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A study on initial fire behaviour in low-energy houses

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Master thesis submitted in the Erasmus Mundus Study Programme

International Master of Science in Fire Safety Engineering

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April 2012,

Summary/Abstract

Due to environmental, economical and political reasons, there is a clear increase of the number of low-energy buildings during the latest years. Therefore, research on fire safety is relevant to evaluate the safety of people living in low-energy homes in case of fire.

In this thesis, the initial fire behaviour of low-energy houses, complying to the Belgian norm set up by PHP (Passive House Project), is investigated. This means that these buildings are more airtight and more insulated than other, conventional buildings. It is investigated whether these particular properties also translate in a different, possibly detrimental fire behaviour inside the house.

To achieve this goal, many fire safety engineering tools have been used. In first instance, an estimation of the expected situation in the house has been performed by a simple analytical deduction. Afterwards, validated computer software is used to further define the situation. Also, a calculation model has been set up from scratch, showing a first attempt to gain valuable results. The goal is to provide an onset for an evolution to a valuable tool for the fire safety engineer. In the end, scaled experiments are performed to gain further insight in the fire process.

Summary/Abstract

Vanwege het milieu, economische en politieke redenen zien we een duidelijke groei in het aandeel passiefhuizen in de laatste jaren. Daarom toont dit onderzoek zich relevant om de veiligheid te evalueren voor mensen die in passiefhuizen wonen.

In deze thesis wordt het initiële brandgedrag in passiefhuizen onderzocht die voldoen aan de Belgische norm opgelegd door PHP (PassiefHuis Project). Dit betekent dat deze gebouwen meer luchtdicht zijn en beter geïsoleerd dan andere, conventionele gebouwen. Er wordt onderzocht of deze specifieke eigenschappen zich ook vertalen in een ander, mogelijks negatief brandgedrag in het huis.

Om dit doel te bereiken werden veel tools van fire safety engineering gebruikt. In eerste instantie werd een schatting van de verwachte situatie in het huis gemaakt door een simpele analytische afleiding. Daarna werd gevalideerde computersoftware gebruikt om de situatie verder te definiëren. Er werd ook een berekeningsmodel ontwikkeld uit basisvergelijkingen en zal een eerste poging tonen om waardevolle resultaten te winnen. Het doel zou zijn om een aanzet te geven voor een evolutie naar een bruikbare tool voor de fire safety ingenieur. Op het eind werden geschaalde experimenten uitgevoerd om verder inzicht te krijgen in het proces.

Faculty of Engineering

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Master thesis in function of achieving the degree of IMFSE, International Master in Fire Safety Engineering

Year 2011–2012

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Gent, May 2012

The author

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Summary

An experimental and computational investigation on the development stage of fires in low-energy houses
by
Brecht DEBROUWERE

A thesis submitted in fulfilment of the requirements for the degree of international master in fire safety engineering

Academic year 2011–2012
Promotor: Prof. dr. ir. B. Merci
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Summary

In this thesis, we shall investigate the initial fire behaviour of low-energy houses, complying to the Belgian norm set up by PHP (Passive House Project). This means that these buildings are more airtight and more insulated than other, conventional buildings. We will investigate whether these particular properties also translate in a different, possibly detrimental fire behaviour inside the house.
To achieve this goal, a lot of tools of fire safety engineering have been used. In first instance, an estimation of the expected situation in the house has been performed by a simple analytical deduction. Afterwards, validated computer software is used to further define the situation. Also, a calculation model is set up from scratch and will show a first attempt to gain valuable results. The goal would be to provide an onset for an evolution to a valuable tool for the fire safety engineer. In the end, scaled experiments are performed to gain further insight in the fire process.
Keywords: fire, fire safety, low-energy houses, experimental study, CFD

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List of Abbreviations

Abbreviation	Units	Meaning
n50	[/]	This value shows what volume of air, relative to the inside air volume of the house, is lost per hour if a pressure difference of 50 Pa is imposed.
t_p	s	Thermal penetration time
δ	m	Thickness of the insulating material
α	m^2/s	Thermal diffusivity
k	W/(m·K)	Conductivity
ρ	kg/m^3	Density
c	J/(kg.K)	Specific heat
p	Pa	Pressure
m	kg	Mass
$\Re$	J/(kg.K)	Specific gas constant
V	m^3	Volume
T	K or °C	Temperature
Δt	s	Time step
Δp	Pa	Pressure step
f	[/]	Friction factor
L	m	Length
D	m	Hydraulic diameter
v_{mean}	m/s	Average perpendicular velocity
v	m/s	Velocity
Re	[/]	Reynolds number
μ	Pa.s	Dynamic viscosity
A	m^2	Area
$\dot{m}$	kg/s	Mass flux
$\dot{Q}$	W	Energy flux
C_f	[/]	Flow coefficient
h	$W/(m^2.K)$	Heat transfer coefficient
E	J	Energy
u	m/s	Velocity, not the same as v.
g	m/s^2	Acceleration of gravity

Abbreviation	Units	Meaning
l	m	Length scale
Gr	[/]	Grashof number
τ	Pa	Stress
Δh_c	J/kg	Heat of combustion
r	[/]	Stoichiometric mass oxygen to fuel ratio
σ	$W/(m^2.K^4)$	Stefan–Boltzman constant
ϵ	[/]	Emissivity
Pr	[/]	Prandtl number
Y	[/]	Mass fraction
H	J/mole	Enthalpy
$\dot{V}$	m^3/s	Volumetric flow rate

Abbreviation	Meaning
CFD	Computational Fluid Dynamics
OPEC	Organization of Petroleum Exporting Countries
OAPEC	Organization of Arab Petroleum Exporting Countries
NATO	North Atlantic Treaty Organization
PHP	PassiefHuis Platform
EPB	Energy Performance Belgium / Energie Performantie België
MDF	Medium Density Fibreboard
KB	Koninklijk Besluit (Belgian law)
CV	Control Volume
CS	Control Surface
FDS	Fire Dynamics Simulator
DNS	Direct Numerical Simulation
LES	Large Eddy Simulation
HRR	Heat Release Rate
$\propto$	Linearly proportional to

Chapter 1

Introduction

This thesis presents work about fire development in low-energy houses. The research for this thesis has been done in both a theoretical, computational and an experimental way. We try to combine the results of the different sections into one general conclusion and into some proposed improvements with relation to the fire safety in a low-energy house. In this introductory chapter, we will describe every part of the thesis.

In chapter 2, I have tried to give an overview of the history of low-energy housing from a non-technical point of view. I think it is important to reflect on why the market nowadays focuses on low-energy housing and what the historical triggers were. Next to that, there are of course a few very important ecological values which are reflected upon and all this has also been taken into law during recent years - but we're not there yet. The focus will be laid on Belgium and the Benelux more generally spoken.

Chapter 3 goes further into the fire safety aspect of low-energy houses. It defines the problem we have today with fire safety in dwellings, low-energy dwellings being part of it. We go immediately over to a case study of the E-Cube and try to get some insight in the behaviour in fire situations using a high-end theoretical approach.

In the next chapter, chapter 4, calculations have been done using different computational tools. We have used both zone models and CFD calculations to get an understanding of the behaviour inside the house during a fire. The results are shown every time, and parts of the sensitivity analyzes have been shown where applicable. When we put all this researched data together, we can already draw some preliminary conclusions.

We take it up a notch in chapter 5. In this chapter, we will try to assemble a one-zone model of our own using nothing but the theoretical principles of fire behaviour and fire safety engineering. Data from the E-Cube will be used and the results will be shown.

Chapter 6 is probably the most important chapter in this work. I have been given the opportunity to conduct experiments on model scale (1/8). This scale model has been built from scratch and the problems accompanying the building of the model have been solved gradually. In the end, a replica of the E-Cube was built and 4 different setups were tested using this model. The building of the model, from the planning board to execution and the final results, are depicted in this chapter. The results of the one-zone model are also placed next to these results to assess to what extent this zone model can be used and whether the submodels used are appropriate.

Finally, general conclusions have been made in chapter 7 with regards to fire safety, more specifically on the points of life safety and firefighter safety.

Chapter 2

History of low-energy housing in the Benelux

2.1 Introduction

In this chapter, we mean to investigate how the evolution from a classical building design to a low-energy building design has evolved over the course of the last decades.

Essentially, a low-energy house has evolved out of ever growing technological advancements as well as an ever growing awareness that a lack of insulation and over ventilation causes a loss. In the initial years of the search for better performing insulation, this loss was measured in purely economical terms, but the latest years, this evolution is mostly kept in motion by an ecological perspective. More than ever, the awareness has grown that a sustainable way of living should be reached and our ecological footprint should be lowered [7].

There is also a second part in this story of evolution towards a low-energy house, and that is ventilation. As already stated, keeping the energy in the form of heat (commonly referred to as warmth) in a house, requires both insulation and ventilation to be up to par. Overventilation in winter essentially means that too much cold air enters through the ventilation system and the hot air inside is expelled through the openings in the walls and joints. In summer, too much hot air enters through the ventilation system and expells cool air. In both cases, too much energy has been used to regulate the inside temperature and air quality.

It is of course necessary to ventilate. If there would not be an adequate ventilation, the quality of the inner air would deteriorate significantly, proven by a lot of older school buildings: in those days, ventilation was not the major concern, resulting in under ventilation during class hours. One entering a classroom right after a class then comes immediately to the conclusion that the quality of the air is not ok [8]. The air smells bad and the temperature regulation is almost non existant.

In the past, the evolution of ventilation went separate from the evolution of insulation materials and techniques. However, the last few decades, more and more holistic integration has begun, when people noticed that living comfort combined with an economical and ecological lifestyle is largely determined by a well performing insulation and ventilation.

2.2 History of insulation in the Benelux

Since the dawn of man, insulation has been around. People found out very early that insulating their houses with straw or with clay kept them either warm in winter or cool in summer. So, we can not say that insulation is a story of the last few decades, that would not put things into the right perspective. It rather is a continuous evolution where more and more knowledge is gained on the theory behind insulation and on production processes: where up until the late industrial revolution only natural materials were being used, people in the last few decades use more and more synthetic and processed mineral products, which often have a lot of better capacities: a lot of natural insulating products are prone to rotting and mold.

Either way, in this section we will look at the major evolutions in insulating materials and techniques in the past few decades. We will see that there are a few major events in recent history that really triggered the research for better insulation materials and ventilation. Also, the legal system has been involved for the last 2 decades.

2.2.1 A natural evolution

Technological advancements after the 1800's made the building of houses a lot faster than they used to be built. Before the industrial revolution, residential houses were mostly constructed out of completely natural materials, like wood, baked clay, lime, chalk, and processed wood (planks). After the industrial revolution, the range of building materials was greatly enhanced with steel and other metals, concrete, synthetic polymers, gypsum,... [9]

Combined with the explosive population growth after the industrial revolution - due to better health care and better understanding of diseases - a lot of new buildings were needed, and fast. The wars that tore up Europe also meant that the buildings destroyed needed to be built up again. The new materials helped in building houses faster, and after the second world war, this helped in rebuilding the ravaged Europe. However, personal comfort in homes was not at all an issue back then. Indeed, a lot of people did not even have a bathroom in their house, so a draft somewhere in the house or a cold spot were not a problem - only part of the house would be heated and if that part was warm, you could warm yourself using blankets and such in the other rooms.

This lack of attention to personal comfort resulted in houses being built not to be kept warm during all of the winter time and therefore not insulated as would be the case today. This has as an obvious consequence that those houses are not at all energy efficient, and that a lot of fuel would be needed to heat up those houses. That was not an issue in the decades right after the second world war, since fuel (coal, oil, wood and such) were relatively cheap. It would only be around the 1980's that attention would rise for temperature comfort inside homes. This is also the decade in which the percentage of houses with double glazing would increase dramatically.

There is another reason why some people decided to build more energy efficient, and that has mainly to do with the European May 1968 uprisings and the American hippie movement. As much as these movements were about personal freedom, they also had a large back-to-basics factor. This was focused on the argument that modern man has evolved too far from nature and that one should build again using natural materials and build with respect for nature (in other words, energy efficient) [9].

2.2.2 The oil crisis

The major reason why most people started to build more energy efficient came during the international oil crisis. In the 1960's the oil production in the US peaked. So, this was a golden period for the Western world, in which lots of technological advancements were made. Germany reached its production peak in 1966, Venezuela and the United States in 1970, and Iran in 1974.
Canada's conventional oil production peaked around this same time (though non-conventional production later helped revive Canadian production to some degree).

Though production in other parts of the world was increasing, the peaks in these important areas began to put substantial upward pressure on world oil prices. Equally as important control of the oil supply became an increasingly important issue as countries like Germany and the U.S. became increasingly dependent on foreign suppliers for this key resource.
Following the Yom Kippur war, in October 1973, the members of Organization of Arab Petroleum Exporting Countries or the OAPEC (consisting of the Arab members of OPEC, plus Egypt and Syria) proclaimed an oil embargo in response to the U.S. decision to re-supply the Israeli military during the Yom Kippur war; it lasted until March 1974. OAPEC declared it would limit or stop oil shipments to the United States and other countries if they supported Israel in the conflict. With the US actions seen as initiating the oil embargo, the long-term possibility of embargo-related high oil prices, disrupted supply and recession, created a strong rift within NATO; both European countries and Japan sought to disassociate themselves from the US Middle East policy.

Nonetheless, the prices skyrocketed: the OPEC members also agreed to use their leverage over the world price-setting mechanism for oil to stabilize their real incomes by raising world oil prices. This action followed several years of steep income declines after the recent failure of negotiations with the major Western oil companies earlier in the month. The 1973 'oil price shock', along with the 1973–1974 stock market crash, have been regarded as the first event since the Great Depression to have a persistent economic effect. Figure 2.1 shows this effect.

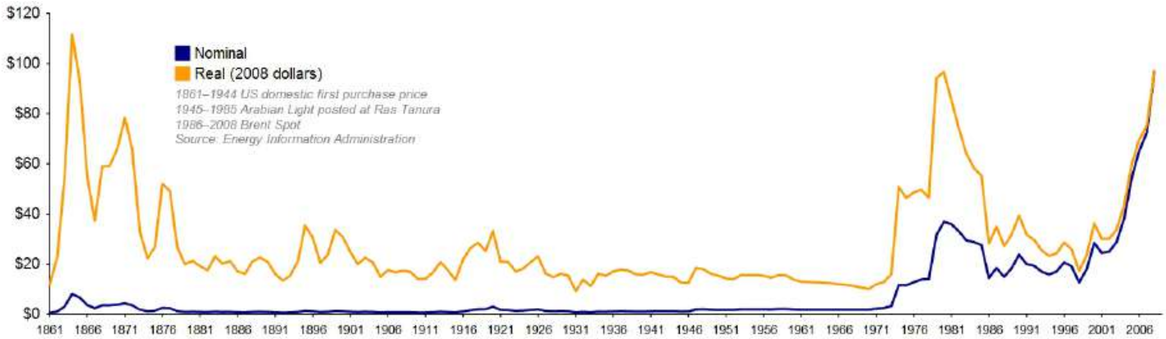

Figure 2.1: The evolution of oil prices. The orange line shows the price after correction for inflation. Taken from [1].

The amount of coal in the soil in the Benelux also could not bring any relief. The production of the coal mines in Belgium and the Netherlands peaked in the fifties, but declined shortly thereafter. The simple reason was that there was just not enough coal in the soil - and the steel manufacturers needed those cokes to keep on producing. So, the price of those coals also rose during those days [1].

The consequence was that heating your home would be more expensive than before. Since a lot of the heating systems in the seventies were based on either oil, coal or gas (which is often a byproduct from crude oil), the prices increased dramatically. This made people think and started a wave of incentives to more efficiently heat the house; thus increasing insulation.
Some gouvernments also wanted to see this in law form, for example, the first law on the use of insulation material in France was written in 1974 [10]. Other countries, like Belgium, trusted on the rules of craftmanship of the architects and the contractors.

2.2.3 The law

For this section, I have heavily relied on the 'Bouw-wetboek' [11], which clarifies the Belgian legislation with regard to building and construction. It took quite some time for legislation to formulate an opinion on building, because on one hand, environmental concern only started at the end of the 80's, beginning 90's, and on the other hand, it isn't straightforward to oblige people to build according to a law. This would mean intruding in their personal freedom, for some.

There are a few passages that are of great interest here, of these the most important ones are:

- Sted XVIII/A
- Erk III
- Pre II/A
- Pre II/C
- Pre VIII/B & Pre VIII/I-B

Sted is about **Sted**elijke wet, Urban law, **Erk** is about **Erk**enning or Recognition and **Pre** is about **Pre**mies or Tax reductions.

The earliest of these laws is Erk and is over 20 years old, it's a law that originated in 1990. This is actually the first step in making laws for construction: making sure that not just anyone is allowed to install anything. People who are professionals are recognised in this law as being people who know how to follow the rules of good craftmanship and as such, these people should be installing the insulation at your home.
Next in line is the Pre-laws, which regulate tax reductions and paybacks for work done to some homes. The first one in the row, Pre II/A, was in force in 1992 and was a bonus for people wanting to rebuild their house which had to be over 20 years old. It also would help people to expand their home. The law also clearly states that insulation should be added as one of the measures of rebuilding.
This means in practice that the gouvernment wanted to refurbish the old houses with more insulation and wanted people to provide enough insulation in the newly built additions to the home. This would lower the dependency of Belgium on foreign oil and means a cleaner environment.

The last and probably most important law to us is the Sted XVIII/A. This is the Belgian adaptation of the European Directive 2002/01/CE, which states that all newly built buildings and most of the rebuilt buildings must comply to a certain level of thermal insulation and energy efficiency. On top of that, a minimal and controlled ventilation must be assured.

The EPB-norm has 3 kinds of demands:

1. Strict thermal insulation-demands:
These are prescribed in maximal K-values (global insulation level of the building) and U-values (insulation values per wall). The lower these values are, the better.

2. Energy prestation demand or E-level:
This is prescribed as a complete energy usage level of a building, including all amenities. It accounts for the compactness of the building, the insulation, the airtightness, the energy production, the type of ventilation, protection from the sun,...
The lower this value, the better the score.

3. Minimal ventilation demands.

The values are (from 2014 on) for Flanders: A maximal K-value of K45 (sometimes K40); a maximal E-value of E70, and application of the ventilation norm NBN D50-001. Other regions have similar, though slightly different values.

There is however a problem with this law: low-energy houses which are certified by PassiefHuis Platform (PHP) did not score good enough in the EPB (Energie Performantie België) software currently used by licensed EPB reporters. It will be impossible in the future to let the PHP control and monitor all houses, so in the best situation, the EPB software is altered and/or the training of EPB reporters is improved. A different approach is to have an international, independent organisation certifying all the low-energy houses [12].

2.2.4 Green roof or solar energy?

There are now two distinct choices when using the roof of a building. Both of these options are around for a long time, but recent changes has put them again in the interest field of many architects. These both choices are:

- Green roofs;
- Roofs harvesting the energy of the sun.

Green roofs, usually flat (but also possible with an inclination!), have been around for a very long time, the hanging gardens of Babylon being a prime example. It is however in recent years that more research has been done to a durable way of implementing these. The architect and occupants want a roof without having to maintain it a lot, obviously. The choice of plants is therefore usually a low maintainance plant, such as moss.

The advantages of green roofs are pretty apparent: in densely populated areas, this is a very nice way of using unoccupied space, thus creating an enjoyable place. The added soil on top of the roof is said by the specialised firms [13] to add more insulation to the roof, but the use of water in this soil would make it a poor insulator. More research would be needed to give a clear answer to this question. However, the use of that water does make it a good cooling agent in summer - when the sun shines on the roof of the house, inside temperatures might climb up considerably fast. However, plants on the rooftop evaporate quite a lot of water, and the soil on the rooftop does the same thing. Evaporation of water uses energy - that energy would otherwise heat up the rooftop. Therefore, during summer, a cooling effect is achieved. So, logically, there is a large amount of architects and designers jumping on the trend of green roofs. There are already a few applications of low-energy projects using this technology [14].

The other choice is to use the energy of the sun to the advantage of the house. This is done by using solar panels or a solar hot water system. These two extract energy from the radiation from the sun. The first does this by converting the radiation to electricity and then the occupants of the low-energy house can either use that electricity or sell it on the electricity network. Solar panels use light energy (photons) from the sun to generate electricity through the photovoltaic effect. Depending on construction, photovoltaic panels can produce electricity from a range of frequencies of light, but usually cannot cover the entire solar range (specifically, ultraviolet, infrared and low or diffused light). Hence much of the incident sunlight energy is wasted by solar panels, and they can give far higher efficiencies if illuminated with monochromatic light. Therefore, another design concept is to split the light into different wavelength ranges and direct the beams onto different cells tuned to those ranges. This has been projected to be capable of raising efficiency by 50%. Currently the best achieved sunlight conversion rate (solar panel efficiency) is around 21% in commercial products, typically lower than the efficiencies of their cells in isolation. [1]

Solar hot water systems use the energy in a different way: the sun can heat up water on top of a roof while this water circulates in piping installed on the roof - either pumped through this piping or through natural convection. There are records of solar collectors in the United States dating back to before 1900, comprising a black-painted tank mounted on a roof. In 1896 Clarence Kemp of Baltimore, USA enclosed a tank in a wooden box, thus creating the first 'batch water heater' as they are known today. Although flat-plate collectors for solar water heating were used in Florida and Southern California in the 1920s there was a surge of interest in solar heating in North America after 1960, but especially after the 1973 oil crisis. Again, we see the oil crisis coming up as a major incentive for people to keep track of their energy use. Technological advancement in building these systems also make them more practical, so more people will consider installing these.

These last two systems, where the energy of the sun can be actively used by the occupants of the house, seems to win the market over the use of green roofs. It can however be expected that for socially important buildings (such as the school building in Sweden [14], figure 2.2), the concept of green roofs is still an interesting option.

Figure 2.2: A view on the newly built school.

2.3 History of ventilation in the Benelux

2.3.1 Need for ventilation

It is very difficult to find older books on ventilation in dwellings, even technical books make little to no reference to ventilation. The only issue of ventilation in books before the 90's is the question whether insulation materials for outer walls should be ventilated or not to keep them dry. No reference has been made to inner ventilation what so ever.

This is a clear indication that ventilation has been very often overlooked, and not only in a technical way, also in a legal way. The protection of the labour force in a work environment is something pretty easy to put in a law, but obliging people to put ventilation systems in their own homes is clearly a step which has only recently been taken.

The advantages of a good ventilation system are however very clear and there are a lot of them. All have to do with either comfort or health of the occupants of the space. The comfort is increased if a good quality of air is ensured. This means air which does not smell bad as when you would enter for example an older classroom right after a class [8]. This however also means that there are less pollutants in the air, having a good effect on asthma patients

and on allergy patients [1]. It improves comfort as a whole.
A different reason is that a good ventilation helps to fight and prevent condensation problems. These problems are highly unwanted and deteriorate the comfort in a dwelling enormously.

A good book has recently been published about ventilation in dwellings in the UK, 'Handbook of Domestic Ventilation' [15], which puts the finger on the sore wound: '...The one feature about all these sources is that there is little if any dedicated coverage of the ventilation of dwellings. This is most surprising, given that dwellings form such a large proportion of the UK's building stock. A common view is that ventilating houses is not complicated, and therefore there is no real point in getting too interested in the subject. This view is not consistent with the current state of the housing stock with respect to the incidence of condensation problems. We still have not got it right.'

Another passage shows that there is indeed a real problem on the UK market:
'Whilst the reasons for having a book about ventilation are fairly clear, perhaps this might not, at the first sight, seem to be the case for dwellings. From the perspective of building services engineering, houses are small and relatively of a small range of room configurations. The amount of air required for ventilation purposes is correspondingly small, and the measures required to ensure effective ventilation might be viewed as being relatively simple to implement.
This seeming simplicity does not reconcile with the statistics. A series of English House Condition Surveys reveal the ongoing issues with the performance of the housing stock. As the total stock level approaches the 20 million mark, condensation and mould growth problems are reported within about 15% of properties. This percentage has shown very little improvement over the past 20 years.'

And even if a ventilation system is fitted in a home: 'Whatever is being designed into a dwelling, someone somewhere will conspire to render it ineffective or inoperable. Ventilation systems are particularly vulnerable in this respect. The author has seen many condensation problems caused by blocked off air inlets and outlets, and switched off or even deliberately damaged fans.'

However no real literature has been published on the matter, I believe that the situation in the Benelux is similar, given the similar climate and the similar building techniques.

2.3.2 The law

As already mentioned, the first law about ventilation was 'Veiligheidswet', the law which controls the safety and comfort conditions for people on the job. This law has now been replaced by the 'Welzijnswet'. The Veiligheidswet was first published in 1952 and had a chapter about necessary ventilation. In this case, it was more on safety than on comfort and was only referring to ventilation in a work environment. For example, mines had to be (and have to be) ventilated in order to get rid of explosive mine gas.

It is however more interesting for our purpose to look at ventilation in a dwelling environment. There are a few interesting laws which mention ventilation in the 'Bouw Wetboek' [11]:

- Sted XVIII/A
- Erk III

These two laws are also of great importance to the insulation story. This is because in domestic applications, insulation and ventilation are closely interlinked and have a big influence on each other.

As already stated, **Sted** is about **Sted**elijke wet, Urban law and **Erk** is about **Erk**enning or Recognition.

The earliest of these two laws is the Erk, which was voted in 1990. This is actually the first step in making laws for construction: making sure that not just anyone is allowed to install anything. People who are professionals are recognised in this law as being people who know how to follow the rules of good craftmanship and as such, these people should be installing the ventilation at your home.

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The lower this value, the better the score.

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The values are (from 2014 on) for Flanders: A maximal K-value of K45 (sometimes K40); a maximal E-value of E70, and application of the ventilation norm NBN D50-001. Other regions have similar, though slightly different values.

2.4 Low-energy housing

With low-energy housing, we mean housing and dwellings which comply with the demands set by PHP, the PassiefHuis Project. These demands are more strict than those set by Sted XVIII/A. They are formulated as follows [16]:

- Space heat demand $\leq 15kWh/(m^2a)$
- Heating load $\leq 10W/m^2$
- Excessive temperature frequency 10% (> 25°C)
- Primary energy demand $\leq 120kWh/(m^2a)$
- n50 value ≤ 0.6

An n50 value is a value that shows what volume of air, relative to the inside air volume of the house, is lost per hour if a pressure difference of 50 Pa is imposed.

Every time we mention the term low-energy housing, we mean all dwellings complying to the demands formulated above and intended for living occupation by families.

2.4.1 The current situation

The amount of low-energy houses has been steadily increasing over the last few years. However, Belgium is not at the top of the European league, countries such as Sweden, Germany, Austria,... have a larger percentage of low-energy houses. One of the reasons is, as already mentioned, the certification problems [12].

According to [17], the situation in Belgium for newly built buildings looks as follows:

	Standard houses	Low-energy houses	Ratio
Flemish Region	31741	143	0.5%
Brussels Region	2542	3	0.1%
Walloon Region	12955	25	0.2%
Total	47238	171	0.4%

Table 2.1: The situation in Belgium in 2009. Taken from [17].

These numbers are from 2009.
There is however a strong tendency towards building low-energy houses, as they don't need a lot of extra energy for heating (which makes an energy efficient heat pump a valuable alternative for heating the house); which is an improvement for the environment and also for the independence of the Western world on foreign energy supply.

2.4.2 The future

More and more, the Belgian government wants to invest in and regulate the transition of current building techniques to a more durable approach of the building market. This is grouped in a management style called transition management [18].

Transition management is the whole of coping with uncertainties, the cooperation of process and content and the central learning process. In other terms, it is using all possible tools to direct the transition.
It has the following properties:

- It uses long term thinking as a basis for the short term policies
- It uses different gouvernment domains and levels, the whole policy is integrated over the different gouvernments
- It assumes a cooperation of different actors
- It's a learning by doing and doing by learning process
- It opens up a wide range of tools

The ultimate goals are to improve and innovate systems for planning and building low-energy houses.

Now, a view for 2030 has been established. This view was at the date of writing the article (2007) still very high end and because of the political impasse in Belgium the recent years, not a lot of elaboration has happened. However, 2030 is approaching fast and it is expected that, since energy prices are once again steadily rising, the problem of energy supply will only grow. So, it can be expected that the funding of the gouvernment is going to increase in the future in the sense that low-energy building will be promoted. This means that the percentage of houses in the whole housing market will steadily increase in the future. We have already witnessed the first wave of energy efficiency related laws, in the next years a new wave will happen. It is therefore interesting that we understand all technical aspects of low-energy houses (such as fire safety) into detail.

Chapter 3

Definition of the problem

We have now set out the history and logical evolution path of low energy houses. The next question for a fire safety engineer is:
"What about the fire safety in a low energy house" ?

We will try to find an answer to this question using a range of tools. The first one is a high-end theoretical approximation, trying to set out the big lines of what is expected to happen in a low energy house. We will use the principles of heat transfer and we will look at the basic properties of a low energy house: we will look into the ventilation parameters to assess what kind of burning is expected (a ventilation controlled or a fuel controlled regime).
We go on to computational models, using two 2-zone models (CFAST and OZONE). The advantage of a 2-zone model is that the calculation time is fast, thus enabling us to do a lot of simulations in a low timespan. It is expected that it will not give us very accurate results, but it will give us a good idea what the order of magnitude of the different parameters is.
A CFD (Computational Fluid Dynamics) calculation is then performed using FDS. FDS is used all throughout the community of fire safety engineering. If it can be shown that FDS gives good results for a simulation of a fire in a low energy house, then that would serve the fire safety community greatly without the need for a specialised program. We will shortly go through the available literature on the subject, inspecting if FDS has already been validated for this kind of application and we will compare the results to some experimental results.
In a last computational approach, a 1-zone model is generated from scratch. This approach might deliver interesting insights and might lead to a well working package that can serve the fire safety community. The essential basic physics are explained and brought together in a 1-zone model. I've opted for a 1-zone instead of a 2-zone model because of the nature of the fire: because of the low amount of leak in a low-energy house, a stratified case is highly unlikely and most probably 1 single zone is formed, in which the hot gas layer descends to the floor level. This does not have to smother the fire, as the ventilation keeps an inflow of unused oxygen probable.

After the high-end theoretical and these computational approaches, we go further with an experimental set-up. This set-up is essentially a scaled version of a low-energy house, in which we set a pan of fuel and light the fuel. The results of the experimental set-up can be coupled to the computational predictions and we can check to what extent the computational models are reliable.

3.1 Definition

The ever growing use of and research for better insulation materials in a low energy house has led to an increase in kinds of insulating material. This has not always happened with fire safety in mind; one of the examples is the use of EPS (expanded polystyrene) and XPS (extruded polystyrene) as insulating materials. Both of them show a good insulating behaviour, but a bad reaction to fire: they ignite easily.

A second problem is that fire safety engineers are usually not involved in the design of a low energy house. This is because low energy houses often are built for private owners, these private dwellings require no special demands on fire safety. Therefore, the interior of a low energy house can be finished in whatever way possible - even a way that threatens the fire safety and thus the safety of the occupants. An example of this:
The E-Cube is a project by the University of Gent to participate in the prestigious Solar Decathlon. They were the only European team allowed to participate in the finals in the US. In their design however, they finish the interior with MDF (medium density fibreboard), a material that easily ignites [19]. The fact that such a design was voted to be amongst the best of the designs shows that in architectural areas, not a lot of effort is done to make buildings safe in regard to fire. This is not the only design that shows a lack of fire safety engineering: the winning team, of the University of Maryland, has chosen for wood to be the main material. They have fitted a sprinkler installation, but this is not obliged in the Benelux, since this would be a residential dwelling. Thus, on the market, the expensive sprinkling installation might very well be not installed, creating a possible fire hazard. The response on the question why the sprinkling installation was installed was unanymous: the US law prescribes a publicly accessable building to be sprinklered.

It is even not necessary to follow the annex 2 in the KB concerning fire safety in Belgium, since:

Annex 2/2010: Low-rise buildings

0 GENERAL POINTS

0.1 Purpose.

These basic regulations set out the minimum conditions to be satisfied in the design, construction and layout of low-rise buildings (BB) in order to:

- prevent fires from starting, developing and spreading;
- ensure the safety of persons;
- preventively facilitate the intervention of the fire service.

0.2 Scope.

This annex applies to all low-rise buildings for which a planning permit application is submitted after the first day of the third month following its publication in the Belgian Official Journal.

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The following are excluded from the scope of this annex:
- Industrial buildings;
- buildings of no more than two storeys having a total surface area not exceeding 100 m²;
- Single-family dwellings.

Figure 3.1: This shows the current problem with fire safety and low energy housing. Taken from [2].

It is a bit unrealistic to expect that on every building project, a fire safety engineer would be mandatory in Belgium. The major reason is that there are simply not enough fire safety engineers.
Nonetheless, it is necessary that the freedom of architecture in general is looked at from a fire safety point of view as well. This is the cause of this thesis. We try to get an insight in the development of fire in a low energy house in the first couple of minutes of the fire. As soon as the residents have left the house, the safety aspect gets less important: fire fighters can opt not to go inside a residential dwelling if the fire is too big. On the other hand, phenomena such as backdraught must be taken into account as they can form real dangers to the firefighters.

As a reference work for how a low energy dwelling looks like, the E-Cube has been chosen. Being a project of the same university as where I'm doing my thesis, it helps in collecting the data necessary to form an image of a practical low energy house. The simple geometry of course also helps to gain insight in how the processes involved in fire will behave.

3.2 The E-Cube

The E-Cube is an example of how low-energy houses could be designed in the future. It was a project for Ghent University to compete in the Solar Decathlon, and the text below, integrally taken over from the website for the E-Cube [3], shows the motivation of the architects and engineers to implement their design in the building market as it is:

> *'Ghent University's E-Cube is an affordable, do-it-yourself building kit for a solar-powered house that is pre-engineered, factory-built, and easily assembled without special skills.*
>
> *The house begins with a starter unit, which can be upgraded with enhancements to the PV system and interior finishes as well as with extensions to the living space. This allows home-owners to personalize the house according to their time and budget.*
>
> *Although not intended as a single solution for all people and lifestyles, the E-Cube will provide Solar Decathlon 2011 visitors unique insight into Belgian sustainable building design.'*

The E-Cube would not be equipped with a sprinkler installation as this is currently not required by the Belgian legislation. This would increase the risk of a serious fire: consequences would be higher than without sprinklers.

As mentioned in 2.4, to be an official low-energy house, the E-Cube has to perform according to the following limitations:

- Space heat demand $\leq 15kWh/(m^2a)$
- Heating load $\leq 10W/m^2$
- Excessive temperature frequency 10% (> 25°C)
- Primary energy demand $\leq 120kWh/(m^2a)$
- n50-value ≤ 0.6

This all results in a very insulated and airtight building.

The shape of the E-Cube is, as the name implies, a cube with sides of 8m. The major idea around which the E-Cube was designed was modularity and a DIY-idea (Do It Yourself). These two concepts would make low-energy housing a lot more practical to build and use:
For one, the DIY-approach would lower the cost of building a low-energy house considerably. One of the major costs of a low-energy house is not the material, but the amount of labour involved in constructing a low-energy house, since this has to be done with the utmost care: it

is not easy at all to reach the specifics written down by official instances, even for professional construction crews. To reach a level of airtightness and insulation that large, time and a lot of effort is needed. Going to an idea of a DIY low-energy house with modularity also means that the construction would be highly simplified. Indeed, reading the project manual [20] clarifies the initial intention of the E-Cube.
The other advantage of the E-Cube is its modularity (denoted in the project manual as a Plug and Play principle). Being able to add modules greatly increases the flexibility of the house, if required an additional room can be built within the existing building, thus ensuring that a low-energy house is indeed a feasable goal for starting families.

The main idea around the E-Cube is trying to get low-energy housing closer to middle-class people nowadays, whereas most of the other contestants in the Solar Decathlon programme were more focusing on the architectural interest around their building. This however made the buildings also a lot more expensive than the E-Cube design.
Therefore, it can be expected that future low-energy houses are constructed according to the principles set forth in the E-Cube design. The final shape of a commercial low-energy building design will probably still change before people start to construct low-energy houses en masse, but the basic principles are set.

Below, a few inside and outside views are presented to be able to form an idea of the E-Cube.

Figure 3.2: This figure shows a rendered outside view. Taken from [3].

Figure 3.3: This figure shows the inside of the E-Cube once it's finished. The final market version will of course look more finished on the inside. Taken from [3].

Figure 3.4: A possible inside view of a finished E-Cube. Taken from [3].

3.3 Short theoretical approach

Essentially, it is important to look at the different subaspects that make up a low-energy building. We can break up the building in those aspects and theoretically deduce what would be the impact of all of these aspects. Afterwards, we can weigh them off against each other and try to make general conclusions from these aspects. There are, as already mentioned, two major factors we need to take in account when assessing the fire hazard in a low-energy house, being the insulation and the ventilation.

3.4 The insulation

As we already established, the demands for insulation for a low-energy house are more strict than those for a normal house. The insulation in a low-energy house serves its purpose for temperature shifts that go gradually, such as the temperature differences during the course of the day and night, and the differences during seasons.

The behaviour during a fire situation is not so well established. On one hand one might think the insulation has a big influence on the fire by keeping all the heat inside. This however cannot be concluded from the good insulating behaviours in the other scenarios: in all of the other scenarios, the temperature fluctuations during night and day and during seasons, we have a very large time scale. Typically, the temperature would change a few degrees Celsius over the course of a night. Even in extreme situations, these fluctuations are low and easily followed by the thermally thick insulation.
This makes clear that the behaviour of the insulation during a fire situation will not be the

same. The time scales are typically a lot lower, in the order of minutes, sometimes even seconds. The temperature differences are also a lot bigger, temperatures can easily climb up to hundreds of degrees difference in just a few minutes. This means a fast behaviour of the fire and the surrounding air, entrapped in the low-energy building, versus an insulation with a high level of thermal inertia. This high thermal inertia is completely due to the sheer amount of insulation necessary to reach the standards. Assuming a kind of insulation is used which does not ignite, we can state that the insulation will initially take up heat before it passes it on to the outside. The time during which this takes place, can be found when we use the method given to us in the book Enclosure Fire Dynamics [4]. The derivation of equation 6.14 in this book would lead us too far from the goal we try to obtain here, so the equation shall be quoted as such:
The thermal penetration time is defined as

$$t_p = \frac{\delta^2}{4\alpha} \tag{3.1}$$

and indicates the time at which 15% of the temperature increase on the fire-exposed side has reached the outer side of the solid. Here α is the thermal diffusivity, also given by the relation $\alpha = k/\rho c_p$, and given in $[m^2/s]$.

A typical low-energy house is finished with typically 20cm of insulation material. If we assume this material to be plates of mineral wool with an α value of 5.1 10^{-7}, we get a thermal penetration time of that material of 5,4 hours. So during this time period, the shell of the house works as a wrapped around heat sink.

It is now important to assess how long this initial behaviour will last. To assess a timescale, it is important to look at the global picture of fire risks and fire fighting. We find on the website of the Belgian Senate that arrival times for firefighting services should not exceed 12 minutes [21]. If we now consider a small safety factor, we can assume an initial time period of 15 minutes. We see from the results that indeed, in this time period the walls will act as heat sinks. The temperature distribution through the insulation material will be expected to look like in figure 3.5.

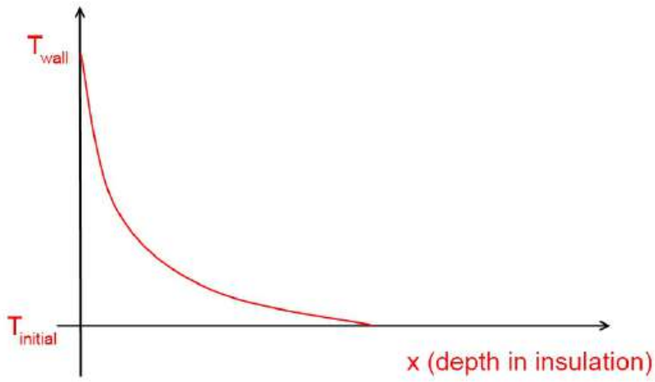

Figure 3.5: A sketch showing how the temperature distribution will look like.

Nothing suggests that the insulation cannot participate in the fire, we will as such assume that it will participate if ignited.

3.5 The ventilation

The ventilation is twofolded:

- on one hand we have natural ventilation caused by leaks in the shell of the building.
- on the other hand we have the mechanical ventilation which pumps in fresh air and extracts polluted air.

Both of these aspects will influence the building in a different way.

3.5.1 The natural ventilation

The behaviour of this ventilation completely revolves around pressure differences. A pressure difference will cause a flow to move through the leakage, much as a flow causes pressure loss in the fluid itself.
This initial pressure difference will be led by a sudden increase in temperature when the fire is ignited. We know the ideal gas law:

$$pV = m\Re T \tag{3.2}$$

with V being the volume of the control volume (CV), m being the mass present in the CV, p being the pressure in the CV, T being the temperature in the CV and $\Re$ being the specific gas constant for air, 287 J/kgK.

Due to the fact that a low-energy house does not have a lot of leakage openings, compared to a traditional building, we can assume that the volume in a very small time step (Δt) will not immediately change. There is an initial pressure difference that has to be overcome before a flow can start, thus changing the mass inside the control volume (whilst assuming we keep the control volume as the inside of the low-energy house). We can, in other words, assume from this equation that once a fire starts, the temperature inside rises, thus increasing the pressure inside the set volume. This will lead to a flow.

We can now show the behaviour of a flow in a pipe (or through a leakage hole) by using the Darcy-Weisbach equation for pressure loss due to flow in a pipe. This equation is formulated as:

$$\Delta p = f \frac{L}{D} \frac{1}{2} \rho v_{mean}^2 \tag{3.3}$$

In this equation, f would be the friction factor, L the length of the canal, D the hydraulic diameter of the canal, ρ the density of the fluid, and v_{mean} the average perpendicular speed on a cross section of the canal.

So, would this then mean that a pressure loss would be quadratic with the velocity through the leak? Not quite:

Notice the friction factor in this formula. This friction factor can be read from a so-called Moody diagram, as can be seen in figure 3.6. We can clearly see that there is a different behaviour in the friction factor values for low Reynolds numbers and for large Reynolds numbers - in other words, the friction factor behaves differently for laminar or turbulent flows.

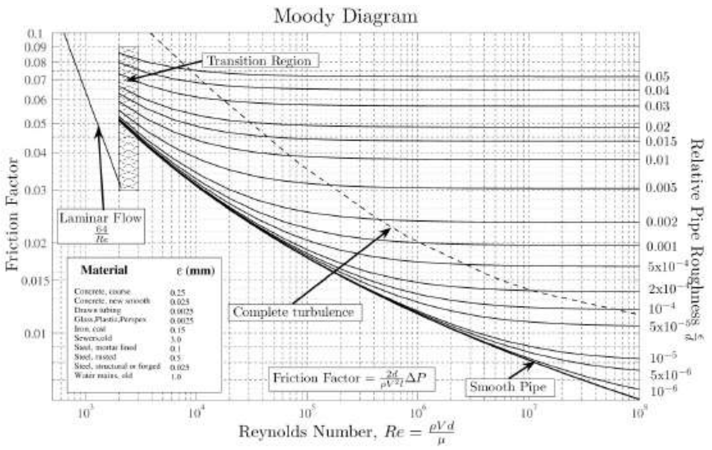

Figure 3.6: The Moody diagram.

This Moody diagram is clearly constant for turbulent flows (a high Reynolds number). It means that the behaviour of the Darcy-Weisbach formula will indeed be quadratic.

For laminar flows however (a low Reynolds number), we see that the friction factor follows the formula $64/Re$. So, the Darcy-Weisbach formula changes into:

$$\Delta p = \frac{64}{Re}\frac{L}{D}\frac{1}{2}\rho v_{mean}^2 \tag{3.4}$$

We can see that the transition zone is around $Re = 2000$. Looking at the Reynolds number:

$$Re = \frac{\rho v_{mean} D}{\mu} \tag{3.5}$$

so that:

$$\Delta p = 64\mu\frac{L}{D^2}\frac{1}{2}v_{mean} \tag{3.6}$$

Or, the behaviour becomes linear.

We just have established that the pressure behaviour strongly depends on the Reynolds number in the flow. The problem now is that it is really hard to establish what the Reynolds number will be: it is typical for leaks (also in reality!) that these range in size; but since the Reynolds number depends on the diameter of the leaks, this will result in a mixed behaviour of quadratic and linear pressure rise. For an identical velocity of $5m/s$, density of $1,2kg/m^3$, viscosity of $1,78.10^{-5}Pa.s$, we get a laminar behaviour for leaks up to about 6mm of hydraulic diameter. A typical house will have leaks both bigger and smaller than this.

From the book Enclosure Fire Dynamics [4], we find a calculation method for the pressure rise in a leaky compartment. It applies to a fixed volume with a small opening at floor level, just what a low-energy building is: a leaky compartment, though the leakage is limited, thus giving rise to a pressure rise. It might be interesting to take a more detailed look at the calculation method:

Pressure Rise in a Leaky Compartment

Consider a fixed volume, but this time with a small opening at floor level. The fire is considered as a source of heat only; see figure 3.7. We use the equation of the conservation of energy:

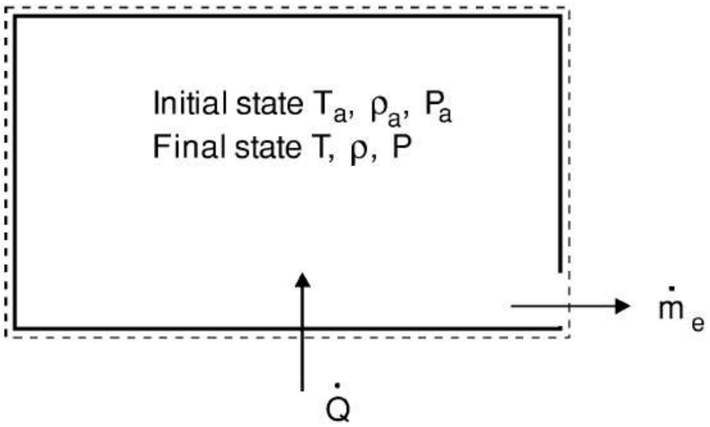

Figure 3.7: Control volume for a leaky compartment. Taken from [4]

$$\frac{\mathrm{d}}{\mathrm{d}t}\int\int\int_{CV}\rho u dV + \int\int_{CS}\rho h v_n dS = \dot{Q} \tag{3.7}$$

u and h are defined as $u = c_v(T–T_a)$ and $h = c_p(T–T_a)$ where T_a is some reference temperature. Here, it will be useful for us to express these in terms of total internal energy per unit mass and total enthalpy per unit mass. This will simplify our treatment. We therefore take the reference temperature T_a to be zero degrees Kelvin (0 K) and write

$$u = c_v T \tag{3.8}$$

and

$$h = c_p T \tag{3.9}$$

thus expressing the total internal energy and total enthalpy per unit mass.

First term in Equation 3.7

We are interested in arriving at an expression that allows us to evaluate the dynamic pressure in an enclosure with a leakage opening, and we must therefore write the first term in equation 3.7 in terms of pressure. We can do this by using the ideal gas law to express the density as:

$$\rho = \frac{p}{\Re T} \tag{3.10}$$

Using equation 3.8 we can write the first term as

$$\frac{\mathrm{d}}{\mathrm{d}t}\int\int\int_{CV}\frac{p}{\Re T}c_v T dV$$

which becomes

$$\frac{\mathrm{d}}{\mathrm{d}t}\int\int\int_{CV}\frac{p}{\Re}c_v dV$$

Performing the integration results in $\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{pc_v}{\Re}V\right)$, since p, c_v, and $\Re$ are not dependent on volume. This expression in turn results in $\frac{\mathrm{d}p}{\mathrm{d}t}\frac{Vc_v}{\Re}$, since V, $\Re$, and c_v are not dependent on time. To summarize, we have found that

$$\frac{\mathrm{d}}{\mathrm{d}t}\int\int\int_{CV}\rho u dV = \frac{\mathrm{d}p}{\mathrm{d}t}\frac{Vc_v}{\Re} \tag{3.11}$$

We shall use this result in our final expression.

Second term in Equation 3.7

Using equation 3.9 to express the total enthalpy per unit mass of the gases flowing out of the compartment, we can rewrite the second term in equation 3.7 as

$$\int\int_A \rho v c_p T dA$$

since the area A is the only part of the control surface allowing mass to exit. Further, we can write v for velocity instead of v_n, since the direction of the flow is perpendicular to the surface of the opening. We know that the mass flow rate through an opening of area A can be written $\dot{m} = \rho v A$ if the density and velocity are constant over the area and the velocity normal to the surface of A.

Adopting the suffix 'e' to denote 'exit', we can express the mass flow rate exiting the opening as $\dot{m}_e = \rho_e v_e A_e$. Performing the integration over the opening area we find that the second term in equation 3.7 can be written as $\rho_e v_e A_e c_p T_e$ or $\dot{m}_e c_p T_e$. To summarize, we have found that

$$\int\int_{CS}\rho h v_n dS = \rho_e v_e A_e c_p T_e = \dot{m}_e c_p T_e \tag{3.12}$$

Third term in Equation 3.7

The third term consists of the chemical heat release rate (assumed to be released as a point source) minus the heat losses to the boundary or, $\dot{Q} = \dot{Q}_{ch} - \dot{q}_{loss}$. **Resulting equation:** Combining the three terms in equation 3.7, we can rewrite the equation as

$$\frac{c_v V}{\Re}\frac{\mathrm{d}p}{\mathrm{d}t} + \dot{m}_e c_p T_e = \dot{Q} \tag{3.13}$$

From previous results, we found that the rate of pressure rise, dp/dt, was very high for the first few seconds in a completely closed compartment. Thus, leakage areas would be established relatively quickly, resulting in a constant level of pressure as shown in figure 3.8. This therefore suggests that the constant pressure assumption is reasonable. To simplify our application of equation 3.13 we can now assume that $dp/dt \approx 0$ and therefore arrive at the expression

$$\dot{m}_e c_p T_e = \dot{Q} \tag{3.14}$$

If T_e and $\dot{Q}$ are known, we can now calculate the mass flow rate out of the opening.

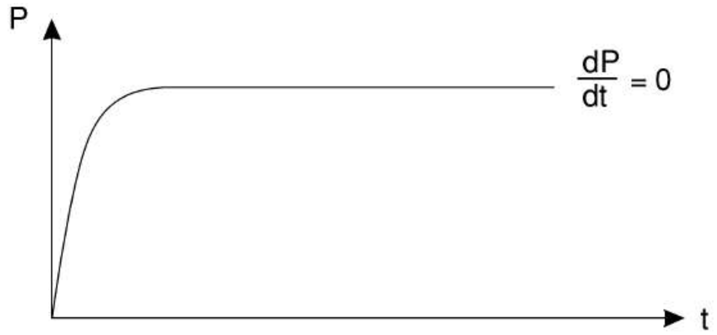

Figure 3.8: Rate of pressure rise in a leaky compartment. Taken from [4]

This formula shows the problem of applying this methodology to low-energy buildings. We know that the amount of leakage in the house is very low. We also know that the ventilation system might not deliver enough oxygen to sustain a flaming combustion, or in other words, the fire might be smothered by a lack of oxygen. This means that $\dot{Q} \approx 0$ when $dP/dt \approx 0$, so $\dot{m} \approx 0$.

In turn, this would show that the pressure rise inside is 0. The next equation shows this very well:

$$\Delta p = \frac{1}{2\rho_e} \left(\frac{\dot{Q}}{c_p T_e A_e C_f} \right)^2 \tag{3.15}$$

with C_f being the flow coefficient. We immediately see that for $\dot{Q} \approx 0$, $\Delta p \approx 0$.

To be fair, this problem is also stated in the shortcomings and assumptions of the method:

- ...
- Constant pressure is assumed, neglecting the initial rate of pressure rise.
- ...

So, in this case we cannot use this calculation method. The final pressure rise would be 0Pa, since the fire source will most probably extinguish itself by a lack of oxygen. We however are interested in the temporary pressure rise when the fire is not extinguished yet; which renders a steady state analytical calculation per definition useless. We will have to resort to computer modeling (zone modeling and CFD) to calculate the transient phase of the pressure behaviour.

3.5.2 The mechanical ventilation

We can assume that the mechanical ventilation will refresh the air in the room; it will extract smoke and air that has participated in the combustion, thus lower in oxygen content, and replace it by fresh air which is 23 % oxygen by mass, at ambient temperature.

However, this story is not entirely sure and true. As already discussed, the pressure will rise in the room. This pressure rise has its effect on the ventilation: as there is a bigger pressure difference to overcome, the volumetric amount of fresh air blown into the room diminishes. On the other hand, the volumetric amount of hot smoke extracted will be bigger; and eventually it is possible that the input of fresh air stops completely because the pressure would be too high. Backflow in other words, is possible in the inflow ducts. This is also shown in the technical manual of the ventilation system:

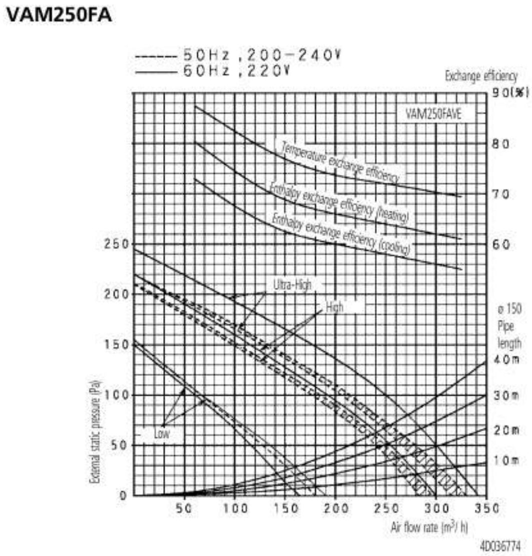

Figure 3.9: An excempt of the technical manual for the ventilation system. Taken from [5], this is the actual ventilation system fitted in the E-Cube.

It is possible to model this behaviour in computer modeling programs. However, to successfully scale this in a real experiment is quite a huge task. The advantage of modeling the ventilation in a better way does not outweigh the large amount of extra money and time needed to make this work. Moreover, the system would be so dependent on pressure changes that the hardware would not be able to catch up. After a discussion with the technicians at the test lab, it was decided not to go through with the detailed modeling of the mechanical ventilation. A different way was chosen: one experiment would be done with an excessive amount of mechanical ventilation, thus adding more oxygen than actually is going to happen in a low-energy house, while one of the other experiments looks at the effects if no ventilation is on. The real situation will lie somewhere in between these two; so conclusions that can be made for both situations will also apply.

Chapter 4

Application of computational methods

Before we start with a first analysis using computational methods, I would like to remind the reader that a lot of computational methods are not the best way to tackle this problem. The major problem with a lot of computational packages, be it one-zone, two-zone or CFD models, is that the submodels for combustion are not fit to accurately calculate what will happen to a fire in a low-oxygen environment. Indeed, all of these have submodels defining whether there would be combustion or not; but most of the time, these submodels do not work accurately in real situations. One of the biggest problems is that re-ignition is not well modeled; fires that die in actual situations don't die when modeling them in one-zone, two-zone or CFD models. This draws attention to the role of the engineer working with these models: (s)he has to be aware that indeed, the software can deliver false results, even with perfect input. This is why the engineer should always be aware of the interacting submodels.

Now that this warning has been heeded, we can take a look at what the computational models predict. We will try to predict the temperatures, oxygen content and the pressure rise in the model, since we can compare this then to the experiments carried out. For comparison, I would like to refer to section 6.2.5. For a description of how the model eventually looks like; see chapter 6. An FDS rendered model of the setup is shown below:

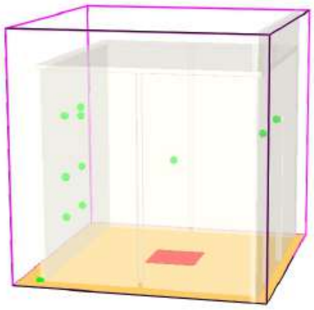

Figure 4.1: A 3D view of the model.

4.1 Approach with two two-zone models

In this section, we will try to solve the problem with two two-zone models: one of them being OZone, the other being CFAST, both very well known in the fire safety engineering field. There is already a disadvantage for two-zone models, in the sence that they average out the temperatures over all of the hot gas layer, whilst local temperatures will define whether combustion takes place or not.

Due to the higher temperatures in the fire, the oxygen molecules move around a lot faster, just as the fuel molecules do. This increases the chances of interaction with each other, and this is also an explanation why combustion can take place at seemingly too low oxygen levels. So, this is a negative for the two-zone models. The averaging of the temperatures prevents us from seeing local hot spots.

Nonetheless, we hope to get some orders of magnitude out of these calculations.

4.1.1 CFAST

CFAST is a two-zone fire model used to calculate the evolving distribution of smoke, fire gases and temperature throughout compartments of a building during a fire. These can range from very small containment vessels, on the order of $1m^3$ to large spaces on the order of $1000m^3$. The modeling equations used in CFAST take the mathematical form of an initial value problem for a system of ordinary differential equations (ODEs). These equations are derived using the conservation of mass, the conservation of energy (equivalently the first law of thermodynamics), the ideal gas law and relations for density and internal energy. These equations predict as functions of time quantities such as pressure, layer height and temperatures given the accumulation of mass and enthalpy in the two layers. The CFAST model then consists of a set of ODEs to compute the environment in each compartment and a collection of algorithms to compute the mass and enthalpy source terms required by the ODEs. The outputs of CFAST are the sensible variables that are needed for assessing the environment in a building subjected to a fire. These include temperatures of the upper and lower gas layers within each compartment, the ceiling/wall/floor temperatures within each compartment, the visible smoke and gas species concentrations within each layer, target temperatures and sprinkler activation time [22]. Version 6.1.1.54 is used.

Now that we have an initial idea what CFAST is, we can enter the inputs needed to start a calculation. We define a box, 1m on 1m on 1m, according to the scaled model in chapter 6. We can model the ventilation in it; but we'll model the ventilation just as it is modeled in the experimental model. This means we put in a net ventilation input which is not dependent on the pressure inside the compartment. Some screenshots below show the input for the model:

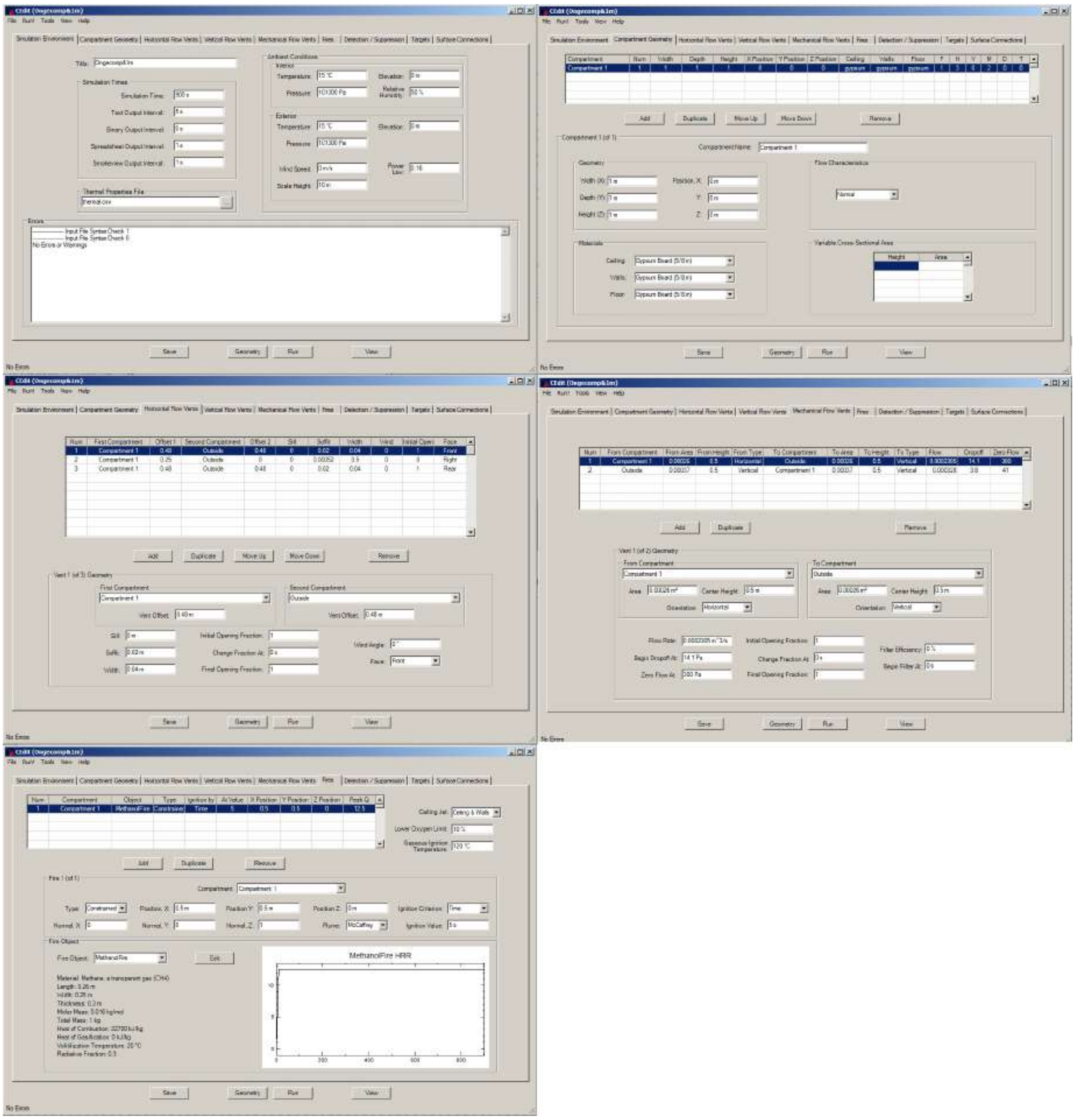

Figure 4.2: The modeled inside of the low-energy house.

Results

Results can be consulted either through the use of SMOKEVIEW, or by using the spreadsheets generated by CFAST. Further on, we will use only the spreadsheets, since these give the raw numerical values rather than some visual answers.

CFAST has conducted its calculations with time steps of 1 second. This is an important parameter, since this will also determine what the uncertainty on the result is; since we expect a fast pressure rise (the growth phase of a methanol fire as modeled in the small scale model happens very fast), we also expect that the time period needed for pressure rise is small. Therefore, we must perform a sensitivity analysis determining how sensitive pressure rise (and thus maximum pressure) is versus time step size.

Several results are combined in one graph (figure 4.3) below.

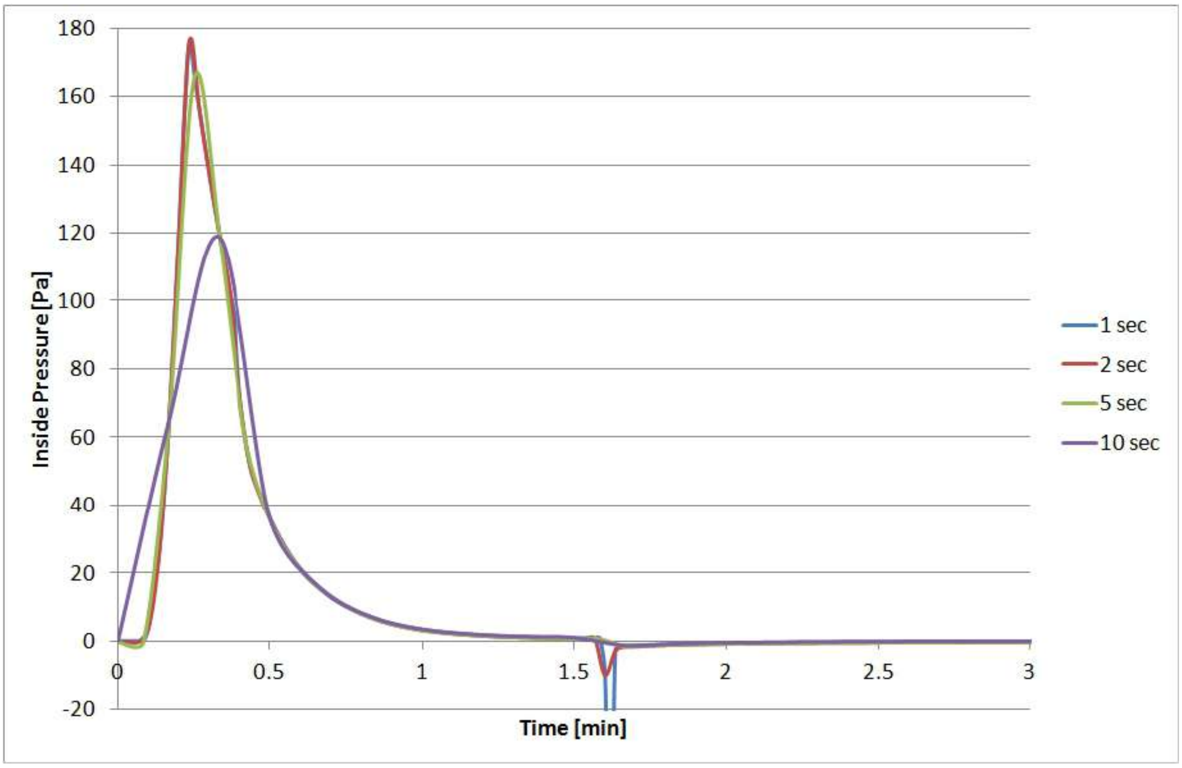

Figure 4.3: A sensitivity analysis on the pressure profile.

As for the average temperatures, figure 4.4 below shows a sensitivity analysis on the temperatures.

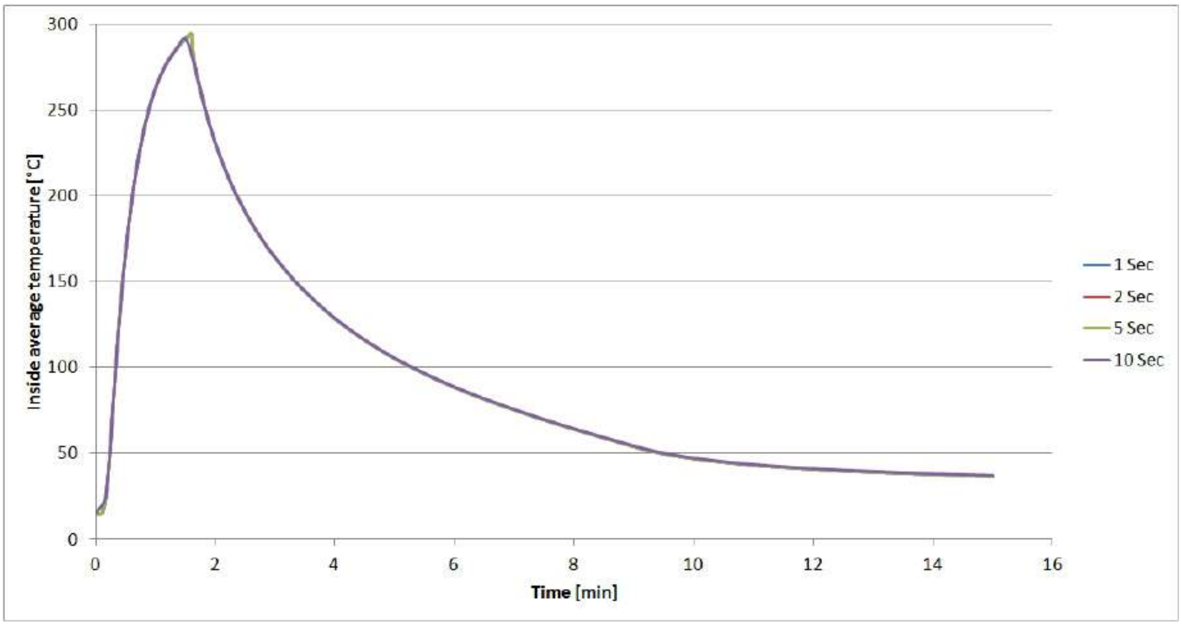

Figure 4.4: A sensitivity analysis on the temperature profile.

Finally, the figure below shows a sensitivity analysis on the oxygen concentration present in the scale model.

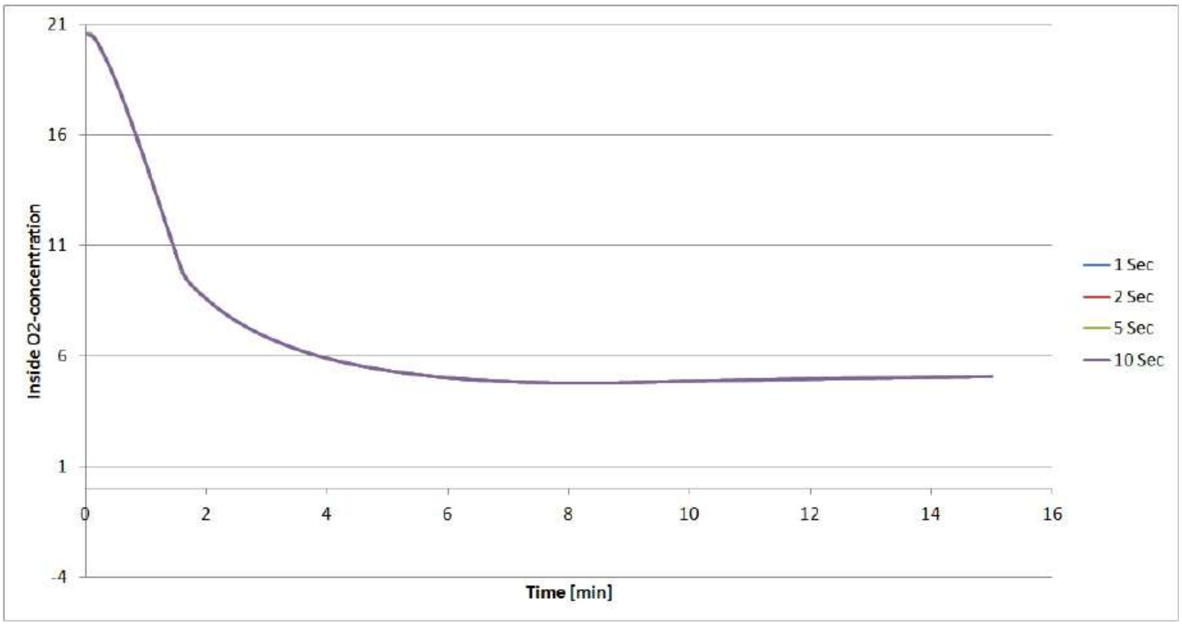

Figure 4.5: A sensitivity analysis on the oxygen concentration present.

We can see that the model is not very sensitive of the time step. As long as the time step is smaller than 5 seconds, we get decent results.

It is also expected that the size of the opening and the flow coefficient of that opening is going to have a big influence on the pressure rise in the compartment. Therefore, a different sensitivity analysis is done determining how sensitive pressure rise (and thus maximum pressure) is versus leakage area.

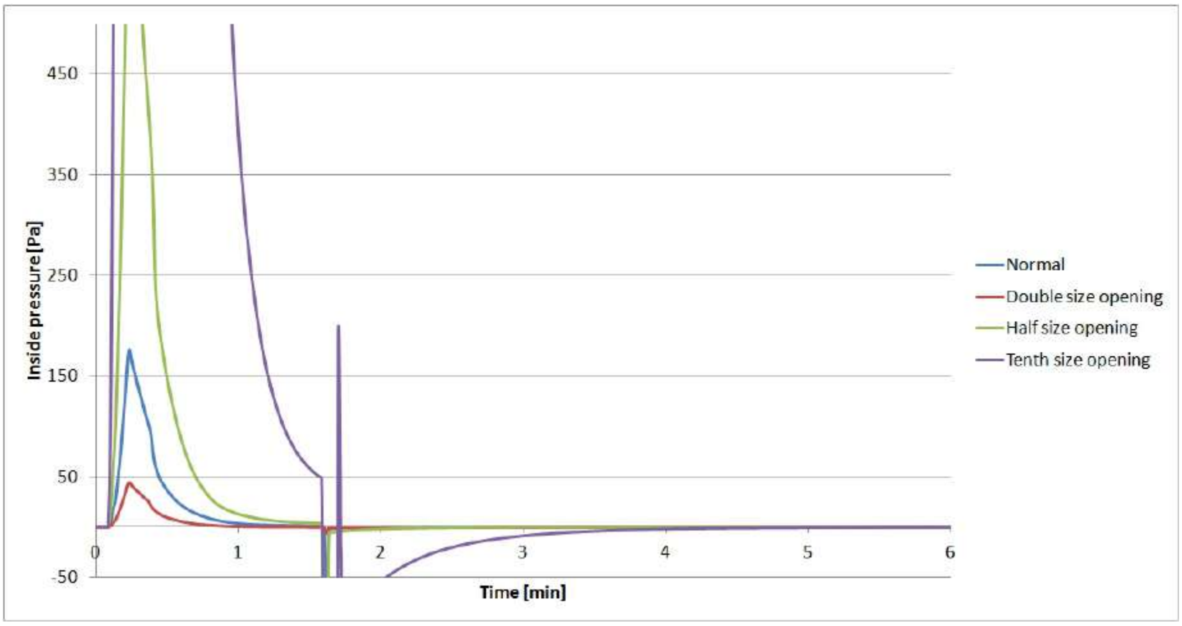

Figure 4.6: A sensitivity analysis on the pressure profile. The variable is here the leakage area.

We use 0,05 as a lower limit for the flow coefficient. In reality, this will probably be higher (as shown in the Belgian norm: for windows, this is significantly larger than 0,05 [23]). We have chosen to model the opening as big as it is in the scale model (see chapter 6). That way, we can compare the outcomes. We see that the inside pressure is indeed very dependent on the right choice of leakage openings.

We however do not expect the temperatures and oxygen concentrations inside to be very dependent on the size of the opening; verification also shows this is indeed not very sensitive. We do see that the oxygen concentration does not drop below 5% and therefore, the lower limit for combustion is here 5%.

4.1.2 OZone

OZone is a code developed in 2001 at the University of Liege, and is a code which is quite known in the present fire safety engineering community. It was extensively verified when it was developed. The latest version is version 2.

OZone V2 is a code which includes a two zones and a one zone models with a possible switch

from two to one zone if some criteria are encountered. It thus deals with localised and fully engulfed fires. OZone V2 is an improvement of OZone V1 which was a one zone model developed in the NFSC1 research.
In OZone several improvements on existing zone models have been made. The wall model is made by the finite element method and is implicit. And finally different combustion models have been developed to cover different situations of use of the code [24]. Version 2.2 is used. The graphic user interface makes it easy and straightforward to work with the code. This also brings a problem with it, the user should know the submodels and how they work, because it is important to stay in the validity zone of the submodels. The easier a software is, the less knowledge it requires about the submodeling, and this might end up in wrong results.

Now that we have an initial idea what OZone is, we can enter the inputs needed to start a calculation. We define a box, 1m on 1m on 1m, according to the scaled model in chapter 6. We can model the ventilation in it; but we'll model the ventilation just as it is modeled in the experimental model. This means we put in a net ventilation input which is not dependent on the pressure inside the compartment. Some screenshots below show the input for the model:

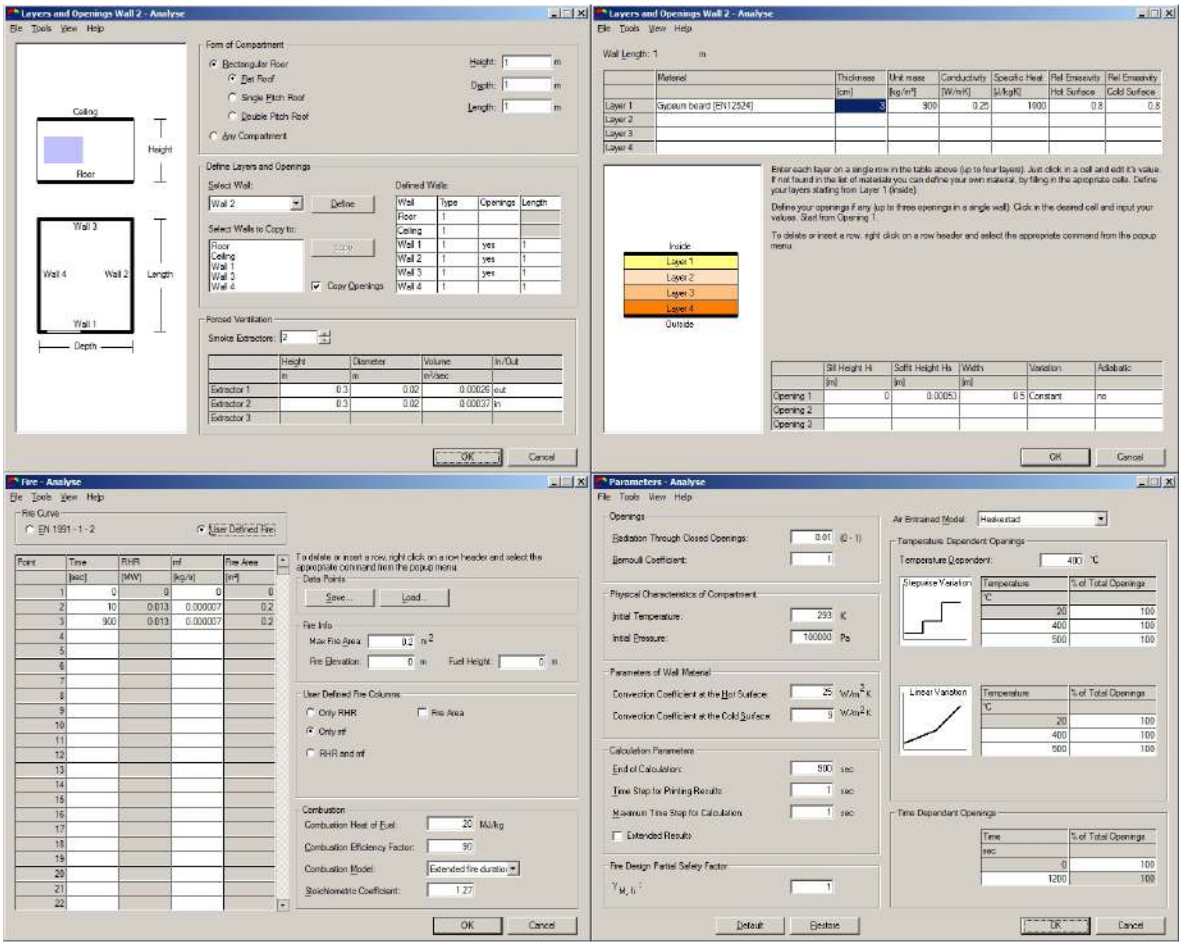

Figure 4.7: The modeled inside of the low-energy house.

We see that the strategy uses a combination of a two-zone and a one-zone model. The expectation is that the one-zone model will quickly be used, since the smoke layer descends very fast (according to CFAST).

Results

Results can be consulted by using the spreadsheets generated by OZone. OZone has conducted its calculations implicitly. This means that there is no set time step as in CFAST. A sensitivity analysis on the time step is therefore not really possible.

The results are shown (figure 4.8) below.

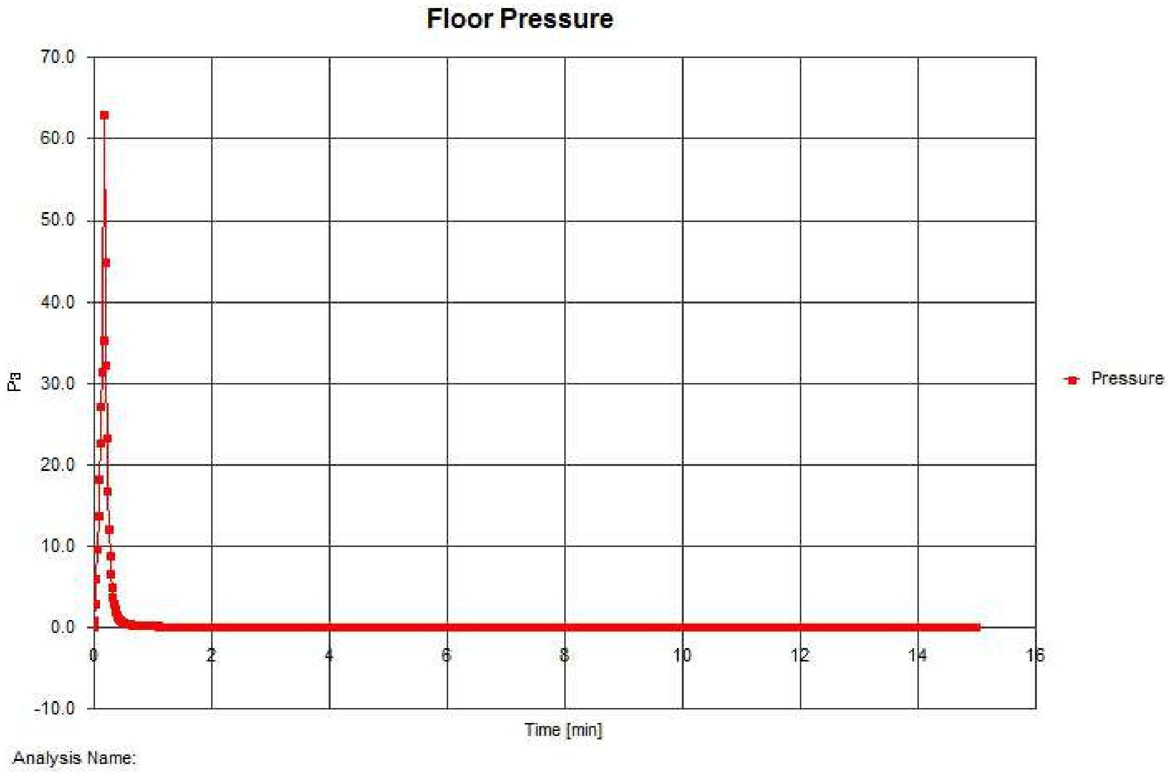

Figure 4.8: The pressure profile.

As for the average temperatures, figure 4.9.

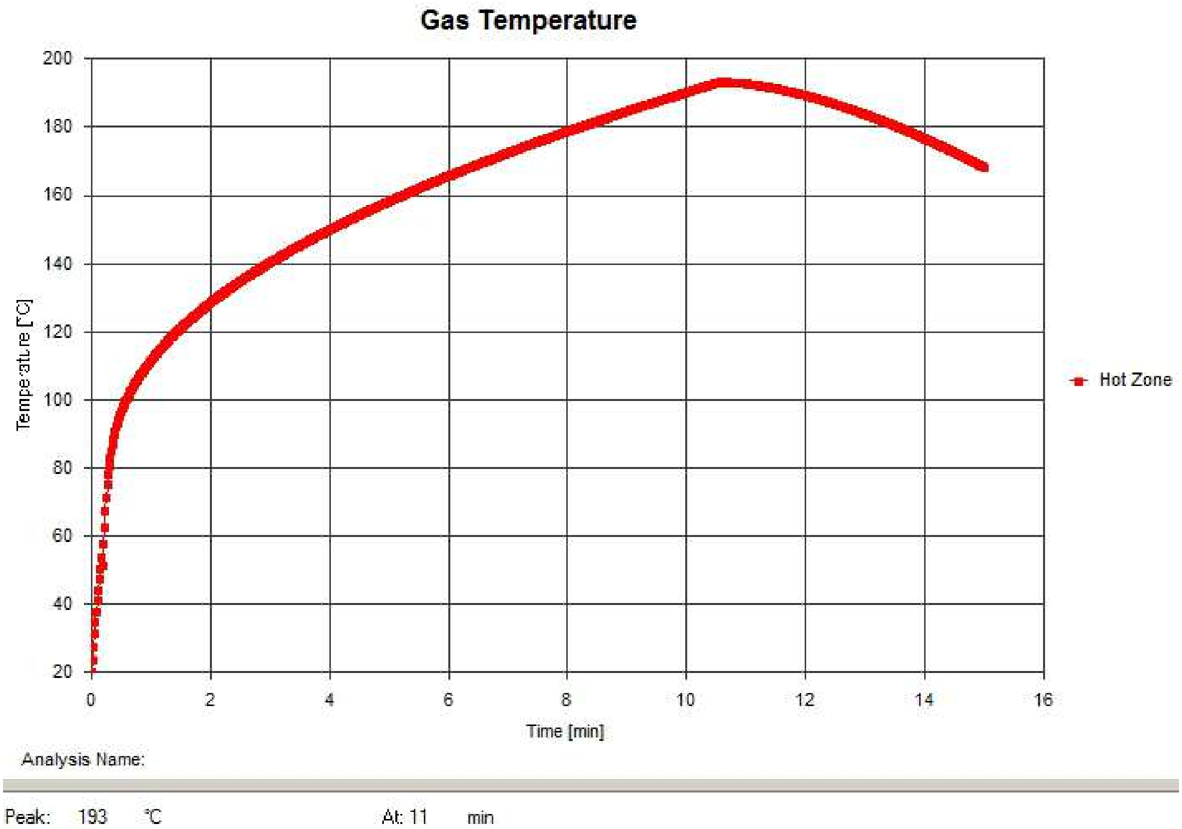

Figure 4.9: The temperature profile.

We can indeed remark that the results are alltogether different than expected. Apparently, the use of a different submodel for combustion did not help. This is shown in the graph below.

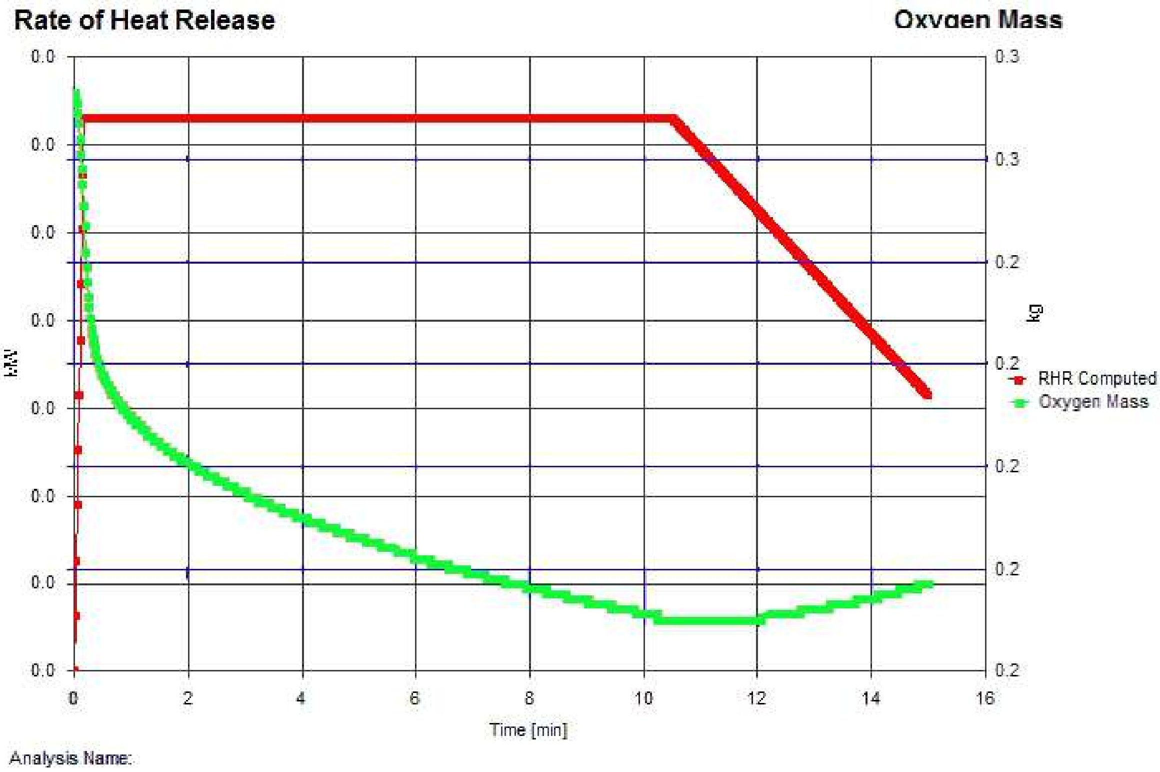

Figure 4.10: The submodel does not respond fast enough to the changes in oxygen.

So, however the concentration of oxygen drops, the HRR stays on a more or less constant level. It is clear that in reality, the combustion efficiency would drop significantly.

The conclusion is that OZone is not capable to model the behaviour we expect in a low-energy house. But we also have to keep in mind that OZone was not developed with this particular application in mind, so this result is not very surprising.

4.2 Approach with CFD

CFD does not have the disadvantage that two-zone models have. CFD is capable of calculating fairly local temperatures, and as such determining whether combustion will take place or not. Nonetheless, the fairly simple combustion model of FDS does not capture the complex chemical physics happening during combustion. The problem is that this would be computationally costly, it would seriously increase the amount of cells needed in the fire, and the amount of species per cell, thus also increasing the amount of equations.

4.2.1 FDS

Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) model of fire-driven fluid flow. FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. Smokeview is then a separate visualization program that is used to display the results of an FDS simulation. The results can however also be shown on point locations, only requiring the use of spreadsheet software. This will be the main way of showing the results here.

The first version of FDS was publicly released in February 2000. To date, about half of the applications of the model have been for design of smoke handling systems and sprinkler/detector activation studies. The other half consist of residential and industrial fire reconstructions. Throughout its development, FDS has been aimed at solving practical fire problems in fire protection engineering, while at the same time providing a tool to study fundamental fire dynamics and combustion [25].

Hydrodynamic Model

FDS solves numerically a form of the Navier-Stokes equations appropriate for lowspeed, thermally-driven flow with an emphasis on smoke and heat transport from fires. The core algorithm is an explicit predictor-corrector scheme, second order accurate in space and time. Turbulence is treated by means of the Smagorinsky form of Large Eddy Simulation (LES). It is possible to perform a Direct Numerical Simulation (DNS) if the underlying numerical mesh is fine enough. LES is the default mode of operation.

Combustion Model

For most applications, FDS uses a single step chemical reaction whose products are tracked via a two-parameter mixture fraction model. The mixture fraction is a conserved scalar quantity that represents the mass fraction of one or more components of the gas at a given point in the flow field. By default, two components of the mixture fraction are explicitly computed. The first is the mass fraction of unburned fuel and the second is the mass fraction of burned fuel (i.e. the mass of the combustion products that originated as fuel).

Geometry

FDS approximates the governing equations on a rectilinear mesh. Rectangular obstructions are forced to conform with the underlying mesh.

Boundary Conditions

All solid surfaces are assigned thermal boundary conditions, plus information about the burning behavior of the material. Heat and mass transfer to and from solid surfaces is usually handled with empirical correlations, although it is possible to compute directly the heat and mass transfer when performing a Direct Numerical Simulation (DNS).
Version 5 has been used here.

The input file used for the calculations is shown in the appendix (appendix 7).

Results

As already mentioned, the results can be shown through a graphical representation using SMOKEVIEW. However, these results don't really show detailed values and since we want to know the temperatures, pressure increase and oxygen concentration as a function of time, using spreadsheets is a better way of showing the results.
Grid dependency is an important matter in CFD, and therefore, we need to check if the result is grid independent enough. This is why several calculations must be done. However, practical reasons limit us to 2 calculations:

- For the sake of continuity of the mesh and therefore continuity of the result, it is better to work with one mesh if possible.
- Since the leakage openings are only a few cm^2, we don't really have an option to choose a larger grid size.

Because of these two reasons, we have chosen to use only 2 different grid sizes. We see that there is a very slight difference between the two, meaning that the result is grid independent enough.

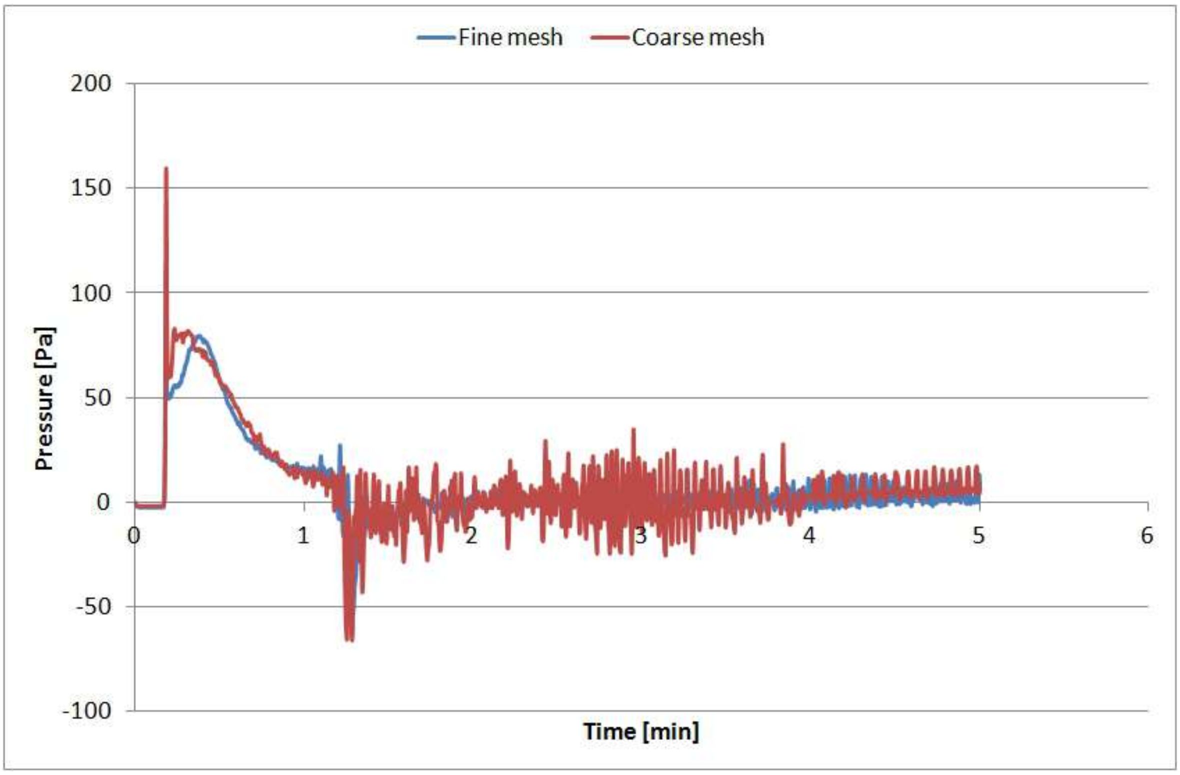

Figure 4.11: The pressure inside for 2 different grids.

We see that both the fine mesh and the coarse mesh have a peak at ignition of the fire of about 150Pa. After this first initial peak, both pressures drop rapidly to lower values, to rise a bit again and eventually even out completely. We also see that the result is fluctuating a lot. It is very hard to establish whether this has to do with numerical instabilities or whether this is something physical - a comparison with the results of the experiments should to give us an answer.

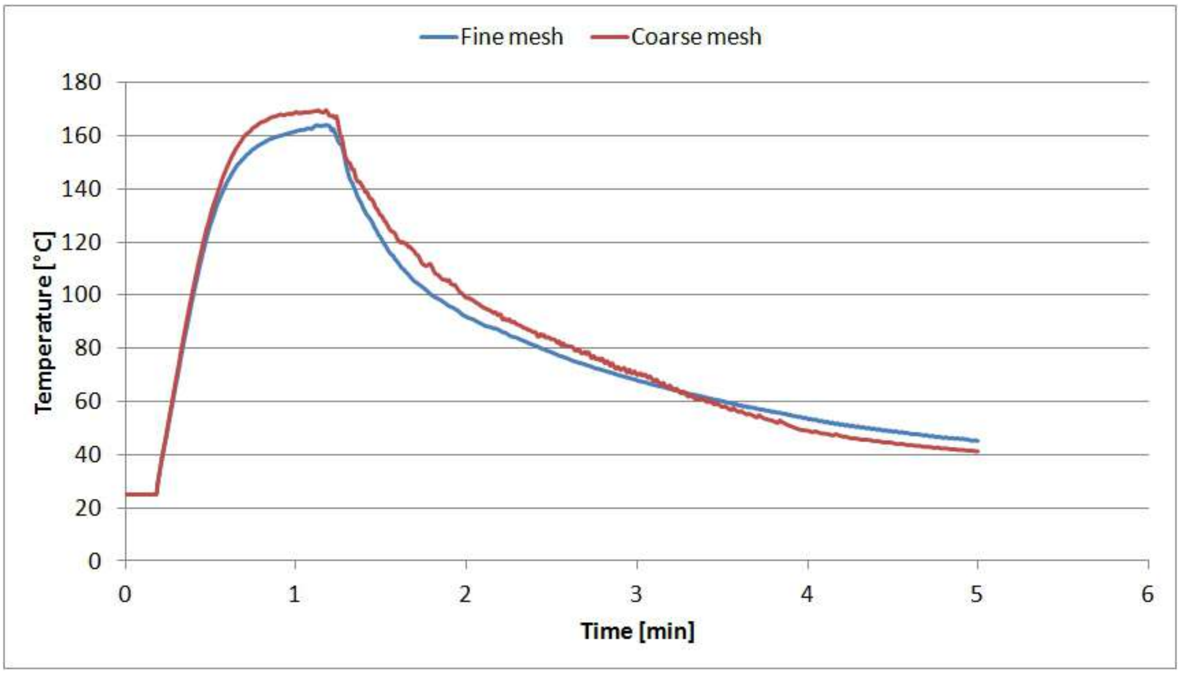

Figure 4.12: The average temperatures inside for 2 different grids.

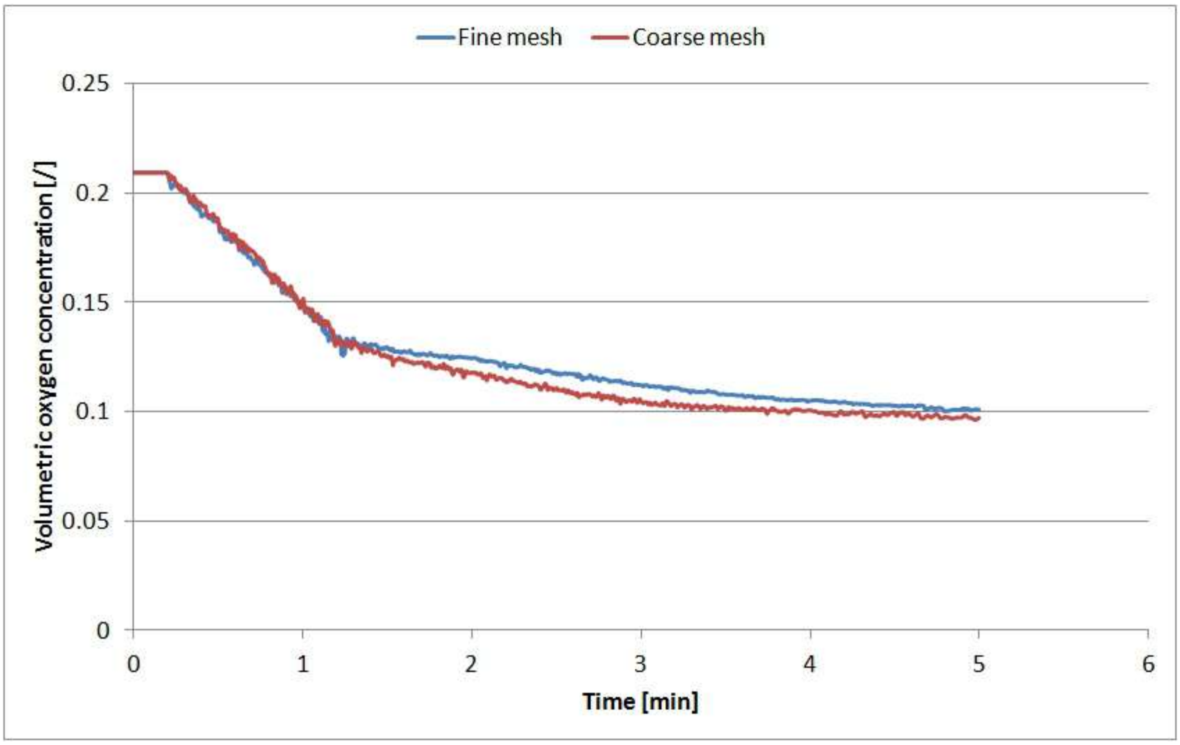

Figure 4.13: The oxygen concentration for 2 different grids.

All in all, we can conclude from these results that the chosen mesh, whether it is the coarse one or the fine one, yields very similar results.

4.3 Conclusions

We can conclude that we see in all of the used software packages a similar behaviour of the pressure and of the temperatures and the oxygen concentration. Also, the order of magnitude is similar for all of them.

A big problem for all packages is that they apparently can't model an extinguishment of the fire. Once the oxygen concentration hits the lower value, the combustion stops - momentarily. We do however expect that the experiments will show that when the fire is extinguished, it won't ignite again.

In the two-zone models CFAST and OZone, we noticed that the two-zone assumption is not valid for a long time. It might therefore be better to model it immediately as a one-zone fire, but only OZone gives this possibility explicitly. In the next chapter, I will try to provide an additional one-zone model which will - hopefully - turn out to be a helpful tool to get an idea of expected pressures in similar buildings. I will focus on using understandable, basic submodels and software everyone can use.

Chapter 5

Generation of a one-zone computational model

In this chapter, the setup has been to establish the foundations of a one-zone model. The goal that was set is to build up, from basic principles of fire science, a working one-zone model to model what would happen in the low-energy building shell. The used submodels should also be quite easy to understand, since the intention is to make a useful tool for not just engineers, but everyone possibly gaining on the information of the modeling.

This necessity has risen due to the fact that the existing software to model what would happen does not account for some of the important and defining features of a fire in a low-energy house. For example, the modeling of an underventilated fire is not always done very precisely. This has different reasons, one of the most important ones is to save computational cost. The submodels used in the other software are very often not developed for use in low oxygen situations.

In essence, it is very hard to grasp what happens with a fire in a low oxygen environment. To really understand the events that take place, we need to look to the smallest scales in the burning process, and further examine the burning process. Very often, the burning process is looked upon as being a very simple, one step equation in which the defining parameter for the smoke temperature and thus smoke buoyancy and smoke movement is the heat release rate. But, this is not true anymore in a low oxygen situation. Since the low oxygen will lower the efficiency of burning of the fuel, we cannot simply prescribe the heat release rate as one of the parameters as we usually do. No, in this case we need to correctly model the burning process with all the secondary steps, which would be computationally expensive and require a large insight in the chemical side of fire science. On the other hand, we also could work with a submodel, but then we need a fairly simple one designed for low oxygen conditions. It also could limit the use of this one-zone model to low oxygen conditions. Here, the second approach will be used.

5.1 Assumptions

There are some key assumptions we have to make to be able to make a good choice as for submodels and other decisions. This will also define the applicability to its utmost boundaries: the application area will probably be smaller than the limitations set by the assumptions, but this will have to show through a validation. The goal here is however not to establish a big piece of software, just a simple tool to get an idea for pressures and (mean) temperatures.

The key assumptions that we already can make, are:

- We assume the initial time, the time period which is of interest to us, as 15 minutes. This is typically an above limit for firefighter intervention [21] in the Benelux.
- We assume the windows not to break in the given time period. This also assumes that temperatures inside will not be too high for too long. This assumption is mostly based on a couple of studies that test glass strength when a mechanical force is applied [26], [27]. However, these studies do not focus on the temperatures. We do know from construction guides, such as [8], that it is common practice nowadays to put triple glazing in low-energy housing; thus also improving the mechanical strength and resistance to non-uniform heating of the window.
- Air and smoke are assumed to behave as ideal gases.
- We assume the only leakage to the outside to happen when windows and doors are closed, as is the intent of a low-energy house. As such, the only leakage occuring is due to construction gaps, which are inevitable. The low-energy house is however assumed to perfectly comply to the standards as described: in a blower door test, only 0.6 times the volume of the house should leak per hour to the outside when a pressure difference (inside - outside) of 50Pa is imposed [16].
- We assume structural stability for at least the time period considered.
- We assume no explosive behaviour in the fuel. This could otherwise create problems with the amount of oxygen present right next to the fire source, thus creating local conditions which are impossible to grasp in a one-zone model.
- We assume the flow to behave perfectly quadratical in respect to a rising pressure difference (so, we assume the flow to be fast enough at all times).
- We assume in first instance here that the ventilation system delivers a set volume of air. We do not look at the influence of back flow through ventilation. In essence, it is a quite easy adaptation to make if we want to take this influence in account.
- We assume the fire to be large enough to make the hot and cold gas layers mix, or at least a fire large enough to make the hot smoke layer quickly descend down.

5.2 Conservation of mass

A one-zone model has been built to calculate a pressure increase through an input of fresh air in a leaky although quite airtight volume. Combustion and its effects (temperature increase, heat loss through walls and air leaks, pressure increase,...) will not be looked at in first instance. The reigning equations will be looked at now.

We know the volume which is under view. We assume that the air and the smoke inside will behave as an ideal gas, a very common assumption. This volume will therefore correspond to the ideal gas law:

$$pV = m\Re T \tag{5.1}$$

Therefore, it is also valid that:

$$\frac{\mathrm{d}pV}{\mathrm{d}t} = \frac{\mathrm{d}m\Re T}{\mathrm{d}t}$$
$$\text{and } p\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{\mathrm{d}m}{\mathrm{d}t}\Re T$$

assuming that the pressure and the temperature changes are slower than the mass and volume changes. This is true for the inflowing air (ambient conditions). We could also point out that:

$$\frac{m}{V} = \frac{p}{\Re T} = \rho \tag{5.2}$$

which is the density of the incoming air, and indeed, we can assume that this is constant.

With the ideal gas law at hand, we can model the inside of the low-energy house as a control volume as shown in figure 5.1

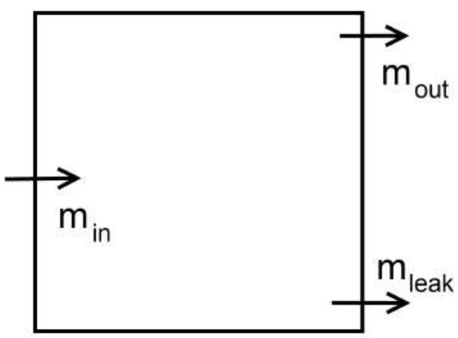

Figure 5.1: The modeled inside of the low-energy house.

It follows then from the conservation of mass (of air) that:

$$\dot{m}_{change} = \dot{m}_{in} - \dot{m}_{out} - \dot{m}_{leak} \tag{5.3}$$

where we choose the sign of $\dot{m}_{in}$, $\dot{m}_{out}$ and $\dot{m}_{leak}$ as being positive if the flux is in the direction of the arrows. So, in for $\dot{m}_{in}$, out for $\dot{m}_{out}$ and out for $\dot{m}_{leak}$.

The problem is that usually we do not know how much mass of air is supplied to the low-energy house. Ventilation systems usually work with a volumetric flow rate, which makes the flow of air in or out of the house dependent on the temperature inside and outside. The temperatures is one of our assumptions necessary in the model. If we have the temperatures, we can just use the ideal gas law.
A second problem is that the amount of leakage in the model is never clearly defined. We know how much leak is allowed in low-energy housing for a set pressure, but since we expect a non-constant pressure due to the temperature changes inside, the leak also changes. We can however model the leak through the allowed construction gaps.

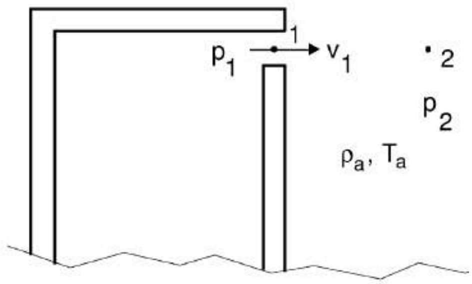

Figure 5.2: A sketch as an example to use Bernoulli's principle on.

In this figure, we can say that $p_2 = p_{atm}$, $v_1 = v$ and $v_2 = 0$ and that p_1 equals the inside pressure of the model.

We know that in figure 5.2:

$$\frac{p_2}{\rho_2} - \frac{p_1}{\rho_1} = \frac{v^2}{2} \tag{5.4}$$

This follows directly from Bernoulli's principle.
So:

$$v = \sqrt{2\left(\frac{p_2}{\rho_2} - \frac{p_1}{\rho_1}\right)} \tag{5.5}$$

We also know:

$$\dot{m} = C_f \rho A v \tag{5.6}$$

In which C_f is the flow coefficient, determining the aerodynamic efficiency with which the flow moves through an opening. This is dependent on the geometrical factors impeding exit velocities. In this case, this factor is very difficult to estimate, since we can't really investigate

the leak through the building in detail.
If we combine equations 5.5 and 5.6, we end up with:

$$\dot{m}_{leak} = C_f \rho A \sqrt{2\left(\frac{p_2}{\rho_2} - \frac{p_1}{\rho_1}\right)} \tag{5.7}$$

5.3 Conservation of momentum

In this approach, we do not look at the conservation of momentum: we just assume that all the mass enters and leaves in one moment in or out of the low-energy building, thus eliminating the problem of conservation of momentum. This is a very common approach.

Usually, one would use submodels in a two-zone model to model the behaviour of the plume or the smoke layer (the decending smoke layer); but in this case, I assume that the hot gas layer and the cold gas layer are immediately united. Both of these form one zone with an average temperature, thus eliminating the submodels needed. This is only valid for fires large enough to make the upper and lower layer mix.

5.4 Conservation of energy

Figure 5.3 gives a model of how the conservation of energy works:

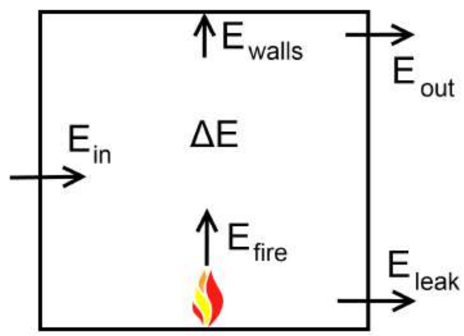

Figure 5.3: The conservation of energy in the model.

The energies E_{in}, E_{out} and E_{leak} are due to the energy comprised in the air entering and leaving the model. We know the following formula is applicable:

$$\dot{m} c_p \Delta T \Delta t = E = \dot{Q} \Delta t \tag{5.8}$$

with c_p being the specific heat of air. We could also say:

$$\dot{m} c_p (T - T_{ref}) = \dot{Q} \tag{5.9}$$

and we can choose the reference temperature T_{ref}. To make things easier, we choose $T_{ref} = T_{ambient}$, the ambient temperature. This makes $E_{in} = 0$.
The second phenomenon is heat transfer to the walls through E_{walls}. We know that the walls will behave thermally thick, because of the calculation method given in [4]. The derivation of equation 6.14 in this book would lead us too far from the goal we try to obtain here, so the equation shall be quoted as such:
The thermal penetration time is defined as

$$t_p = \frac{\delta^2}{4\alpha} \tag{5.10}$$

and indicates the time at which 15% of the temperature increase on the fire-exposed side has reached the outer side of the solid. Here α is the thermal diffusivity, also given by the relation $\alpha = k/\rho c_p$, and given in $[m^2/s]$. Some typical values are given here.

Typical Values of Thermal Properties for Some Common Materials

Material	*k* (W/m·K)	c (J/kg·K)	ρ (kg/m³)	*k*ρc (W²s/m⁴K²)	α (m²/s)
Aluminium	218	890	2700	$5.2 \cdot 10^{8}$	$9.1 \cdot 10^{-5}$
Copper	395	385	8920	$1.4 \cdot 10^{9}$	$1.2 \cdot 10^{-4}$
Steel (mild)	45	460	7820	$1.6 \cdot 10^{8}$	$1.3 \cdot 10^{-5}$
Brick (common)	0.69	840	1600	$9.3 \cdot 10^{5}$	$5.2 \cdot 10^{-7}$
Concrete	0.8–1.4	880	1900–2300	$2 \cdot 10^{6}$	$5.7 \cdot 10^{-7}$
Lightweight concrete	0.15	1000	500	$7.5 \cdot 10^{4}$	$3.0 \cdot 10^{-7}$
Glass (plate)	0.8	840	2600	$1.8 \cdot 10^{6}$	$3.7 \cdot 10^{-7}$
Cork plates	0.08	1000	500	$4.0 \cdot 10^{4}$	$1.6 \cdot 10^{-7}$
Fiber insulating board	0.041	2090	229	$2.0 \cdot 10^{4}$	$8.6 \cdot 10^{-8}$
Gypsum plaster	0.48	840	1440	$5.8 \cdot 10^{5}$	$4.1 \cdot 10^{-7}$
Mineral wool, plates	0.041	800	100	$3.3 \cdot 10^{3}$	$5.1 \cdot 10^{-7}$

Figure 5.4: Some typical material values [4].

For a typical finishing material as gypsum board (labelled as the brand name gyproc in the Benelux), with a thickness of 1,5 cm, which has an α-value of 4.1 10^{-7} $\frac{m^2}{s}$, the thermal penetration time is 140 seconds. This is less than the 15 minutes, but we should keep in mind that there is still a big amount of insulation behind that finishing material, which defines the behaviour of the low-energy house: a typical low-energy house is finished with typically 20 cm of insulation material. If we assume this material to be plates of mineral wool, we get a thermal penetration time of that material of 5,4 hours. This is clearly longer than the 15 minutes we're interested in. So, the shell of the house works as a wrapped around cooling plate.

Therefore, the total heat transfer coefficient for this case is:

$$h = \sqrt{\frac{k\rho c_p}{\pi t}} \tag{5.11}$$

in which k, ρ, c_p are the conductivity, density, and specific heat of the compartment surface material, respectively.

E_{fire} is arguably the most difficult parameter to determine. We can calculate with a few easy models how much a pool fire would produce in open conditions, and we can quite easily define a growing HRR curve in conditions with plenty of oxygen. However, as already mentioned before [25], the low-oxygen conditions make it very hard to be able to accurately model incomplete combustion in an easy submodel.

Based on the approach FDS 5.3 uses [28], I have developed my own submodel which tries to grasp the incomplete combustion. It is, as said before, very hard to come up with a submodel for incomplete combustion in a complete room, since not only does this depend on the individual concentrations of oxygen in places in the room, it also depends on the individual temperatures of oxygen in places in the room:

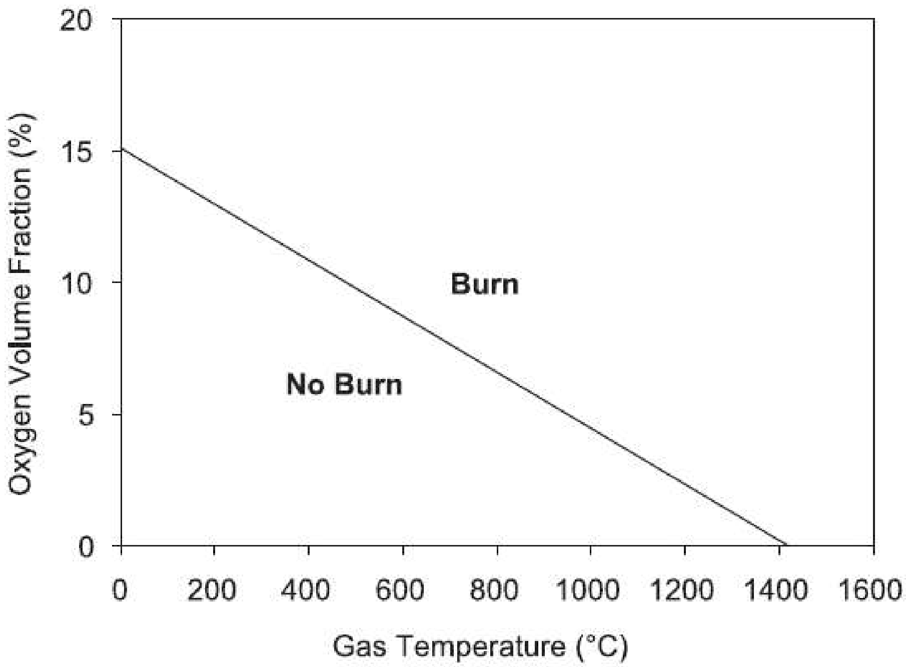

Figure 5.5: The approach FDS uses: clearly temperature dependent.

In my own submodel, I have assumed that the efficiency of the combustion goes hand in hand with only the oxygen concentration, since it is impossible to focus on individual spot temperatures: I only calculate the average temperature in the room.
However, to respect the fact that temperature indeed changes the behaviour, I have worked with a linear regression of efficiency of combustion with respect to oxygen concentration. The efficiency becomes 0 at 11 vol% of oxygen in the air, and is 1 at 23 vol% in the air. However,

using this kind of approach, we can never model a fire that would go out because of a lack of oxygen. The fire would rather shrink in size due to a lower efficiency, and therefore require less oxygen. This little amount of oxygen is able to be delivered by the leakage of the house. We can however determine that there is a boundary efficiency, under which the fire does not ignite again. This can take in account when the fire would die out in the experiment. I call this the cut-off linear regression efficiency approach.

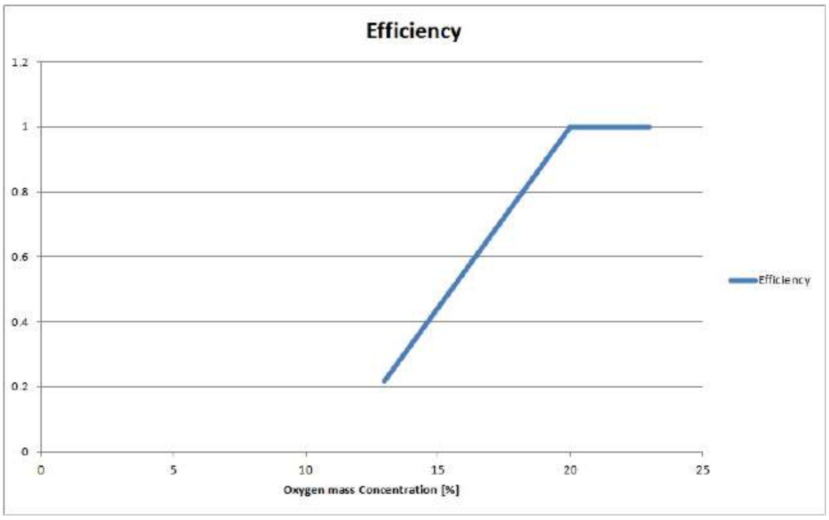

Figure 5.6: The linear regression efficiency approach.

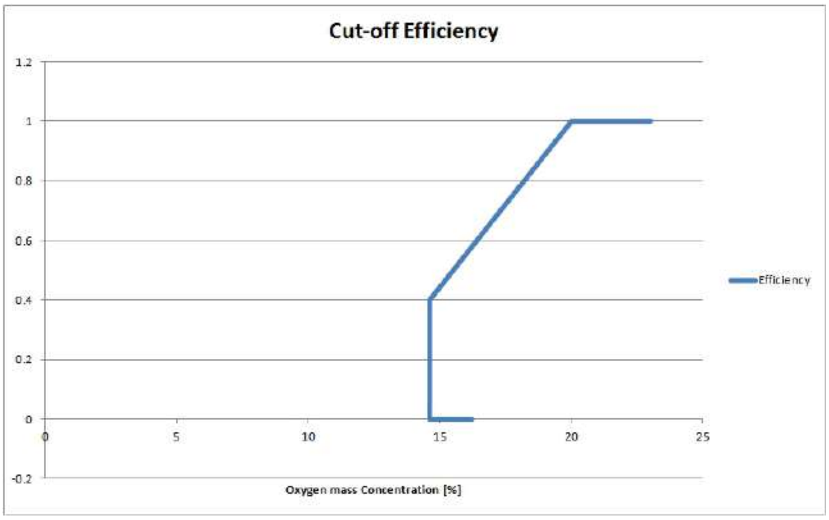

Figure 5.7: The cut-off linear regression efficiency approach.

This simple submodel seems to capture the behaviour of fire quite well, as will be shown in the results of the experiments.

All in all, low oxygen combustion models is a field that would deserve a lot of extra research.

This all now leads to a $\Delta E = E_{fire} - E_{leak} - E_{out} - E_{walls}$, which heats up the gases according to:

$$m_{inside} c_p \Delta T = \Delta E \tag{5.12}$$

5.5 Some screenshots

Some screenshots are presented showing the input needed in the file and the output calculation rows.

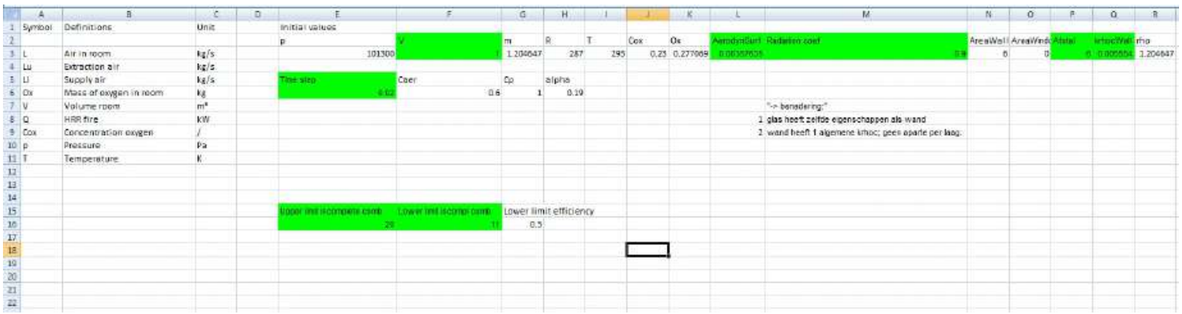

Figure 5.8: A screenshot of the input needed for the one-zone model.

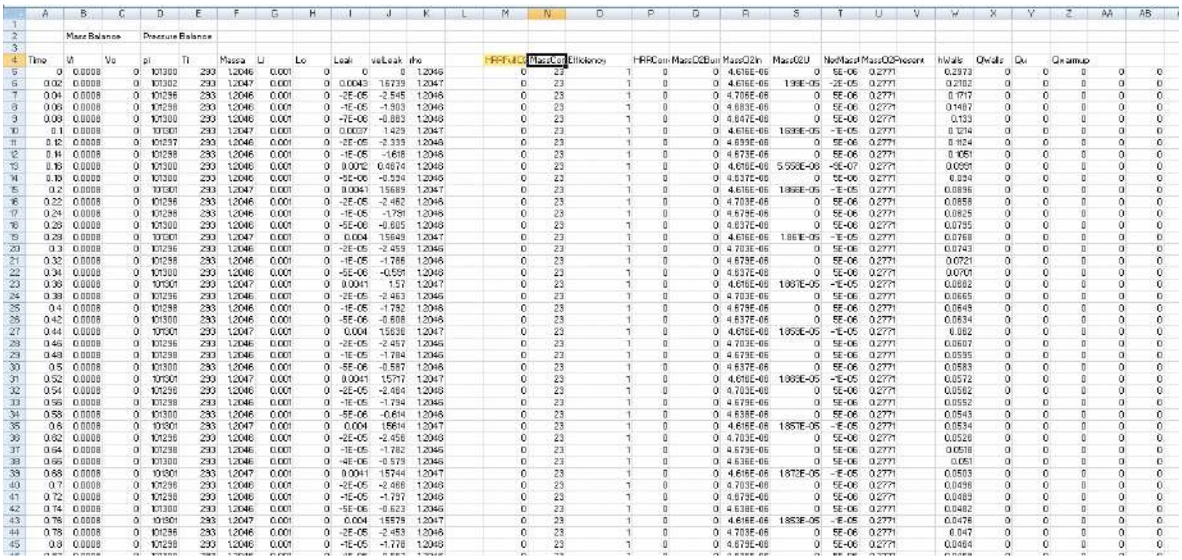

Figure 5.9: A screenshot of the output generated by the one-zone model.

Results of this one-zone model will be compared with the experimental results further on.

Chapter 6

The experimental approach.

In this section, we will focus on an experimental setup and extract actual measured data from this experiment. This data will be examined and checked versus the data we had from the computational models.

We have opted for a scaled model of the E-Cube, and this for two clear reasons:

- The cost of building and then destructively testing on a full scale low energy house is just too high.
- The possibilities of measuring equipment in the testing facility only allows testing of smaller scale objects.

We have opted to use a scale model of $1m^3$, or in other words, a cubic box of 1m on 1m on 1m. Inevitably, rescaling an experimental setup holds consequences for the parameters in view.

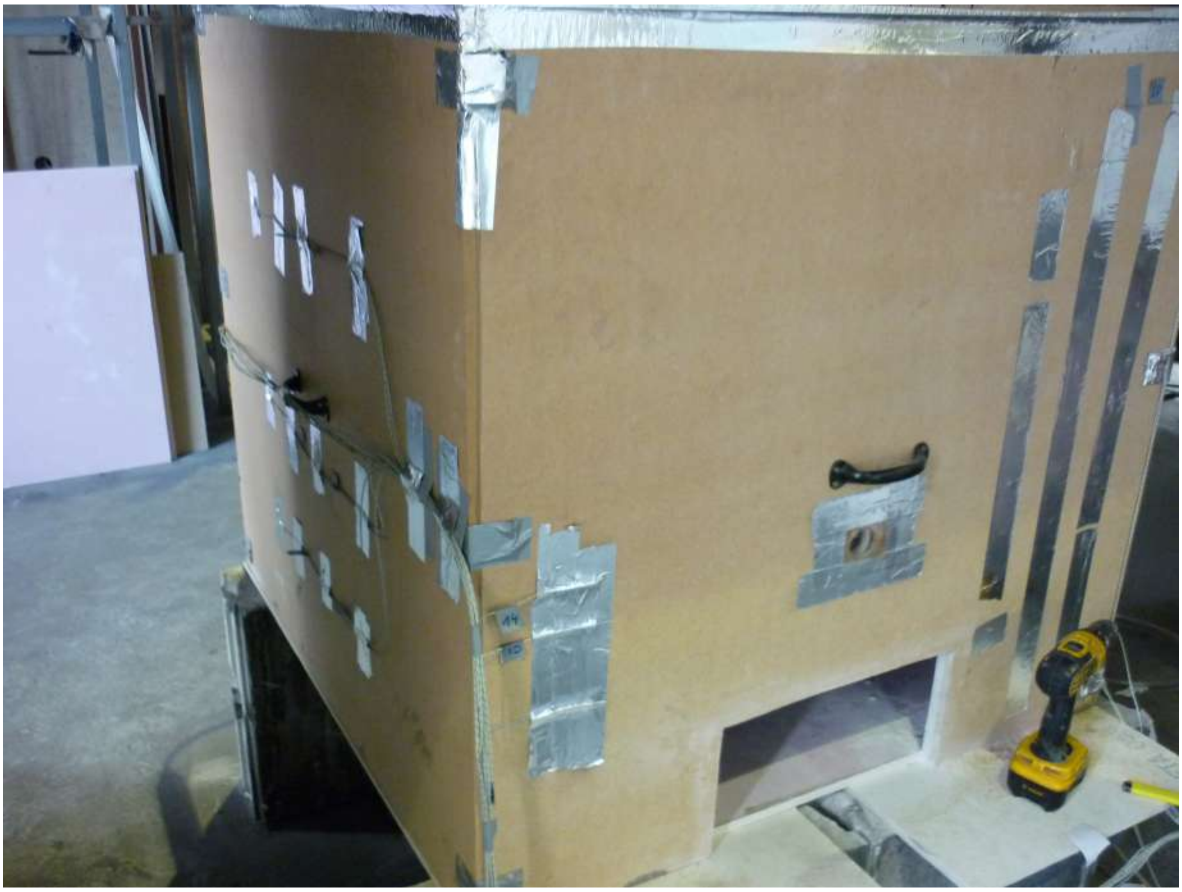

Figure 6.1: A picture of the test setup, seen from the outside.

6.1 Theory

First of all, it is interesting to start off discussing the theoretical part of rescaling this particular experiment. This section will show that we will have to make some approximations, due to partial scaling in some instances.

6.1.1 General rescaling theory [6]

Scaling has always been a very important tool for scientists and researchers, even today. While the basic equations of fluid dynamics have been established for nearly 200 years, they still cannot be solved completely on the largest of computers. Therefore, scaled experiments have a big role in fluid dynamics research and will always be an important branch of research. As there has already been a lot of research on and application of scaling, this is a relatively well developed science.

Scaling happens through the preservation of dimensionless groups, assuring that the parameters of interest can be applied on any scale by multiplying each one of them with a scaling factor. A typical example of a dimensionless group that everyone involved in fluid dynamics knows is the Reynolds number. Indeed, the Reynolds number (Re number) is a dimensionless ratio of momentum to viscous forces in a flow, or:

$$Re = \frac{\rho u^2 l^2}{\mu (u/l) l^2} = \frac{\rho u l}{\mu} \tag{6.1}$$

where Newton's viscosity law has been used (stress = $\mu\times$ velocity gradient) and μ is viscosity, ρ is density, u is velocity and l is a length scale.
There is however a problem with scaling: many phenomena require the preservation of too many dimensionless groups to ensure complete similarity. Fire falls into that category.
However, that does not preclude the use of scale models or dimensionless correlations for fire phenomena to extend the generality to other scales and conditions. This incomplete process is the art of scaling. Partial scaling requires knowledge of the physics for the inclusion and identification of the dominant variables. Many fields use this technique, for example ship design. There the Froude number, $Fr = u^2/gl$, is preserved at the expense of letting the Re be what it will, as long as it is large enough to make the flow turbulent. Indeed, after scaling, we will see that the whole flow within the resized low-energy house will be turbulent, while the flow exiting the box through cracks will be laminar, due to the size of the cracks.

While correlations might be developed from small-scale experiments, they have not necessarily been designed to replicate a larger scale system. Such a process of replication is termed scale modeling. It can prove very powerful for design and accident investigation in fire. Again, the similarity basis will be incomplete, since all the relevant dimensionless groups cannot be preserved. Since this is one of the first experiments on a low-energy house and no large scale tests have been done before, there is not a lot of information on the applicability of scaled fire tests on low-energy houses. However, more general applicability of scaled fire tests has been discussed by (amongst others) Tilley [29], Heskestad [30], Thomas [31] and more.

The first step is to determine the important dimensionless groups in our case. These can be determined in 3 ways:

- The Buckingham pi method
- The partial differential equation method
- Dimensional analysis

Describing all three of these methods would lead us too far in the discussion on scaling. Interested readers are referred to Quintieres Fundamentals of Fire Phenomena [6].
The dimensionless groups that are of importance to fire phenomena will be derived from the third approach using dimensional forms of the conservation equations. The density will be

taken as constant, ρ_∞ without any loss in generality, except for the buoyancy term. Also, only the vertical momentum equation will be explicitly examined. Normalizing parameters for the variables will be designated as $()^*$. In some cases, the normalizing factors will not be the physical counterpart for the variable, e.g. x/l, where l is a geometric length. The pi groups will be derived and the dimensionless variables will be preserved, e.g. $\hat{u} = u/u^*$ and $\hat{x} = x/l^*$. After deriving the pi groups $\{\Pi_i\}$, we will then examine their use in correlations, and how to employ them in scale modeling applications. Common use of symbols will be made and therefore they will not always be defined here.

6.1.2 Conservation of mass

From figure 6.2 the mass flow rate can be derived as:

$$\dot{m} = \rho u A \tag{6.2}$$

The area will be represented in terms of the scale length of $A \propto l^2$ and similarly l^3 for volume.

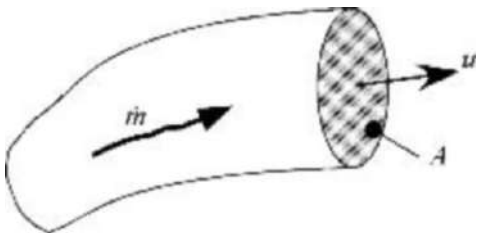

Figure 6.2: Mass flow rate. Taken from [6].

6.1.3 Conservation of momentum

Consider a form of the vertical momentum equation (Equation (3.24)) with a buoyancy term and the pressure as its departure from hydrostatics. In functional form,

$$\rho V \frac{\mathrm{d}u}{\mathrm{d}t} + \dot{m}u \propto (\rho_\infty - \rho) g V + pA + \tau S \tag{6.3}$$

as demonstrated in figure 6.3.

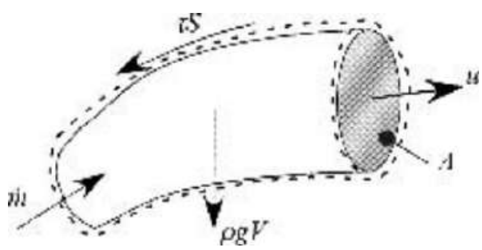

Figure 6.3: Momentum equation. Taken from [6].

The relationship between the terms in equation 6.3 can be used to establish normalizing parameters. For example, under nonforced flow conditions there is no obvious velocity scale factor (e.g. u_∞). However, one can be determined that is appropriate in natural convection conditions. Let us examine how this is done.
Relate the momentum flux term to the buoyancy force:

$$\rho u^2 l^2 \propto (\rho_\infty - \rho) g l^3 \tag{6.4}$$

By the perfect gas law (under constant pressure)

$$\frac{\rho_\infty - \rho}{\rho} = \frac{T - T_\infty}{T_\infty} \tag{6.5}$$

Hence, it follows that

$$u \propto \sqrt{\left(\frac{T - T_\infty}{T_\infty}\right) g l} \propto \sqrt{gl} \tag{6.6}$$

And therefore an appropriate normalizing factor for velocity is

$$u^* = \sqrt{gl} \tag{6.7}$$

This need not be the only choice, but it is very proper for natural convection and represents an ideal maximum velocity due to buoyancy.
Similarly, by equating the unsteady momentum term with buoyancy gives a timescale

$$t^* \propto \frac{u^*}{g} \propto \sqrt{\frac{l}{g}} \tag{6.8}$$

The pressure and stress can be normalized as

$$\tau^* \propto p^* \propto \rho_\infty g l \tag{6.9}$$

Using Newton's viscosity law,

$$\tau^* \propto \mu \frac{\partial u}{\partial x} \propto \mu \frac{u^*}{l} \tag{6.10}$$

and equating the momentum flux and stress terms gives

$$\rho_\infty u^{*2} l^2 \propto \mu \frac{u^*}{l} l^2 \tag{6.11}$$

with the ratio as the Reynolds number:

$$Re = \Pi_1 = \frac{\rho_\infty u^* l}{\mu} \propto \frac{\text{momentum}}{\text{shear force}} \tag{6.12}$$

Alternatively, writing equation 6.11 in terms of the dimensionless velocity, and using the first part of equation 6.6 for u^* gives (an approximate solution)

$$\hat{u} \propto \left[\frac{\mu}{\rho_\infty \left[(T - T_\infty)/T_\infty\right]^{1/2} \sqrt{gl} l}\right]^{1/2} \equiv \left(\frac{1}{Gr}\right)^{1/4} \tag{6.13}$$

Where Gr denotes the Grashof number. The Gr is an alternative to Re for purely natural convection flows.

6.1.4 Energy equation

It is the energy equation that produces many more Π groups through the processes of combustion, heat transfer, evaporation, etc. We will examine these processes. Figure 6.4 is the basis of the physical and chemical processes being considered, again in functional form.

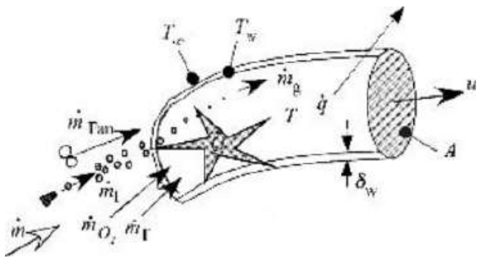

Figure 6.4: Energy equation. Taken from [6]

The mass flows include fuel (F), oxygen (O_2), liquid water (l), evaporated water vapor (g) and forced flows (fan). The chemical energy or firepower is designated as $\dot{Q}$ and all of the heat loss rates by $\dot{q}$. The functional form of the energy equation is

$$\rho c_p V \frac{\mathrm{d}T}{\mathrm{d}t} + \dot{m} c_p (T - T_\infty) \propto \dot{Q} - \dot{q} - \dot{m}_w h_{fg} \tag{6.14}$$

with the last term being the energy rate required for evaporation of water droplets. Recall that the firepower within the control volume is either

$$\dot{Q} = m_F \Delta h_c, \qquad \text{fuel controlled} \tag{6.15}$$

or

$$\dot{Q} = \frac{\dot{m}_{O_2} \Delta h_c}{r}, \qquad \text{ventilation-limited} \tag{6.16}$$

Relating the unsteady energy term (or advected enthalpy rate) with the firepower gives the second Π group commonly referred to as Q^* (or the Zukoski number for Professor Edward Zukoski, who popularized its use in fire):

$$Q_1^* \equiv \Pi_2 = \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g} l^{5/2}} \propto \frac{\text{firepower}}{\text{enthalpy flow rate}} \tag{6.17}$$

where here Q_1^* is based on the length scale l. It should be noted that this group gives rise to an inherent length scale for fire in natural convection:

$$l^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/5} \tag{6.18}$$

This length scale can be associated with flame height and the size of large-scale turbulent eddies in fire plumes. It is a natural length scale for fires.

6.1.5 Heat losses

The heat fluxes to solid boundaries of an enclosure are summarized here for the purpose of producing the relevant Π groups. Consider first the radiant loss rate through a flow surface, A, of a control volume surrounding the enclosure gas phase in Figure 6.4:

$$\dot{q}_o = A\sigma\left[\epsilon(T^4 - T_\infty^4) + (1-\epsilon)(T_w^4 - T_\infty^4)\right] \tag{6.19}$$

where ϵ is the gas emissivity and the walls have been assumed as a blackbody. The gas emissivity may be represented as

$$\epsilon \propto 1 - \mathrm{e}^{-\kappa l} \tag{6.20}$$

with κ being the absorption coefficient, and hence, another Π is

$$\Pi_3 = \kappa l \propto \frac{\text{radiation emitted}}{\text{blackbody radiation}} \tag{6.21}$$

This group is difficult to preserve for smoke and fire in scaling, and can be troublesome.

An alternate empirical radiation loss to the ambient used for unconfined fires produces the dimensionless group,

$$X_r \equiv \Pi_4 = \frac{\dot{q}_o}{\dot{Q}} \tag{6.22}$$

The heat transfer to the walls or other solid surfaces takes a parallel path from the gas phase as radiation and convection to conduction through the wall thickness, δ_w. This wall heat flow rate can be expressed as

$$\dot{q}_w = \dot{q}_k = \dot{q}_r + \dot{q}_c \tag{6.23}$$

The radiation exchange for blackbody walls can be represented as

$$\dot{q}_r \propto \epsilon\sigma(T^4 - T_w^4)S \tag{6.24}$$

and convection as

$$\dot{q}_c \propto h_c S(T - T_w) \tag{6.25}$$

where S is the wall surface area. The heat transfer coefficient, h_c, can be explicitly represented in terms of a specific heat transfer correlation, i.e.

$$h_c \propto \frac{k}{l} Re^n Pr^m \tag{6.26}$$

The conduction loss is

$$\dot{q}_k \propto \frac{k_w S(T_w - T_\infty)}{\delta} \tag{6.27}$$

where $\delta \propto \sqrt{(k/\rho c)_w t}$ for a thermally thick wall, and $\delta = \delta_w$ for one that is thermally thin.

Pi heat transfer groups can now be produced from these relationships. Let us consider these in terms of Q^* 's, i.e. Zukoski numbers for heat transfer. Normalizing with the advection of enthalpy, the conduction group is

$$Q_k^* \equiv \Pi_5 = \frac{k_w T_\infty l^2 / \sqrt{(k/\rho c)_w t^*}}{\rho_\infty c_p T_\infty \sqrt{g} l^{5/2}} \propto \frac{\text{wall conduction}}{\text{enthalpy flow}} \tag{6.28}$$

Substituting for t^* from equation 6.8 gives

$$Q_k^* = \frac{(k\rho c)_w^{1/2}}{\rho_\infty c_p g^{1/4} l^{3/4}} \tag{6.29}$$

Similarly, for convection,

$$Q_c^* \equiv \Pi_6 = \frac{h_c}{\rho_\infty c_p \sqrt{gl}} \propto \frac{\text{convection}}{\text{enthalpy flow}} \tag{6.30}$$

For radiation, we get

$$Q_r^* \equiv \Pi_7 = \frac{\sigma T_\infty^3}{\rho_\infty c_p \sqrt{gl}} \propto \frac{\text{radiation}}{\text{enthalpy flow}} \tag{6.31}$$

In addition, for a wall of finite thickness, δ_w, we must include

$$\Pi_8 = \frac{\delta_w}{\delta} = \left(\frac{\rho c}{k}\right)_w^{1/2} \left(\frac{g}{l}\right)^{1/4} \delta_w \propto \frac{\text{thickness}}{\text{thermal length}} \tag{6.32}$$

It is interesting to estimate the magnitude of these Zukoski numbers for typical wall materials that could be exposed to fire:

Q_c^* and $Q_k^* \propto 10^{-3}$ to 10^{-2}
$Q_r^* \propto 10^{-2}$ to 10^{-1}

Hence, under some circumstances the heat losses could be neglected compared to $Q^* \propto 10^{-1}$ to 1, the combustion term.

6.1.6 Mass flows

There is a counterpart to the energy Zukoski number for mass flows. These Zukoski mass numbers can easily be shown for the phenomena represented in figure 6.4 as

$$m_{Fan}^* \equiv \Pi_9 = \frac{\dot{m}_{Fan}}{\rho_\infty \sqrt{g} l^{5/2}} \propto \frac{\text{fan flow}}{\text{buoyant flow}} \tag{6.33}$$

6.1.7 Heat flux and inconsistencies

In the implementation of scaling or even in the development of empirical correlations, it is almost universally found that radiation heat transfer is not completely included. In addition, the wall boundary thermal properties are rarely included in fire correlations. Let us consider the example of geometric scale modeling in which l is a physical dimension of the system. Then, for geometrically similar systems, we seek to maintain the same temperature at homologous points $(\hat{x}, \hat{y}, \hat{z})$ and time $\hat{t} = t\sqrt{g/l}$. Figure 6.5 shows the model and prototype systems. Let us examine the consequences of the fire heat flux for various choices in scaling. Note by preserving $Q^*(\Pi_2)$, it is required that the model firepower be selected according to

$$\dot{Q}_m = \dot{Q}_p \left(\frac{l_m}{l_p}\right)^{5/2} \tag{6.34}$$

or $\dot{Q} \propto l^{5/2}$. From equation 6.14, if all the heat losses also go as $l^{5/2}$, then $T \propto l^0$, or temperature is invariant with scale size. Let us examine the behavior of the wall or surface heat losses under various scaling schemes to see if this can be accomplished. It will be seen that all forms of heat transfer cannot be simultaneously preserved in scaling.

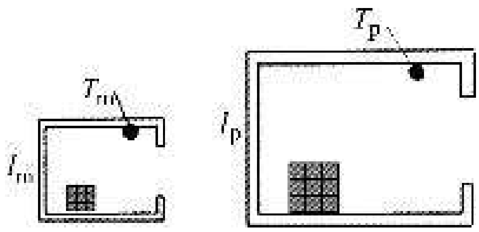

Figure 6.5: Model & prototype. Taken from [6]

For complete scaling in model heat transfer, the following must be preserved:

$$\begin{array}{ll}
\Pi_3 = \kappa l & \text{so, } \kappa \propto l^{-1} \\
\Pi_5 = Q_k^* = \frac{(k\rho c)_w^{1/2}}{\rho_\infty c_p g l^{3/4}} & \text{so, } (k\rho c)_w \propto l^{3/2} \\
\Pi_6 = Q_c^* = \frac{h_c}{\rho_\infty c_p \sqrt{gl}} & \text{so, } h_c \propto l^{1/2} \\
\Pi_7 = Q_r^* = \frac{\sigma T_\infty^3}{\rho_\infty c_p \sqrt{gl}} & \text{so, } T_\infty \propto l^{1/6} \\
\Pi_8 = \frac{(k\rho c)_w^{1/2}}{k_w} \left(\frac{g}{l}\right)^{1/4} \delta_w & \text{so, } \delta_w \propto \left(\frac{k_w l^{1/4}}{(k\rho c)_w^{1/2}}\right)
\end{array}$$

In addition, for turbulent convection it is commonly found that the Nusselt number is important, $Nu \equiv \frac{h_c l}{k}$. Since

$$h_c \propto \frac{k}{l} \left(\frac{\rho_\infty \sqrt{g} l^{3/2}}{\mu}\right)^{4/5} \propto l^{1/5}$$

(for laminar flow we would have, instead, $h_c \propto l^{-1/4}$), we see that inconsistencies emerge: $h_c \propto l^{1/2}$ or $l^{1/5}$ and $T_\infty \propto l^{1/6}$, while it should be $\propto l^0$ as it is difficult to control the ambient temperature.

Several strategies can be employed to maintain partial scaling. This is the meaning of the art of scaling. It requires some insight into the importance of competing effects. Let us first consider maintaining Π_5 and Π_8 constant. This preserves wall conduction effects.
Consequently, recognizing that $k_w \propto \rho_w$, usually for materials, and then assuming $c_w \propto l^0$ (since specific heats for solids do not vary much among materials),

from Π_5: $\quad k_w \propto \rho_w \propto l^{3/4}$

and

from Π_8: $\quad \delta_w \propto l^{1/4}$

Conduction heat flux follows:

$$\dot{q}'' = \frac{k_w}{\delta_w}(T_w - T_\infty) \propto \frac{l^{3/4}}{l^{1/4}} \propto l^{1/2} \tag{6.35}$$

and the wall conduction heat loss rate varies as required, $l^{5/2}$. Let us try to preserve convection. If we ignore Π_6 but maintain the more correct turbulent boundary layer convection (equation 6.26), then

$$\dot{q}'' \propto h_c(T - T_w) \propto l^{1/5} l^0 \propto l^{1/5} \tag{6.36}$$

Finally, consider radiation. Under optically thin conditions ($\Pi_3 = \kappa l \propto$ small),

$$\dot{q}'' \propto \kappa l \sigma T^4 \propto \kappa l \tag{6.37}$$

and for the optically thick case ($\kappa l \propto$ large),

$$\dot{q}'' \propto \epsilon \sigma T^4 \propto 1 - \mathrm{e}^{-\kappa l} \tag{6.38}$$

with equation 6.20. If we could preserve Π_3, then

$$\dot{q}'' \propto l^0, \text{ optically thin} \tag{6.39}$$

and

$$\dot{q}'' \propto l^0, \text{ optically thick} \tag{6.40}$$

This preservation requires that $\kappa \propto l^{-1}$. It could in theory be accomplished by changing the fuel in the model to one that would yield more soot. This may not be done with great accuracy, so it might all in all be better not to try to rescale radiation and leave it out of the scaling analysis. In the particular case of the beginning of a fire, the radiation does not yet play a significant role, so in this thesis, radiation will be left out of the scaling.

Preserving Π_5, Π_6 and Π_8 yields $\dot{q}'' \propto l^{1/2}$, which is inconsistent with the radiation flux (equation 6.39). However, if the same fuel would be used in the model as in the prototype and no change occurs in κ as $\kappa \propto Y_i$, then the radiation flux is

$$\dot{q}'' \propto l, \text{ for } \kappa \text{ small}$$

and

$$\dot{q}'' \propto l^0, \text{ for } \kappa \text{ large}$$

If the fuel is modified such that $\kappa \propto l^{-1/2}$, then the radiant flux for $\kappa \propto$ small becomes consistent with conduction as $\dot{q}'' \propto l^{1/2}$, and the radiation heat loss goes as required, $l^{5/2}$. Alternatively, if radiation is believed to dominate, it might be useful to consider κ large and ignore Π_5 but require that

$$\dot{q}'' \propto \left(\frac{k_w}{\delta_w}\right) T \propto l^0 \tag{6.41}$$

As a consequence of this choice, while still maintaining Π_8 and therefore $\delta_w \propto l^{1/4}$, then $k_w \propto \rho_w \propto l^{1/4}$. Hopefully, this discussion has shown some of the issues related to achieving complete scaling. However, thoughtful partial scaling is still a valid approach for obtaining fairly accurate results for complex geometries. Remember, in scaling, the turbulence and combustion phenomena are inherent in the system, and therefore no empirical models are needed as in CFD approaches. In addition to the above inconsistencies, it is also not possible to preserve the Re number throughout (equation 6.12). However, if the pressure of the system is altered in order to change ρ_∞ between the model and the prototype, Π_1 can be preserved.

Another alternative is to conduct a scale model experiment in a centrifuge in which g is now increased. Modifying both p and g in the model can allow the preservation of more groups. Thus, scaling in fire is not complete, but it is still a powerful tool, and there are many ways to explore it.

Altering the pressure or performing the experiment in a centrifuge would however increase the complexity of the experiment to an unmanageable point. In this experiment, no rescaling of the *Re* number is considered, we just make sure that the flow inside the room is turbulent, whilst the flow exiting the room is laminar. This will be briefly explained later.

6.1.8 Summarizing table

The table below is extracted and summarized from [6]. It contains the way the important parameters for the low-energy house experiment scale.

Variable/group	Dimensionless	Scaling/comment
	Dependent:	
Velocity, u	$\hat{u} = \frac{u}{\sqrt{gl}}$	$u \sim l^{1/2}$
Temperature, T	$\hat{T} = \frac{T}{T_\infty}$	$T \sim l^0$
Pressure, p	$\hat{p} = \frac{p}{\rho_\infty g l}$	$p \sim l$
Concentration, Y_i	$\frac{Y_i}{Y_{i,\infty}}$	$Y_i \sim l^0$
Droplet number, n	$\frac{n}{n_{ref}}$	$n \sim l^{3/2}$
Droplet diameter, D_l	$\frac{D_l}{l}$	$\Pi_{12} \to D_l \sim l^{1/2}$
Burning rate per area, $\dot{m}''_F$	$\frac{\dot{m}''_F l}{\mu}$	$\dot{m}''_F \sim \frac{h_c l}{\mu c_p} = \frac{Nu}{Pr}$
	Independent:	
Coordinates x, y, z	$\frac{x_i}{l}$	$x_i \sim l$
Time, t	$\frac{t}{\sqrt{l/g}}$	$t \sim l^{1/2}$
	Pi groups:	
$\Pi_1\left(\frac{\text{inertia}}{\text{viscous}}\right)$, Re	$Re = \frac{\rho_\infty \sqrt{g} l^{3/2}}{\mu}$	Usually ignored
$\Pi_2\left(\frac{\text{firepower}}{\text{enthalpy rate}}\right)$, Q^*	$\frac{\dot{Q}}{\rho_\infty c_p T \sqrt{g} l^{5/2}}$	Significant in combustion
$\Pi_3\left(\frac{\text{radiant emission}}{\text{ideal emission}}\right)$	κl	$\kappa \sim l^{-1}$, gas radiation important
$\Pi_4\left(\frac{\text{radiant loss}}{\text{firepower}}\right)$, X_r	$X_r = \frac{\dot{q}_r}{\dot{Q}}$	$X_r \sim l^0$, important for free burning
$\Pi_5\left(\frac{\text{conduction}}{\text{enthalpy}}\right)$, Q^*_k	$\frac{(k\rho c)^{1/2}_w}{\rho_\infty c_p g^{1/4} l^{3/4}}$	$k_w \sim \rho_w \sim l^{3/4}$, conduction important
$\Pi_6\left(\frac{\text{convection}}{\text{enthalpy}}\right)$, Q^*_c	$\frac{h_c}{\rho_\infty c_p \sqrt{gl}}$	$h_c \sim l^{1/2}$, convection important
$\Pi_7\left(\frac{\text{radiation}}{\text{enthalpy}}\right)$, Q^*_r	$\frac{\sigma T^3_\infty}{\rho_\infty c_p \sqrt{gl}}$	$T_\infty \sim l^{1/6}$, inconsistent with others
$\Pi_8\left(\frac{\text{thickness}}{\text{thermal length}}\right)$	$\left(\frac{\rho c}{k}\right)^{1/2}_w \left(\frac{g}{l}\right)^{1/4} \delta_w$	$\delta_w \sim l^{1/4}$, thickness of boundaries
$\Pi_9\left(\frac{\text{fan flow}}{\text{advection}}\right)$, m^*_{Fan}	$\frac{\dot{m}_{Fan}}{\rho_\infty \sqrt{g} l^{5/2}}$	$\dot{m}_{Fan} \sim l^{5/2}$, forced flows

Figure 6.6: A summarizing table of rescaling factors. Taken from [6].

6.2 Application of rescaling on a specific low-energy house

In the previous section, section 6.1.1, we have discussed the general principles of scaling and rescaling. We have seen that we cannot keep all parameters correctly proportioned, this is because some of the dimensionless groups create contradictions. Therefore, we need to either decide which dimensionless groups are of the most importance, or we try to eliminate these groups. If one of the dimensionless groups is not present, then it will not be present either in the rescaled version.

We find that eliminating the influence of dimensionless groups is not easy to do. However, with some acceptable simplifications, this becomes a far easier task to do.

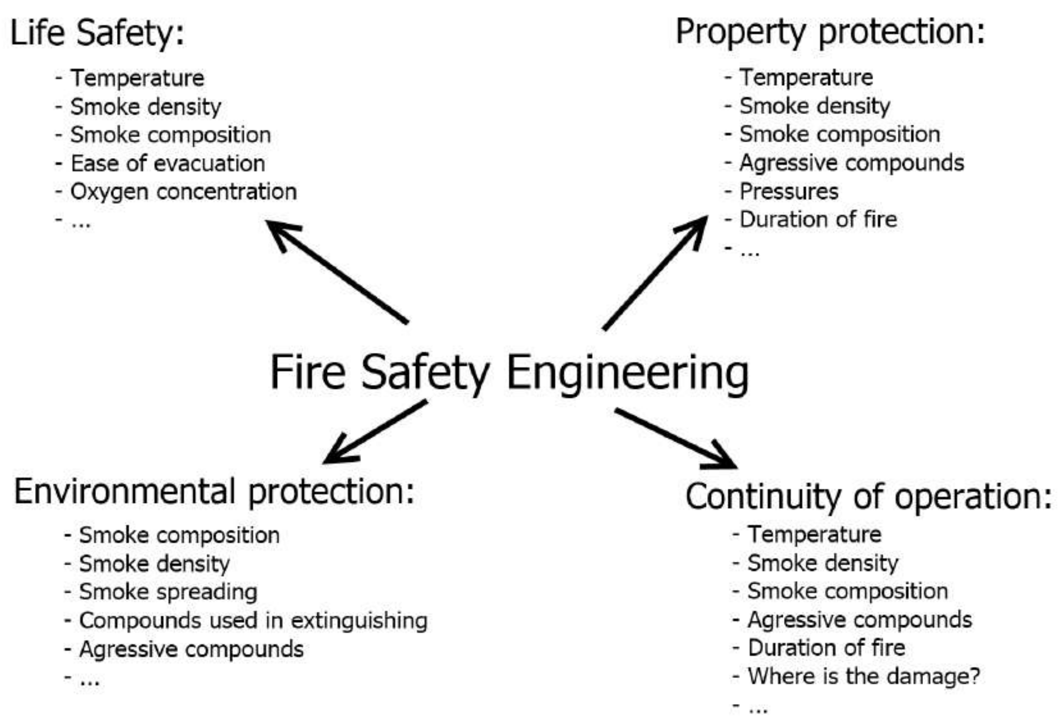

Figure 6.7: This graph shows which goals could be of importance. This is a non-exclusive list and can contain a lot more parameters, but these are usually the main goals of a performance based approach.

We need to start of establishing what dimensionless groups are of main importance for us. This is dependent on the goal and scope of this study. Since the goal of this study is protecting life safety and as such not immediately on structural preservation, nor on continuity of operation or ecological considerations, we established that the scope of the study comprises the initial phase of the fire. Given that an intervention of the fire services takes at the most about 15 minutes [21], we model the fire for 15 minutes. By that time, the inhabitants should have left the house.

So, we have a few parameters to rescale:

6.2.1 The fire source.

First of all, we need to select a fitting fire source. From previous experience and personal experience, as described in the risk assessment on the new UGent student homes [32], we came to the conclusion that a sofa is one of the biggest risks in a private house setting. Not only is the fuel load particularly high, also the risk of ignition is significant (smoking in the sofa, arson during parties) and next to that, the placement of the sofa is so bad that high consequences are very possible (its placement on the ground floor makes for a wide smoke plume by the time the plume impinges on the ceiling, thus polluting a lot of air). So, in this study, a sofa has been selected to serve as a fire source.

Modeling a sofa on a smaller scale brings about some problems. One of the most obvious problems is the soot production problem. A sofa produces quite a lot of soot and smaller particles, as well as some toxic and irritating gases. With the amount of soot production goes the problem of the radiation, which, as described previously, is very difficult to scale.
Another aspect is the HRR curve. I assume that the HRR growth curve follows a αt^2 curve, this is an assumption that has been made lots of times. However, in rescaling this, we have on one hand the time which rescales with $\propto \sqrt{l}$ and the HRR which rescales with $\propto l^{5/2}$.
Taking these problems into account, and given it takes quite a lot of effort, time and money to then choose and rebuild a scale model of a sofa, I have instead chosen for a different approach, one which is actually more flexible. As a fire source, a pool of methanol was chosen with the same peak HRR as a normal household sofa. This would assure a similar behaviour for the sofa, and since the methanol pool fire will reach its peak HRR before the sofa does, this is in fact a conservative choice.

Now for the choice of peak HRR. We can use the data gathered in the project undertaken by Stefan Särdqvist [33]. In this project, fire tests have been conducted for several types of materials, sofas included. We find the following graph:

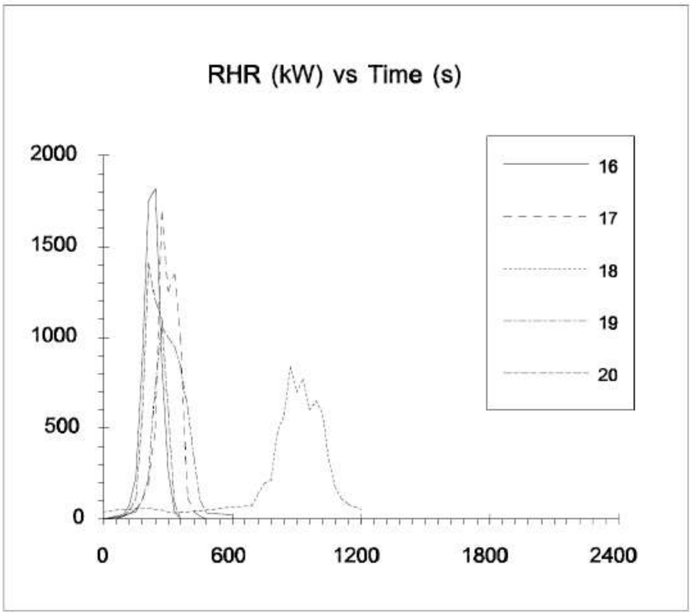

Figure 6.8: A typical HRR for a sofa.

We can see that the upper limit is about 2MW. This means, after rescaling with a factor $8^{5/2}$, that we get a fire size of about 12,5kW.

It is now possible to calculate the diameter needed for the fuel pan to deliver 12kW. We use some formulas from the book Enclosure Fire Dynamics for this cause [4]:
We know:

$$\dot{m}'' = \dot{m}''_{\infty}.(1 - e^{-k\beta D}) \tag{6.42}$$

where $\dot{m}''$ is the free burn mass loss rate per unit area and $\dot{m}''_{\infty}$ and $k\beta$ depend on the liquid type. For methanol and a diameter $> 0,2m$; these values are:

$\dot{m}''_{\infty} = 0,017kg/m^2s$

$k\beta$: Value of $\dot{m}''$ independent of diameter in turbulent regime

The burning rate is defined as:

$$\dot{Q} = \dot{m}\Delta h_c \chi \tag{6.43}$$

We assume $\chi = 0.9$, since there is not a lot of radiation for methanol. ΔH_c is the complete heat of combustion, being 20MJ/kg [4].
This means:

$$12,5 = \dot{m}20000.0,9$$
$$\dot{m} = 6.94444.10^{-4}kg/s$$
$$\dot{m} = A.\dot{m}'' = 0,017.A$$

Therefore:
$$A = 0.0408m^2$$

So, we should have a fuel pan with a diameter of 23cm, which does indeed fall within the limits to use the above method.

6.2.2 The ventilation

The ventilation also has to be downscaled, this has to happen according to figure 6.6. In other words, the factor to downscale the ventilation is $8^{5/2}$, or a factor 181.

As described previously, the mechanical ventilation exists out of two different functions. One of the functions is to extract polluted air, while the other function is to bring in make-up air. However, to incorporate this in the small scale model would require two independent ventilators, both specifically designed so their behaviour would be a perfectly downscaled replica of the full scale ventilators.
This is in theory possible. For the experiment, we will use (due to the high cost of this equipment) only one mass flow controller. It is however possible to design a control loop where the mass flow controller gets feedback from the pressure measurements done.
Although this sounds great in theory, this does hold two serious problems:

- A mass flow controller cannot simulate backflow through the ventilation system.
- The mass flow would be VERY dependent on the pressure rises. Since these also rescale by a factor of 8, the ventilation system would now already suffer from backflow at pressures as low as 25Pa.

Due to the fact that these problems are very hard to overcome (we only would measure pressures on 2 points!) and to the small improvement they would deliver to the experiment, we have opted not to model the ventilation in so much detail. Therefore, we have rescaled the net inflow at a constant rate, leaving any pressure rise or drop out of the equation. The net inflow would be $60m^3/h$, which would in the model be $0,353m^3/h$ or $9,8.10^{-5}m^3/s$ or 5,88 nl/min (norm liter/minute).

There is one more obstacle to effectively model the ventilation. A mass flow controller is in principle a device which delivers pressurized air at a certain volumetric rate. This means that the air which is entering is pressurized, and as such has a high entrance velocity over a small entrance surface. This local high velocity should be redistributed over the whole of the entrance surface. The problem has been solved by the use of a homemade divergent, looking as follows in sketch 6.9.

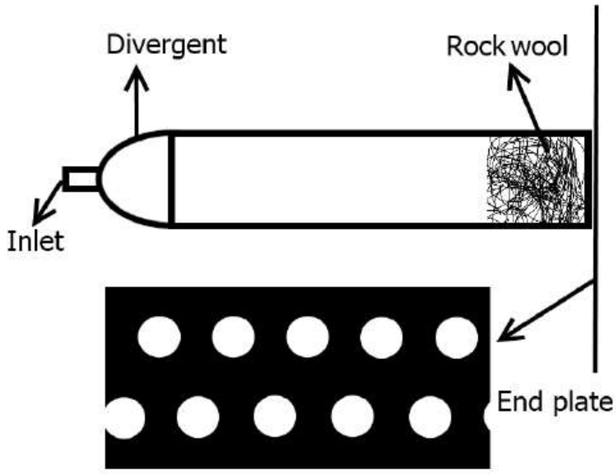

Figure 6.9: A sketch of the divergent. The end plate is there to keep the rock wool from flying out.

Figure 6.10: This is how the homemade divergent looks like, this will be attached on the model.

6.2.3 The insulation

Last but certainly not least the insulation also has to be downscaled. Some decisions will have to be taken to be able to successfully model the behaviour of insulation in a full scale model.

In figure 6.6, there is a reference to the thickness of the shell insulation, but this rescaling factor can not be used, for the following reason:
We have established that the insulating walls to the outside will work during the first 15 minutes as heat sinks, because their thermal inertia is so large. This is not within the scope of the formula referenced in figure 6.6, this rescaling factor is applicable rather to insulating walls in regime. Therefore, we cannot simply copy this formula.

We do know however that, when a wall is in its thermal transient phase, the wall can be looked upon as a semi-infinite boundary: the outside temperature does not change the way in which the heat is transferred to the inside of the wall, since the heat did not reach the outside yet. Only the initial temperature of the wall is of importance. We can now attempt to achieve a similar behaviour for the walls by calculating the time to thermal regime. If this takes longer than 15 minutes (rescaled), then this is a suitable thickness of material. This will be done using ABAQUS, we know from our calculations that the expected temperature rise within the compartment will be less than 155°C on average (from 20°C to 175°C). So, if we apply 155K to one side of the walls for 15 minutes time and at the end of that time the wall is still in the thermal transient phase, we know that we have a wall with a semi-infinite character during that time. The results of the ABAQUScalculations are to be found in figure 6.11.

Before we can start to model in ABAQUS, we need to know what material we are going to use. We can opt to either:

- choose to rescale the material properties and try to find a material which suits our needs;
  or
- choose a readily available material to build our model with.

I have chosen to follow the second approach with the following reasoning behind it:
Since we are talking about a residential home, the finishing of the inside will probably change throughout the buildings existance. The original wall lining, being mere MDF-boards (medium density fibrewood) is hardly aesthetic and will most likely not please the inhabitants. Also, the finishing of the walls, the kind of material, the roughness of the final wall,... will all influence the heat transfer capacities of the hot air and smoke to the wall. So, this introduces even more unknowns. Therefore, I have chosen to use gypsum board, which is one of the most widely used construction materials used for finishing interiors in the Benelux [34]. This also keeps the cost of the model down.

Knowing the properties of gypsum board, we can now calculate what the necessary thickness (amount of boards) is to keep the wall acting as a semi-infinite barrier:

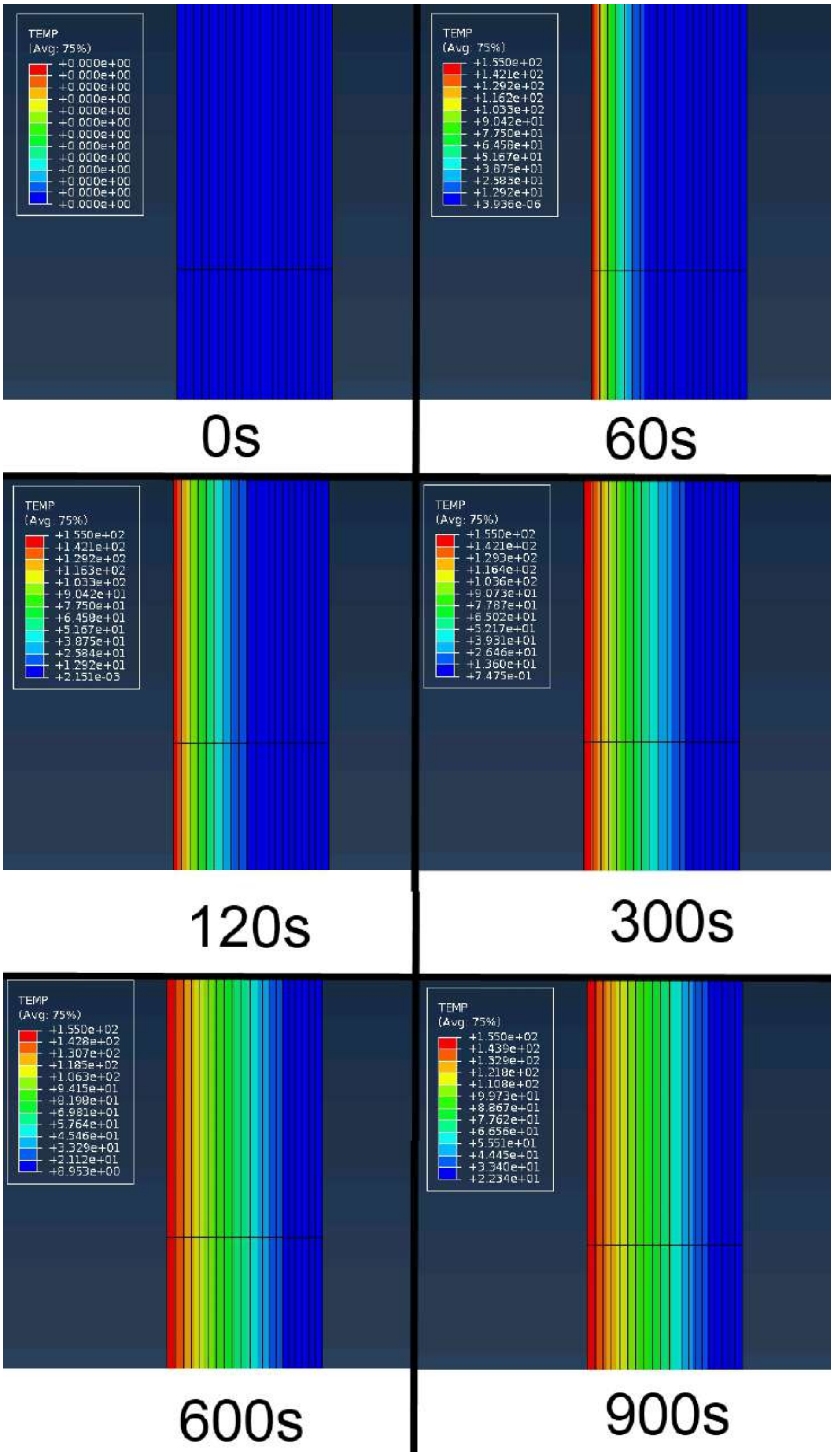

Figure 6.11: These different screenshots show that indeed the temperature profile stays transient. The outer MDF-board even stays almost completely cool.

We find that 2 boards totalling 3cm of gypsum board should be enough.

6.2.4 Recapitulation

Below, a summary is shown which parameters are rescaled. These parameters are deemed to have a very important impact on the modeling of the low-energy house. Other parameters are not rescaled, because either they are too hard or expensive to rescale (in theory the ambient temperature should rescale, but this is in practice too hard and expensive) or their effect is deemed neglegible (inertia will not be rescaled through the Reynolds number, since we accepted in chapter 3.5.1 that the flow will be a combination of laminar and turbulent flow).

Parameter	Original value	Scaling factor	Rescaled value
Size [m]	8; 4; 2	8	1; 0,5; 0,25
Pressure [Pa]	From experiment	8	From experiment
Temperature [K]	From experiment	1	From experiment
Concentration [/]	From experiment	1	From experiment
Time [s]	From experiment	$\sqrt{8}$	From experiment
Fire source [kW]	2000	$8^{5/2}$	12,5
Net ventilation [m^3/h]	60	$8^{5/2}$	0,353
Insulation thickness [cm]	over 20, thermally thick	complex	over 3, thermally thick

Table 6.1: The rescaled values

6.2.5 Results of the experiments

As described in the previous section, there were 4 different experimental setups. All of these setups described a similar behaviour of the fire and a similar behaviour of the modeled building. These results will be described in this section.

Pre-setup

Before the actual start of the tests, it is necessary to do some preliminary tests. They will point out possible problems and actions might be necessary to alter the design so it does meet its requirements.

One of the first things to test is the pan that will hold the fuel. I have chosen a classical casserole dish for this purpose, for two reasons:

- A casserole dish is made to be on a stove for a long time. This means that it is capable of handling a prolonged heating.
- Since the casserole was made to be on a stove, it can handle high temperatures quite well. If it fails, it doesn't fail brittle, so the fuel doesn't spill and there wouldn't be any problem for the safety of the people testing.
- This particular casserole dish is black. This helps in absorbing the small amount of radiation coming from the fire. This in other words, eliminates the radiation factor even more.

The casserole dish will be filled with a bit of water and with the fuel. The fuel, being lighter than the water, will float on top. The water will remain in the bottom of the casserole making sure that the casserole does not heat up too much when all of the fuel is burned. The water basically works as an insulator and a heat sink.

A picture of said casserole dish is presented below.

Figure 6.12: A picture of the used casserole dish.

A preliminary test has been conducted by filling the casserole dish with 1kg of fuel and igniting it. In the Small Burning Item setup (figure 6.13), the output power of the fire was measured. The result is presented in figure 6.14. We can see on this figure that the calculated value of 12,5kW is reached. At ignition, the heat release rate grows quickly to 10kW, and from there on slowly increases to 15kW. This can be explained as such: at ignition, the temperature of the fire suddenly rises quite a lot. There is a cooling effect of the fuel pan on the way the fuel burns and at the edge of the pan, the cooling effect slows down evaporation, thus reducing the effective diameter of the burning surface. The pan slowly heats up and thus slowly goes to a heat release rate of 15kW. So, we can assume an average value of 12,5kW for the first few minutes.

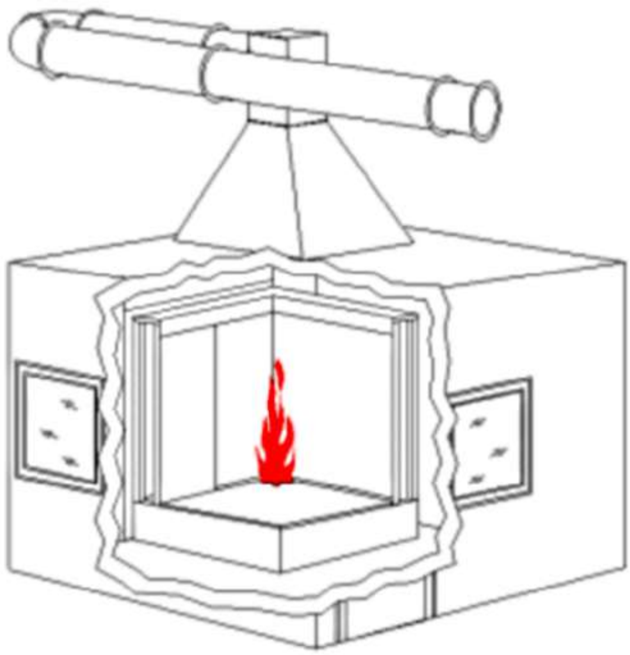

Figure 6.13: A sketch showing the SBI setup.

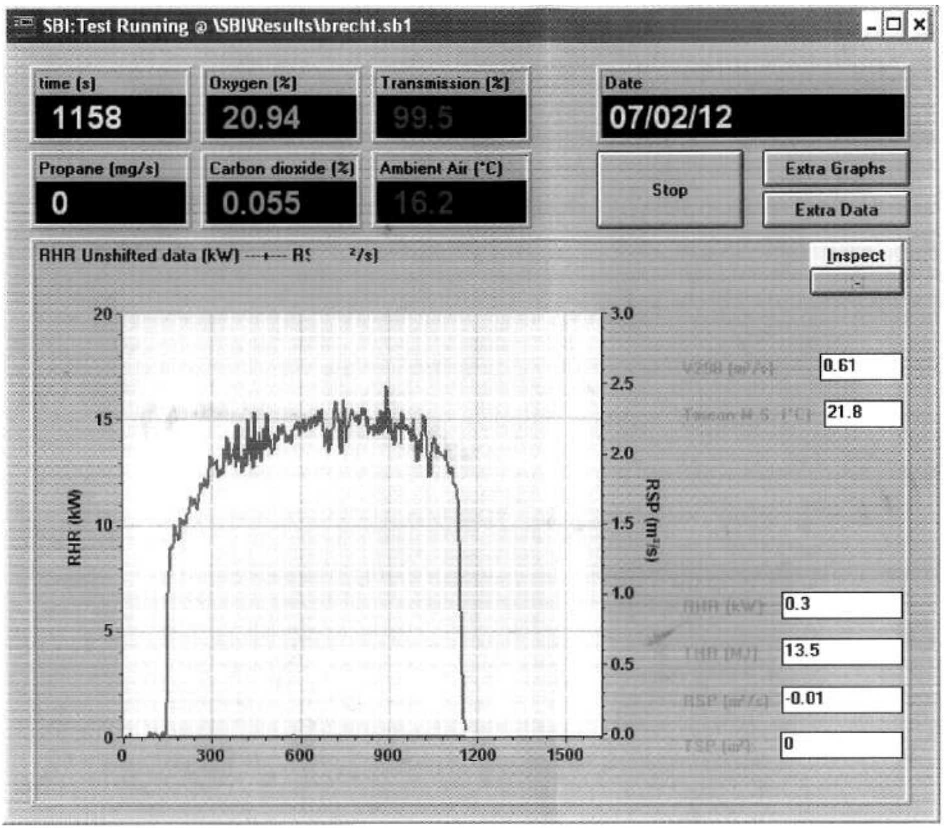

Figure 6.14: The results of the preliminary test.

The only output we are interested in is the amount of heat which is generated. A temperature would not tell us anything important and a production rate for product gases is also not important: the very different ventilation conditions in the model will change the products produced and their concentration and production rates as well.

On the other hand, it might be interesting to know how much oxygen was used during the experiment, so we can calculate the used oxygen back to an energy release (rate). However, the uncertainty of that number arising from 1 experiment is so high that it is actually better to use values calculated in the literature, coming from a mean from different experiments [35]. According to a theoretical approach: since

methanol + oxygen → carbondioxide

$2\ CH_3OH + 3\ O_2 \rightarrow 4\ H_2O + 2\ CO_2$

So, with this reaction formula, we can calculate the amount of energy released per mole and as such gram of oxygen used. We do this in the following way (values taken from [35]):

$$H_f(O_2) = 0kJ/mole$$
$$H_f(CO_2) = -393.5kJ/mole$$

$$H_f(H_2O) = -241.8kJ/mole$$
$$H_f(CH_3OH) = -238.4kJ/mole$$

So:

$$2H_f(CH_3OH) + 3H_f(O_2) - 4H_f(H_2O) - 2H_f(CO_2) = \text{ heat released for 3 moles of oxygen}$$

3 moles of oxygen weighs 32*3 grams, so 1 kg of oxygen would produce 13.3MJ.
According to [35], for methanol, 13.22kJ is produced per gram of oxygen used in the combustion. This is very close to the theoretical value just calculated.

Another very important parameter to check is a flow rate-pressure curve. This will give us some interesting information on the way the leakage works: we know that [36]

- Turbulent flow has a pressure loss $\propto \dot{V}^2$
- Laminar flow has a pressure loss $\propto \dot{V}$

with $\dot{V}$ being the volumetric flow rate.

Graph 6.15 shows the pressure difference inside-outside of the model versus the flow rate. This has been found by increasing the input of the mass control unit from 0% up to 100%, being 0 to 500 nl/min (500 norm liters/minute). A norm liter is a liter of air under atmospheric conditions and at 20°C.

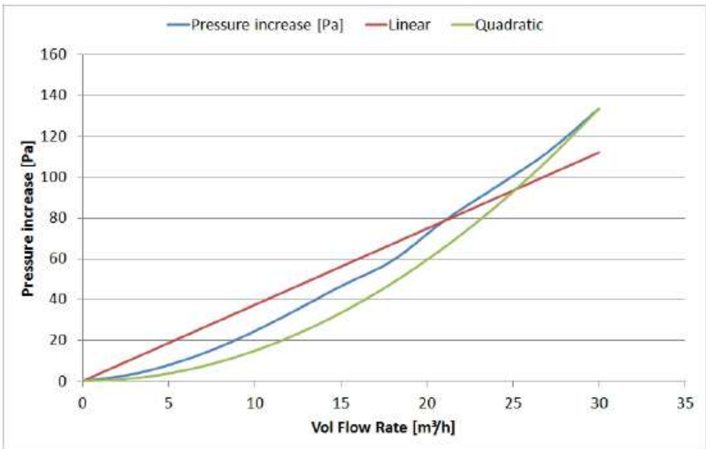

Figure 6.15: Pressure increase inside the model vs volumetric flow rate in the model.

This graph shows that the behaviour is neither perfectly laminar nor completely turbulent. So, calculating with a quadratic behaviour as we have done in the preliminary theoretic approach is not the best way of tackling this problem. Another remark to be made is that it is clear from this graph that at the higher flow rates, the behaviour becomes more quadratic than at the lower flow rates. This is normal behaviour. The *Re*-number determines whether the behaviour is laminar or turbulent. This number is dependent on the velocity in the flow, which is higher at higher flow rates. So, the *Re*-number increases, as does the turbulent behaviour.

It is also clear from these results that we do not get an overpressure of 6Pa at less than 10% of the ventilation flow (being $3m^3/h$), the measured overpressures are lower. This means in other words that the model leaks too much. This is however not a problem: if the results point out that the house is too much enclosed, as we expect, then a real low-energy house will be too enclosed as well.

One of the last pre-setup factors we need to consider is the position of the thermocouples. We have to know where the thermocouples are installed if we want to produce a decent outcome and decent results for the test setup.

- Thermocouples 1 to 6 are installed on the wall next to the ventilation inlet. This position makes sure that there is no effect of the ventilation inlet on the temperature measurements. Thermocouples 1, 2 and 3 are positioned at 25 cm of the wall and thermocouples 4, 5 and 6 are positioned in the half of the box, half a meter from the side wall. As for the height: thermocouples 1 and 4 are positioned at 75cm of the floor, thermocouples 2 and 5 at 45cm of the floor (to measure the temperature just under the false ceiling in further experiments) and thermocouples 3 and 6 at 25 cm of the floor (rescaled, this would be at 2m, head height of the ground floor). See figure 6.16.
- Thermocouple 7 measures the inflow temperature of the ventilation. See figure 6.16.
- Thermocouples 8 to 13 are installed on the wall parallel to the ventilation inlet. This position could have an effect of the ventilation inlet on the temperature measurements. Thermocouples 1, 2 and 3 are positioned at 25 cm of the wall and thermocouples 4, 5 and 6 are positioned in the half of the box, half a meter from the side wall. As for the height: thermocouples 1 and 4 are positioned at 75cm of the floor, thermocouples 2 and 5 at 45cm of the floor (to measure the temperature just under the false ceiling in further experiments) and thermocouples 3 and 6 at 25 cm of the floor (rescaled, this would be at 2m, head height of the ground floor). See figure 6.17.
- Thermocouples 14, 15 and 16 are positioned on the opposite wall of the ventilation, certainly feeling an influence of the inflow of fresh air. Thermocouple 16 is positioned exactly opposite from the ventilation. Expected is that the warmed up flow beam is deflected upwards, and will impinge on thermocouples 14 and 15, respectively 15cm higher and 10cm higher. See figure 6.18.
- Thermocouple 17 measures the temperature in the center of the box top, immediately above the fire.

- Thermocouple 18 measures the temperature of the escaping hot smoke in front of one of the top pressure vents.
- Thermocouples 19 and 20 measure whether the properties of the wall are satisfactory: these two measure if the heat transfer through the wall will go into steady state. Thermocouple 19 is placed in the middle of the wall (2cm deep) and the other thermocouple is placed on the wall.

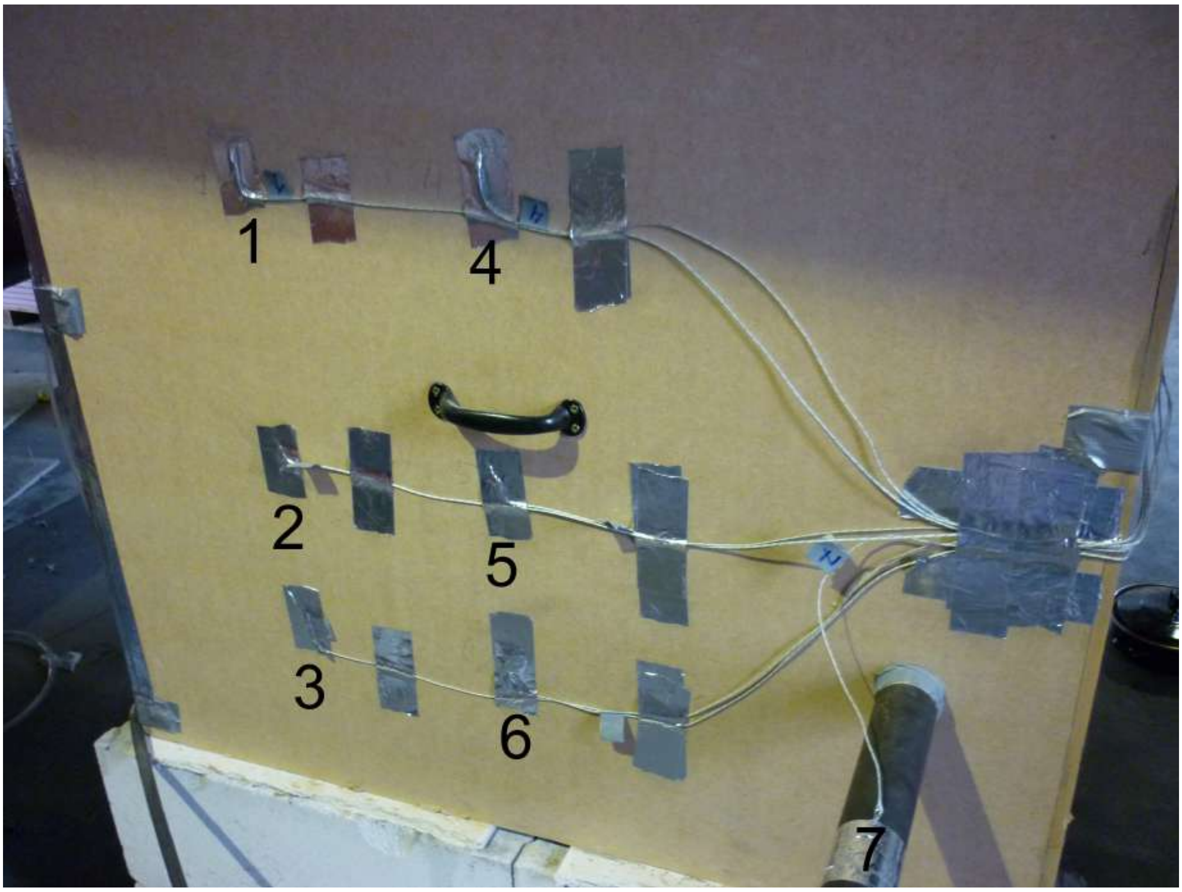

Figure 6.16: Thermocouples 1 to 7.

Figure 6.17: Thermocouples 8 to 13.

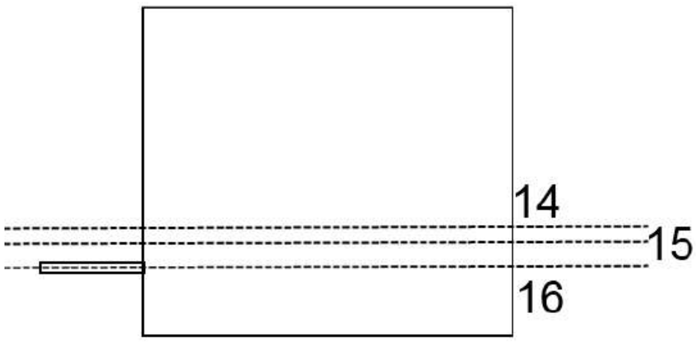

Figure 6.18: Thermocouples 14 to 16.

Four experiments are conducted:

- Ventilation is turned on, the building is completely uncompartmented.

- Ventilation is turned off, the building is completely uncompartmented.
- Ventilation is turned on, a false ceiling is installed, but the building is uncompartmented.
- Ventilation is turned on, a false ceiling is installed and as such the building is compartmented.

Setup 1: an uninterrupted cube interior

In this setup, we target the case where the E-Cube would be used as one whole room. Regarding the architectural desire to work with large, open spaces, this approach is one which the architect would probably use.

Given the problems to accurately regulate the inflow of the ventilation system in the model, we have overestimated in this setup the inflow. In the next setup, this inflow will be downscaled to zero, thus comparing an overestimation of the inflow of fresh air with a serious underestimation. This will lead to conclusions that apply for an actual setup where the ventilation characteristics are somewhere in between the two.
Specifically, for this test setup, we chose to have an inflow of about 10% of 500 nl/min (500 norm liters/minute). A norm liter is a liter of air under atmospheric conditions and at 20°C. In other words, there is an inflow of 50 nl/min or $3m^3/h$ of inflow of air.

We found out in the previous section that the net inflow of air in the low-energy house was significantly lower: about $0.35m^3/h$ (according to section 6.2.2). This is clearly a large overestimation, but this is what we would like to have.

A further description of the whole setup is to be found in the previous sections.

The ambient temperature was 13.3°C. The pressure was normal atmospheric pressure. Before the tests, the setup had been acclimatised for a night.

The results of the temperature measurements are shown below:

For thermocouples 1 to 6:

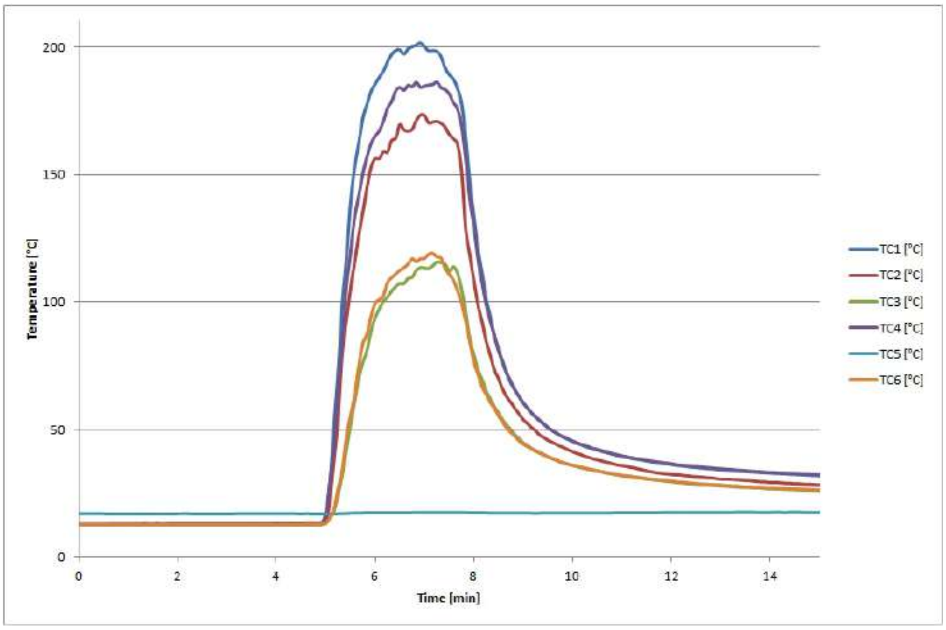

Figure 6.19: Thermocouples 1 to 6.

These graphs show immediately that TC5, thermocouple 5, is not functioning. TC5 is located at the same height as TC2, so we would expect the temperatures measured by TC5 to be at least comparable to them. There is however redundancy in the measurements as thermocouples 8 to 13 measure at the same heights.

It is also important to keep in mind that the scaling has been done so that the temperatures are the same for the full-scale case. So, we see that the temperatures, although initially rising fast, do not climb very high. I expect this to be the cooling effect of the walls. As described before in the theoretical approximation(3.4), the strong insulating potential of the house does not have an effect here: since the thermal inertia of the wall is so high, a lot of the heat generated by the fire goes to the walls. Another part of course is expelled through the leakage in the walls (inside the cracks, under the doors and such).

Another effect which is important to understand, is the apparent lack of a cold layer and a hot smoke layer. This has to do with the amount of buoyancy comprised in the hot smoke. Since the smoke has quite a lot of momentum, the impinging smoke on the ceiling forms a strong ceiling jet and also plunges down the side walls, thus strongly and quickly mixing the two layers. This behaviour has been shown in the FDS-approach. However, we cannot claim that this behaviour will always happen in a real fire in a low-energy house, since there is a very fast growth rate for a pool fire such as this; and in most cases the fire scenario will not be a pool fire.

A last effect I would like to draw attention to, is the decay phase of the fire. This decay phase

is clearly too soon to have used up all the fuel present in the fuel pan. The reason is rather that the oxygen present in the room has all been used up, or at least been used up to the point where sustaining a flame and a fire is impossible. We see the temperatures converging to ambient temperature.
All of this behaviour is also visible in thermocouples 8 to 13:

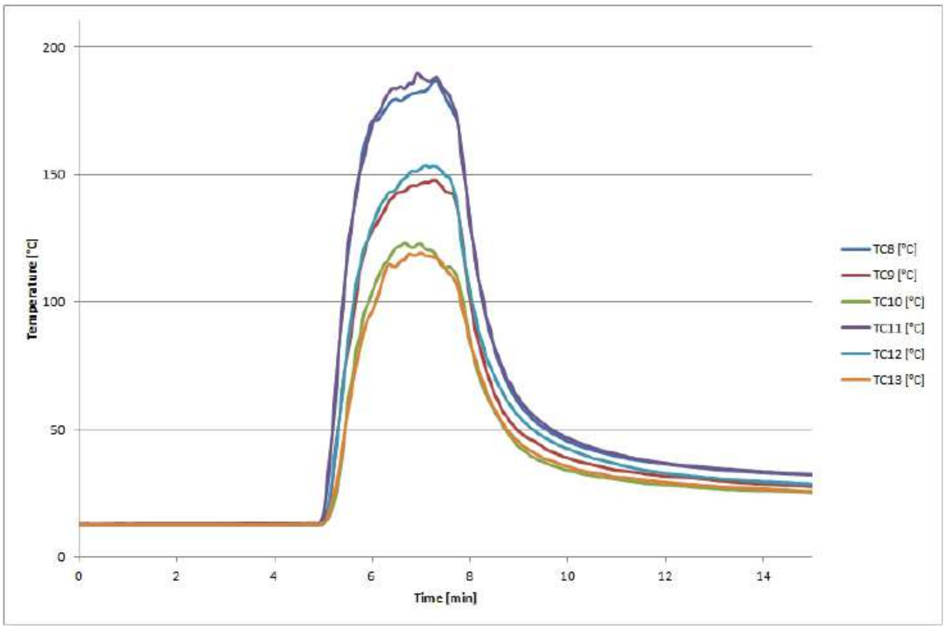

Figure 6.20: Thermocouples 8 to 13.

Figure 6.20 shows that the conclusions drawn for thermocouples 1 to 6 are valid and are shown even more clearly here. In the following cases, I will only show the results from thermocouples 8 to 13, omitting the results from thermocouples 1 to 6. There is no use in showing results where one thermocouple does not work when I do have redundant results that can be used.

Important to remark in these results is that indeed TC8 and TC11 are at the same height and it is indeed correct that these should show a similar behaviour in temperature rise and should reach the same maximum temperatures. This indeed happens here. An entirely identical story arises for thermocouples TC9 and TC12 and for TC10 and TC13.
We also see that the decay phase shows an identical behaviour as for thermocouples 1 to 6 with the same time constant. Also the maximum temperatures for the different heights are very much alike. So, we can conclude that measurements for thermocouples 8 to 13 are identical to thermocouples 1 to 6. The only difference is that all of the thermocouples work, thus showing important trends. For the next experimental setups, only these measurements will be taken into account.

We see that the temperatures at head height are quickly too high to be safely accepted (120°C in half a minute, this would be 120°C in barely 1 minute and a half!). However, we see a fast cooling afterwards.

Thermocouples 14 to 16:

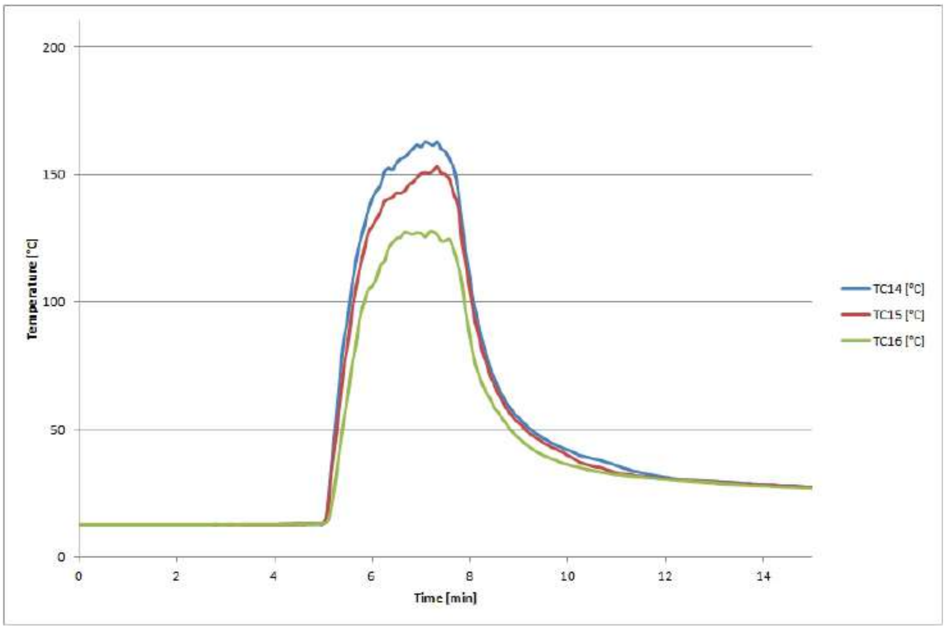

Figure 6.21: Thermocouples 14 to 16.

These three thermocouples were installed on the opposite side of the ventilation inlet in the model (see figure 6.18). This is to see whether the ventilation inlet has any influence on the flow behaviour around the fire or on the temperature field around the fire. If this would be the case, there would be a clear discrepancy between two measured values and the measured values would be clearly different from similar values measured at the same height. During installation, care has been taken to install thermocouples 15 and 16 at about the height of thermocouples 9 and 12. We see indeed that the values measured for thermocouples 14 to 16 show very normal behaviour and that no influence of the ventilation has been measured. This shows that the measures taken to redistribute the flow are working (see paragraph 6.2.2). This assures that the ventilation indeed behaves as would be the case in a full-scale low-energy house. This pattern will appear throughout the other experiments, so after having mentioned this fact here, I will no longer show this result for the other cases.

Thermocouple 17:

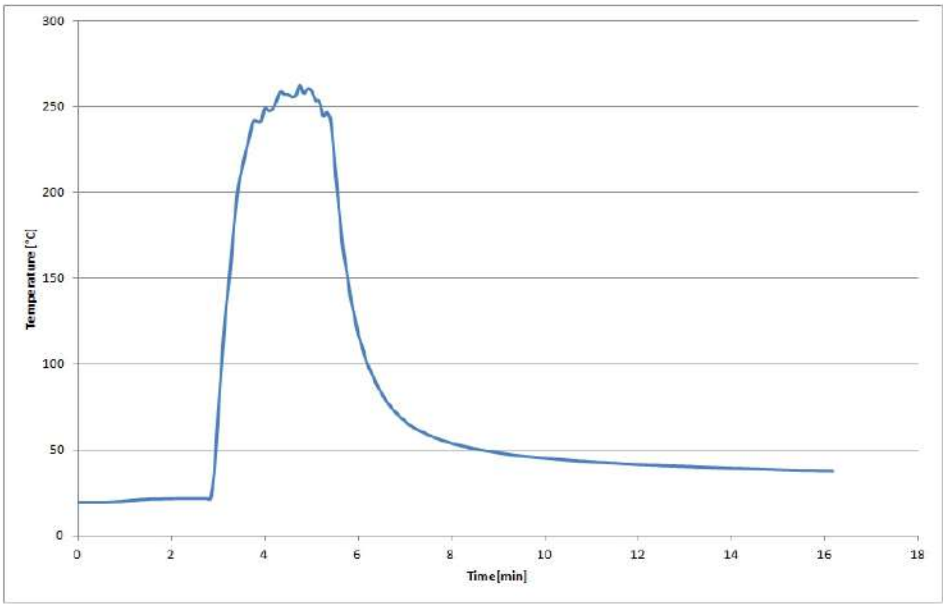

Figure 6.22: Thermocouple 17.

Thermocouple 17 is positioned straight above the fire, as already has been mentioned. This is the place where we can accurately estimate when the fire started and when the fire went out. The duration of the fire was about 3 minutes, and since we know that time rescales with a factor $\sqrt{8} = 2.8$, we know that in a full scale fire the fire would last for about 9 minutes.

Thermocouple 18:

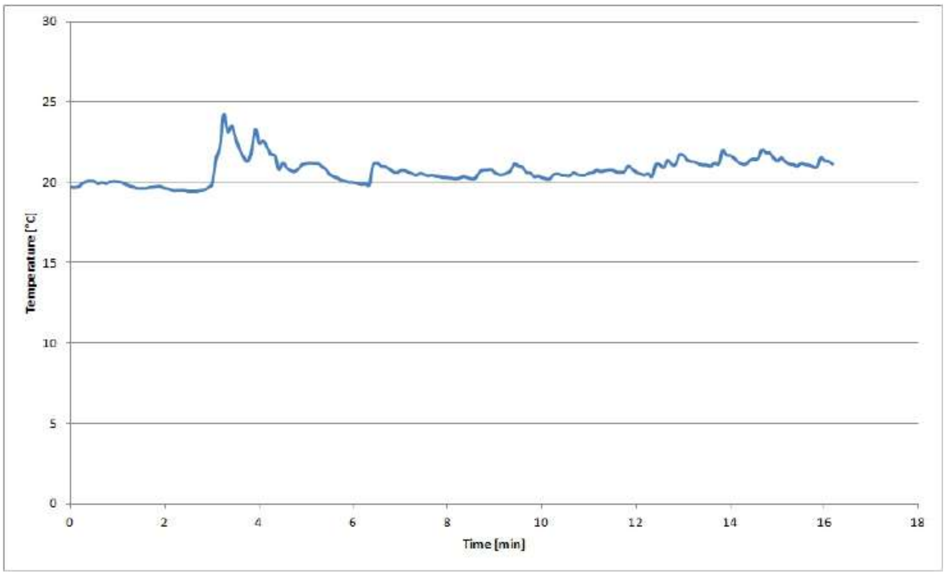

Figure 6.23: Thermocouple 18.

Thermocouple 18 is installed in front of one of the leakage openings. The goal was to measure the temperature of the smoke leaving the model. However, it is clear from these results that no useful measurements have been made: this is mainly due to the incorrect placement. The thermocouple was placed a bit away from the opening, as to not impede the flow exiting (impeding the flow would mean a real increase in pressure peak). We will however see that this placement is good enough to measure the temperature of the smoke in some setups, but we will not pay extra attention to this measurement.

Thermocouples 19 and 20:

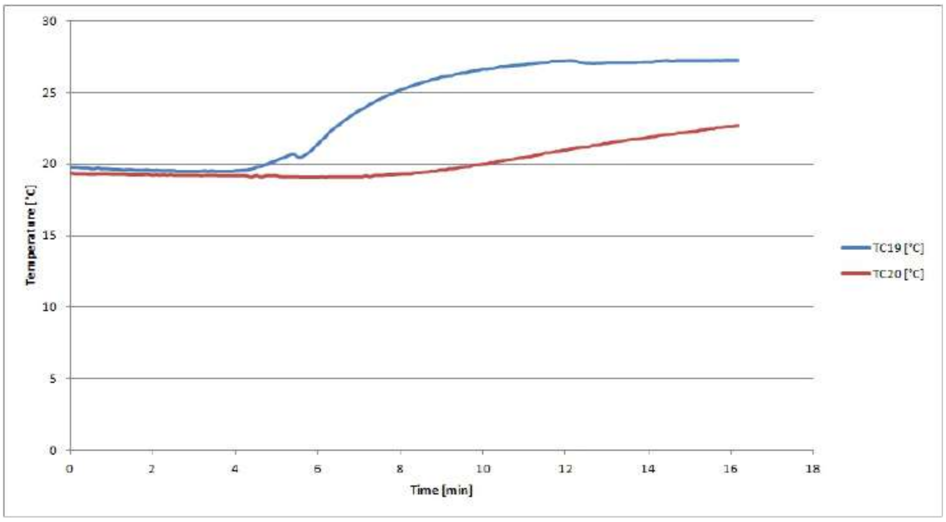

Figure 6.24: Thermocouple 19 & 20.

These thermocouples attempt to measure the temperature increase inside the wall. This measurement of the temperatures in the wall would allow us to better understand what exactly would happen in the insulation material of a low-energy house in case of fire.

As already mentioned before, thermocouple 19 is installed in the middle of the wall, measuring whether the wall would heat up due to the fire. Thermocouple 20 is, on the other hand, installed on the outer wall itself.

We can conclude from this measurement that the walls will indeed heat up (which is normal), but that the inside of the wall only starts to heat up at around 6 minutes, this is when the fire has actually already extinguished itself (by lack of oxygen). This leads to an important conclusion: the wall takes up the heat of the inside, even after the fire has gone out. This means that the wall would act as a kind of heat sink for the fire. This confirms the theoretical deduction made in paragraph 3.4. The temperature of the outside wall stays on a very acceptable level, and given that the thermal inertia in a low-energy house is a lot higher, the heat sink effect would show itself even more. As the inside combustion gases cool down, the walls heat up. In essence, this gives the combustion gases two ways to cool down, on one hand due to the ventilation (convection), and on the other hand due to the heat sink effect of the walls (convection followed by conduction).

The results of the pressure measurement and the oxygen measurement are shown here:

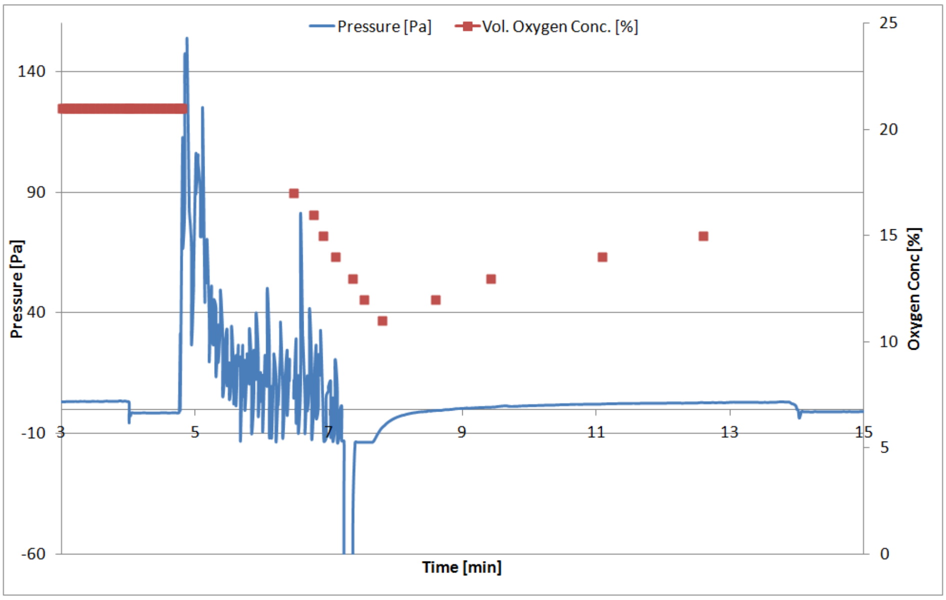

Figure 6.25: Pressure measurement and oxygen concentration.

This is one of the most interesting results. We can see that the pressure peaks at about 140Pa, this would give a rescaled pressure difference inside-outside of about 1120Pa. Given that in the Belgian standard for smoke control in indoor car parks [37], an upper limit for pressure difference is set to 60Pa, we see that this pressure is a few times too high.

The fast, initial rise is due to the fast ignition of the fire and the fast temperature increase following that ignition. This means the pressure increase and the rate of pressure increase is also dependent on the fuel, or further, on the rate of temperature increase. We see that, as the temperature becomes somewhat stable, the pressure difference evens out. When the fire extinguishes itself, the temperature on the inside drops, creating an underpressure also shown here. Due to the inflow of fresh air (leakage + ventilation), the pressure stabilizes again.

We can now assess how big the problem is, if we use the same criterium as in the Belgian standard on car parks (NBN S21-208-2). Rescaling the upper value, 60Pa, means a maximum allowable rescaled pressure of 7.5Pa. We however see that the pressure is about 1 minute higher than 7.5Pa. If we rescale the time, we find that the time becomes about 3 minutes.

In other words, this means that the pressure stays too high for 3 minutes for people to effectively open a door. Given that doors on houses in Belgium tend to open to the inside instead of to the outside, this overpressure which lasts for 3 minutes can form a real problem. If people find out they cannot open the door, they might go looking for other means of escape - and this might give problems.

Next to the problems with the pressure increase, we can see that the low level of oxygen may also give serious problems. It might be of importance to remark that the oxygen measurements have happened at head height of the upper floor, so this is quite a bit away from the fire. Although, because of the strong mixing of the smoke plume in combination with the small dimensions of the room, the oxygen level is most likely to be quite the same over the whole room. The fire uses all the oxygen in the room, and after this has happened, it takes quite a long time before the oxygen level gets back to an acceptable value. We have seen that the lowest level of oxygen was around 10.5%, at this point, people would suffocate. Given that in the model, it takes 5 minutes (rescaled 15 minutes) to get the oxygen level back to a mere 15%, still not high enough to ensure safety of occupants, it is of the highest importance that people get out of the burning house as soon as possible. It only takes 2 minutes in the model, about 6 in complete scale, to get levels of oxygen which are dangerously low to human beings. And, we should keep in mind that in this setup, in the first minute (3 minutes rescaled), it is impossible to open the door. As already mentioned, the size of the pressure increase depends on the type of fuel.

Setup 2: an uninterrupted cube interior, without ventilation

This setup was established to see the effect of the ventilation. If we get similar results as for setup 1, we can conclude that a low-energy house will indeed behave in this way. The true behaviour of a low-energy house will be somewhere in between.

The results of the temperature measurements are shown below:

Thermocouples 8 to 13:

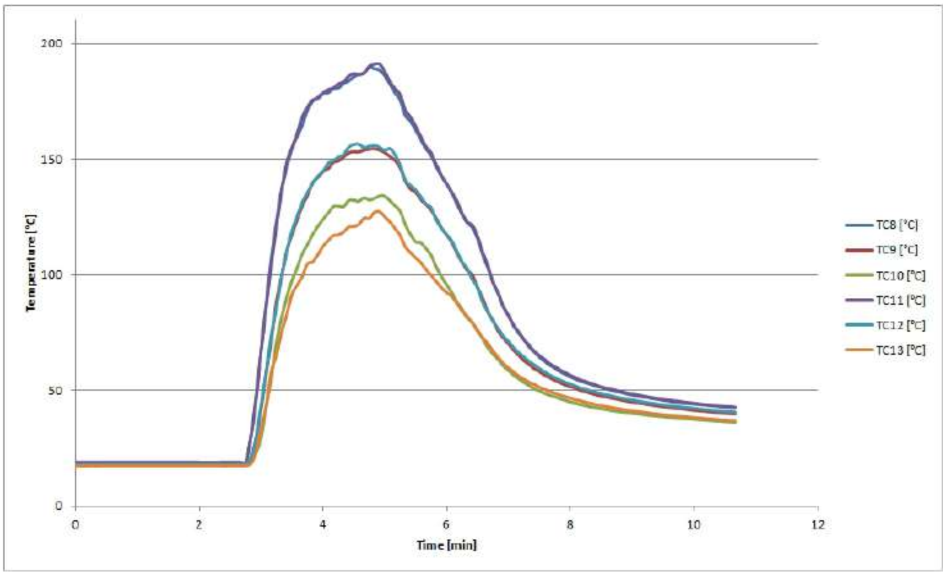

Figure 6.26: Thermocouples 8 to 13.

We can see that the values of the temperatures are quite similar as in setup 1. The pressure rise and the maximum temperatures do not change significantly. What we do notice, however, is that the decay phase in the temperature takes a significantly longer time. This is easy to explain: since the ventilation is turned off, there is also no inflow of fresh air, expelling the combustion gases and replacing them with fresh air. The only way of cooling down the inner cumbustion gases are the following methods:

- On one hand, leakage combined with the underpressure will suck in cool air, cooling the gases down
- On the other hand, the wall will work as a heat sink, taking up heat from the combustion gases.

We can show the effect of the wall cooling by using a software program as ABAQUS. We simulate the progress of the fire by first implementing a boundary temperature similar to the experimental temperature (as measured here), and then we replace that temperature by an adiabatic boundary condition. We do expect however that the cooling in ABAQUS, only due to the heat sink capacity of the wall will go somewhat slower, this is because there will be no effect of the inflow of air through the leakages.

The result and a comparison with the actually measured data are shown here:

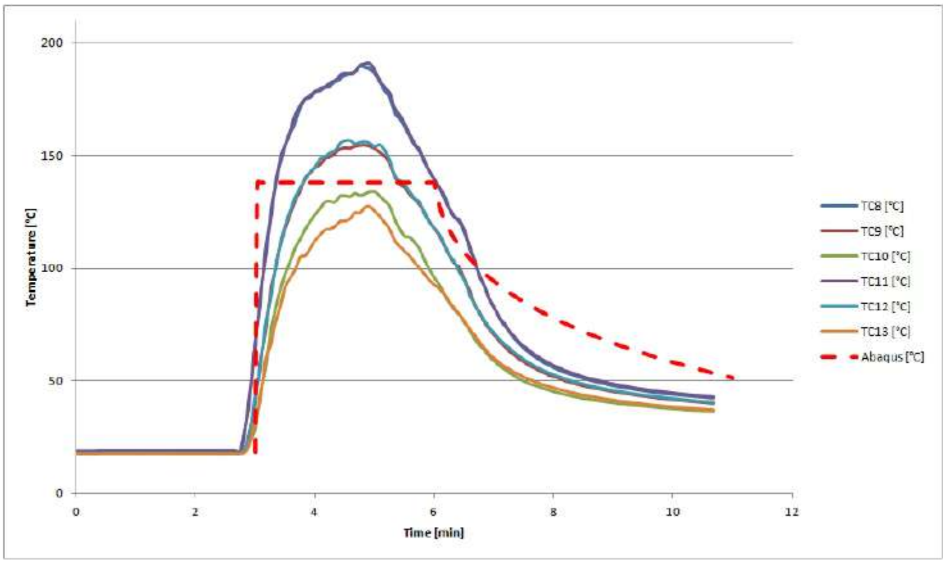

Figure 6.27: A comparison between the cooling: calculation with ABAQUS and experimentally measured.

Indeed, as expected, the cooling effect in Abaqus works slower.

Thermocouple 17:

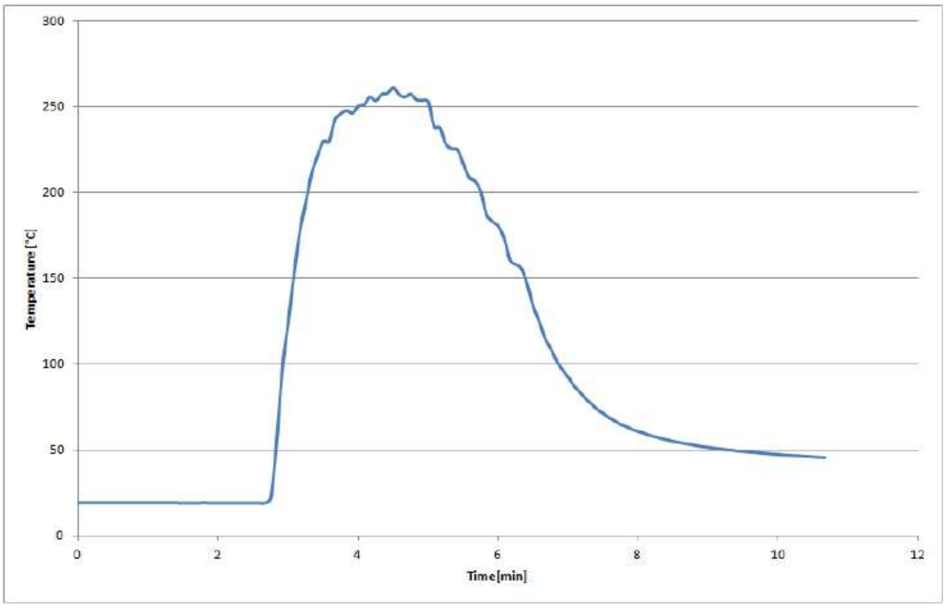

Figure 6.28: Thermocouple 17.

As expected, thermocouple 17 shows once again the highest temperatures. There is no seperation within the box.

Thermocouple 18:

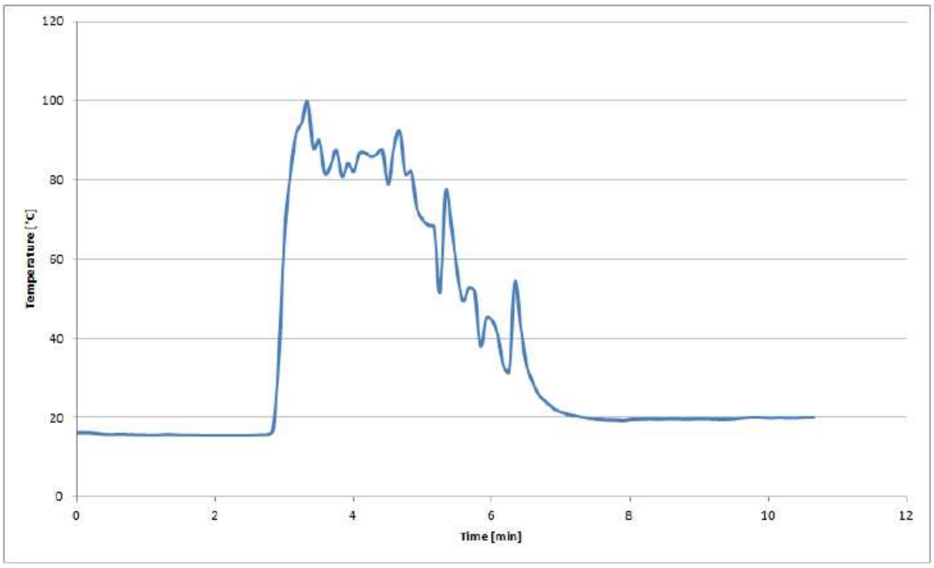

Figure 6.29: Thermocouple 18.

As stated in setup 1, this time we have actually measured an increase in temperature here. This increase in temperature is due to the hot combustion gases leaving the box, but as the uncertainty on this value is clearly too large, we will not consider this value further.

Thermocouples 19 and 20:

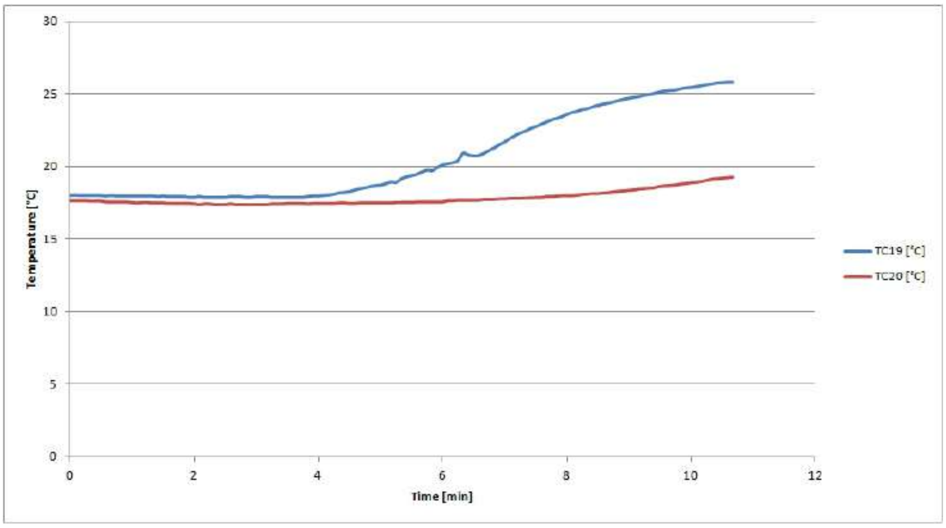

Figure 6.30: Thermocouple 19 & 20.

Once again, we see a similar behaviour as in the other setup.

The results of the pressure measurement and the oxygen measurement are shown here:

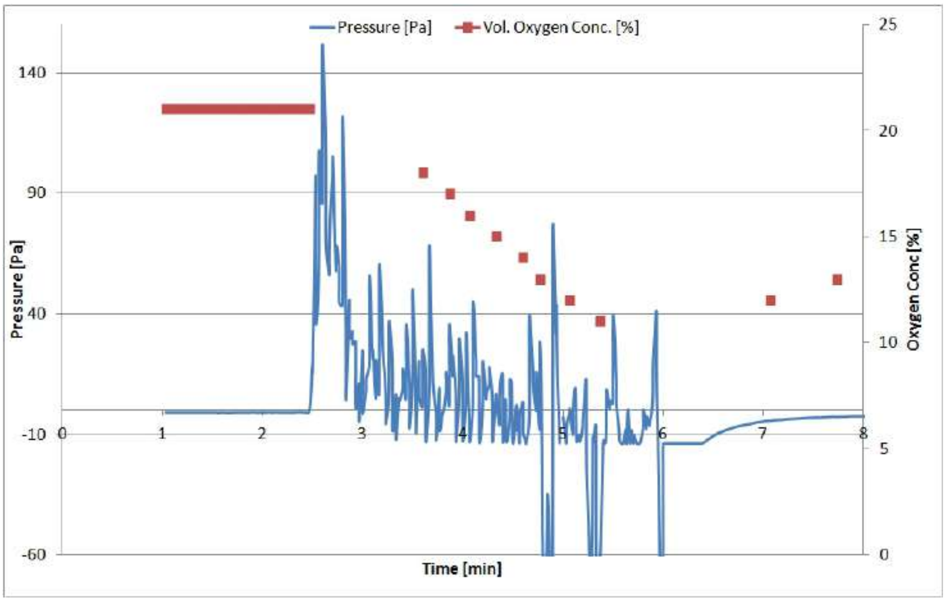

Figure 6.31: Pressure measurement and oxygen concentration.

We see that the problem of pressure increase is about as big as in setup 1. We see that there is indeed difficulty to open a door in the house in the first minute (rescaled the first 3 minutes). Furthermore, the rate of oxygen consumption is comparable, leading to dangerously low oxygen concentrations in barely 2 minutes (6 minutes full scale). Not explicitly shown here, but as observed in the experiments, it did take a longer time to get the oxygen levels back up to a safe level; the time needed was in the order of 8 minutes (24 minutes full scale). This is of course due to the lack of ventilation, so there wouldn't be a lot of fresh air coming in the house.

Setup 3: uncompartmented with false ceiling, with ventilation

This setup was established to see if a typical division of a house would bring a solution. A house typically has one staircase leading up and leaving a gap to the upper floor. We would like to see if this division brings a solution to the temperatures which are too high and if it brings a solution to the pressure increase.

The results of the temperature measurements are shown below:

Thermocouples 8 to 13:

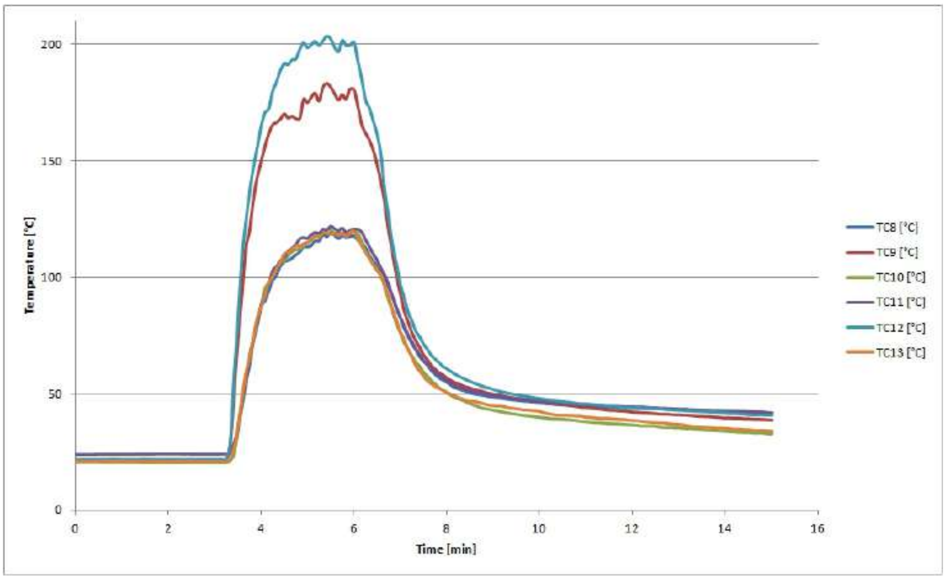

Figure 6.32: Thermocouples 8 to 13.

As the temperatures on the second floor on head height have lowered considerably (TC 8 & 11), we see that the temperatures just under the false ceiling rise higher than in the previous cases. This is due to the impinging smoke plume on the false ceiling, redirecting the fumes into a ceiling jet straight to the thermocouples on the side walls. Indeed, we see a clear rise in temperatures just under that false ceiling.
One cannot deny however that this solution is indeed beneficial for the temperatures on head height on the second floor.

We see that the temperatures on the second floor, at head height, are very much alike to the temperatures on the first floor at head height. This could be coincidence, and depend entirely on the size of the gap for the stairs. To make sure that this is indeed a coincidence and that this is entirely dependent on the gap size, we have modelled this setup also in FDS. The gap size has been chosen slightly different, and if the temperatures are indeed once again the same at head height on floor 1 and 2, we should investigate what effect lies at the base of this.

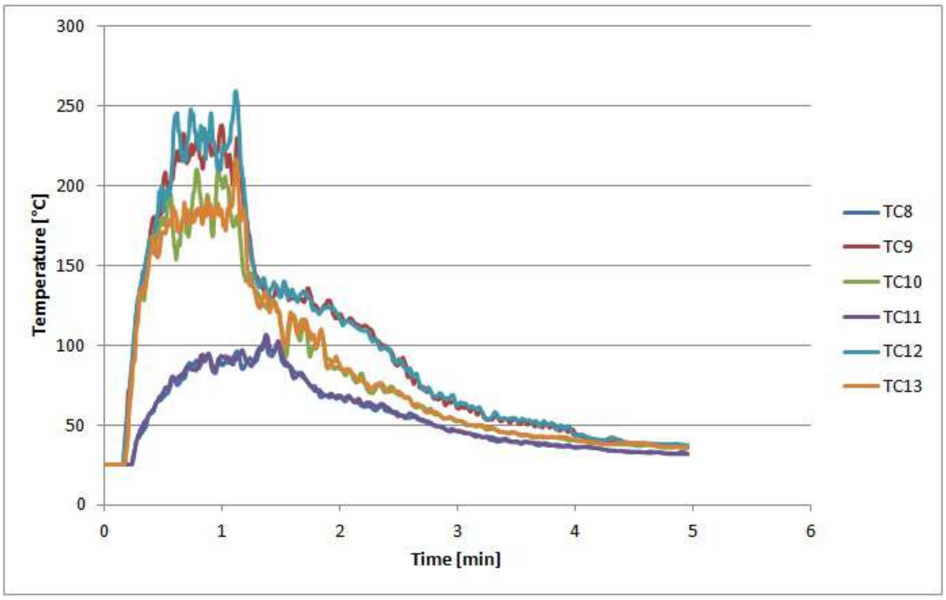

Figure 6.33: The results of the model in FDS.

We see that this was indeed a coincidence.

Thermocouple 17:

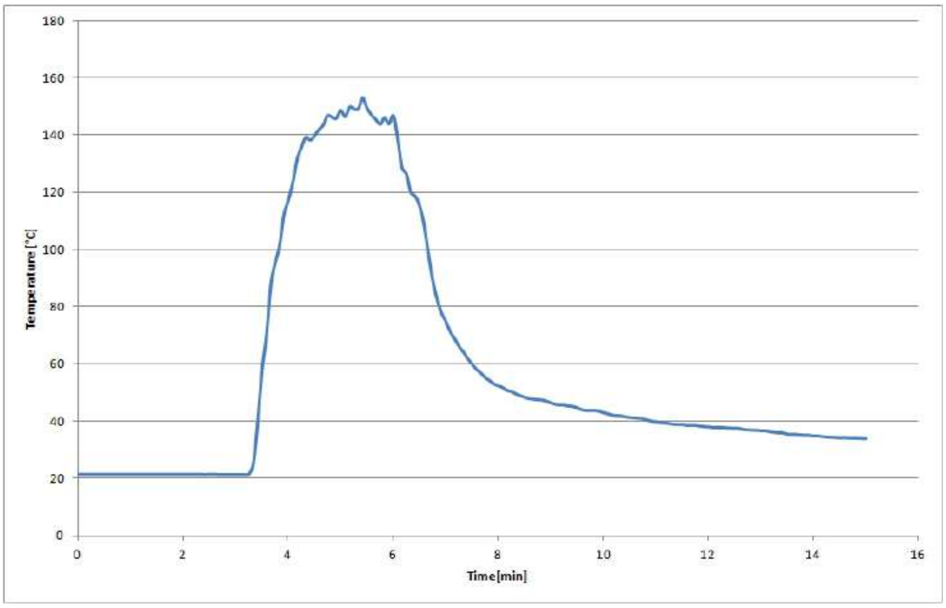

Figure 6.34: Thermocouple 17.

We see that thermocouple 17 has a lower value than thermocouples 9 and 12, which are just below the false ceiling. The reason is that the hot plume does not impinge directly on the thermocouple.

Thermocouples 19 and 20:

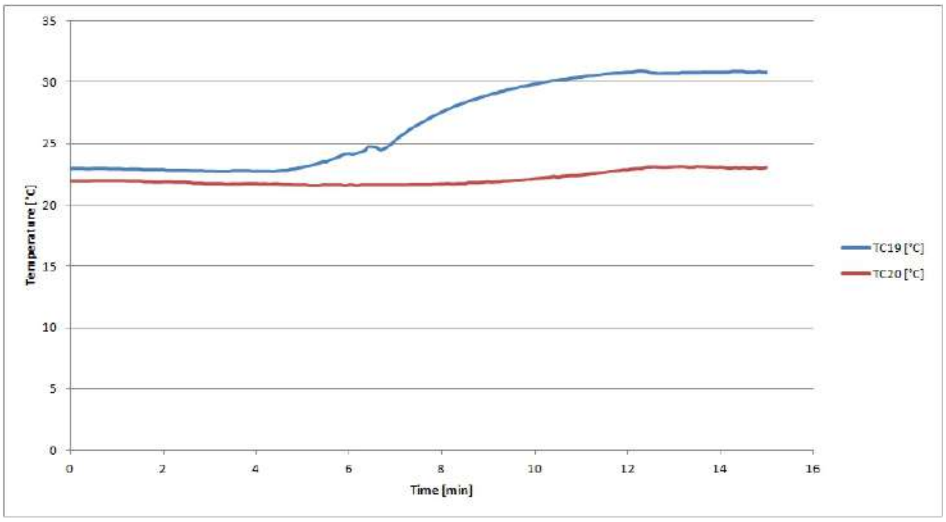

Figure 6.35: Thermocouple 19 & 20.

A similar behaviour is observed as in the other setups.

The results of the pressure measurement and the oxygen measurement are shown here:

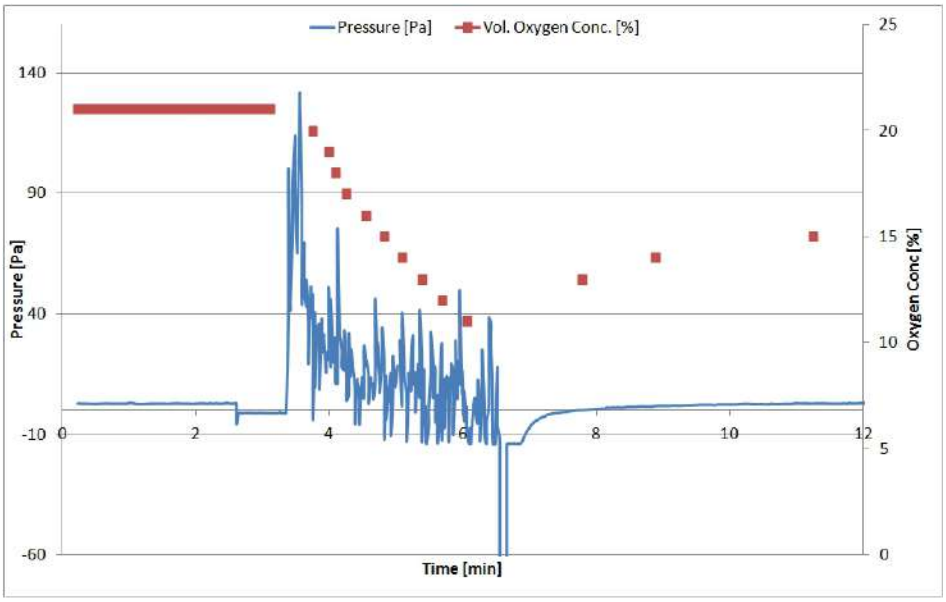

Figure 6.36: Pressure measurement and oxygen concentration.

Although this approach showed somewhat the principles of compartmentation, we can't see an improvement on the behaviour in comparison to setup 1. We still have the problem of the pressure level being too high, taking too long to level out and the oxygen concentration not recuperating fast enough. So, if we want to have improvement on the behaviour, the next setup is the logical choice.

Setup 4: compartmented with false ceiling, with ventilation

As stated in this title, this setup looks at what would happen if we decide to completely compartment the lower part of the low-energy house. We expect to save the upper part of the house from high temperatures, we expect to have a shorter duration of the fire, we expect to remain with considerably higher oxygen levels at the end (generally spoken, the oxygen level on the lower floor will most likely be unacceptably low, whilst the oxygen level on the upper floor will be almost ambient). As the lower part of the house is smaller, the ventilation which has not changed will deliver more fresh air, relative to the volume, this should get the oxygen levels back faster to acceptable levels.
In other words, this should deliver the ideal solution, but during construction of the house, this would mean a surplus cost.

The results of the temperature measurements are shown below:

Thermocouples 8 to 13:

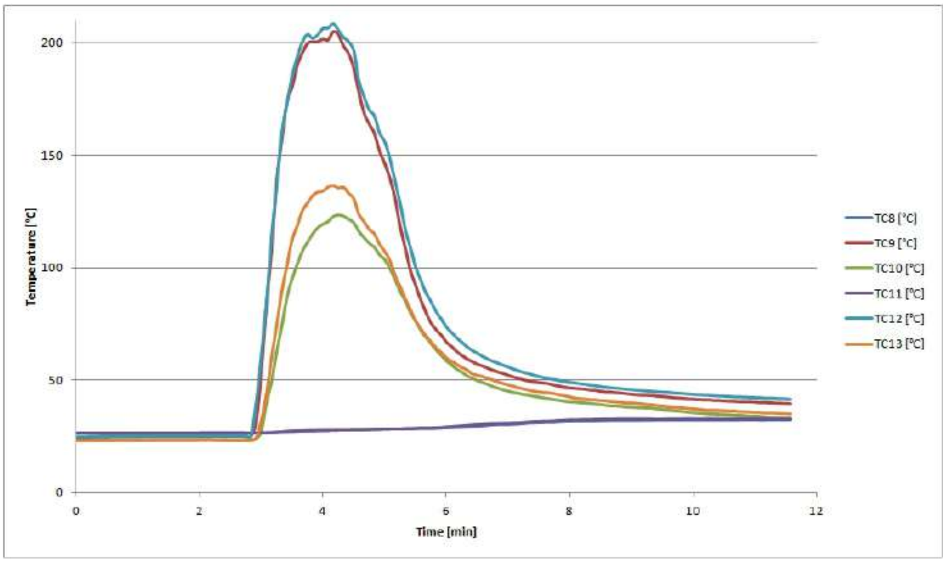

Figure 6.37: Thermocouples 8 to 13.

Indeed, the duration of the fire is shorter. The temperatures on head height are comparable to the temperatures measured in the other setups, but the temperatures measured at the false ceiling are a lot higher. This is of course due to the ceiling jet delivering the hot plume straight to the thermocouples just under the false ceiling. On the upper floor, we see almost no temperature increase at all.

Thermocouple 17:

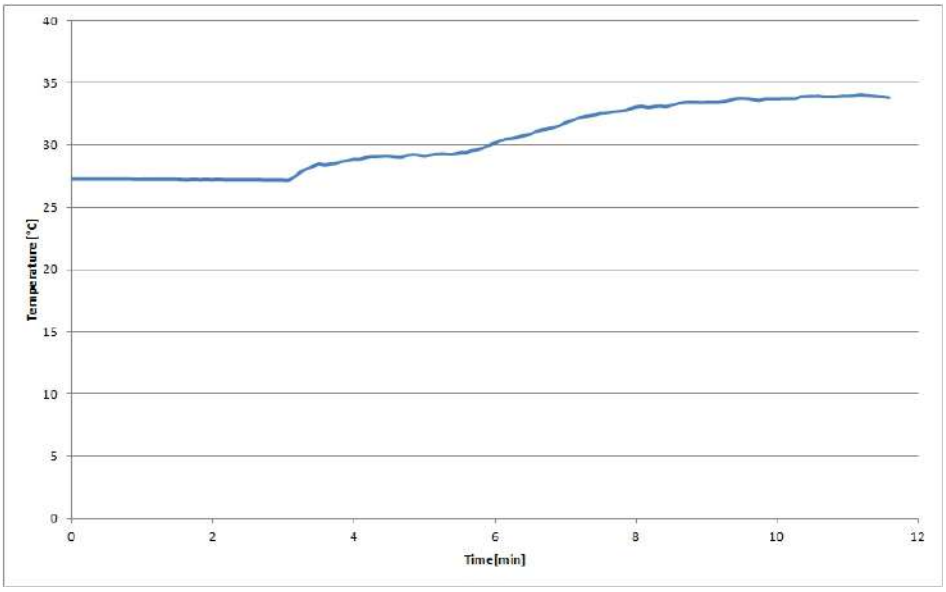

Figure 6.38: Thermocouple 17.

It is clear that no hot gases have entered the upper layer of the house during the fire. Only after the fire, we see a small increase in temperature, this could be due to some leakage. But this would not give problems, the leaked oxygen in the other direction would not be consumed as the fire has already died.

Thermocouples 19 and 20:

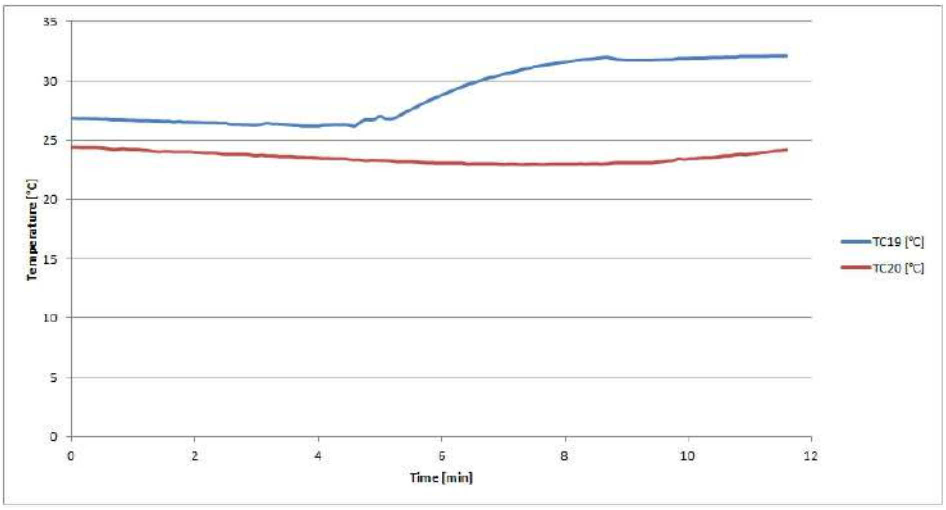

Figure 6.39: Thermocouple 19 & 20.

A similar behaviour is observed as in the other setups.

The results of the pressure measurement and the oxygen measurement are shown here:

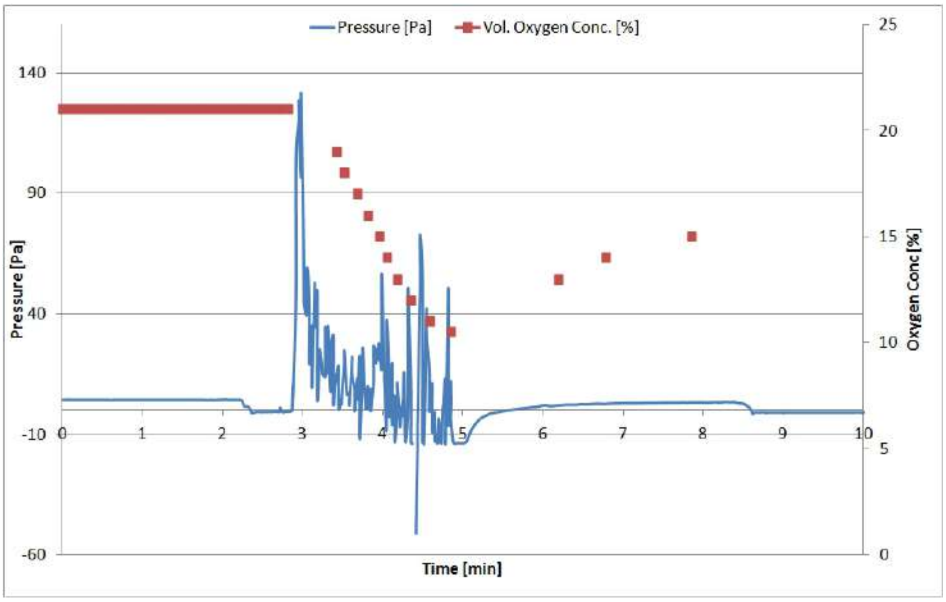

Figure 6.40: Pressure measurement and oxygen concentration.

We see indeed from this figure that the timescale has become shorter. The pressure peak has become slightly, although not considerably, lower.
The main effect of the compartmentation is to be found in the speed with which the pressure lowers to an acceptable level. In this particular setup, the pressure has leveled out after 30

seconds, which would be about a minute and a half. We however also see that the oxygen levels drop faster to unacceptable levels, in about a minute we have oxygen levels which are dangerously low (3 minutes full scale). What we also see, is that the oxygen level rises again to 15% in about 3 minutes, which would be 9 minutes in full scale. This is the fastest recovery of oxygen level of all setups - and the real oxygen level will be influenced by the oxygen level on the floor above. The floor above still has atmospheric levels of oxygen concentration, slightly warmed up. All this together means that I am quite convinced that this setup would be the most beneficial one for people safety.

6.2.6 The results of the one-zone model

As promised, the results of the one-zone model will be shown here. In this way, they can be compared to the results gained from the experiments, more specifically, setup 1.

It is important to remark that I have not really tried to get the temperatures right, since this is quite impossible in a one-zone model: I could only get an average temperature over all of the inside of the model, due to the restrictions of a one-zone model. However, the results gained on the pressure profile in time and the results gained about the oxygen consumption seem to agree with what was measured experimentally. The same order of magnitude was achieved.

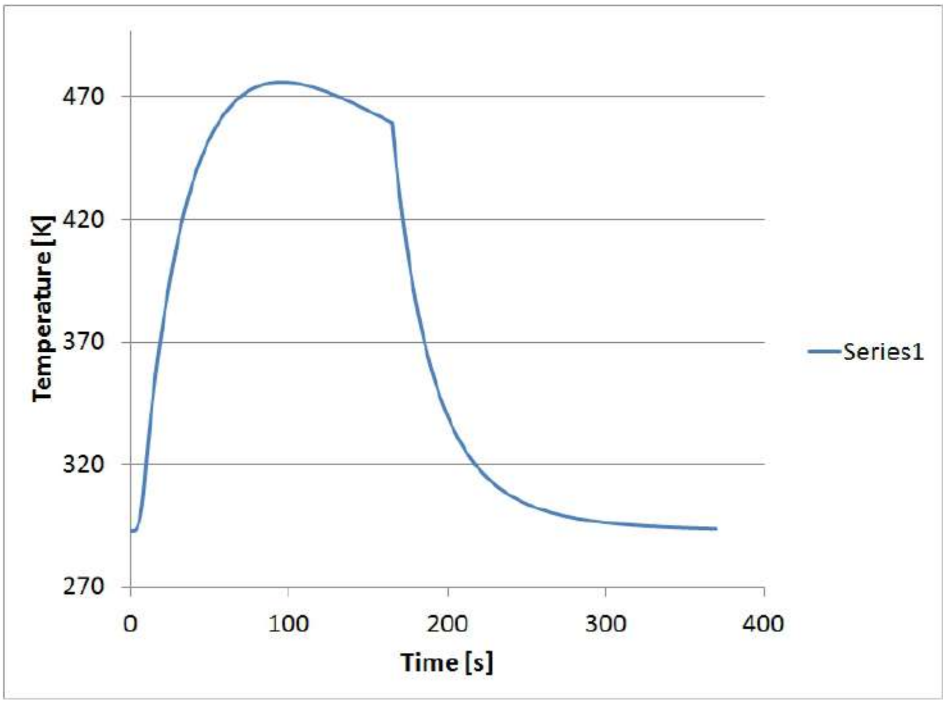

Figure 6.41: Prediction of the average temperature achieved inside.

We can see that the temperature is somewhat overestimated. However, it is still clear that the order of magnitude is correct.

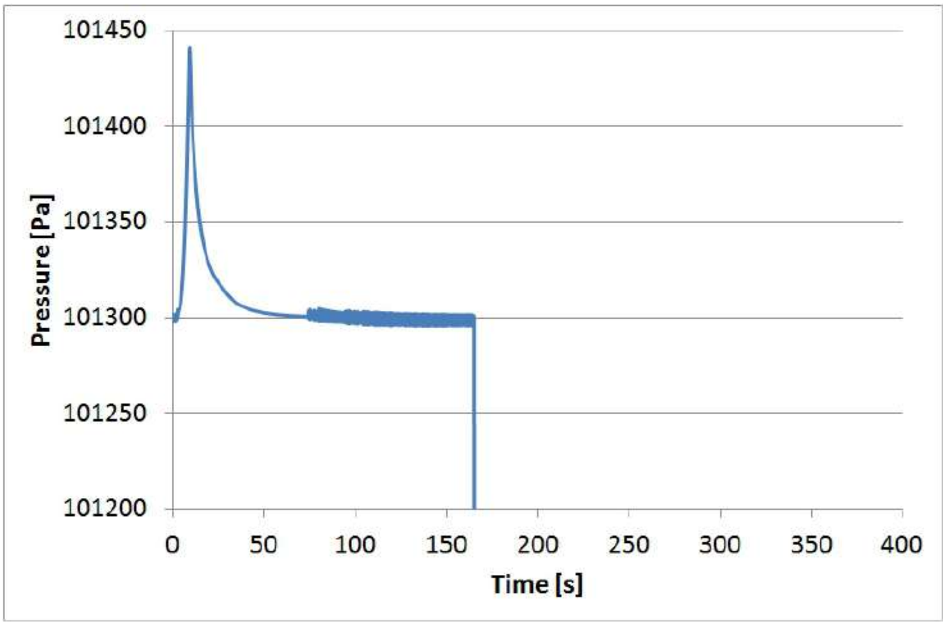

Figure 6.42: Prediction of the average pressure achieved inside.

Indeed, the pressure reaches about the same value. The size of the openings was determined by first running the model without a combustion model. Then, the openings in the model were changed so that they agreed with the first test on the experimental model (see figure 6.15). Using this data, with a combustion model, this result was achieved.

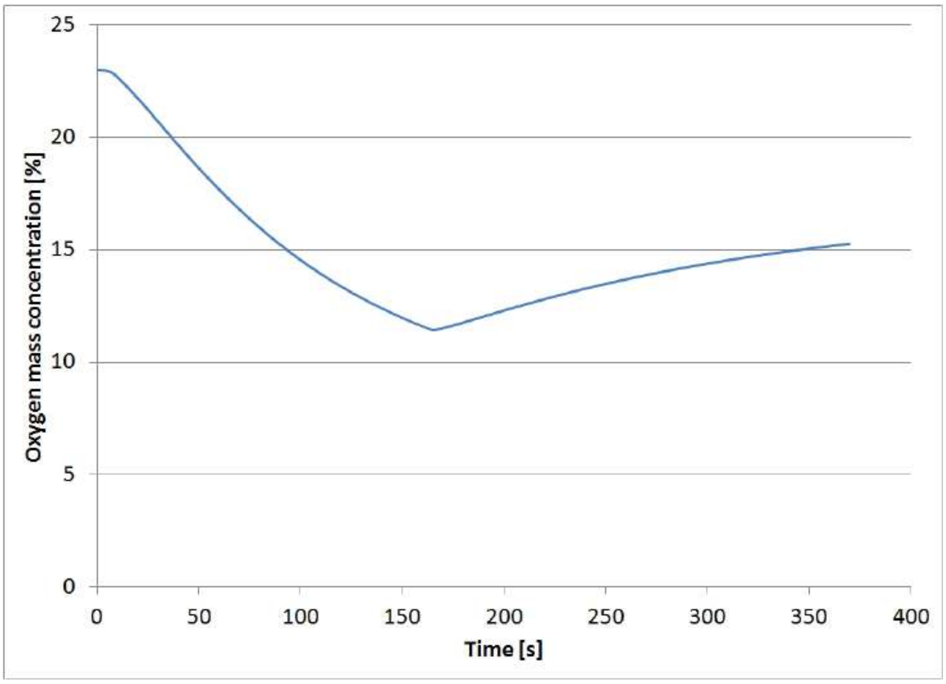

Figure 6.43: Prediction of the oxygen mass concentration achieved inside.

This result shows that indeed the relevant time periods are in the correct order of magnitude. The used combustion model can without doubt still be improved, but we see that for this simple example, the model delivers quite decent results.

Chapter 7

Conclusions

After analysis of all the collected data, we can make the following conclusions:

For occupant life safety:

- The biggest problem for the occupants is the short amount of time in which the problem can develop. Due to the small scale of the house in comparison to other building projects like tunnels, car parks,... the problem is able to manifest itself earlier and faster. It is therefore mandatory that notification happens as soon as possible. Fire alarms have to be fitted and have to respond fast.

- It is possible during the construction phase of the house to make the house a more safer environment. As seen in the experimental results, compartmentation would be a good solution. But, given that complete compartmentation is expensive, it is better to provide some kind of 'compartmentation' than no compartmentation at all. It is for example better to provide a complete second floor with only one gap for the stairs than to keep the complete house open. The biggest effect will be in keeping the temperatures lower on the upper floor as we have seen in setup 3 in the experiments. So, if possible, use compartmentation, if not, try to use walls and ceilings to contain the problem.

- When a serious fire occurs, the best solution is to evacuate all occupants and to close the openings in the house behind you. The effect will be the same as in the experiments: the fire will go out because of a lack of oxygen. It is best to then wait for professionals, as they will be able to assess the situation better.

- We saw a problem with the oxygen concentration inside during the fire. This concentration dropped fast to unacceptable low levels. This also underlines the importance of fast evacuation.

- A second major problem was found to be the pressure increase. This pressure increase is very capable of blocking the possibility to exit. It's very important to make sure people can evacuate at all times, and this can be achieved by making sure the doors open to the outside, so the overpressure will not be able to block people escaping. Another possibility would be to use sliding doors. This conclusion has to be taken with some care though, as this situation would arise when temperature increase inside happens fast. This was the case with the chosen fuel, but it's not certain with other types of fuel.

- Temperatures stay reasonable, although rapidly too high for occupants. This is not because of the walls, due to the large thermal inertia of the walls, heat will actually be extracted. This is (in the initial minutes) similar to the behaviour in a normal house. I would however like to stress that it would be best to investigate seperate cases individually, since fire sources can greatly vary, depending on the house.

For firefighter and other intervention life safety:

- If the occupants have evacuated and have indeed closed the house when they exited, the fire will behave as found in the research in the previous chapter. There won't be a flashover, and the best course of action to take is to wait it out at first and investigate whether the fire has indeed gone out. According to the research, this should be the case after a few minutes (in this thesis, 12 minutes full scale after ignition).
- When the fire has gone out, it is advisory to wait a few minutes before entering the house, except if entering would prove absolutely necessary. The results of this thesis show that the temperatures lower very fast after the fire has gone out, in just 6 minutes (full scale time), the temperatures have dropped to an acceptable level (under 50°C). This would on one hand increase the safety of people entering, and on the other hand make sure that on opening the door, there would (under normal circumstances) be no risk of backdraft due to hot spots. If there would be an external ignition source, the air would most likely contain unburnt volatiles, and as such, care has to be taken.
- Notice that in this thesis, I have made no assumptions on the type and the amount of unburnt volatiles that would be present. Neither have I given an amount of other gas species present in the air, except for oxygen. This has a very good reason: because the fire does not spread and is contained to the initial (major) fire source, the volatiles are very dependent on the major fuel package that started the fire. This means that, depending on the fire source, a different mix of volatiles can be comprised in the air, sometimes even irritants. Therefore, I would advise that the intervention forces try as best as they can to get to know what fuel was the cause of the fire and where the fire was to make an assessment on the type of volatiles before entering the house.

I would like to end this conclusion with the following remarks:
All research has been conducted on scale models of an actual low-energy house. This scale

model holds limitations, of course. A piece of glass was installed to observe the fire, but it cannot be concluded that the door leading to the outside would not fail under these conditions: as for temperatures the door should hold, but it's more likely that the sudden pressure increase to about 1000Pa, or 2000N for a typical door, could prove too much. It has been assumed that the door is sturdy enough, and indeed, if we look at a normal entrance door to a house (not even a low-energy one), it is usually a sturdy door, meant to keep the house safe from unwanted intrusion.

However, to get absolute certainty about this and to make sure that the house would indeed behave as in these experiments, a next study can be conducted with a full scale low-energy house. Given the increasing amount (relative and absolute) of low-energy houses, this seems like a very important research project.

Finally, during this research, I noticed there was a lack of knowledge on combustion models in low oxygen environments for zone models. Additional research would be very helpful in the future to find a working submodel which describes the behaviour in a satisfactory way.

Word of gratitude

I would like to take a moment of your time to thank everyone that has had a positive impact on the course of this thesis. I'll try to do this in everyones own language:

Eerst zou ik graag mijn promotor bedanken, prof. Bart Merci. Dankzij zijn actieve steun is deze thesis mogelijk geweest en heb ik de kans gekregen de experimenten te doen. Ik zou dan ook graag Patrick Ysebie van harte bedanken voor zijn sterke ondersteuning tijdens de experimenten! Ook mijn vader, Geert Debrouwere, heeft me heel wat geholpen om het model ineen te zetten.

Jag skulle också väldigt gärna tacka Caroline Andersson från botten av mitt hjärta. Genom sitt aktiva, kärleksfulla stöd under de ibland tuffa stunder under avhandlingen, jag lyckades framhärda. Älskling, jag kommer till dig snart! Jag vill också tacka alla i Lund som hjälpte mig, som lärare i LTH, mina vänner i F-korridoren och resten av Lund!

Finally, I'd like to thank everyone in Edinburgh, the teachers who gave me the great opportunity to improve my knowledge in fire safety, and my friends in Edinburgh to improve my knowledge of the social life in Edinburgh. I would also like to give a huge thanks to everyone of the IMFSE program, all of you guys and girls are great! There will always be at least one door in Belgium (or Sweden) which will be open for you. I'm really looking forward to see all of you again!

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To sum it all up: thank you very much, each and every one of you! Next round is on me!

Brecht

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Paper for Fire Forum 2012

Deze Appendix bevat de paper aanvaard voor de (België).

Een experimenteel en computationeel onderzoek naar de initiële fase van brand in passiefhuizen

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Abstract:
Dit onderzoek bekijkt de initiële fase (pre-flashover) van een brand in een passiefhuis. Er wordt aan de hand van zowel experimenten als CFD en zonemodellen bekeken hoe de brand in een passiefwoning zich gaat gedragen en wat de beste reactie is door bewoners en brandweer in geval van een brand. De scope beperkt zich tot residentiële passiefhuizen.

I. Inleiding

Deels door economische, deels door ecologische overwegingen, is er de laatste tientallen jaren een grote evolutie opgetreden in de manier waarop huizen gebouwd worden. In de jaren '60 werd nog niet veel aandacht besteed aan isolerende eigenschappen van materialen [1]. De eerste golf van beter isoleren en zuiniger ventileren kwam er door een besef dat de grondstoffen niet onuitputtelijk zijn en dat er economisch een voordeel te doen is indien beter geïsoleerd wordt. De tweede golf, die nu begint, steunt op het besef van het eindige draagvermogen van de planeet [2]. Daarom worden woningen steeds beter geïsoleerd en geventileerd, tot op het punt van passiefwoningen. Een precieze definitie van passiefwoning werd voorzien [3]:

- Energiebehoefte voor verwarming < 15kWh/m²/jaar
- Bij een ΔP=50Pa moet het aantal luchtverversingen lager dan 0.6 per uur zijn
- Het percentage van oververhitting in het gebouw (T>25°C) moet ≤5%.

Er kan verwacht worden dat de aard van het gebouw, zowel qua ventilatie als isolatie, invloed zal hebben op het brandgedrag. Om de veiligheid van bewoners en brandweer te garanderen, dient meer inzicht te worden verkregen in het brandgedrag in passiefhuizen. Recent werd aan de universiteit van Mons hierop onderzoek verricht [4].

Deze paper is gebaseerd op de masterproef van Brecht Debrouwere [5] ter afronding van de International Master of Science in Fire Safety Engineering [6].

II. Methodologie

Als specifiek voorbeeld voor residentiële passiefhuizen wordt de E-Cube bestudeerd. Dit is een prototype van een mogelijks commercieel toe te passen gezinswoning, ontworpen volgens de principes van passiefbouw [7]. De plannen zijn vrij beschikbaar zijn en de geometrie is eenvoudig, wat experimenteel onderzoek en schaling makkelijker maakt. Een aanzicht van de E-Cube is te zien op Figuur 1:

Figuur 1: aanzicht E-Cube

Het probleem werd op 3 manieren (zonemodellering, CFD, experimenten) bestudeerd en door deze resultaten met elkaar te vergelijken zullen we aanbevelingen doen om de eventuele brandveiligheidsproblemen bij passiefhuizen aan te pakken.

III. Computermodel

In eerste instantie worden enkele computermodellen gebruikt om een inzicht te verkrijgen in het gedrag. De gebruikte software is:

- Zonemodellen: CFast6.1.1.54 en Ozone2.2.6 [8]
- CFD-modellen: FDS5.5.3 [9] en ISIS3.0.1

Een grote beperking van al deze pakketten is dat de modellen niet goed kunnen rekenen met incomplete verbranding. Gegeven dat er heel weinig ventilatie aanwezig is in een passiefhuis, kunnen we verwachten dat de zuurstof snel opgebruikt raakt. We kunnen dus stellen dat vanaf de verbranding onvolledig wordt, de resultaten met een korrel zout genomen moeten worden. Dit wil echter niet zeggen dat we de resultaten onbruikbaar worden. Bij vergelijking met experimentele resultaten kunnen we de computermodellen proberen te valideren en hun toepassingsgebied voor passief-woningen bepalen.

IV. Experimenteel ontwerp

Eigenschappen van de brandhaard dienden voor het experimentele ontwerp herschaald worden. Gezien de complexe aard van verbranding moest gebruik worden gemaakt van partiële herschaling. Dit betekent dat er onvermijdelijk afwijkingen optreden bij het herschalen. Het primaire getal dat constant blijft, is het Froudegetal. Er wordt ook voor gezorgd dat de temperaturen in het schaalmodel overeenkomen met die in de werkelijkheid. Onderstaande tabel toont het resultaat van de herschaling.

	reëel	test
Hoogte	8m	1m
Breedte	8m	1m
Diepte	8m	1m
Brandhaard	1,5MW	8,8kW
Ventilatietoevoer	60m³/h	3m³/h

Belangrijke ontbrekende parameters hierbij zijn straling en de dikte/materiaaleigenschappen van de muren. Dit is een bewuste keuze, gebaseerd op volgende redeneringen:

Straling: aangezien we te maken hebben met partiële herschaling, zou straling bij de keuze van een kleinere brandhaard gezorgd hebben voor een onevenredige invloed van de straling. Een tweede reden is dat we kijken naar de initiële fase van een brand. Daarbij zal de keuze van de brandstof bepalend zijn voor de straling: een gemiddelde roetproductiefactor kan niet worden gebruikt. Daarom werd gekozen voor een brandstof die zo goed als geen straling afgeeft: methanol. Zo worden onzekerheden m.b.t. straling kleiner (en stelt het vermogen van de brandhaard eigenlijk een 'convectief' vermogen' voor).

De dikte van het isolatiemateriaal werd ook niet herschaald. De thermische inertie is zo groot dat de isolatie na 15 minuten de warmte nog altijd gebruikt om op te warmen. Dit werd bevestigd met computersimulaties.

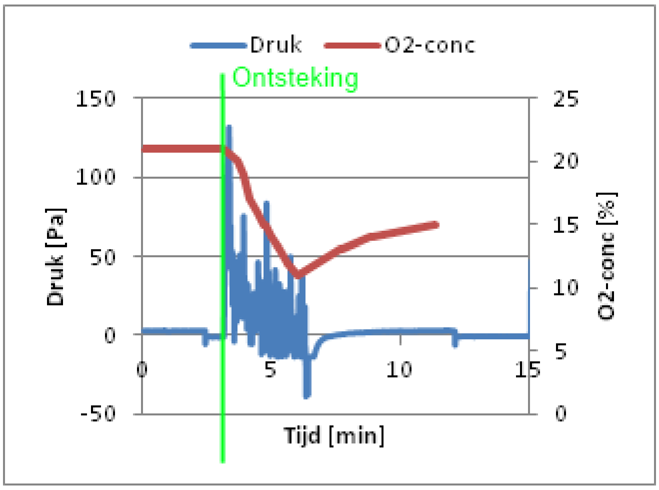
De testopstelling bestaat uit een houten kubus binnenin bekleed met brandvertragende gyproc. Er werd op gelet dat de thermische inertie van de volledige constructie groot genoeg is, zodat in de initiële fase van de brand (de eerste 15 minuten) de warmtedoorgang door de wanden zich nog in de transiënte fase bevinden. De thermisch dikke wanden werken daarentegen eerder als koelplaat.

4 set-ups werden getest:

- Ventilatie ingeschakeld, ongecompartimenteerd
- Ventilatie uitgeschakeld, ongecompartimenteerd
- Plaat tussen verdiepingen, ongecompartimenteerd
- Verticaal gecompartimenteerd

Uit de 4 verschillende set-ups zijn algemene tendensen waar te nemen: de belangrijkste betreffen druk (in een reële situatie wordt dit 8 maal groter herschaald) en zuurstofconcentratie.

Setup 3 heeft als resultaat:



V. Conclusies

Uit de experimenten en het vergelijk met de computermodellen zijn er enkele algemeenheden te destilleren:

- De zuurstofconcentratie daalt snel tot ongeveer 10,5%. Zo dooft de brandhaard.
- De overdruk stijgt tot waardes waarbij het onmogelijk is voor een persoon de deur te openen.
- De invloed van de voorziene ventilatie is minimaal. De ventilatie is ook niet ontworpen voor brand.
- De temperaturen binnenin dalen na het uitdoven van het vuur erg snel door de absorberende werking van de thermisch dikke isolatie.
- Concentraties van gassen zijn onzeker: door de korte, hevige brand is slechts 1 brandstof betrokken in de brand, dus is dit zeer brandstofafhankelijk. De nauwkeurigheid van computermodellen voor het berekenen van concentraties kan worden verbeterd.

VI. Aanbevelingen

Uit deze conclusies zijn enkele aanbevelingen te maken:

- Detectie gebeurt idealiter zo snel mogelijk, ook 's nachts.
- Deuren gaan best naar buiten open, zodat geen probleem ontstaat met overdruk.
- Eenmaal geëvacueerd, sluiten bewoners best de deur. Zo zal de brand vanzelf uitgaan.
- Risico op backdraft is laag, als we er van uitgaan dat "hot spots" voor ontsteking zouden moeten zorgen. De temperaturen blijven laag, zodat de pyrolyse naar alle waarschijnlijkheid ophoudt.

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The used FDS-code

```
Schaalmodel_1m_ongecompMetVentilatie.fds

Headers:
&HEAD CHID='Schaalmodel_1m_ongecompMetVent'/
&TIME T_END=300.00/
&MISC SURF_DEFAULT='Gipsplaat',TMPA=25., CO_PRODUCTION=.TRUE. /


Definition of mesh:
&MESH ID='MESH', IJK=48,48,48, XB=-0.1,1.10,-0.1,1.10,0.00,1.20/
MESH ID='MESH2', IJK=24,24,48, XB=-0.1,1.10,-0.1,1.10,0.00,1.20/



Definition of pressure zones:
&ZONE XB=-0.1, 1.02,-0.1, 1.1, 0.0, 1.2 / Pressure Zone 1
&ZONE XB=1.04, 1.1,-0.1, 1.1, 0.0, 1.2 / Pressure Zone 2


Definition of materials:
&MATL ID='GYPSUM PLASTER',
      FYI='Quintiere, Fire Behavior - NIST NRC Validation',
      SPECIFIC_HEAT=0.84,
      CONDUCTIVITY=0.48,
      DENSITY=1440/

&SURF ID='Gipsplaat',
      MATL_ID(1,1)='GYPSUM PLASTER',
      MATL_MASS_FRACTION(1,1)=1.00,
      THICKNESS(1)=0.05 /


Definition of fire: reaction and fuel

&REAC ID='Methanol',
      C=1.00,
      H=4.00,
      O=1.00,
      N=0.00,
      HRRPUA_SHEET=200.00/

&SURF ID='Branderopp',
      COLOR='RED',
      HRRPUA=200.00/


Definition of ventilation:

&SURF ID='Uitlaat',
      RGB=26,128,26,
      VOLUME_FLUX=2.30897E-004,
      DUCT_PATH=1,2, MAX_PRESSURE=41.
      POROUS=.TRUE. /

&SURF ID='Inlaat',
      RGB=51,51,204,
      VOLUME_FLUX=3.27807E-004,
```

```
      DUCT_PATH=2,1, MAX_PRESSURE=41.
      POROUS=.TRUE. /


Definition of obstacles, defines boundaries model.

&OBST XB=0.00,0.02,0.00,1.04,0.00,1.00, RGB=212,208,200, TRANSPARENCY=0.50, SURF_ID=
'Gipsplaat'/
&OBST XB=0.02,1.04,1.02,1.04,0.00,1.00, RGB=212,208,200, TRANSPARENCY=0.50, SURF_ID=
'Gipsplaat'/
&OBST XB=1.02,1.04,-0.10,1.10,0.00,1.20, RGB=212,208,200, TRANSPARENCY=0.50, SURF_ID=
'Gipsplaat'/
&OBST XB=0.02,1.02,0.00,0.02,0.00,1.00, RGB=212,208,200, TRANSPARENCY=0.50, SURF_ID=
'Gipsplaat'/
&OBST XB=0.00,1.04,0.00,1.04,1.00,1.02, RGB=212,208,200, TRANSPARENCY=0.50, SURF_ID=
'Gipsplaat'/

Definition of ventilation shafts:
&OBST XB=1.02,1.02,0.20,0.225,0.70,0.725,  SURF_ID='Uitlaat', PERMIT_HOLE=.FALSE. /
&OBST XB=1.02,1.02,0.575,0.60,0.70,0.725,  SURF_ID='Inlaat', PERMIT_HOLE=.FALSE. /

False ceiling:
&OBST XB=0.025,0.83,0.025,1.02,0.53,0.55, SURF_ID='Gipsplaat', PERMIT_HOLE=.FALSE. / Vals
plafond




Holes made for leakage and ventilation purposes:
&HOLE XB=0.475,0.50,0.925,1.075,0.00,0.025/ Hole
&HOLE XB=0.475,0.50,-0.075,0.075,0.00,0.025/ Hole
&HOLE XB=0.575,1.10,0.2,0.225,0.70,0.725/ Hole
&HOLE XB=0.575,1.10,0.575,0.600,0.70,0.725/ Hole

Definition of outer boundaries:
&VENT SURF_ID='OPEN', XB=-0.10,1.10,-0.10,1.10,1.20,1.20, OUTLINE=.TRUE. / Vent
&VENT SURF_ID='OPEN', XB=-0.10,1.10,1.10,1.10,0.00,1.20, OUTLINE=.TRUE. / Vent
&VENT SURF_ID='OPEN', XB=-0.10,1.10,-0.10,-0.10,0.00,1.20, OUTLINE=.TRUE. / Vent
&VENT SURF_ID='OPEN', XB=-0.10,-0.10,-0.10,1.10,0.00,1.20, OUTLINE=.TRUE. / Vent
&VENT SURF_ID='OPEN', XB=1.10,1.10,-0.10,1.10,0.00,1.20, OUTLINE=.TRUE. / Vent

Timer identifying when fire starts:
&DEVC ID='TIMER', QUANTITY='TIME', XYZ=0.00,0.00,0.00, SETPOINT=10.00/
&VENT SURF_ID='Branderopp', XB=0.39,0.65,0.40,0.64,0.00,0.00, DEVC_ID='TIMER'/ Brandhaard


Output data:
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBZ=0.70/
&SLCF QUANTITY='PRESSURE', PBX=0.50/
&SLCF QUANTITY='PRESSURE', PBY=0.50/
&SLCF QUANTITY='TEMPERATURE', PBY=0.50/
&SLCF QUANTITY='TEMPERATURE', PBX=0.50/
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBZ=0.01/

&DEVC ID='Pressure_MASS MEAN', QUANTITY='PRESSURE', STATISTICS='MASS MEAN', XB=0.02,1.02,0.02
,1.02,0.00,1.00/
&DEVC ID='Pressure_MEAN', QUANTITY='PRESSURE', STATISTICS='MEAN', XB=0.02,1.02,0.02,1.02,0.00
,1.00/
```

```
&DEVC ID='Pressure_VOLUME MEAN', QUANTITY='PRESSURE', STATISTICS='VOLUME MEAN', XB=0.02,1.02,
0.02,1.02,0.00,1.00/
&DEVC ID='TEMPERATURE MEAN', QUANTITY='TEMPERATURE', STATISTICS='VOLUME MEAN', XB=0.02,1.02,
0.02,1.02,0.00,1.00/
&DEVC ID='TC8', QUANTITY='TEMPERATURE', XYZ=0.05,0.25,0.75/
&DEVC ID='TC9', QUANTITY='TEMPERATURE', XYZ=0.05,0.25,0.45/
&DEVC ID='TC10', QUANTITY='TEMPERATURE', XYZ=0.05,0.250,0.25/
&DEVC ID='TC11', QUANTITY='TEMPERATURE', XYZ=0.05,0.50,0.75/
&DEVC ID='TC12', QUANTITY='TEMPERATURE', XYZ=0.05,0.50,0.45/
&DEVC ID='TC13', QUANTITY='TEMPERATURE', XYZ=0.05,0.50,0.25/
&DEVC ID='GAS', QUANTITY='MASS FRACTION', SPEC_ID='oxygen', XYZ=0.0528,0.4883,0.71/
&DEVC ID='FLOWDoorGat1', QUANTITY='VOLUME FLOW', XB=1.02,1.02,0.20,0.225,0.70,0.725/
&DEVC ID='FLOWDoorGat2', QUANTITY='VOLUME FLOW', XB=1.02,1.02,0.575,0.600,0.70,0.725/
&DEVC ID='GAS02', QUANTITY='VOLUME FRACTION', SPEC_ID='oxygen', XYZ=0.05,0.50,0.75/


&TAIL /
```