-side
&OBST XB=0.0,1.0,   0.0,1.0,   0.0,0.0, SURF_ID='PLASTERBOARD'/ floor
&OBST XB=0.0,2.4,   0.0,1.0,   1.0,1.0, SURF_ID='PLASTERBOARD'/ ceiling

================================LEAKAGE=================================
&OBST XB=1.0,1.0,   0.0,1.0,      0.0,1.0, SURF_ID='LEAK10'/
&ZONE XB=0.0,1.0,   0.0,1.0,    0.0,1.0, LEAK_AREA(0)=0.01/
================================DEVICES==================================
&DEVC QUANTITY='TEMPERATURE', XYZ=0.5,0.5,0.5, ID='temperature'/
&DEVC QUANTITY='PRESSURE', XYZ=0.5,0.5,0.5, ID='pressure'/
&TAIL/
```

Polyurethane (SIM_62)

```
&MATL ID = 'POLYURETHANE'
CONDUCTIVITY = 0.034
SPECIFIC_HEAT = 1.040
DENSITY = 20. /
```

Concrete (SIM_63)

```
&MATL ID = 'CONCRETE'
DENSITY = 2200.
CONDUCTIVITY = 1.2
SPECIFIC_HEAT = 0.88 /
```

Quasi perfect insulator (SIM_64)

```
&MATL ID = 'PERFECTINSULATOR'
CONDUCTIVITY = 0.0000001
SPECIFIC_HEAT = 0.0000001
DENSITY = 0.0000001 /
```

9.16 Script for fire tests

Script full-scale test passive housing

Installation: checks before test day.

- Install connections for thermocouples and pressure transducers. (diameter 6mm)
- Check if there is enough plasterboard available for all the tests.
- Mark plasterboard from one side, so it may in worst case scenario be reused if turned around. (or from the first room to the second.
- Make sure that there is light in the data container.
- Check all the thermocouples are connected and in place.

Blower door test

contact person: Wolf Bauers(UGent) Takes 1 day.

Script test 1

Date and time of the test:

The first test will take place on xxxxxxxx at xx.xx. Everybody should be around by xx:xx. Take into account that timing can be delayed.

Who is around in during the test:

1. Coordinator: this person is on the computers and coordinates the test. He decides when to stop.
2. Note taker: this person will light the fire and close the volume in the correct way. This person also notes all observations after the fire is lighted.
3. Photographer: this person will film everything, and take pictures from the lightning to the possible observations afterwards. He works close together with the note taker.
4. Fire fighter: This person will wear equipment during the test and be ready to attack the fire if something goes wrong. This person will open the door and extinguish the fire in the very end of the test.

WHAT AND WHEN: responsibilities for the different roles.

Before the test:

Coordinator

- Check if computers and dataloggers work and are connected properly.
- Check if fire source is ok.
- Check if the fire load is installed as described.
- Control if everybodies checks are done.

Note taker

- Check that pen and paper is available.
- Train the fire lighting scenario.
- Diesel and lighter available.
- Write temperature and wind speed down.

Photographer

- Check that enough space and battery is available on the camera.
- Train the fire lighting scenario.
- Take a picture of the installed fire load.

Fire fighter

- Check water supply and equipment is available.
- Know at what time to open the door.

During the test

- No entering or exiting of the datacontainer, since pressure is measured here. Opening or closing a door will disturb this pressure measurement.
- If unsure/mistake, ask the coordinator!

	Coordinator	**Note taker**	**Potographer**	**Fire Fighter**
-10min	Last briefing before the test. Going over the tasks to see if all the checks are OK.			
-5min	Sit all together and set the chronometers to zero.			
-4min	Go to datalogger.	Go to prepare the fire.	Take pictures of fire source.	Wears his outfit, starts pump and goes to his position in front of the building.
-3min			Start footage outside	
-2min	Start data log	Be ready to light	Take camera	

	"START LOG"	the fire. Note when someone enters or exits the datacontainer. (possible pressure		
-1min	Check the data logging			
0min	"START FIRE"	Light the fire "FIRE LIGHTED"		
30 s		Close door "DOOR CLOSED"		
1 min				
During test	Observe if data is saved well.	Make notes of all observations. Note times	Picture all observations. Note times.	Stay into position.
11 min	"ONE MINUTE LEFT"			Prepare to open the door
12 min	"OPEN DOOR"		Take video from side of the door.	Open door: "DOOR OPENED"
+-20 min	"STOP DATA LOG"			Extinguish the fire.

<u>After</u>

Coördinator:

- Check that the data is saved well. Make backups on USB sticks. Save as: "DD_MM_YYYY_Hainaut_nr1.doc"

Note taker

- Give notes to coordinator

Photographer:

- Make sure that pictures are taken of how the fire load looks like afterwards.
- Make sure it is filmed from the side when the door is opened after the test.
- Save pictures on pc of coordinator and back up them on the USB sticks

Fire fighter:

- Stay with self-contained breathing apparatus (SCBA) and check that the fire stays completely out.

Material needed

WHAT	WHO
Camera for footage	
Camera for pictures	
Chronometers	
Notebook	
Pens	
Diesel to start fire	
Something to soak into the diesel	
Lighters	
2USB sticks	
2 Electricity splitters.	
3 Tables	
Safety equipment	

Preparation day for test 2

- Clean fire load.
- Prepare fire for next day.
- Type notes of note taker.
- Change the plaster board