CHALMERS

The behavior of aerogel blankets as insulation material in external walls at high temperatures

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design

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Division of Building Technology
Building Physics
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Master's Thesis 2012:147

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Examensarbete / Institutionen för bygg- och miljöteknik,
Chalmers tekniska högskola 2012:147

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Chalmers Reproservice / Department of Civil and Environmental Engineering
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ABSTRACT

The aerogel blanket is a new material that has very low thermal conductivity that makes the material a good candidate for insulating of walls. In fact, nowadays aerogel blankets are used to improve the energy performance of the existing walls.

Using aerogel blankets as insulation material in a wall means replacement of existing insulation material. When a material in a building component is replaced in order to improve a specific performance, it is important to verify the influence of the other functional requirement of the wall such as fire performance. The purpose of this study is to evaluate fire performance of a non-load bearing external wall insulated by aerogel blankets.

In order to achieve this aim, experiments and numerical simulations were carried out. First, two wall models using aerogel blankets as insulation materials were designed. The fire behavior of the designed walls was investigated and the models were modified according to the fire requirements. Finally, the moisture properties of the aerogel blanket were measured and compared to other common insulation materials.

The results indicated that although aerogel blankets thermal properties were excellent, its fire reaction was not so advantageous. However, if aerogel blankets are placed in a safe position of the wall, the thickness of the wall can be reduced. Because of this thickness reduction, using aerogel blankets as insulation material could be an interesting alternative wherever space is an important topic.

It is important to mention that in this project constant energy consumption was considered. Further studies are needed for evaluation of other functional requirements of the wall, e.g. heat and moisture transfer, fire resistance and acoustics.

Key words: Aerogel blankets, Non-bearing external wall, Insulation materials, Energy performance, Fire performance.

Contents

Preface

In this work, experiments and numerical simulation were performed in order to evaluate the possibility of using aerogel blankets as insulation material in external walls at high temperatures. The study was made during February 2012 to September 2012 at the Department of Civil and Environmental Engineering, Building Physics, Chalmers University of Technology, Sweden. The experiments were done at Chalmers University of Technology and at Lund Technical University.

This project was carried out with Bijan Adl-Zarrabi as supervisor who advised me and guided me through my project. I am also thankful for the help from Patrick Van Hees and Marek Machowski during the experiments. Finally, I also would like to thank Aida Ciruela Pérez for her help in the writing of this report.

Göteborg October 2012

Olaya Ciruela Pérez

Notations

Roman upper case letters

A	Area [m^2]
D	Diffusivity of water vapor in air [m^2/s]
Q	Heat flow rate [W]
R	Thermal resistance [m^2.K/W]
RH	Relative Humidity [%]
T	Temperature [K]
U	Thermal transmittance [m^2.K/W]
Z	Vapor resistance [m/s]

Roman lower case letters

c_p	Specific heat capacity [J/kg.K]
d	Thickness [m]
g	Steady-state moisture flux [kg/m^2.s]
m	Mass [kg]
q	Density of het flow rate [W/m^2]
t	Time [s]
v	Air humidity by volume [kg/m^3]

Greek lower case letters

δ_v	Vapor permeability coefficient [m^2/s]
λ	Thermal conductivity [W/m.K]
μ	μ-factor [-]
ρ	Density [kg/m^3]

1 Introduction

Among the environmental issues in today's world, none is as present as the Greenhouse gases (GHGs) emissions. Greenhouse gases (GHGs) emissions present a big current issue in developed countries and in many nations. Leaders state their concern for reducing these emissions while discussing ambitious targets. For example, the EU has decided that 2020 emissions levels should be 20% lower than those emitted in 1990. The awareness of this issue continues to grow and, on this basis, an intense debate is underway studying technical and economic ways to achieve these objectives. One of the most cost-effective actions for greenhouse gas abatement is to improve the residential and commercial buildings insulation (McKinsey & Company, 2009). It is obvious that in order to have a better insulation in buildings, traditional insulation can be used in thicker or multiple layers. Nevertheless, new materials with better thermal properties, such as aerogels and vacuum insulated panels, are being investigated for buildings applications (Ruben Baetens, Bjørn Petter Jelle & Arild Gustavsen 2010).

In this project, the increasing importance of aerogel based materials as new building insulation materials was studied. Aerogel is not still a common material although it was discovered in early 1960s. However, since five years ago, the aerogel technologies have become more important in the global insulation market (M. Cagliardi 2009). Moreover by using aerogel based materials, thinner walls can be built with the same insulation capacity than by using the conventional insulation materials. This characteristic can be very useful in big cities where there are lots of buildings and the area allocated for each new construction building is limited, considering that it might allow rooms with bigger areas. Not only this increase of the living area makes the building more comfortable for the tenant, but it also represents an economic benefit for the owner.

Nonetheless, the change of wall materials can affect the behavior of the wall such as the fire performance.

1.1 Aim

The purpose of this study is to evaluate fire performance of a non-load bearing external wall insulated by aerogel blankets.

1.2 Method

First, a literature study was carried out in order to get information about the insulation capacity requirements of external walls considering the energy consumption. Taking into account this information, two external reference walls were designed by using steady-state heat transfer calculations. These reference designs were a reference wood based wall and a reference concrete based wall. For the calculations, the thermal conductivities of the wall insulation materials were required. This information was found by using Eurocode, manufacturers' datasheets and scientific articles. However the thermal conductivity of aerogel blankets was measured.

The common insulation materials of the reference designs were replaced with aerogel blankets, keeping the same thermal performance.

The second part of this project was the study of the fire behavior of the designed walls. A literature study of some relevant concepts related with fire was done. Then, the reference designs were simulated using a finite element program based on a transient heat transfer study and considering a fire in the inside part of the external wall. For the simulations, the temperature dependency of the wall material properties was necessary as well as their fire reaction. The reaction to fire and specific heat capacity of the aerogel blanket were measured. Using the results of the numerical simulations made it possible to find out the temperature distribution over cross section of the wall and a second alternative model for having thinner walls with the same insulation capacity than the reference wall designs.

The study of the aerogel blanket material was completed with a comparison between the experimental vapor permeability of aerogel blankets and the vapor permeability of some common insulation materials.

Finally, a discussion took place in order to find a final solution for having thinner walls with the same insulation capacity by using aerogel blankets.

1.3 Limitations

This project focused in an external non-load bearing wall which was a part of a fire department in a multi-family house. But only two types of walls were studied, one was a wood based wall and the other a concrete based wall.

1.4 Short about aerogel based materials

Aerogels are dried gels with small pores and high porosity well known for their low densities and its material properties. They were invented sometime between 1929 and 1930 by Dr. Samuel Stephens Kistler but its first commercialization did not happen until 1950´s (Aerogel.org).

Silica aerogels are the most common type of aerogels and also the ones utilized in building applications.

A picture of a silica aerogels piece is shown in Figure 1.1.

Figure 1.1 Silica aerogels (Aspen Aerogels 2012).

Synthesis

The synthesis of aerogels, and particularly the synthesis of silica areogels, consists in three general steps. Firstly, the gel is prepared by using a sol-gel process in which the solid components of the gel are spread in a dissolvent liquid and after some chemical reactions the mixture reaches the gel point. The second step is the ageing process where the gel becomes stiffer and stronger. Finally, the drying process takes place and it is the most critical step. In contrast to xerogels, on which the wet gels are normally dried by evaporation, aerogels are normally dried by supercritical drying. Through the use of this drying method, where the liquid inside the pores is removed above both the critical temperature and pressure to avoid capillary tension which can produce the facture of the pores, the dried samples have the same porous texture as the wet state. (Ruben Baetens, Bjørn Petter Jelle & Arild Gustavsen 2010).

Solid properties

Silica aerogels have a cross-linked internal structure of SiO_2 chains with a large number of small air-filled pores whose size is around 5-70mm (Ruben Baetens, Bjørn Petter Jelle & Arild Gustavsen 2010). Since this structure, where the 95-97% is air, this material has remarkable physical, thermal, optical and acoustic properties very attractive for building applications.

The high porosity of silica aerogels makes this material the lightest solid material known at the moment. Furthermore, silica aerogels are transparent; it makes them very attractive for window insulation. Finally, it has been found that granular aerogels are exceptional reflectors of audible sound (Ruben Baetens, Bjørn Petter Jelle & Arild Gustavsen 2010).

The most important property for this project is its low thermal conductivity. The combination of small pores and a small fraction of solid silica cause this low value of thermal conductivity. Moreover, by adding some kind of opacifying agent, the radioactive conduction in the aerogels can be reduced decreasing even more its thermal conductivity (Axel Berge & Pär Johansson 2012). This makes aerogels to be considered one of the possible new materials for thermal insulation in building.

As a negative aspect, aerogels are also a very fragile material because of its structure. Fortunately, this problem can be solved by incorporating it in a fibrous matrix. They are known as aerogels blankets (Ruben Baetens, Bjørn Petter Jelle & Arild Gustavsen 2010).

1.4.1 Aerogel Blankets

The aerogel blankets are textile-like blankets as the Figure 1.2 shows. This product should be prepared adding fibers or a fibrous matrix to the pre-gel mixture which contains gel precursors, then the gel can be dried (Ruben Baetens, Bjørn Petter Jelle & Arild Gustavsen 2010).

An aerogel blankets picture is shown in Figure 1.2.

Figure 1.2 Aerogel blanket (Aspen Aerogels 2012).

Health and safety

On account of aerogels blankets are made by amorphous (non-crystalline) silica with 97% of particles larger than 45µm, aerogel insulation sheets suffer from dust production. Some healthy institutes; such as the International Agency for Research on Cancer (IARC), the Organization for Economic Co-operation and Development (OECD) and the Occupational Safety and Health Administration (OSHA); after having studied the amorphous silica particles, claim that these particles are not toxic for the human health. Whereas, the typical breathable dust rate for most of the commercial aerogel insulation products is 5mg/m^3, while the limit for amorphous silica established by OSHA is 80 mg/m^3. (Aspen Aerogels 2012).

The personal protective equipment (PPE) suggested by Aspen Aerogels Company consists of a P100 respirator, work gloves and safety glasses. However, these recommendations are only from comfort and convenience, not because there is eye, inhalation or dermal risk. But it is true that the contact with these particles can produce a sensation of dryness to skin and irritation to eyes, skin and respiratory tracts (Aspen Aerogels 2012).

Environmental impact

Aerogel blankets are fully recyclable and they have been rated as Silver in Cradle to CradleSM certification from McDonough Braungart Design Chemistry. This strict certification process examines a product's manufacturing and as well as its ecological impact in order to know if the product's wastes are entirely eliminated in agreement with a healthy and sustainable society (Cabot Corporation 2011).

Furthermore, Aerogels blankets have ZERO Ozone Depleting Potential (ODP) which means the relative amount of degradation that a chemical compound can cause to the ozone layer. And making reference to the greenhouse gas emissions, it is worth mentioning that this product has a Global Warming Potential (GWP) less than 5 (Aspen Aerogels 2012).

Continuing with the environmental restrictions, this insulation material is fully compliant with the regulation, evaluation, authorization and the restriction of chemicals (REACH). And the substances restricted by the Restriction of Hazardous Substances Directive (RoHS) are not contained in the finish product when concentration is higher than the limits stated.

Applications

Aerogel blankets have different applications in many fields. Some examples are presented below (Aspen Aerogels 2012):

- Aerospace & Military
- Building & Construction
- Clothing & footwear
- Industrials Plants
- LNG & Cryogenics, which is the production of materials at very low temperature
- Subsea Pipelines

Aerogel blankets are an innovated alternative to traditional insulation materials in Building and Construction applications. Even though, its cost is still high in the building industry.

Some examples of aerogel blankets Building & Construction applications are presented below (Aspen Aerogels 2012):

- Roof insulation
- Floor & Balcony insulation
- External insulation
- Internal insulation
- Heat Bridge Treatments, e.g. located on the ledges of the windows
- Services, e.g. pipe insulation

One manufacturer that develops this product is Aspen Aerogels (INC.), in which the aerogel blanket product used for wall insulation is named Spaceloft®. They use Spaceloft® to improve the insulation capacity of existing walls. Although the blankets of 10 mm of thickness are currently available, it is also possible to have them in higher thickness or apply it in several layers. Aspen Aerogels (INC.) was consulted in order to discover when the material should be applied to the walls.

In external insulation, the Spaceloft® layer or layers are directly applied to the existing wall using mechanical and/or adhesive to attach the blanket to the wall (Aspen Aerogels 2012).

Some examples of external insulation are shown in Figure 1.3. A mechanical fixing example is shown in Figure 1.4.

Figure 1.3 External insulation (Aspen Aerogels 2012).

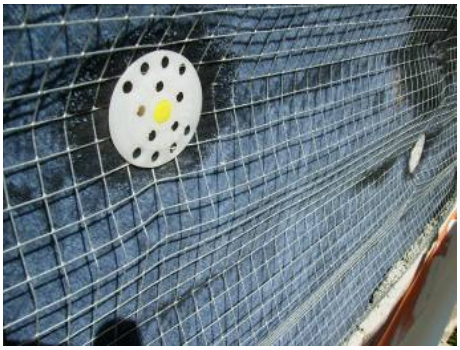

Figure 1.4 Mechanical fix of aerogel blankets in external insulation (Aspen Aerogels 2012).

When external insulation is not possible because of a complicated facade system or the external façade belongs to a heritage, the wall can be insulated internally. Spaceloft® is applied to the existing wall using standard plaster to guaranty the full contact and avoiding any air layer between aerogel blankets and the existing wall which could affect the thermal performance of the wall (Aspen Aerogels 2012).

By using Spaceloft®, which is the thinnest material available for internal insulation, it is possible to preserve living space in small areas improving the U-value of the wall. This product is easy to transport, to fix and it does not need a specific maintenance. Moreover, the indoor air quality is maintained (Aspen Aerogels 2012).

2 Wall design based on energy performance

During the design of the project walls, it was aimed to ensure a good thermal insulation. Thus, it was established a constant value of the thermal transmittance (U-value) of the designed walls. In the concrete based walls, the U-value was remained constant at 0.2W/m^2.K. This number is based on a Post-Kyoto target of 85% CO_2-emissions-saving for the building stock (Eurima 2007). In the wood based walls, the U-value was remained constant at 0.17W/m^2.K because it was prioritized the common studs used in wood houses which are 45x45mm plus 45x145mm.

The two reference walls, wood based reference wall and concrete based reference wall, were designed by steady-state heat transfer calculations. Furthermore, the insulation material of the reference walls were replaced with aerogel blankets keeping the same thermal performance resulting in the first alternative walls, i.e. first alternative wood based wall and first alternative concrete based wall.

In the wall design, the thermal conductivities of the wall insulation materials were required.

2.1 Determination of aerogel blankets thermal conductivity

Thermal conductivity (λ) of aerogel blankets was determinate by the Heat flow meter method. The test equipment follows the procedure described in EN 12667 which is the Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus (LambdaLab LLC).

A picture of the instrument used in this experiment is presented in Figure 2.1.

Figure 2.1: Holometrix Rapid-k apparatus, Chalmers University of Technology.

The heat flow meter method is based on establishing a steady state one-dimensional heat flux through a test specimen. A sample is placed between two parallel plates whose temperatures are constant, hot and cold plate. For example, if the hot plate temperature is 30^{0}C and the cold plate temperature is 10^{0}C, the mean temperature in the test specimen will be the average of the other two and it is said that the measured thermal conductivity corresponds to 20^{0}C. When the steady state condition is achieved, the thermal conductivity of the test specimen can be calculated considering the Fourier´s law, which takes into account the temperature difference, the heat flux and the geometry of the sample (J. Randall Lawson et al. 2005).

The Heat flow meter operation is illustrated in Figure 2.2.

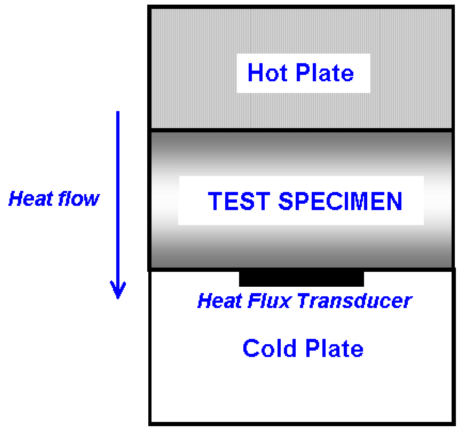

Figure 2.2: Scheme of the Heat flow meter operation

The samples required in this method are square samples of 30 x 30cm and a thickness of 0.5-10 cm. The central area of the sample is tested to guarantee that the temperature is constant in the test specimen. The thermal conductivity range goes from 0.015 to 0.43 W/m.K and the mean temperature of the sample can be from -5 to 100^{0}C (LambdaLab LLC).

The method is a non-destructive experiment, which means that a same sample can be tested several times at different temperatures. Nevertheless for the experiments executed during this project, different samples were used in each test. Because the properties of the material tested could change with the temperature and this material produced dust during sample preparation.

Samples of aerogel blanket, *Spacetherm®* purchased from A. Proctor Group (Ltd.) were prepared for measurements. Two types of *Spacetherm®* were tested; one was defined as 'black color' while the other one was defined as 'white color'. Although both materials are classified, by A. Proctor Group (Ltd.), under the same named, *Spacetherm®*, the 'white color' is the new version of the 'black color'.

Five samples of aerogel blankets were prepared; three samples were 'white color' and two were 'black color'. The 'white color' samples were tested at 10, 20 and 40^{0}C, while the 'black color' samples were tested one at 10^{0}C and the other at 40^{0}C.

The results of the experiments are presented in Table 2.1.

Table 2.1 Experimental λ of black and white aerogel blanket samples [W/m.K].

$T(^0C)$	White color	Black color
10	0.015	0.014
20	0.015	
40	0.016	0.015

There was difference between the experimental values of the two samples types. The 'white color' aerogel blankets results were utilized for the simulations because it was the newer version.

2.2 Walls design

Two reference walls were chosen to be studied. The first wall was a wood based wall, which is a common wall material in Sweden. And the other wall was a concrete based wall because the concrete is used in multi-family houses. The studied walls were non-load bearing external walls of multi-family houses.

The designed reference walls were modified by adding aerogel blankets, keeping constant the thermal performance of the walls. The calculations were performed by using the constant thermal conductivity of the wall insulation materials at room temperature.

The used thermal conductivities are presented in Table 2.2.

Table 2.2 Thermal conductivity of insulation materials.

Insulation material	λ [W/m.K]	Comments
Aerogel blankets (AB)	0.0155	Experimental value
Mineral wool (MW)	0.0320	Literature value
Polystyrene (PS)	0.0312	Literature value

2.2.1 Wood based walls design

Mineral wool was used as insulating material and it was placed between wood studs with a spacing distance of 600mm. The wall stud dimensions were standards dimensions available in the market; two wood studs of 45x45 mm and 145x45 mm were used because they are the most common ones in external walls.

In the inside part of the wall, a gypsum board with a thickness of 16 mm was used and a vapor barrier was placed behind the gypsum board. A wind protection was added behind the mineral wool.

In the outside part of the wall, wood external cladding, which is very common in wood houses, was used. There exist two different types of wood cladding: vertical panels and horizontal panels (Carl Michael Johannesson 1992). In the façade system, the wood horizontal cladding panels (22mm thickness) were fixed onto nail studs (34x45mm) which were fixed over the timber frame leaving a well-ventilated cavity between them (Svenskt Trä).

The structure of the reference wood based wall is shown in Figure 2.3.

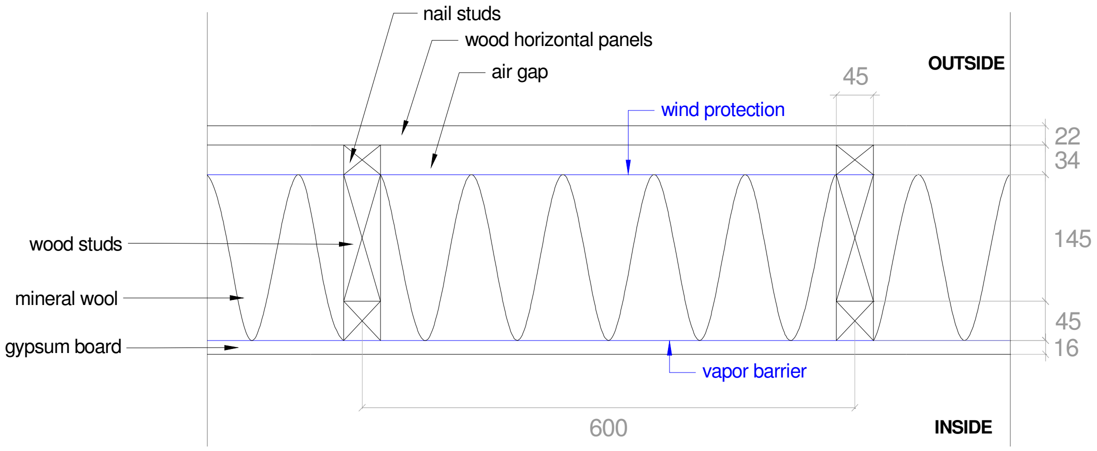

Figure 2.3 Reference wood based wall, units in mm.

Reference wood based wall (WBW_R)

The wood studs used were 45x45 and 45x145mm which means that the thickness of mineral wool should be 190mm. The thermal resistance (R-value) and the thermal transmittance (U-value) of the wall were calculated as:

$$R_{WRW\_R} = \frac{d_{MW}}{\lambda_{MW}} = \frac{0.190}{0.032} = 5.94\ \frac{m^2\ K}{W} \quad (2.1)$$

$$U_{WRW\_R} = \frac{1}{R_{WRW\_R}} = 0.17\ \frac{W}{m^2\ K} \quad (2.2)$$

Where

R_{WRW_R} Thermal resistance of the reference wood based wall (m^2.K/W)
U_{WRW_R} Thermal transmittance of the reference wood based wall (W/m^2.K)
d_{MW} Thickness of mineral wool (m)
λ_{MW} Thermal conductivity of mineral wool (W/m.K)

First alternative wood based wall (WBW_1)

In this model, all the mineral wool was replaced with aerogel blankets and the thermal performance of the wall was kept constant. The aerogel blankets thickness of this model was calculated by Equations 2.3 and 2.4.

$$R_{WBW\_1} = R_{WBW\_R} = 5.94\ \frac{m^2\ K}{W} \tag{2.3}$$

$$R_{WBW\_1} = \frac{d_{AB}}{\lambda_{AB}} = \frac{d_{AB}}{0.0155} = 5.94\ \frac{m^2\ K}{W} \rightarrow\ d_{AB} = 0.092\ m \tag{2.4}$$

Where

R_{WRW_1} Thermal resistance of the first alternative wood based wall (m^2.K/W)

d_{AB} Thickness of aerogel blankets (m)

λ_{AB} Thermal conductivity of aerogel blankets (W/m.K)

2.2.2 Concrete based walls design

The thickness of concrete in a non-load bearing wall can vary from 100 to 200 mm, depending on the sound insulation (Cement Concrete & Aggregates Australia 2009). The thickness of the concrete in the designed wall was 150mm.

Polystyrene was used as insulation material and its thickness had be 156mm to achieve the U-value of 0.20 W/m^2.K. The insulation material was mechanically fastened to the wall using a galvanized expanded metal lath and concrete screws with washer (National Concrete Masonry Association 2010). As this wall was external insulated using polystyrene, a vapor barrier was not required

In the outside part of the wall, plaster was applied in a layer of 3 mm and because there was not air gap a wind protection was not needed.

The structure of the reference concrete based wall is shown in Figure 2.4.

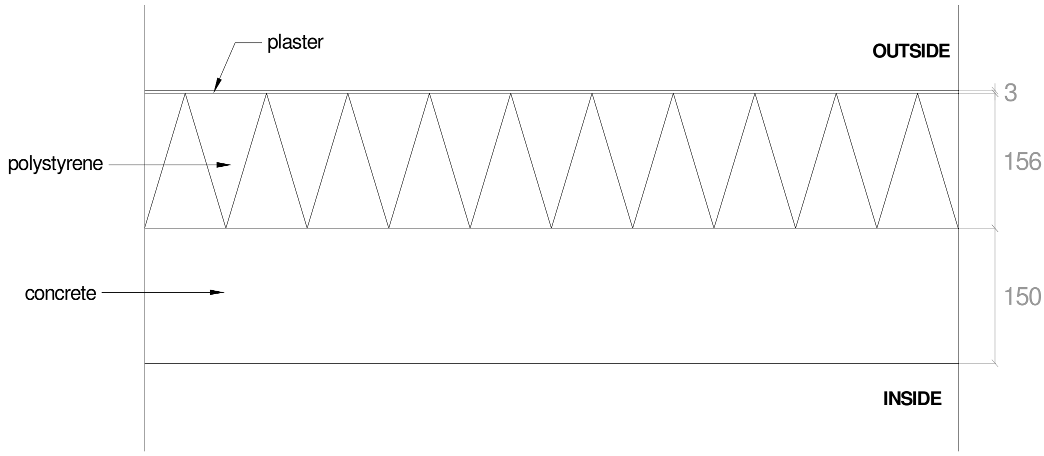

Figure 2.4 Reference concrete based wall, units in mm.

Reference concrete based wall (WBW_R)

The U-value was fixed at 0.20 W/m^2.K which means that the R-value and the thickness of the polystyrene were calculated using Equations 2-5 and 2.6.

$$R_{CBW\_R} = \frac{1}{U_{CBW\_R}} = 5.0\ \frac{W}{m^2\ K} \tag{2.5}$$

$$R_{CBW\_R} = \frac{d_{PS}}{\lambda_{PS}} = \frac{d_{PS}}{0.0312} = 5.0\ \frac{m^2\ K}{W} \rightarrow\ d_{PS} = 0.156\ m \tag{2.6}$$

Where

R_{CRW_R} Thermal resistance of the reference concrete based wall (m^2.K/W)

U_{CRW_R} Thermal transmittance of the reference concrete based wall (W/m^2.K)

d_{PS} Thickness of polystyrene (m)

λ_{PS} Thermal conductivity of polystyrene (W/m.K)

First alternative concrete based wall (CBW_1)

In this wall, all the polystyrene was replaced with aerogel blankets and the thermal performance of the wall was kept constant. The aerogel blankets thickness of this wall was calculated by using Equations 2.7 and 2.8.

$$R_{CBW\_1} = R_{CBW\_R} = 5.0 \frac{m^2\,K}{W} \tag{2.7}$$

$$R_{CBW\_1} = \frac{d_{AB}}{\lambda_{AB}} = \frac{d_{AB}}{0.0155} = 5.0\ \frac{m^2\,K}{W} \rightarrow\ d_{AB} = 0.078\,m \tag{2.8}$$

Where

R_{CRW_1} Thermal resistance of the first alternative concrete based wall (m^2.K/W)

d_{AB} Thickness of aerogel blankets (m)

λ_{AB} Thermal conductivity of aerogel blankets (W/m.K)

2.3 Summary of first alternative results

The thicknesses (d) of the reference walls and the first alternative walls by replacing all the common insulation material with aerogel blankets are summarized in Table 2.3.

Table 2.3 Reference walls and first walls thicknesses

	wall d [mm]	insulation d [mm]	U-value [W/m2.K]	Δd [mm]	Δd [%]
WBW_R	262	190 (MW)	0.17		
WBW_1	164	92 (AB)	0.17	98	37%
CBW_R	309	156 (PS)	0.20		
CBW_1	231	78 (AB)	0.20	78	25%

Considering the energy performance, the wood based wall thickness was reduced 37% while the concrete based wall thickness was reduced 25%.

3 Fire performance

Fire safety in buildings requires numerical simulations and fire tests which are expensive. For example, in this study, the wall should be built and tested. The fire safety study in this project was based on numerical simulations.

Before starting the fire performance analysis of the reference wall models, a literature study about concepts related to fire was carried out. The fire behavior was studied and as well as the fire compartment idea due to the fact that the external wall studied was part of a fire department in a multi-family house. The European fire classification of materials, construction products and building elements was also investigated.

To control the fire performance of the reference walls, some simplifications were performed in the wall structure in order to create a simulation models. The simplified models were analyzed using a finite element (FEM) program named COMSOL Multiphysics®. A time dependent heat transfer procedures were used by using boundary conditions described in to Eurocode (EN 1991-1-2:2002). For these simulations, the temperature dependency of the wall material properties was required as well as the fire reaction of the wall materials. The materials properties needed for the FEM simulations were the density (ρ), the thermal conductivity (λ), the heat capacity (c_p) and the fire reaction. Moreover, in the aerogel blanket case, experiments were performed to determinate its properties. The thermal conductivity of the aerogel blanket was found using the Heat flow meter method, this experiment is explained in chapter *Wall design based on energy performance* in the subchapter *Determination of thermal conductivity*, and its heat capacity was determined by using the Transient Plan Source (TPS) method. To know the aerogel blankets fire reaction samples of aerogel blankets were tested using the Cone Calorimeter method because there is not much information about this new material

The simulations performed were: first, a steady state-transient study was done in order to know if the simulation models were correct. Furthermore, a gypsum board study was carried out to investigate when the gypsum board collapses from the reference wood based wall model. Finally, the reference wood and concrete based wall models were simulated in order to determine the temperature distribution over cross section of the wall after one hour of fire exposure.

Using the results of the simulations, a second alternative wall models for having thinner walls with the same insulation capacity than the reference wall models was designed. The second alternative wall models were named second alternative wood based wall model and second alternative concrete based wall model.

3.1 Literature study

Some relevant concepts for the study and related with fire were investigated before the simulations.

3.1.1 Fire behavior in a room

Fire is an uncontrolled chemical reaction that produces both light and the energy enough to damage the human skin (James G. Quintiere 1998). This uncontrolled chemical reaction has a particular thermal behavior which is explained bellow. First of all, it is necessary that the fire starts. This first process is known as 'fire ignition'. After this, the fire grows until the flashover point, which is an event that can occur at temperatures of 500 to 600 ^{0}C. The next step is the full development which is a state of a compartment fire where the flames fill the room and the fire consumes all the combustible. Finally the fire decay takes place (University of South Carolina).

The fire thermal behavior is illustrated in Figure 3.1.

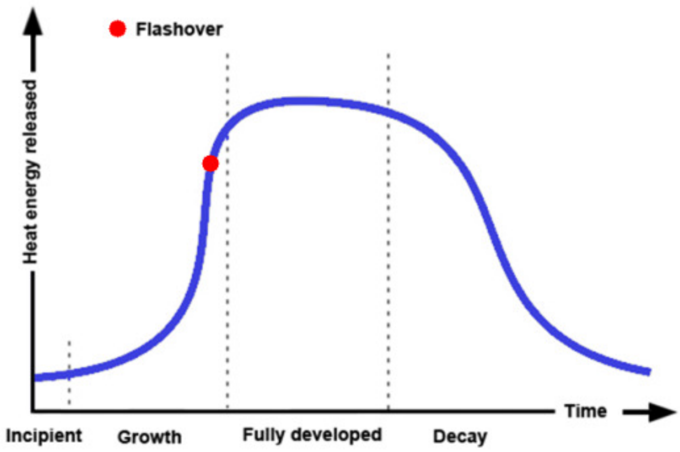

Figure 3.1 Fire grow curve.

3.1.2 Fire compartment division

A fire compartment is a space within building which is enclosed by separation elements that prevent the fire from spreading beyond the compartment during the relevant fire exposure (EN 1991-1-2:2002).

Buildings should be divided into fire compartment so as to both restrict the consequences of fire and ensure sufficient time for evacuation. For small buildings where the consequences of fire are small, such as single-family houses, fire compartments are not needed (BFS 2011:26-5:5).

Buildings classes

Buildings fire protection has difference levels (BFS 2011:26-5:2):

Br0 Very high protection
Br1 High protection
Br2 Moderate protection
Br3 Low protection

Buildings with three of more stories should be designed in building class Br1; this is the case of multifamily houses. However, single-family houses with up to three stories can be designed at class Br2.

The studied wall was a part of a multi-family house, which is classified as class Br1.

3.1.3 European fire classification of materials, construction products and building elements.

Building materials and components should to be tested and classified by the European system in terms of their fire resistant and reaction to fire.

Fire resistance is the ability of a structure, a part of a structure or a member to resist fire for a specified period of time (EN 1991-1-2:2002).

The fire resistance of building components and construction are classified in different fire requirements. These requirements are the following:

R	Load bearing capacity
E	Integrity
I	Insulation
W	Radiation
M	Mechanical resistance
C	Self closure
S	Smoke leakage
K	Fire protection (coverings)

The fire resistance classification is followed by the time limit registered in minutes 15, 30, 45, 60, 90, 120, 180, 240 or 360. This number shows the time which the component should withstand when it is exposed to fire (SP Technical Research Institute of Sweden).

The walls studied were a separating non-load bearing elements of a fire compartment in a building class Br1. This implicates that the walls should be EI60 which means that the surface temperature of unexposed side of the wall should not exceed 160^0C during first 60 minutes (I-Insulation). Furthermore, no smoke and no fire gases should go through the wall (E-Integrity).

The reaction to fire of construction products classification is performed in accordance to the Euroclass system which divides the surface coverings fire reaction into seven main classes (SP Technical Research Institute of Sweden) (Björn Sundström 2007):

A1	Non-combustible material
A2	Limited combustible material
B	Combustible material; no flashover
C	Combustible material; no flashover for 100kW- flashover for 300kW ignition source
D	Combustible material; flashover after more than 2min for 100kW ignition source
E	Combustible material; flashover before 2min for 100kW ignition source
F	Without identifying

The fire reaction classes have the sub index FL when they refer to floors classification.

This fire reaction classification is complemented with the smoke class and the burning droplets class:

s1, s2, s3	From less to more smoke emissions
d0, d1, d2	From less to more burning droplets

The fire properties of the building materials can be measured by several methods. One example is Cone Calorimeter method.

3.2 Determination of aerogel blankets heat capacity

The Transient Plan Source (TPS) method was used to measure the heat capacity at constant pressure (c_p) of aerogel blankets.

The TPS sensor is a very thin double metal spiral with 10 µm thickness sandwiched between two layers of Kapton, which is a polyimide film of 25 mm thickness. This sensor is attached to a gold box of 20mm diameter and a high of 8mm. The sample is placed in the gold box which is covered with polystyrene to achieve adiabatic conditions and locked with a weight to ensure there is no air transferring to the sample (Axel Berge, Bijan A. Zarrabi & Carl-Eric Hagentoft 2012).

The steps to follow in the TPS method are illustrated in Figure 3.2.

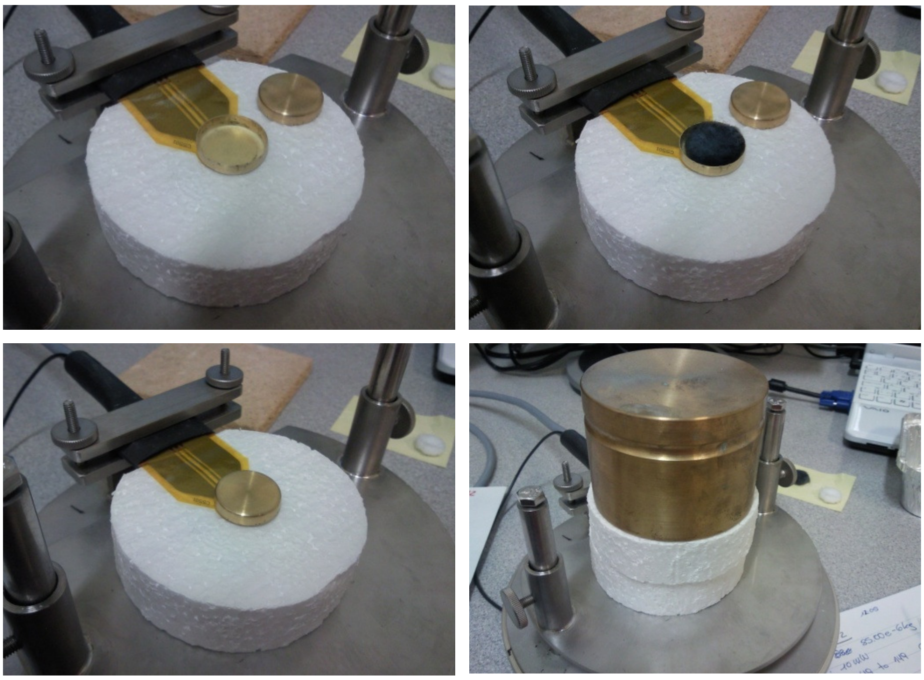

Figure 3.2 Steps to follow in TPS method (Chalmers University of Technology TPS apparatus)

A constant power is applied and the temperature increase of the sensor is recorded during a specific time. With this information and the sample weight, it is possible to calculate the specific heat capacity of the solid samples at atmospheric pressure and at the room temperature where the experiment takes place by the Hot Disk Thermal Constant Analyzer Software. In order to make these calculations, a reference measurement with the gold box empty should be performed (Hot Disk Inc. 2007).

The material tested was the aerogel blanket type *Spacetherm*® 'white' from A. Proctor Group (LTD.). And the mean value was used as input data in simulations at 23^0C.

The results of the measurements are presented in Table 3.1.

Table 3.1 Experimental Cp of aerogel blanket samples at 23^0C

Sample	c_p [J/kg.K]
white_1	934
white_2	928
mean value	931

The mean value was close to the ones presented by Aspen Aerogel (INC.) at 23^0C which was 949 J/kg.K. Linear interpolation was used between 864 J/kg.K at 0^0C and 1000 J/kg.K at 40 ^{0}C.

3.3 Determination of aerogel blankets fire reaction

To study the aerogel blanket fire reaction, experiments were performed using Cone Calorimeter method at Lund University facilities.

The Cone Calorimeter method needs a test specimen with an area of 100mm x 100mm. The sample is exposed to a constant radiant heat flux adjusted from 10 to 100kW/m^2. The effluents from the test are collected and transported through a duct where there is a thermocouple, a pressure sensor and a smoke measurement system. Furthermore, the test specimen is positioned on a load cell and the mass loss of the sample can be recorded during the test. The test results are heat release rate (calculated using oxygen consumption technique), time to ignition, smoke production and weight loss. (Patrick van Hees et al. 2010)

The test equipment is shown in Figure 3.3.

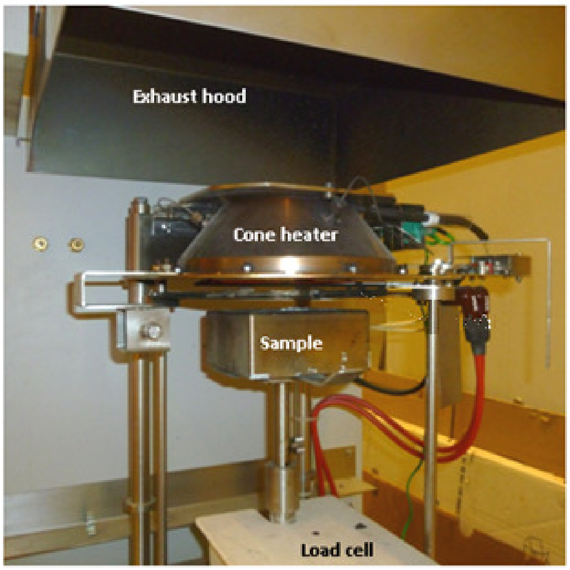

Figure 3.3 Cone Calorimeter apparatus, Lund University.

The Cone Calorimeter results were used for studying the aerogel blankets fire behavior. Furthermore, a thermocouple was added in the backside of some of the samples to know the temperature variation in that part.

3.3.1 Sample preparation

The material utilized for this experiment was the aerogel blanket type *Spacetherm®* from A. Proctor Group (LTD.). Two types of samples were tested; one was named 'black' and the other 'white'. Although both materials were classified by the manufacturer under the same, *Spacetherm®*, the 'white' was a new version of the 'black'.

In total, ten samples of 10 mm of thickness were prepared and tested. Six were 'white' and four were 'black'.

In order to contain all possible burning products the samples should be covered with aluminum paper, see Figure 3.4. Furthermore, the samples were placed in a sample holder with four centimeters of ceramic wool; see Figure 3.5, which is a material similar to mineral wool with better thermal properties, to have adiabatic conditions during the test and to avoid problems with boundary conditions.

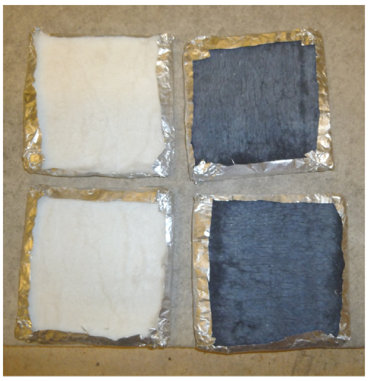

Figure 3.4 Aerogel blanket samples with aluminum paper.

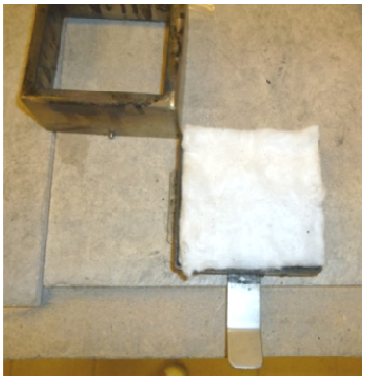

Figure 3.5 Sample holder with ceramic wool.

3.3.2 Tests

The radiant heat flux can be adjusted from 10 to 100kW/m^2. In these experiments the convection was negligible in comparison with the radiation, it was about 10%. Thus, the constant radiation corresponded to heat flow by just radiation. Each radiation level was equivalent to a specific distance from the fire origin and also to a specific intensity of the fire. For example, 25kW/m^2 can be considered as the flux radiation from a hot gas layer in a room close to flashover. This radiation can be considered a high value e.g. sun radiation is around 1.4kW/m^2 (Robert Rosner 1996).

The relation between the cone radiation and the temperature is presented in Figure 3.6. This relation is based on the Boltzmann law which considers the view factor between cone and sample, emissivity and surface temperature. The idea is that a cone temperature and a distance between cone and sample represent radioactive heat energy.

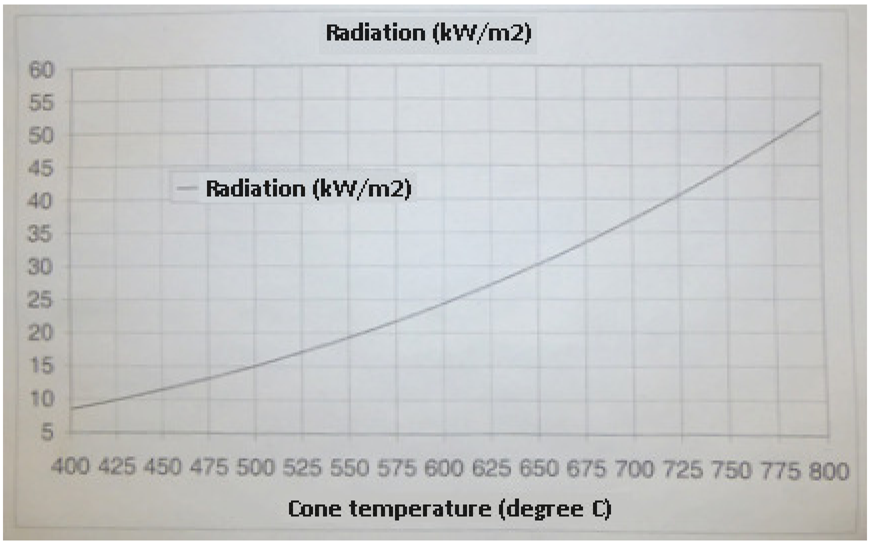

Figure 3.6 Radiation versus cone temperature.

Furthermore, in order to have an idea of the aerogel blanket empirical thermal insulation, in some tests a thermocouple in the backside of the sample was added. The thermocouples were located between the sample backside and the aluminum paper.

The setup of the experiments is presented in Table 3.2. The first test was run at 35kW/m^2 with the 'white' aerogel blanket. The ignition was after few seconds so the next experiments were run at lower radiations.

Table 3.2 Cone calorimeter tests

Name test	Sample type	Cone temp. [^{0}C]	Cone rad. [kW/m^2]	Thermocouple	Test num.
w35	white	700	35	no	1
w25_1	white	600	25	no	1
w25_2	white	600	25	no	2
b25_1	black	600	25	no	1
b25_2	black	600	25	No	2
w20	white	550	20	Yes	1
b20	black	550	20	Yes	1
w17	white	525	17	Yes	1
w15	white	500	15	Yes	1
b15	black	500	15	Yes	1

3.3.3 Results and comments

The results found with the experiments were divided in two groups, the results related to ordinary Cone Calorimeter measurements named: time to ignition and stop flaming time, heat release rate (HRR) and weight loss. And the temperatures measured using a thermocouple in the back side of the samples. Moreover, observations during measuring were discussed.

Reaction to fire results

The ignition time and the stop flaming time of the samples 'white' and 'black' at different radiations are presented in Table 3.3.* indicates that 'white' sample were inert at 15kW/m^2.

Table 3.3 Ignition and stop flaming times.

Name test	ignition time	stop flaming time	
	[s]	[s]	[min]
w35	1.2	12	0.2
w25_1	10.2	40.2	0.67
w25_2	13.2	34.8	0.58
b25_1	12	240	4
b25_2	14.4	240	4
w20	16.2	31.8	0.53
b20	28.8	271.8	4.53
w17	51	468	7.8
w15	*	*	*
b15	21	90	1.5

The results showed that 'black' aerogel blankets needed lower level of radiation to ignite. The minimum radiation for igniting of 'white' aerogel blankets was between 17kW/m^2 and 15kW/m^2 while the 'black' aerogel blanket ignited at lower radiations than 15kW/m^2. One reason could be the 'black' aerogel blanket had higher amount of combustible material. Another reason could be the influence of the color since the black color absorbs more radiation than the white color.

Regarding to heat release rate (HRR) which is the quantity of energy that the fire releases in a second, some of the results are shown in Figures 3.7 and 3.8. For more results see *Appendix A*.

The results indicated that the HRR of the 'black' aerogel blanket was higher than the 'white' one. It could depend on the higher absorption of energy by black color sample, which leaded to higher temperatures and faster burning.

Continuing with HRR, it seems that in the case for the black material the HRR maximum value is almost constant for the flux level and the only difference is that when the radiation is higher the HRR is faster, in other words, the maxim value of HRR is before in time. This behavior is not followed by all materials e.g. plastics and wood. By the way, for the white material the HRR is too small to take conclusions but it is clear that some heat is realized and ignition occurs.

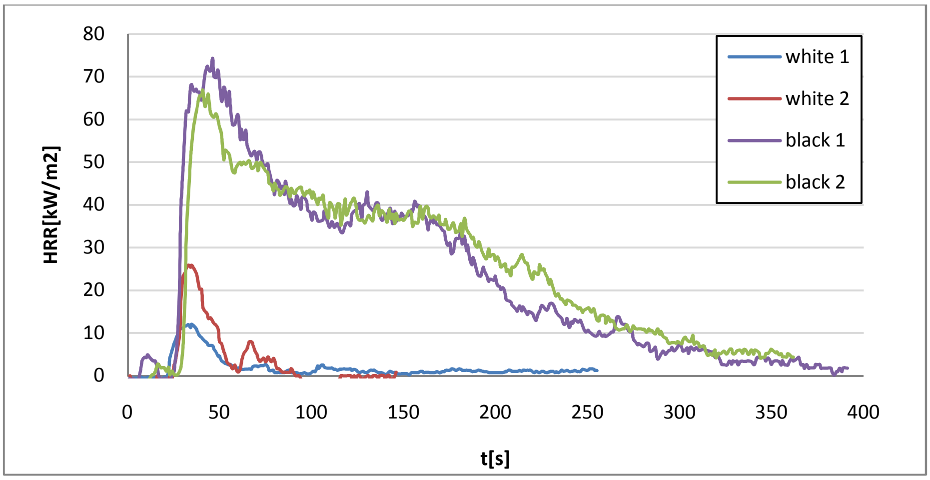

Figure 3.7 HRR of samples exposed to a 25 kW/m2 radiation.

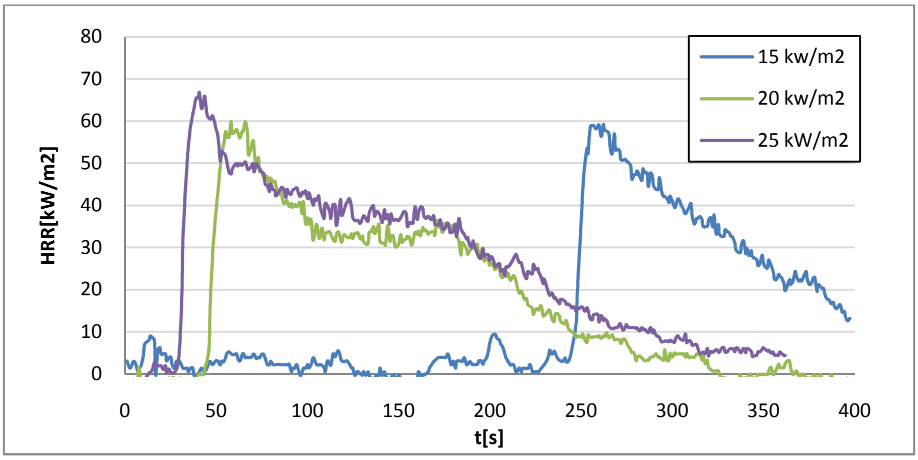

Figure 3.8 HRR of black samples exposed to different radiations.

The mass loss of 'white' and 'black' samples and the back temperatures of the samples are presented in *Appendix B* and in *Appendix C* in that order.

Visual observations

Despite the fact that both samples types, 'black' and 'white', were defined as the same product they had different behavior when they were exposed to fire. For example, although both types started ignition very soon, the 'white' aerogel blanket flaming time was shorter, less than a minute. Furthermore, the 'black' aerogel blanket flaming time was longer because after burning the first layer, it cracked and fire continued burning in the second layer. In other words, the 'white' samples were more compact than the 'black' ones; see Figure 3.9.

Figure 3.9 'Black' and 'white' samples after the test.

3.4 Simplifications

In order to convert the real structure to the numerical simulations, it is necessary to make some simplifications. Thus, the reference wall models were simplified for the fire simulations.

In the reference to the wood based wall model, both the vapor barrier and the wind protection were removed. As well as the connections of the wall materials were neglected. Furthermore, the façade system (cladding) was not included in the model. This last simplification did not affect to the boundary condition of the unexposed side of the wall due to the existence of an air gap.

In the concrete wall model the fixing methods were not taken into account.

3.5 Numerical simulations

Generally, each numerical simulation contains three stages: preprocessing, numerical calculations and port processing.

3.5.1 Preprocessing

The preprocessing includes geometry of the simulation models; material properties and boundary conditions.

3.5.1.1 Geometry

The simulation models were two dimensions and symmetric geometry was used.

The symmetry of the wood based wall model is shown in Figure 3.10.

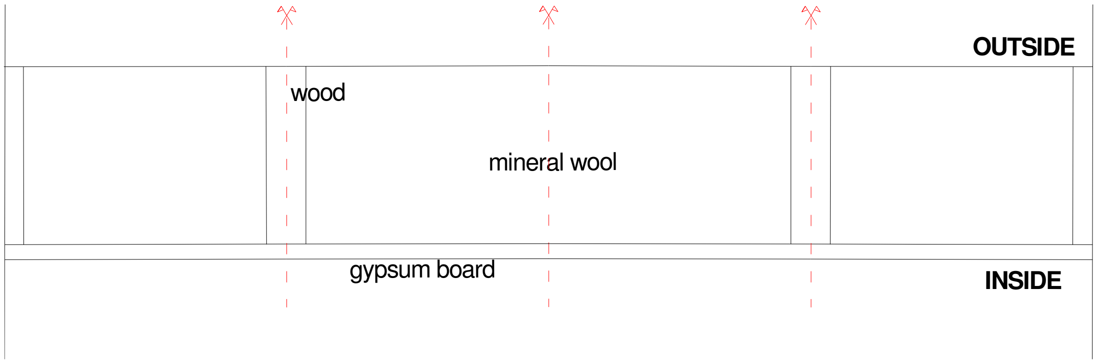

Figure 3.10 Symmetry of wood based wall model.

The wood based wall model used for the simulations is presented in Figure 3.11.

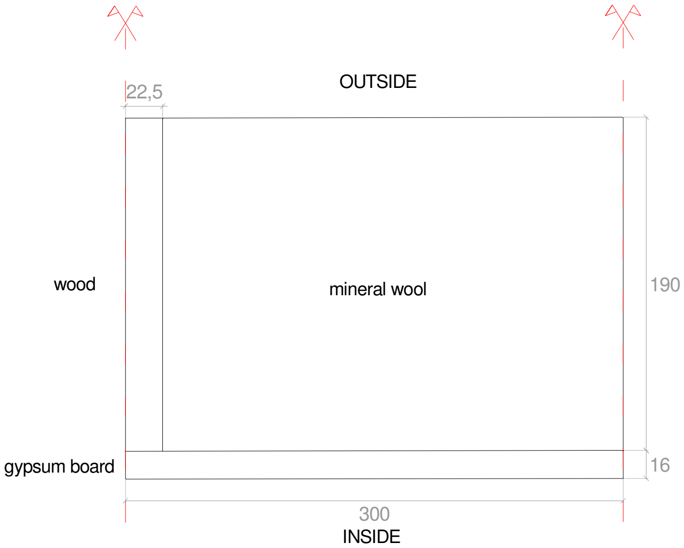

Figure 3.11 Simulation wood based wall model, units in mm.

The symmetry of the concrete based wall model is shown in Figure 3.12.

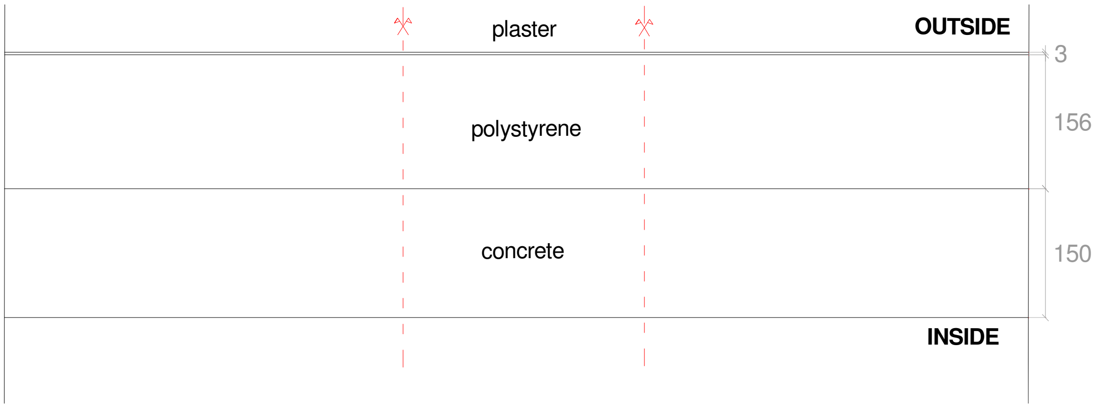

Figure 3.12 Symmetry of wood based wall model, units in mm.

3.5.1.2 Material properties

Fire simulations need material properties at high temperatures but they are not always available. The materials used in the wall models were the followings: aerogel blankets, mineral wool, polystyrene, wood, concrete, gypsum board and plaster. The most relevant material properties for the study were density, thermal conductivity and heat capacity.

In order to use accurate input data, production companies of the materials were consulted. Eurocode and scientist articles were also used. Furthermore, in aerogel blankets case, some experiments were run to measure its properties. For introducing the properties to the simulation program, analytic functions were used when the curve of the material property by temperature was available. Linear interpolation functions were utilized in cases where that curve was not available.

Aerogel blanket

The aerogel blankets material used in this project was the Spaceloft® type offered by Aspen Aerogel (INC.) which is the type normally used in interior and exterior insulation of walls, floors and roofs.

Referring to the fire reaction, the material was tested using Cone Calorimeter method, which is explained in this chapter in the subchapter *Determination of aerogel blanket fire reaction*. The maximum service temperature of aerogel blankets is 200^0C (Aspen Aerogels, INC.).

The aerogel blankets density was considered constant during all the simulations and its value was 150 kg/m^3 (Aspen Aerogels, INC.).

The temperature dependence of the aerogel blankets thermal conductivity is presented in Table 3.4(Aspen Aerogels, INC.).

Table 3.4 Aerogel blankets thermal conductivity

$T[^0C]$	λ[W/m.K]
-160	0.0107
-100	0.0119
-50	0.0130
0	0.0141
10	0.0151*
20	0.0155*
40	0.0160*
100	0.0183
150	0.0231

The temperature dependence of the aerogel blankets heat capacity is presented in Table 3.5 (Aspen Aerogels, INC.).

Table 3.5 Aerogel blankets heat capacity.

T[^{0}C]	c_p[J/kg.K]
-60	576
-40	683
-20	779
0	864
23	931*
40	1000
60	1054
80	1100
100	1150
120	1189
140	1218
150	1234

* is the measured data in this study.

So as to assign thermal properties at higher temperatures than 150^{0}C i.e. 200^{0}C, which is the maximum service temperature of aerogel blankets, linear extrapolation was used.

Mineral wool

Mineral wool is well known wall insulation material. There exist different types of mineral wool depending on the fiber employed as raw material. In this study, stone wool was chosen due to its fire properties, which are better than the glass fibers based products. Moreover, its high melting temperatures (> 1000°C) make it ideal for fire protection and retardation (Netzsch).

It is widely known that at least 96% of mineral wool is made from inorganic fibers derived from basalt, a volcanic rock. And these fibers are glued using a thermosetting resin binder (Industrial Insulation Group, LLC 2012) (Rockwool peninsular).

The mineral wool density was considered constant during all the simulations and its value was 150kg/m^3 (K. Ghazi Wakili, L. Wullschleger & E. Hugi 2008).

Thermal conductivity of mineral wool at different temperatures is presented in Table 3.6. (K. Ghazi Wakili, L. Wullschleger & E. Hugi 2008).

Table 3.6 Mineral wool thermal conductivity.

$T[^0C]$	λ[W/m.K]
0	0.03
170	0.05
430	0.10
590	0.15
700	0.20
790	0.25
850	0.30
900	0.35
1000	0.44

Several companies inform that the mineral wool heat capacity at room temperature is 840J/kg.K. However, the heat capacity of mineral wool at different temperatures was not possible to find and some assumptions were done in order to approximate the specific het capacity.

More than 96% of mineral wool is basalt, which is a volcanic rock, and the other components are minor amounts of binder and oil (Roxul Inc.). Furthermore, when it is exposed to high temperatures the adhesive used to glue the rock fibers burns. Thus, the heat capacity of basalt was used as an approximation of mineral wood specific heat capacity (Peter I. Nabelek, Anne M. Hofmeister & Alan G. Whittington 2012).

The used equation is presented in Equation 3.1.

$$c_p = 2337 - 2.773 * 10^{-1}T + 2.202 * 10^{7}T^{-2} - 2.976 * 10^{4}T^{-0.5} \qquad (3.1)$$

Where

c_p Heat capacity (J/kg.K)

T Temperature (K)

However, at room temperature (20^0C) the c_p, calculated by the Equation 3.1, was 774 J/kg.K which was 66J/kg.K less than the one declared by the mineral wool companies. This difference could depend on the existence of adhesives used but also due to the fibers format of basalt. Another option could have been adding 66J/kg.K to the Equation 3.1 but it would have resulted a higher c_p value, in other words it would have taken less time to achieve steady state. Furthermore, at the same time the temperature in the material would be lower. Thus, the c_p of basalt was used and it is in the safe side concerning fire behavior.

Polystyrene

Polystyrene (PS) is one of the most common rigid plastic foam insulation material for residential and industrial insulation. It can be either found as extruded polystyrene (XPS) or as expanded polystyrene (EPS). Both types of materials are rigid, closed cell and thermoplastic foam materials. However, while EPS is produced from solid beads of polystyrene with small amounts of pentane gas dissolved into the polystyrene base materials to achieve expansion, XPS production starts with solid polystyrene crystals that are extruded along with special additives and a blowing agent. In addition, EPS has a slightly lower value of thermal insulation which remains constant during the life time of the product. It is also easier to work with EPS during its installation and although both products can be recycled, EPS has a better overall environmental impact. However, XPS has a better established reputation as rigid insulation material (Dyplast products 2011). Thus, the extruded polystyrene was selected in the study in of concrete based wall model.

The extruded polystyrene is combustible and can be a fire hazard when it has been improperly installed. This product should not be located in interiors parts where it can be direct exposed to fire, unless an approved thermal barrier, such as a fire resistant gypsum board, is mechanically attached over the foam. In addition, the extruded polystyrene is not recommended for uses where the temperature will exceed 74^0C - 82^0C (DiversiFoam Products). To avoid this problem, external insulation was used instead of internal insulation.

The extruded polystyrene thermal material properties used for the simulations were found in a scientific article (Saleh A. Al-Ajlan 2006).

The XPS density was considered constant during all the simulations and its value was 34kg/m^3.

Thermal conductivity of XPS at different temperatures is presented in Table 3.7. For higher temperatures linear extrapolation was used.

Table 3.7 Polystyrene thermal conductivity.

T[^{0}C]	λ[W/m.K]
22	0.0312
35	0.0324
50	0.0340
65	0.0352

The XPS heat capacity was considered constant during all the simulations and its value was 1280J/kg.K.

Wood

Wood studs were used as structural part of the wood based wall. The wood stud dimensions are:

45x45 mm	45x120 mm
45x70 mm	45x145 mm
45x95 mm	45x170 mm

Spruce is the type of wood chosen for this study. It is very common for structural uses as studs and beams as well as furniture, facades, floorings and doors. Furthermore, Spruce is the most important building and construction timber in Europe (Swedish Wood).

When wood is exposed to fire and subjected to high temperature, a chemical process of incomplete combustion takes places. This process which is known as charring should be taken into account for all surfaces of wood directly exposed to fire. A charring depth should be added to the original member dimensions because the charred part of the member cannot be included in the calculations related to load bearing capacity (EN 1995-1-2:2004). However, as this study focus on non-load bearing walls, the charring of the wood was not taken into consideration.

The dry density of spruce is 440 kg/m^3 (Swedish Wood 2012). However, for this study it was necessary to find out its density in several temperatures. Thus, the dry density was multiplied by the density ratio (EN 1995-1-2:2004). It was considered that the moisture content of the wood at 20 ^{0}C was 12 % (Swedish Wood 2012).

The variation of the wood density with the temperature is presented in Table 3.8.

Table 3.8 Wood density.

T[^{0}C]	Density[kg/m^3]
20	493
100	440
120	440
200	440
250	409
300	334
350	229
400	167
600	123
800	114

The spruce wood is classified as softwood. The thermal conductivity and the specific heat capacity of these types of woods were chosen according to Eurocode (EN 1995-1-2:2004).

The thermal conductivity of spruce at different temperatures is presented in the table 3.9.

Table 3.9 Wood thermal conductivity.

T[^{0}C]	λ[W/m.K]
20	0.12
200	0.15
350	0.07
500	0.09
800	0.35
1200	1.50

The heat capacity of spruce at different temperatures is presented in Table 3.10.

Table 3.10 Wood heat capacity.

T[^{0}C]	c_p[J/kg.K]
20	1530
99	1770
120	2120
200	2000
250	1620
300	710
350	850
400	1000
600	1400
800	1650
1200	1650

Concrete

Concrete is basically a mixture of aggregate and paste. The paste, made with cement and water, binds the aggregates at the same time that the mixture hardens due to a chemical reaction of the cement and the water. The aggregate which is generally divided into two groups, fine and coarse, can be sand and gravel or crushed stone (Portland Cement Association 2012)

The concrete fire reaction is excellent. In fact, concrete does not burn. This makes the concrete acting as an effective fire shield not only between adjacent spaces, but also to protect itself from fire damage (MPA-The Concrete Centre).

The concrete properties present in Eurocode were used in this study (EN 1995-1-2:2004). The concrete density is shown in Table 3.11.

Table 3.11 Concrete density.

T[^{0}C]	Density[kg/m^3]
20	2300
115	2300
200	2254
400	2185
1200	2024

About concrete thermal conductivity, Eurocode gives both the upper and the lower limits. The lower limit was elected as it gives more realistic temperatures for concrete structures. The concrete thermal conductivity was calculated by the Equation 3.2.

$$\lambda = 1{,}36 - 0{,}136\left(\frac{T-273{,}15}{100}\right) + 0{,}0057\left(\frac{T-273{,}15}{100}\right)^2 \qquad (3.2)$$

Where

λ Thermal conductivity (W/m.K)

T Temperature ($293.15K \leq T \leq 1473.15K$)

For the concrete heat capacity it was assumed moisture content of 1.5% of concrete weight. The concrete heat capacity is illustrated in Table 3.12.

Table 3.12 Concrete heat capacity.

T[^{0}C]	c_p[J/kg.K]
20	900
100	900
100.1	1470
115	1470
200	1000
400	1100
1200	1100

Gypsum board

Gypsum board is a product used inside parts of walls and ceiling. There are different types and different thickness which influence its fire reaction. There exist two types of gypsum board, regular and Type X. The main difference between them is that Type X contains noncombustible fibers. The fibers help to maintain the integrity of the core as shrinkage occurs, providing greater resistance to heat transfer during fire exposure (National Gypsum). Regular gypsum board was used for the simulations in this study.

When a wall with gypsum board is exposed to fire, the gypsum board collapses after 15-30 minutes. It depends on the type, the thickness and the way it is attached to the board.

The properties of gypsum board: density, thermal conductivity and heat capacity; were considered constant. The properties used in simulations are presented in Table 3.13 (National Gypsum).

Table 3.13 Gypsum board properties.

ρ[kg/m^3]	λ[W/m.K]	c_p[J/kg.K]
755	0.19	1090

Plaster

The plaster used as exterior of the concrete based wall is named Stucco which is the common name for Portland cement plaster. Stucco is a combination of cement ingredients, aggregate, water and other materials that they are sometimes added so as to achieve different colors and textures. This material is a popular exterior finish for buildings due to the fact that it provides an economical hard surface that is not only rot, rust and fire resistant but it also needs a minimum maintenance routine (Portland Cement Association 2012).

Stucco is basically made of cement materials which provide it a good fire reaction. The plaster was placed in the external part of the wall and it was not affected by the inside fire, at least after an hour. The properties of plaster were considered constant.

The properties utilized in simulations: density, thermal conductivity (Newkem Products Corporation) and heat capacity (Martin A. Wilkinson) are presented in Table 3.14.

Table 3.14 Plaster properties.

ρ[kg/m^3]	λ[W/m.K]	c_p[J/kg.K]
2000	0.65	1000

Summary materials properties

A summary of the origin of the used material properties and the temperature dependence is presented in Table 3.15.

Table 3.15 Material properties characteristics.

Materials	Density (ρ)	Thermal conductivity (λ)	Heat capacity (c_p)	Comments
Aerogel blankets	Constant	Temperature dependent	Temperature dependent	Manufacturer values & experimental values
Mineral wool	Constant	Temperature dependent	Temperature dependent	Literature values
Polystyrene	Constant	Temperature dependent	Constant	Literature values
Wood	Temperature dependent	Temperature dependent	Temperature dependent	Eurocode values
Concrete	Temperature dependent	Temperature dependent	Temperature dependent	Eurocode values
Gypsum board	Constant	Constant	Constant	Manufacturer values
Plaster	Constant	Constant	Constant	Manufacturer values & Literature values

3.5.1.3 Boundary conditions

The boundary conditions for structures exposed to fire are defined in Eurocode (EN 1991-1-2:2002).

In the fire exposed side of the wall, the boundary conditions were:

- The boundary temperature was given by the Standard temperature-time curve, which is defined as:

$$T_{fire} = 20 + 345\ \log_{10}(\frac{8t}{60} + 1) + 273.15 \qquad (3.3)$$

  Where

  T_{fire} Gas temperature in the fire compartment (K)

  t Time (s)

- Convection, where the coefficient of heat transfer by convection was h=25W/m^2.K at fire exposed side.

- The surface emissivity of the member was ϵ_m= 0.8, the emissivity of the fire was ϵ_f = 1.0 and the ambient temperature was T_{amb}=T_{fire}(t)

In the unexposed side of the wall, only convection was considered. The coefficient of heat transfer by convection was h=9W/m^2.K and the external temperature was T_{ext} =293.15 K.

The initial temperature of the model was 293.15 K.

3.5.2 Numerical simulations

COMSOL Multiphysics® software was used for the finite element numerical simulations using 'heat transfer in solids time dependent simulations'.

A 'Steady state-transient study' was carried out in order to evaluate the models. The wood and the concrete wall were both simulated in order to recognize the temperatures of the wall materials, after one hour, to find a safe position of aerogel blankets in the studied walls: 'Wood based wall study' and 'Concrete based wall study'. Previously, in the wood based wall case, a 'Gypsum board study' was made to decide when the gypsum board collapses.

The simulation models were meshed using triangular elements and the element sizes were predefined sizes and calibrated for general physics.

3.5.2.1 Steady-state and transient study of wood based wall

The model used in this study was the reference wood based wall model where mineral wall is used as insulation material.

Mineral wool is a better insulation material than wood material i.e. mineral wool thermal resistance is higher than the wood. Thus, in the inside part, the mineral wool temperature should be higher than the wood temperature and in the outside part the temperature distribution should be opposite.

The theoretical temperature distribution, in the inside and in the outside part of the wall is illustrated in Figure 3.13.

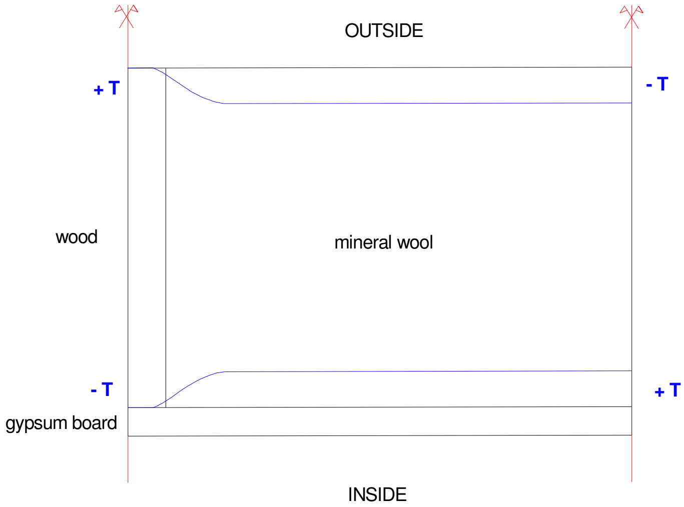

Figure 3.13 Theoretical tempertaure distribution.

The following simulations were performed:

- Steady state with constant material properties
- Steady state with temperature dependent material properties
- Transient calculation with constant material properties
- Transient calculation with temperature dependent material properties

'Constant' means that the material properties did not change with the temperature.

The objective of these calculations was to check if the models were correct as well as to understand the influence of material properties when the temperature changes. To have an answer, transient results and steady-state results were compared. For constant material properties, the properties at 20 ^{0}C were used.

A transient simulation achieves a steady state when temperature does not change with the time. The transient simulation studied never had constant temperatures because the boundary temperature, which was given by the fire temperature equation (EN 1991-1-2:2002), was always increasing. In this study it was assumed that after 30h the difference between temperatures was small enough to consider that the calculations had arrived to the steady state. Consequently, for the transient simulations the presented results were taken after 30h. In case of the steady state simulations, the boundary temperature was fixed at 1455^{0}C which was the temperature value given by the standard temperature-time curve after 30h.

In the steady-state and transient study, 1890 elements of triangular type formed the mesh of the simulation models.

Results

In order to present the results of this study the followed nomenclature was used: *x-axis* corresponds to the longitudinal axis of the simulation model and *y-axis* is the transversal axis.

The geometrical nomenclature of the simulation model is presented in Figure 3.14.

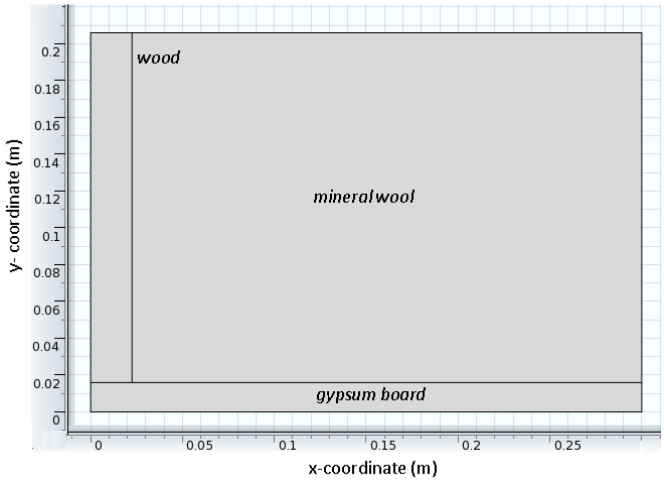

Figure 3.14 Simulation model geometrical nomenclature.

The results of the steady-state and transient study are presented in Figures 3.15, 3.16, 3.17 and 3.18. The results were the temperature in different longitudinal sections (y-position of the simulation models) and the total heat flux of wall external transversal section (y = 205mm).

<u>Results of steady state with constant material properties</u>

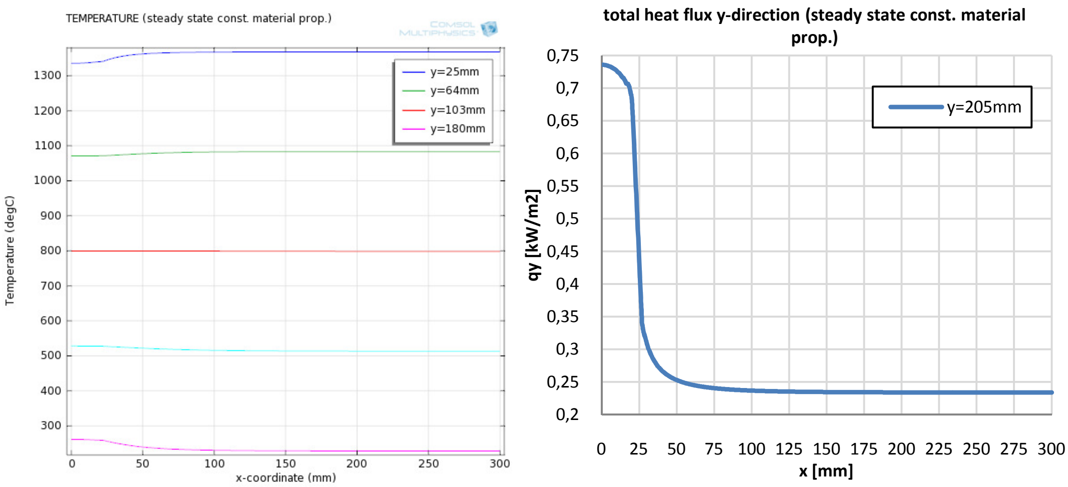

Figure 3.15 Steady-state with constant material properties results.

Results of steady state with temperature dependent material properties

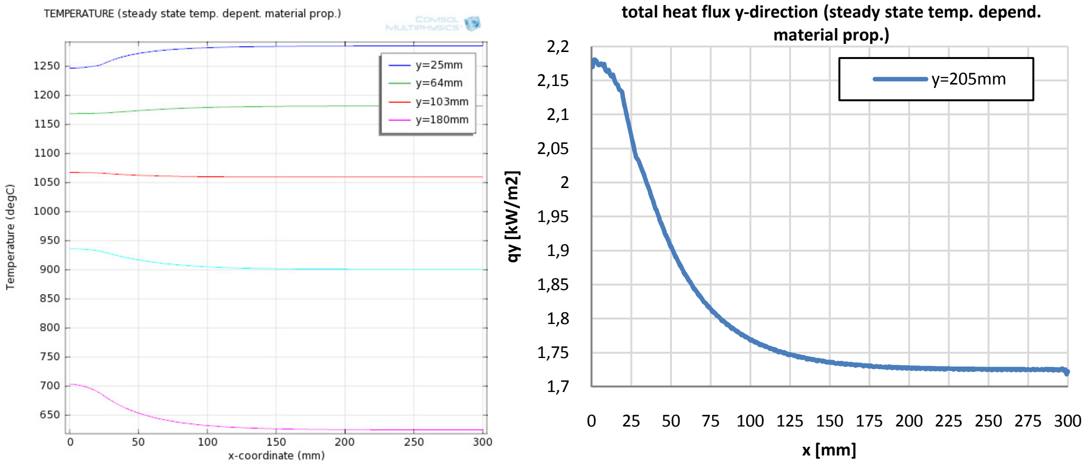

Figure 3.16 Steady-state with temperature dependent material properties results.

Results of transient simulation with constant material properties

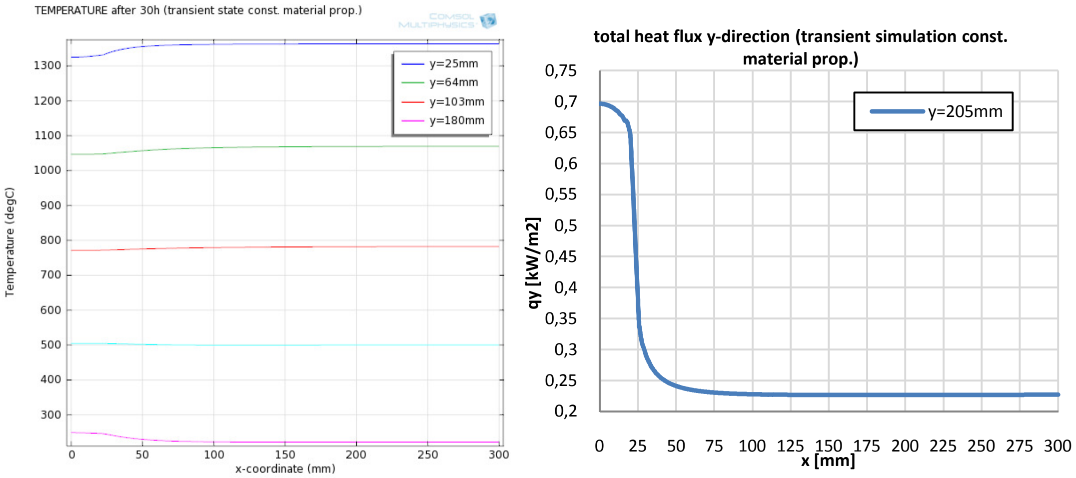

Figure 3.17 Transient simulation with constant material properties results.

Results of transient simulation with temperature dependent material properties

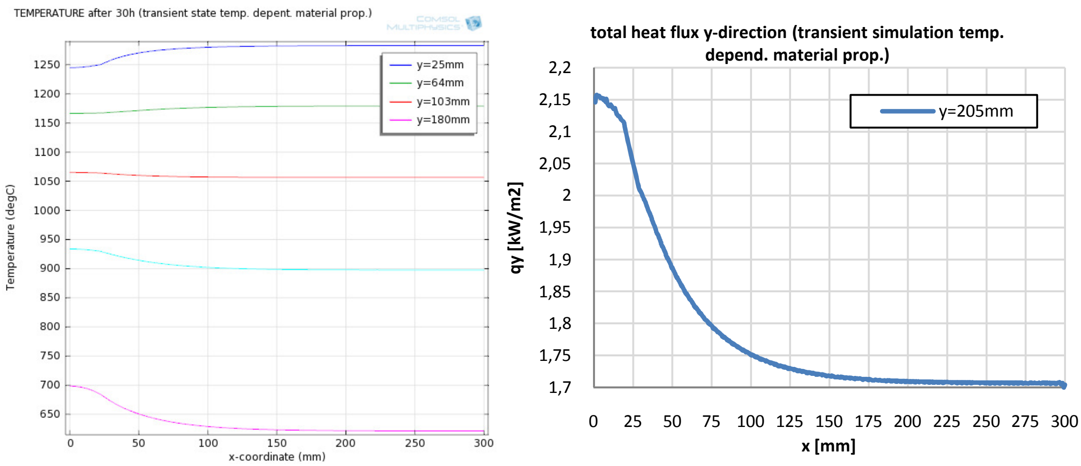

Figure 3.18 Transient simulation with temperature dependent material properties results.

The last simulation, transient simulation with temperature dependent material properties, was the one explained in this project. The temperature evolution in the inside part (y=25mm) and in an intermediate transversal section (y=103mm) at different times are shown in Figure 3.19. It was chosen an intermediate section because after one hour of simulation, the highest temperatures arrived around this section.

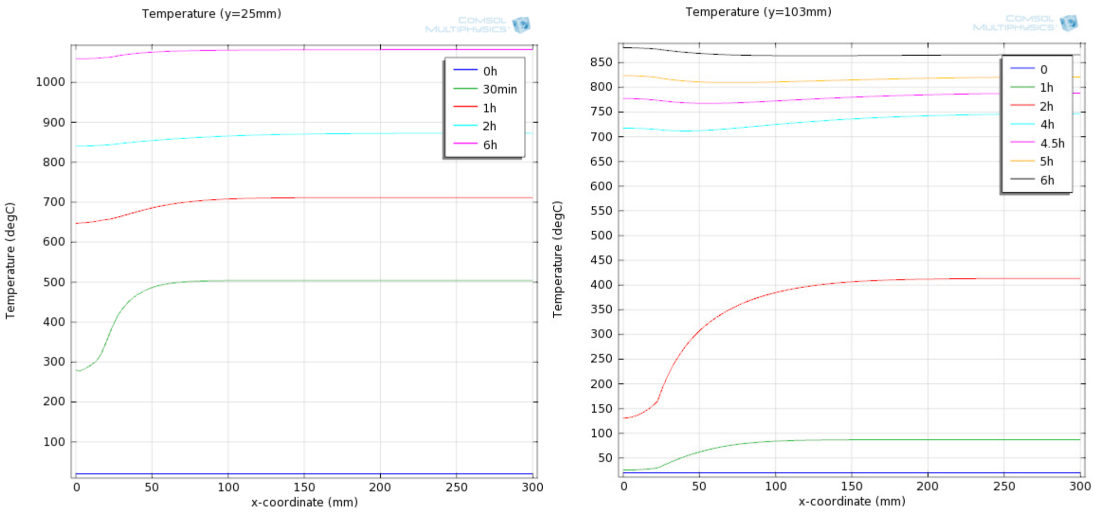

Figure 3.19 Transient simulations with temperature dependent material properties temperatures at different times.

The results of the calculations indicated that transient results achieved the steady state results. Furthermore, all the options follow the theoretical behavior explained in the first paragraph, higher temperature in mineral wool in the inside part and higher temperature in wood in the outside part. The small difference between steady state and transient simulations depends on the boundary temperature which was constant at 1455^0C in steady state simulation, but in transient simulation it was only in the last second the boundary temperature reached 1455^0C.

Figure 3.19, shows that in transient temperature dependent material properties simulation, in the inside part the mineral wool temperatures were always higher that the wood temperatures, as it should be; but in deeper layers there was a change of the temperature distribution. For example, in the middle of the wall, first the mineral wool had the highest temperatures but after 4.5h mineral wool had the lowest temperatures. As this study was analyzed during the first hour period, mineral wool had higher temperatures because the calculations did not achieve the steady state yet.

The heat flux in the y-direction was higher in wood as the theoretical prediction. Furthermore, in order to verify if the total heat flux value obtained with the simulation was correct some calculations were performed. The analyzed model was the steady state model with the material properties constant with the temperature and the values were from the external boundary in the mineral wool section (y=205.9 mm).

$$q = \frac{Q}{A} = U\,\Delta T \qquad (3.4)$$

$$R = \frac{1}{U} = \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} \qquad (3.5)$$

Where

q Density of heat flow rate (W/m^2)
Q Heat flow rate (W)
A Area (m^2)
U Thermal transmittance (W/m^2.K)
ΔT Temperature variation (K)
R Thermal resistivity (m^2.K/W)
d Thickness (m)
λ Thermal conductivity (W/m.K)

In Equation 3.5, the sub-index 1 corresponded to gypsum board where $d_1 = 0.0159mm$ and $\lambda_1 = 0.1871\frac{W}{m\,K}$ and the sub-index 2 made referent to mineral wool $d_2 = 0.190mm$ and $\lambda_2 = 0.032\frac{W}{m\,K}$. About the temperature variation, ΔT= 1407.

The heat flux from the simulations and from the calculations in mineral wool section is presented in Table 3.16. These values were very similar.

Table 3.16 Heat flux in mineral wool section (W/m^2).

	$q_{simulation}$	$q_{calculations}$	deviation
MW section	233.95	233.62	0.14%

The wall models with temperature dependent material properties had a higher value of the heat flux in the y-direction because with the temperature, the thermal conductivity of the materials increases which leads to less resistance to the heat transfer. Thus, temperatures in the inside part were lower while temperatures in the outside part were higher than in the models with constant material properties.

3.5.2.2 Gypsum board study

In a wall structure with gypsum board, after 15-30 minutes the gypsum board collapses and the substrate is exposed to fire. The objective of this study was to investigate how the time that the gypsum board was in its place influenced the temperature distribution in the wall. The reference wood base wall model was used for studding the influence of the gypsum board.

The results of the steady state and transient study showed that the higher temperatures took place in mineral wool. Thus, the section studied here was the transversal section x=300mm. Four cases, which are presented below, were simulated using time-dependent study:

- The gypsum board does not collapse from the wall (GB always))
- The gypsum board collapses after 15min (no GB after 15min)
- The gypsum board collapses after 20min (no GB after 20min)
- The gypsum board collapses after 30min (no GB after 30min)

The temperatures distribution was studied after 1h, 1.5h and 4h.

761 elements of triangular type formed the mesh of the wall model where the gypsum board was still in its place. And 667 elements of triangular type formed the mesh of the wall model where the gypsum board was not included.

Results

The temperature distributions after 1h, 1.5h and 4h of the difference cases in the mineral wool section are presented in Figures 3.20, 3.21, 3.22.

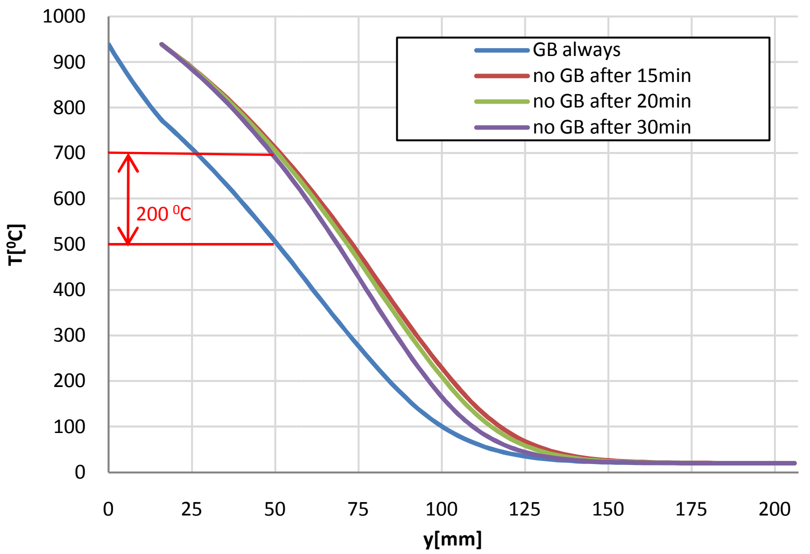

Figure 3.20 Temperatures in mineral wool section after 1h.

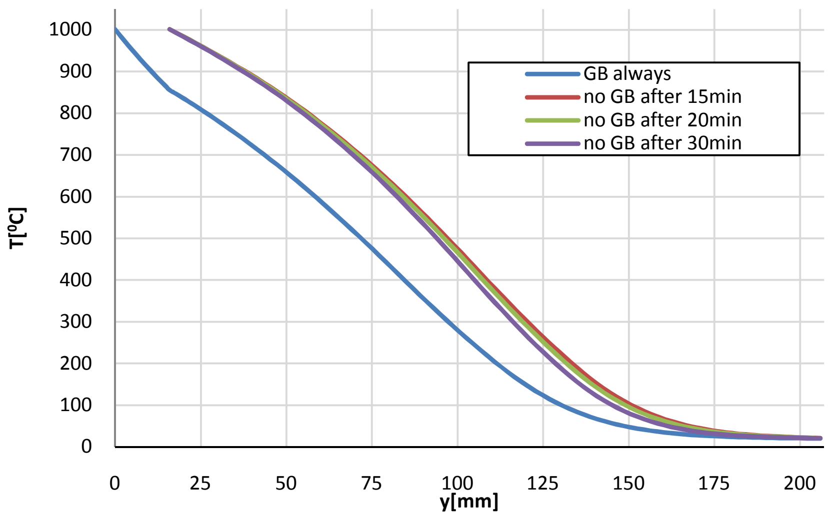

Figure 3.21 Temperatures in mineral wool section after 1.5h.

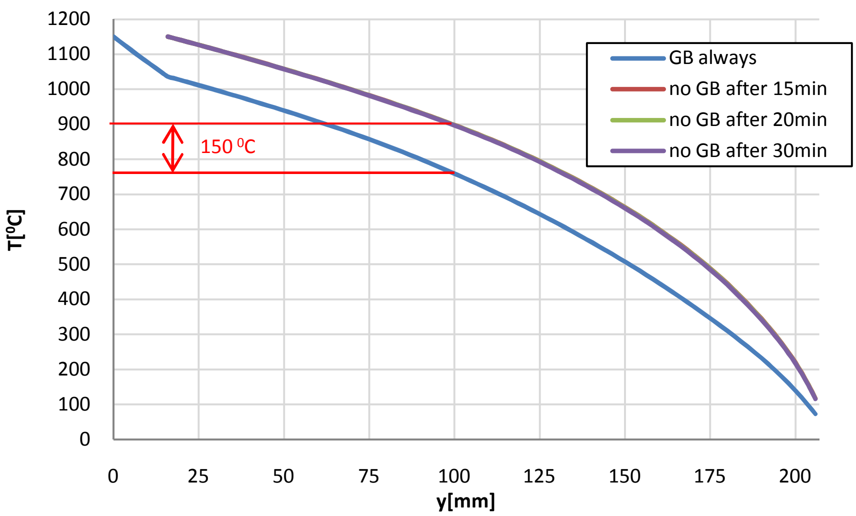

Figure 3.22 Temperatures in mineral wool section after 4h.

The results of the simulations indicated that there was a large difference between the simulation results with and without gypsum board. For example after 1 hour the temperatures in the wall were around 200 degree lower in the case where the gypsum board was still in its place. Consequently as later the gypsum board collapsed, the temperature values were lower. However, at longer time, the temperature difference; between 15, 20 and 30min gypsum boards resistance; decreased due to 150^{0}C.

In Figure 3.20, which gives the most significant results because the studied wall should resist 1h exposed to fire, it could be observed that the temperatures difference between 15 and 20min resistance was not a lot. For that reason, the gypsum board that collapse after 15min of fire exposure was used for the following simulations.

3.5.2.3 Wood based wall study

According to manufacturer the aerogel blanket selected for this study, named *Spaceloft®,* cannot be used at temperatures higher than 200^{0}C (Aspen Aerogels, INC.). Moreover, the results of Cone Calorimeter method showed that the ignition time of aerogel blankets was very short. Simulations were performed to find the 200^{0}C level over cross section of the wall after one hour.

The reference wood based wall model was utilized and two simulations were performed. In the first simulation, the temperature distribution over the wall section was calculated for the first 15 minutes, assuming that gypsum board collapsed after 15 minutes. The results of these calculations were saved. In the second simulation the gypsum board was removed i.e. the substrate was exposed to fire temperature. Furthermore, the temperature distribution obtained by the first simulation was used as initial temperatures for the second simulation. The second simulation time was from 15 minutes until 1 hour and the results were the position of the 200^{0}C which indicated the minimum thickness of mineral wool needed to protect aerogel blankets.

The specific heat capacity of mineral wool was assumed to be in the same level as basalt. A sensitive analysis was performed to determine how the assumption affects the position of 200^{0}C.

The mesh of the models had the same element type and the same number of elements as the gypsum board study.

Minimum mineral wool thickness results

The temperature distribution of the reference wood based wall after 1 hour is presented in Figure 3.23.

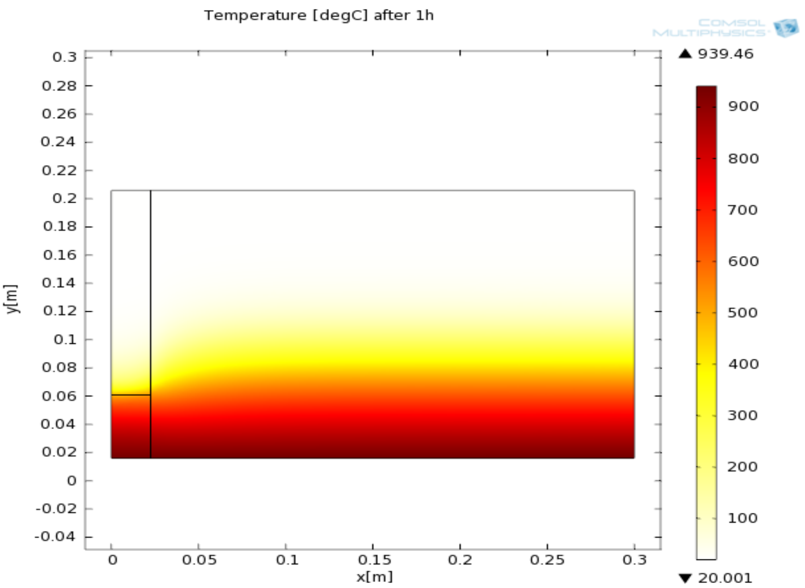

Figure 3.23 Temperature distribution of the reference wood based wall after 1 hour.

The results showed that mineral wool was exposed to 939^{0}C. This value was lower than the maximum service temperature of mineral wool which is higher than 1000^{0}C (Netzsch). The critical temperature for aerogel blankets, 200^{0}C, was found between 80 and 120mm from the fire exposed surface, see Figure 3.23. The temperatures in this section in more detail are presented in Figure 3.24.

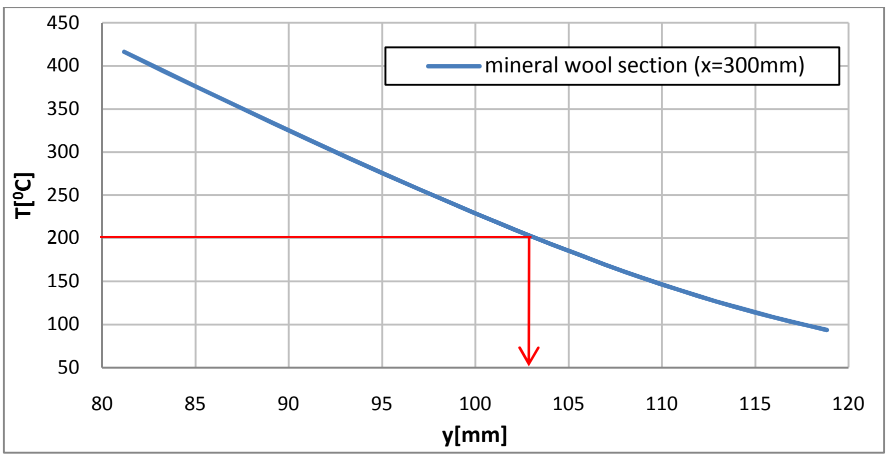

Figure 3.24 Detail of temperature distribution of the reference wood based wall after 1 hour.

Linear interpolation between the results of each node gave the location of 200^{0}C which was 103.29mm from the fire exposed surface. If the gypsum board is not taken in to account, this position corresponds to 87.39mm of mineral wool minimum thickness needed to protect aerogel blankets. However the mineral wool thickness was approximated to 95mm because of the available wood stud dimensions.

Mineral wool sensitive analysis results

In the mineral wool sensitive analysis there cases was simulated:

- Mineral wool heat capacity as basalt heat capacity (MW Cp)
- Mineral wool heat capacity 10% higher than basalt heat capacity (MW Cp + 10%)
- Mineral wool heat capacity 10% lower basalt heat capacity (MW Cp - 10%)

The y-positions in the mineral wool section (x=300mm) of the temperatures close to 200^{0}C after 1 hour of the previous cases are illustrated in Figure 3.25.

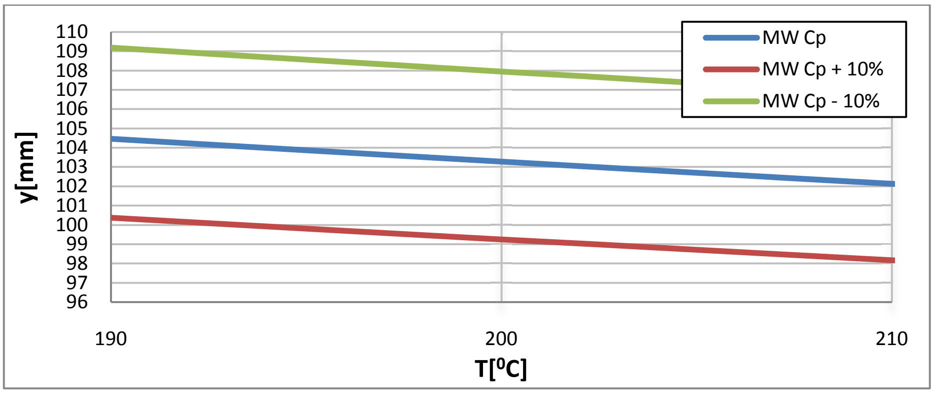

Figure 3.25 Mineral wool Cp sensitive analysis.

The comparison between the 200^{0}C distance from the surface exposed to fire variation (Δy) and the mineral wool heat capacity variation (ΔCp) is presented in Table 3.17.

Table 3.17 Mineral wool Cp sensitive analysis results.

Name	ΔCp[%]	y[mm]	Δy[mm]	Δy[%]
Cp+10%	10.00%	99.29	-4.00	-3.87%
Cp	0.00%	103.29	0.00	0,00%
Cp-10%	-10.00%	107.96	4.67	4.52%

The results agreed with the higher value of Cp, the higher surface temperature. Furthermore, it can be noticed that when the heat capacity of mineral wool varies 10% the critical distance varies approximately 5%. The difference in thickness becomes approximately 5mm which was acceptable.

3.5.2.4 Concrete based wall study

The reference concrete based wall model was simulated in order to find the 200^0C level over cross section of the wall after one hour. The model used polystyrene as insulation material which maximum service temperature is around 74^0C-82^0C (DiversiFoam Products). 90 elements of triangular type formed the mesh of the simulation model.

Results

The temperature distribution of the reference concrete based wall after 1 hour is shown in Figure 3.26.

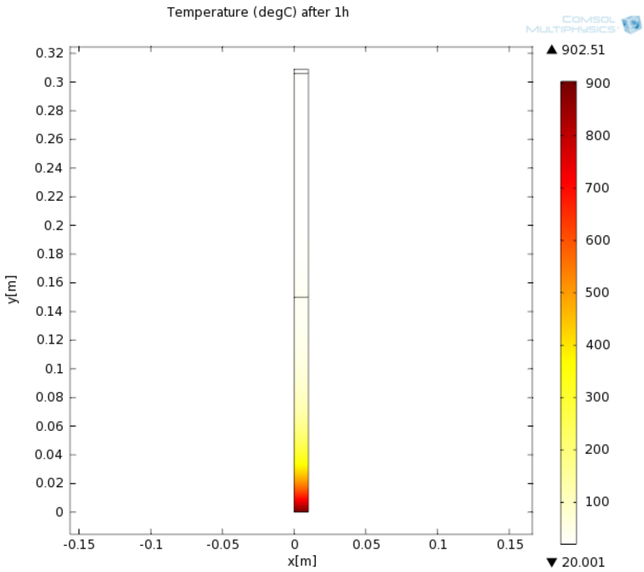

Figure 3.26 Temperature distribution of the reference concrete based wall after 1 hour.

The results, see Figure 3.27, showed that the temperature in polystyrene (y=150mm) was closer to 40^0C which was less than its maximum service temperature. Furthermore, the critical temperature for aerogel blankets, 200^0C, was found to be around 55mm from the fire exposed surface which was in the concrete part. Thus, the polystyrene could be replaced without any further concern.

The concrete based wall temperatures detailed are presented in Figure 3.27.

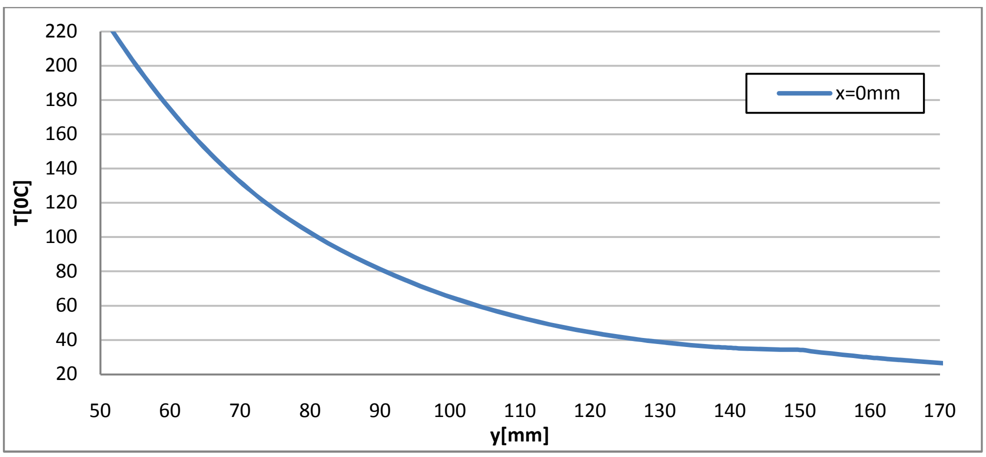

Figure 3.27 Detail of temperature distribution of the reference concrete based wall after 1 hour.

3.6 Second alternative results

In order to design thinner walls with aerogel blankets considering the fire performance new simulations were performed resulting in second alternative wall models: second alternative wood based wall model and second alternative concrete based wall model. It was assumed that the energy performance of the new walls was in the same level as the reference walls designs.

In the new design of the wood based wall, some part of mineral wool was replaced with aerogel blankets. While in new concrete design, all the polystyrene was replaced with aerogel blankets. As the thermal conductivity of the aerogel blankets is lower than the mineral wool and the polystyrene, the new walls thickness was less.

3.6.1 Wood based wall model

According to the 'Wood based wall study', 95mm mineral wool thickness was needed. Thus, the thickness of aerogel blankets became 46mm, see equations 3.6 and 3.7.

$$R_{WBW\_2} = R_{WBW\_R} = 5.94 \ \frac{m^2\,K}{W} \tag{3.5}$$

$$R_{WBW\_2} = \frac{d_{MW}}{\lambda_{MW}} + \frac{d_{AB}}{\lambda_{AB}} = \frac{0.095}{0.032} + \frac{d_{AB}}{0.0155} = 5.94 \ \frac{m^2\,K}{W} \rightarrow d_{AB} = 0.046\ m \tag{3.6}$$

Where

R_{WRW_2} Thermal resistance of the second alternative wood based wall (m^2.K/W)
R_{WRW_R} Thermal resistance of the reference wood based wall (m^2.K/W)
d_{MW} Thickness of mineral wool (m)
λ_{MW} Thermal conductivity of mineral wool (W/m.K)
d_{AB} Thickness of aerogel blankets (m)
λ_{AB} Thermal conductivity of aerogel blankets (W/m.K)

The new model was also simulated during 1 hour of fire exposure using the same conditions as before and 484 elements of triangular type formed the mesh of the simulation model.

The temperatures distribution in the wood based wall is presented in Figure 3.28.

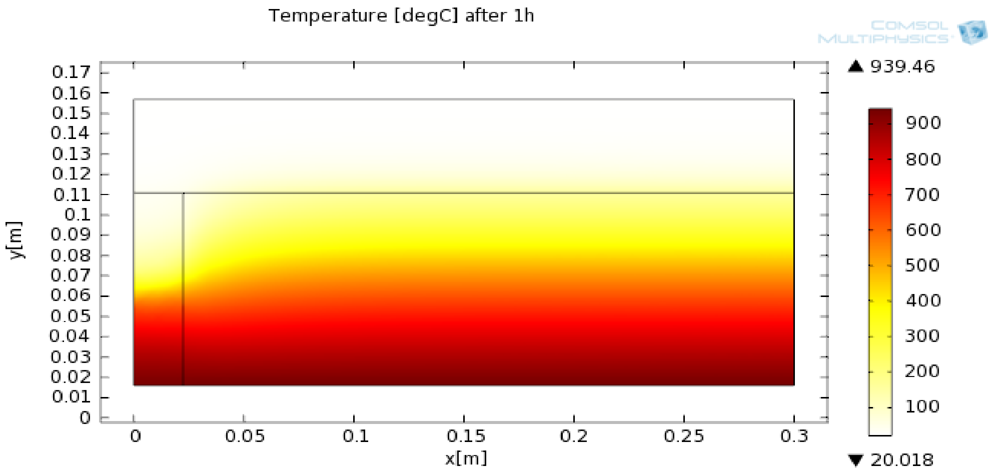

Figure 3.28 Second alternative wood based wall temperature distribution after 1h.

The results, see Figure 3.29, showed that after 1 hour the temperature at y= 110.9 mm, where the aerogel blanket was placed, was around 160^{0}C which is lower than 200^{0}C. Thus, the model was correct concerning fire safety requirement.

The temperatures in the middle section (x=300mm) which are closed to the critical aerogel blanket temperature are presented in Figure 3.29.

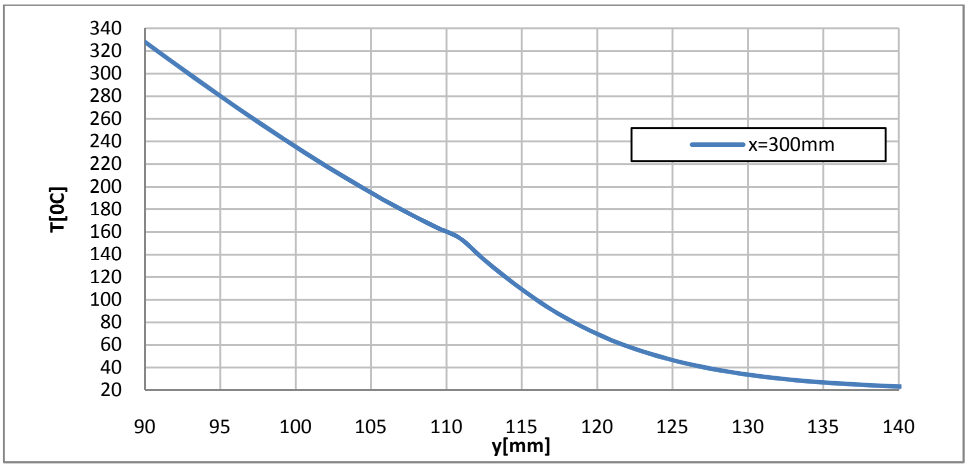

Figure 3.29 Detail of second alternative wood based wall temperature distribution after 1h.

The total thickness of the wall using mineral wool was 261.9mm, while using also aerogel blanket it was 212.9mm. By using the new insulation material, the wall thickness was reduced 19% of its initial thickness which almost corresponds to 5cm.

3.6.2 Concrete based wall model

According to the 'Concrete based wall study', all polystyrene could be replaced with aerogel blankets. Thus, the equivalent thickness of aerogel blankets to have the same energy performance was 78mm, see equations 3.8 and 3.9.

$$R_{CBW\_2} = R_{CBW\_R} = 5.0 \frac{m^2\,K}{W} \qquad (3.8)$$

$$R_{CBW\_2} = \frac{d_{AB}}{\lambda_{AB}} = \frac{d_{AB}}{0.0155} = 5.0\ \frac{m^2\,K}{W} \rightarrow\ d_{AB} = 0.078\ m \qquad (3.9)$$

Where

R_{CRW_2} Thermal resistance of the second alternative concrete based wall (m^2.K/W)
R_{CRW_R} Thermal resistance of the reference concrete based wall (m^2.K/W)
d_{AB} Thickness of aerogel blankets (m)
λ_{AB} Thermal conductivity of aerogel blankets (W/m.K)

The new model was also simulated during 1 hour of fire exposure employing the same conditions as before and 78 elements of triangular type formed the mesh of the simulation model.

The temperatures distribution in the concrete based wall is presented in Figure 3.30.

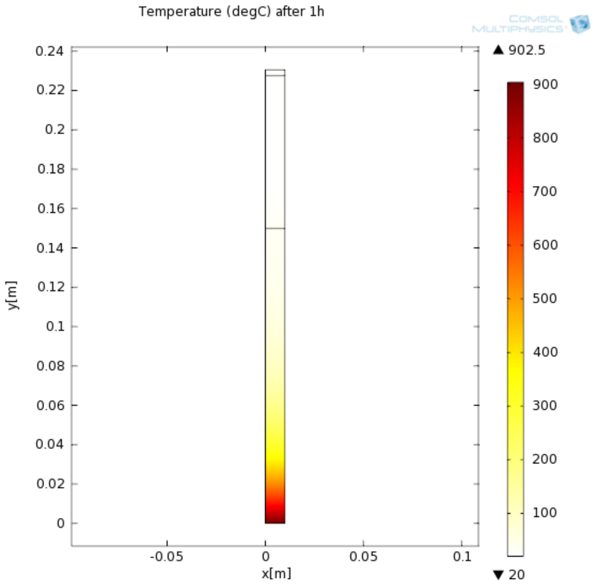

Figure 3.30 Second alternative concrete based wall temperature distribution after 1h.

The results, see Figure 3.31, showed that after 1 hour the temperature at y= 150 mm, where the aerogel blanket was placed, was around 35^0C which is lower than 200^0C. Thus, the model was correct concerning fire safety requirement.

The temperatures in a transversal wall section (x=0mm) close to the critical aerogel blanket temperature are presented in Figure 3.31.

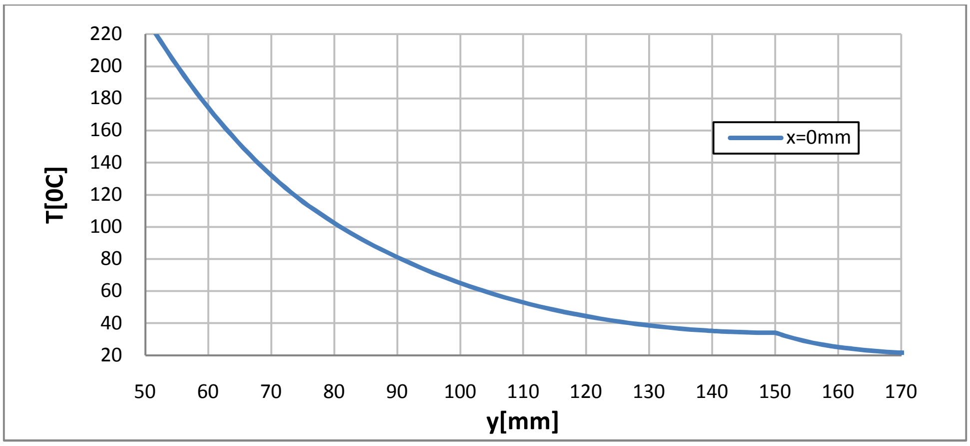

Figure 3.31 Detail of second alternative concrete based wall temperature distribution after 1h.

The total thickness of the wall using polystyrene was 309mm, while using aerogel blanket it was 231mm. By using the new insulation material, the wall thickness was reduced 25% of its initial thickness which almost corresponds to 8cm.

3.6.3 Summary of second alternative results

The thicknesses (d) of the reference wall models and the second alternative wall models by replacing some of the mineral wool with aerogel blankets in the wood based wall case, and by replacing all the polystyrene with aerogel blankets in the concrete based wall case are summarized in Table 3.18.

Table 3.18 Reference walls and second alternative walls thicknesses.

	wall d [mm]	insulation d [mm]	U-value [W/m2.K]	Δd [mm]	Δd [%]
WBW_R	262	190	0.17		
WBW_2	213	141	0.17	49	19%
CBW_R	309	156	0.20		
CBW_2	231	78	0.20	79	25%

Where

WBW_R Reference wood based wall
WBW_2 Second alternative wood based wall
CBW_R Reference concrete based wall
CBW_2 Second alternative concrete based wall

By considering the fire performance, the wood based wall thickness was reduced 19% while the concrete based wall thickness was reduced 25%.

4 Moisture properties

When a wall material in a building component is replaced with another material in order to improve a specific performance, it is important to verify the influence of the replacement on other technical demand, for example risk for condensation of moisture.

In this study the vapor permeability (δ_v) of aerogel blankets was determinate by the Cup method and it was compared with the vapor permeability of other insulation materials.

4.1 Vapor permeability

Although water is essential for all forms of life, it can also deteriorate and disintegrate natural and hand-made material and buildings consist of a large numbers of such materials. Moreover, the interaction of moisture with building materials may significantly influence the thermal performance of buildings (Carl-Eric Hagentoft. 2001).

A first differentiation can be done between moisture in air and moisture in porous materials. The moisture transfer in air or by air can be per diffusion or by convection, while the moisture transfer in porous material is owing to diffusion or capillary suction or a combination of both.

In this study, only the moisture transfer in porous materials by diffusivity was studied. The steady-state diffusivity flux g through a porous material layer with thickness d and air humidity by volume v kept at v_1 in one side of the layer and v_2 on the other side, see Figure 4.1, can be calculated by using Equation 4.1.

$$g = \delta_v \frac{v_1 - v_2}{d} \qquad (4.1)$$

Where

g Steady-state diffusivity flux (kg/m^2.s)

δ_v Vapor permeability coefficient (m^2/s)

v Air humidity by volume (kg/m^3)

d Thickness (m)

The diffusion of water vapor through a material layer is illustrated in Figure 4.1.

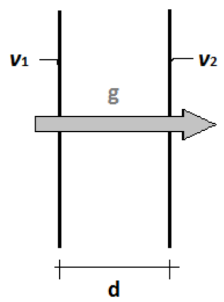

Figure 4.1 Diffusion of water vapor through a material layer.

The vapor permeability coefficient of the material can be compared with the diffusion of moisture in dry air by introducing the *μ-factor*:

$$\mu = \frac{D}{\delta_v} \qquad (4.2)$$

Where

μ μ-factor (-)

D Diffusivity of water vapor in air ($25 \cdot 10^{-6}$ m^2/s at 20^0C)

A high value of μ-factor means that the material has high resistance to water vapor transmission.

The μ-factor given by manufacturers of mineral wool, polystyrene (Natural Building Technologies 2009) and aerogel blankets (Aspen Aerogels 2012) are shown in Table 4.1.

Table 4.1 Insulation materials μ-factor.

	μ-factor
Mineral wool	1
Polystyrene	30
Aerogel blankets	5

4.2 Determination of aerogel blankets vapor permeability

The moisture permeability of aerogel blankets was determined by using the Cup method.

A cup is filled with distilled water to achieve a relative humidity inside the cup around 100%, and later a specimen of the material studied is used to seal the cup. Subsequently, the cup is placed in an atmosphere of constant temperature and relative humidity lower than 100%. This atmosphere can be achieved either in a climate box or directly exposed to the air of a climate room. (Bijan Adl Zarrabi 1998). This method is illustrated in the Figure 4.2.

As the relative humidity is higher inside the cup, there is a moisture flow through the specimen therefore, the weight of the cup decreases. During the test, the cup is weighted regularly until the steady-state condition is reached. After getting these results, the moisture resistance can be calculated using the Equation 4.5. Furthermore, the moisture permeability of the studied material, δ_v[m^2/s], can be calculated by Equation 4.6. The following relations are used in this method: ´

$$g = \frac{\Delta v}{Z_{tot}} \quad (4.3)$$

$$Z_{tot} = Z_{specimen} + Z_{air\ gap} + Z_u \quad (4.4)$$

$$Z_{specimen} = \frac{A\,\Delta t\,\Delta v}{\Delta m} - \frac{d2}{0.025\ 10^{-3}} - Z_u \quad (4.5)$$

$$\delta_v = \frac{d1}{Z_{specimen}} = \frac{d1}{\frac{A\,\Delta t\,\Delta v}{\Delta m} - \frac{d2}{0.025\ 10^{-3}} - Z_u} \quad (4.6)$$

In Equation 4.3 *Δv* is the difference of the humidity by volume over cross section of the specimen. Considering that the relativity humidity of the climate room is 50 % and the relative humidity inside the cup is almost 100%, *Δv* had a value of 8.65E-3 kg.

In Equation 4.4, the first term represents the moisture resistance of the studied material, $Z_{specimen}$[m/s], the second term, $Z_{air\ gap}$[m/s], is the vapor resistance of the air gap between the water surface and the specimen and the third term, Z_u, is the resistance between the surface of the specimen and the external air. Z_u value was estimated to 100s/m using the Lewis formula.

In Equation 4.5, *A*[m^2] is the area of the specimen, *Δm*[kg] is the weight reduction over a time period of Δt[s] and *d2*[m], is air gap thickness.

In Equation 4.6 *d1*[m] is the thickness of the specimen.

Cup method is illustrated in Figure 4.2.

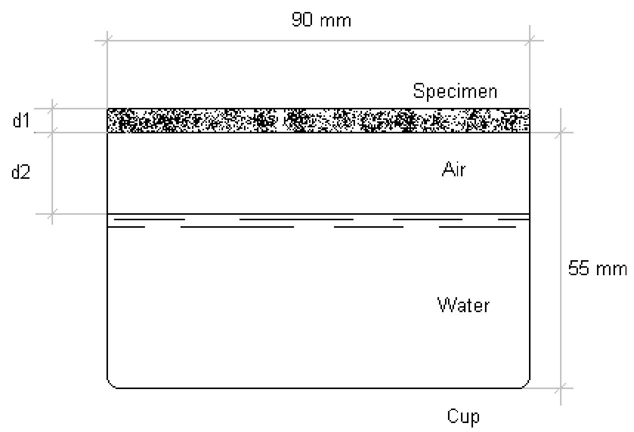

Figure 4.2 Cup method.

4.2.1 Sample preparation

Samples of aerogel blanket, *Spacetherm*® from Proctor Company were prepared for measurements. Two types of *Spacetherm*® were tested; one was defined as 'black' and the other one as 'white'. Although both materials are classified, by the manufacturer, under the same named, *Spacetherm*®, the 'white' was the new version of the 'black'. Four samples were tested; two of each type. Their dimensions were 13cm diameter and 1cm thickness.

As the aerogel blanket is a material made of small particles, it was not possible to fix the specimen to the cup using ordinary ways. The solution found is explained below.

The aerogel blanket sample, which had a larger diameter than the cup, was placed on the cup and an aluminum foil of 5cm width was used to cover the extra specimen material to get one dimension moisture flow. Adhesive paper was used to attach the specimen to the cup.

The final setup of the specimen and the cup is presented in Figures 4.3.

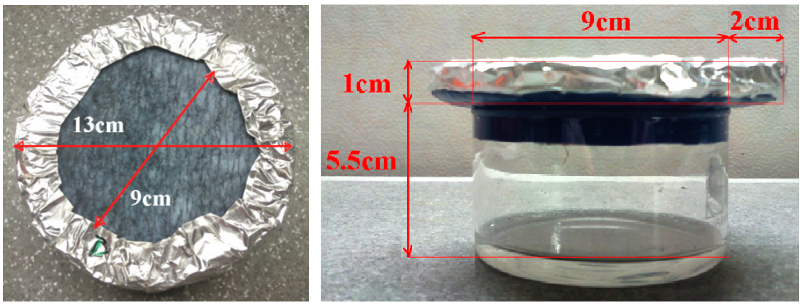

Figure 4.3 Cup method dimensions.

4.2.2 Tests

The cups with the specimens, see Figure 4.4, were directly exposed to the air of a climate room where the temperature and the relative humidity were maintained constant at 20^{0}C and 50% respectively. The cups were weighted regularly during 38 days.

The samples are illustrated in Figure 4.4 and their initial weights are presented in Table 4.2.

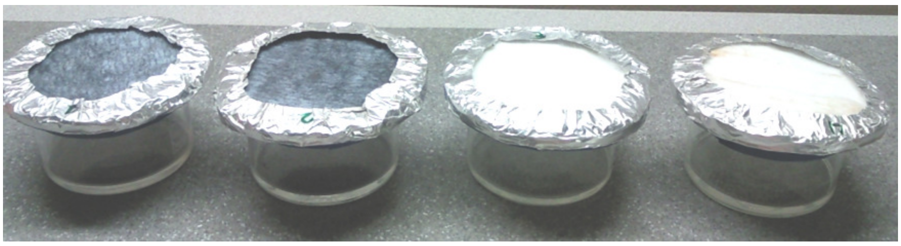

Figure 4.4 Cup method samples.

Table 4.2 Cup method samples initial weights.

Name test	Sample type	initial weight [g]
b_1	black	280,10
b_2	black	280,12
w_1	white	286,38
w_2	white	286,33

4.2.3 Results

The mass variation and the vapor permeability coefficient of the four samples tested are shown in Figures 4.5 and 4.6.

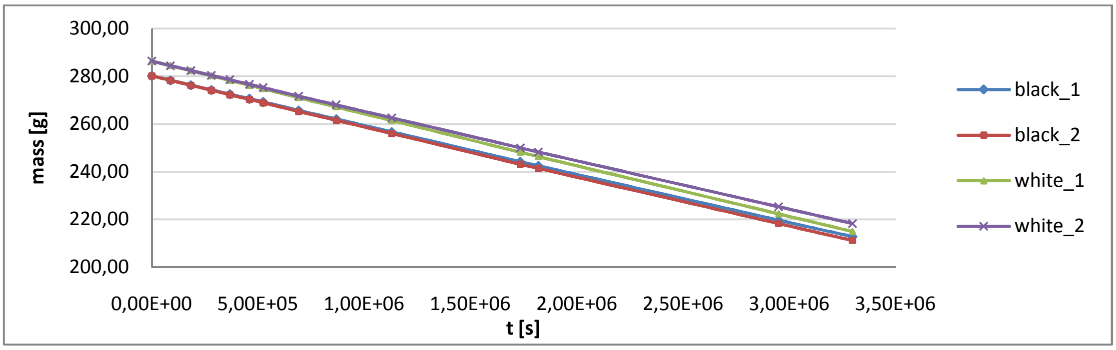

Figure 4.5 Mass variation of Cup method samples.

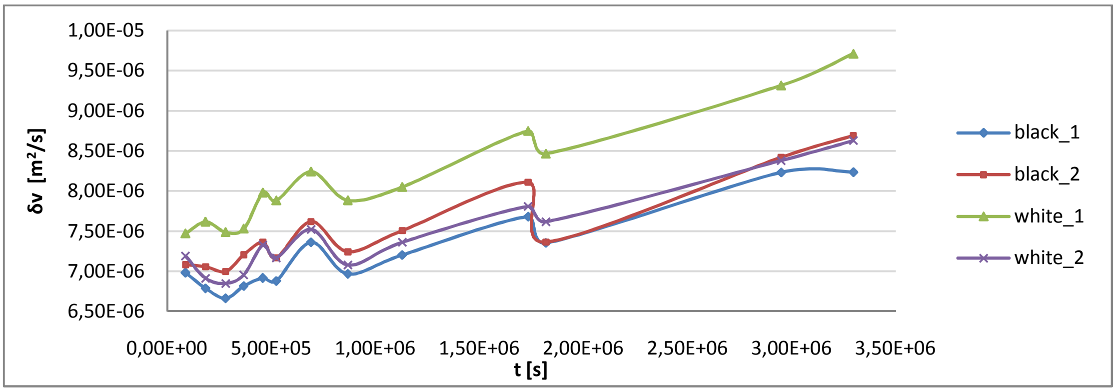

Figure 4.6 Vapor permeability coefficient of Cup method samples.

In order to had an idea about this aerogel blankets moisture property, the vapor permeability was calculated in time interval 35-40 days.

The vapor permeability and the μ-factor values found for the four samples are presented in the Table 4.3.

Table 4.3 Cup method results.

	δv [m^2/s]	μ-factor
black_1	8.30E-06	3.01
black_2	8.55E-06	2.92
white_1	9.50E-06	2.63
white_2	8.50E-06	2.94
mean value	8.70E-06	3.00

5 Discussion

The models studied in the study are presented in Table 5.1. The reference wall models were designed considering energy performance of the walls. On one hand, the first alternative wall models were the solution based on the energy performance. On the other hand, the second alternative wall models were the solution related to fire performance.

Table 5.1 Wall models thickness (d).

	d_wall [mm]	d_insulation [mm]				U-value [W/m2.K]	Δd [mm]	Δd [%]
		Total	MW	PS	AB			
WBW_R	262	190	190	-	-	0.17	-	-
WBW_1	164	92	-	-	92	0.17	98	37%
WBW_2	213	141	95	-	46	0.17	49	19%
CBW_R	309	156	-	156		0.2	-	-
CBW_1	231	78	-	-	78	0.2	78	25%
CBW_2	231	78	-	-	78	0.2	78	25%

Where

WBW_R	Reference wood based wall model
WBW_1	First alternative wood based wall model
WBW_2	Second alternative wood based wall model
CBW_R	Reference concrete based wall model
CBW_1	First alternative concrete based wall model
CBW_2	Second alternative concrete based wall model
MW	Mineral wool
PS	Polystyrene
AB	Aerogel blankets

The structure of the concrete wall before and after adding aerogel blankets did not change. Thus, the final concrete based wall model corresponded to any of the two alternatives concrete based wall models. Concerning to the moisture analysis, as the aerogel blankets vapor permeability has a high value; a vapor barrier should be added in the concrete based wall model when the polystyrene is replaced with aerogel blankets.

In the mineral wool based wall, a minimum mineral wool thickness was needed to protect aerogel blankets from the fire. Therefore, the final wood based wall model corresponded to the second alternative wood based wall model.

Joining aerogel blankets into the other wall members can be performed by either mechanical methods and/or adhesive (Aspen Aerogels 2012).

The final wall models are presented in Figures 5.1 and 5.2.

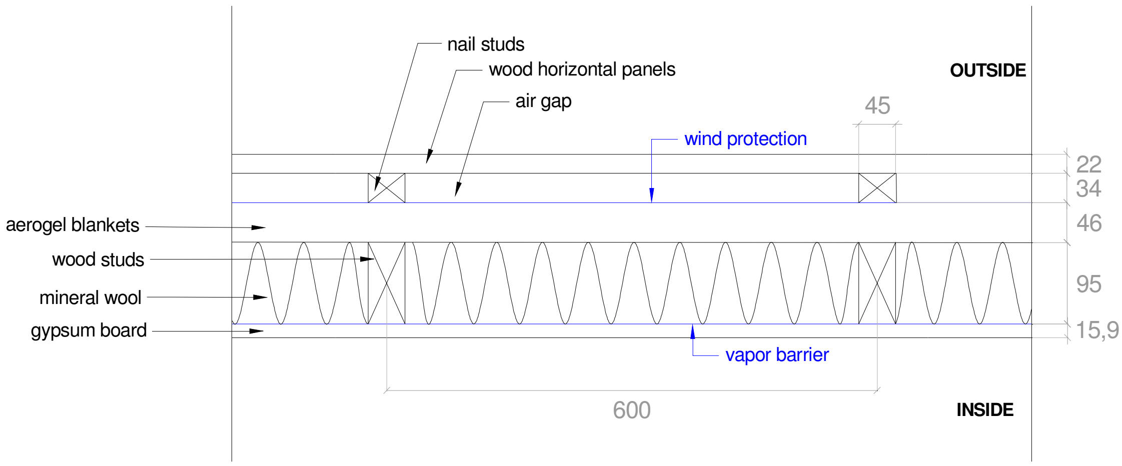

Figure 5.1 Final wood based wall, units in mm.

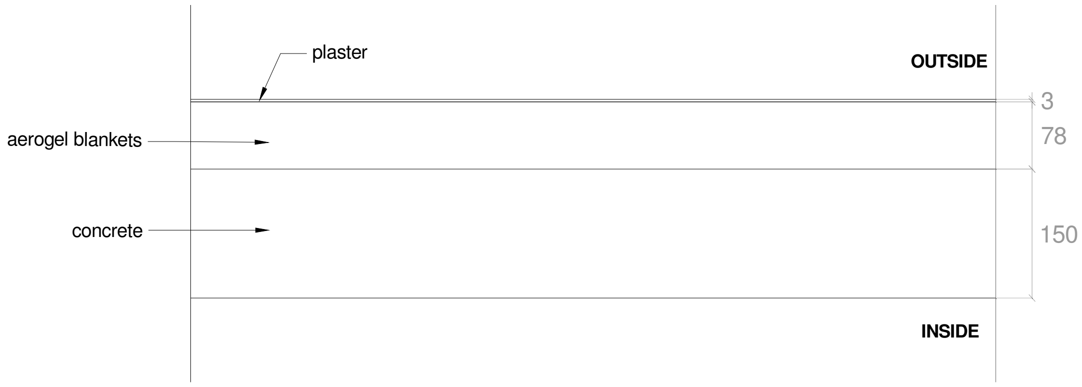

Figure 5.2 Final concrete based wall, units in mm.

Vapor permeability comparison

The μ-factors of the common insulation materials and the μ-factor of aerogel blankets, both the manufacturer value and the experimental value, are demonstrated in Table 5.2.

Table 5.2 Insulation materials μ-factor.

	μ-factor
Mineral wool	1
Polystyrene	30
Aerogel blankets manufacturer	5
Aerogel blankets experiment	3

The μ-factor found after testing aerogel blankets samples was lower than the value given by manufacturer. The difference can be because the experimental value was calculated using results that had not achieved the steady-state yet. The experiment had to be stopped after 38 days because after that time, the mass variations of the specimens became too high. This behavior could have been caused by the large thickness of the air gap which leads to moisture transfer by convection. In the cup method, moisture transport by diffusion should be taken into account.

The used setup should be modified. In the setup, the sample area covered with aluminum paper (69.11 cm^2) was in the same order than the sample area free (63.62 cm^2), which produced a two-dimension moisture transfer, see Figure 5.3. Thus, there were some water losses in the surface that were not considered in the experimental method. These unknown mass of water losses to the edges was a reason that the experimental vapor permeability ($8 \cdot 10^{-6}$ m^2/s) was higher than the literature value ($5 \cdot 10^{-6}$ m^2/s).

The two-dimension moisture transfer of the specimens is illustrated in Figure 5.3.

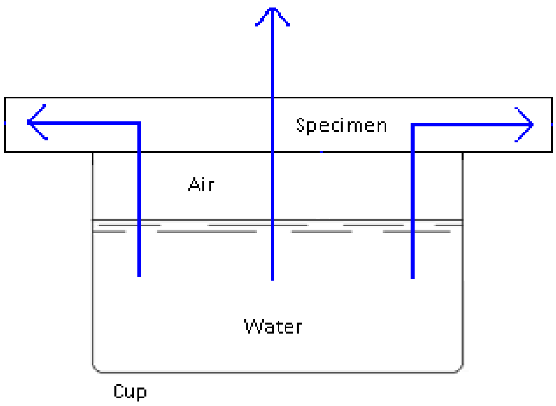

Figure 5.3 Cup method two-dimension moisture transfer.

Finally, the difference could be also due to dependency of vapor diffusivity and relative humidity. The cup method was performed in a climate room at 50% relative humidity (HR) and inside the cup was considered 100%HR which means that the sample vapor permeability value found correspond to 75%HR. However, the level of relative humidity of the used literature value was not determined.

Cost estimation

A cost estimation was performed. The study was focused on the rental price and the price of the insulation materials. An apartment of four rooms in a multi-family house in Sweden was selected for the study.

As the U-value of the reference wall models and the new wall models was keeping constant, there was no change in the energy consumption. For that reason, the difference between the reference wall models and the new wall models was the wall thickness. In this example the position of the external side of the wall was remained. Accordingly, when the wall thickness was reduced the internal area became larger.

The reference and the new internal areas are illustrated in Figure 5.4. The continuous line (──) is the external side of the reference and the new models walls, the dotted line (· · ·) is the internal side of the reference walls while the broken line (- - -) is the internal side of the new walls.

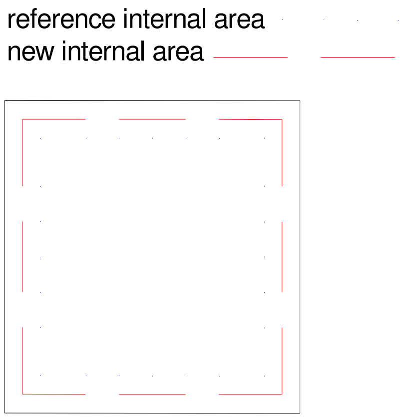

Figure 5.4 Reference and new internal areas.

The price of renting an apartment of 4 rooms in Sweden is 862SEK/(m^2.year) (Ulla Janson 2008). The price of mineral wool is 6.8SEK/(m^2.mm_thickness) (Pink Batts 2008), the price of polystyrene is 3.9SEK/(m^2.mm_thickness) (Foam Sales 2008) and the price of aerogel blankets is 20SEK/(m^2.mm_thickness). In order to simplify the calculations, it was assumed a square apartment with an area of 100m^2 and a height of 2.5m. The variation of the rent area was performed in accordance with the reduction of the wall thickness. And the price of the wall insulation material was performed in accordance with the insulation materials used and their thickness.

The results of the wall insulation thickness, the insulation price, the rent area and the rent price per year of the apartments studied are presented in Table 5.3.

Table 5.3 Reference and new apartment information.

	Insulation thickness [mm]	Insulation price [SEK]	Rent area [m^2]	Rent price [SEK/year]
WA_R	190 (MW)	129200	100	86200
WA_N	95 (MW) + 46 (AB)	158135	101.97	87898
CA_R	156 (PS)	60840	100	86200
CA_N	78 (AB)	158434	103.14	88910

Where

WA_R Reference apartment with wood based walls
WA_N New apartment with wood based walls
CA_R Reference apartment with concrete based walls
CA_N New apartment with concrete based walls

The payoff time for using aerogel blankets were calculated and the results are presented in Table 5.4.

Table 5.4 New apartment variations.

	Δ insulation thickness [mm]	Δ rent area [m^2]	Δ insulation price[SEK]	Δ rent price [SEK/year]	years
WA_N	49	1.97	28935	1698	17
CA_N	78	3.14	97594	2710	36

Aerogel blankets are still expensive in comparison to traditional insulation materials. However, in future the price of aerogel blankets will be reduced and they may be used as the traditional insulation materials. Furthermore, aerogel blankets can be used for specific applications where a limited volume of material is needed.

External fire considerations

A wall exposed to an internal fire was studied in this project. However, in an external wall design, an external fire should be also taken into account. A possible solution could be based on using a facade material satisfying the fire requirements.

6 Conclusions

Aerogel blankets have excellent thermal properties. However, their fire reaction is not so good. The 'white color' aerogel blanket had better fire reaction than the 'black color' aerogel blanket because of its shorter flaming time. Nevertheless, as the aerogel blanket ignition time is very short, this material could help to further development of the fire. Thus, if aerogel blankets are used in building applications, they should be protected from direct exposure to fire by covering it with other materials with better fire resistance. For instance, in the external non load bearing walls studied, it was required 95 mm of mineral wool in the wood based wall and 55 mm of concrete in the concrete based wall.

Moreover this project suggests that if aerogel blankets are placed in a safe position of the wall the thickness of the wall can be reduced, which can be a very interesting alternative wherever space is an important topic. In the external non load bearing wood based wall studied, a wall thickness reduction of 19 % was possible, while in the concrete based wall the thickness of the wall was reduced by 25 %.

In the 'gypsum board study', it was seen that the temperatures of the wall where the gypsum board did not collapse after 1 hour fire exposure were around 200^0C lower. However, to guarantee that the gypsum board does not collapse is very difficult since even the gypsum board cannot support its own weight, due to the water evaporation of the gypsum board structure at high temperatures. The study was carried out using constant gypsum board properties. For more accurate results, the temperature dependence of the gypsum board properties should be considered.

The moisture analysis was not performed because the time limitations of the project. Moreover, in the determination of aerogel blankets vapor permeability, the two-dimension moisture transfer of the test specimens made the results were not reliable.

Last but not least, it is important to mention that this project was carried out considering constant energy consumption of the walls and internal fire requirements. To get a more completed and concise picture concerning if aerogel blankets can be used in new construction walls, other performances of the wall should be studied, for instance: heat, moisture, fire and acoustics performances.

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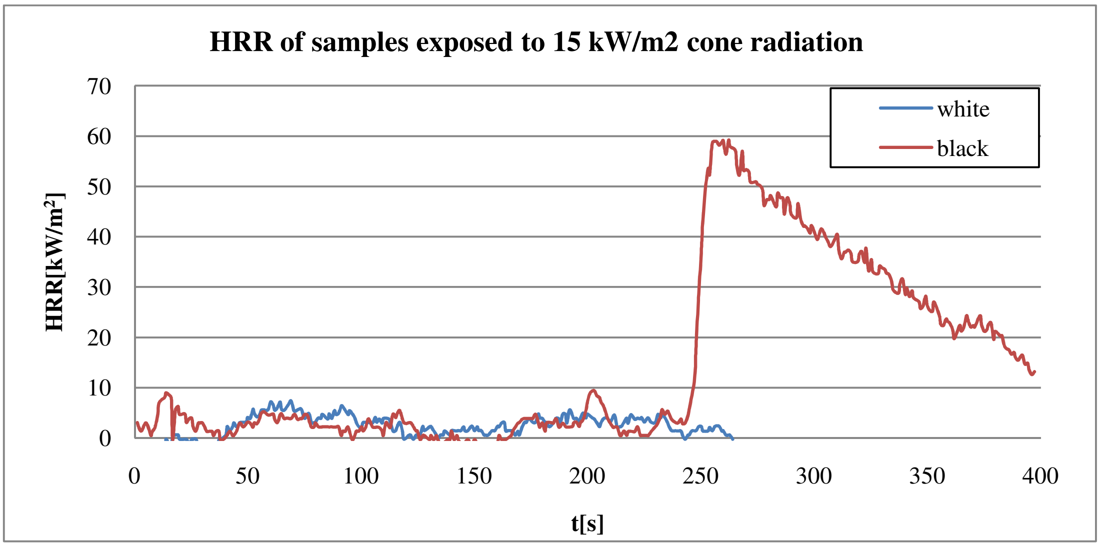
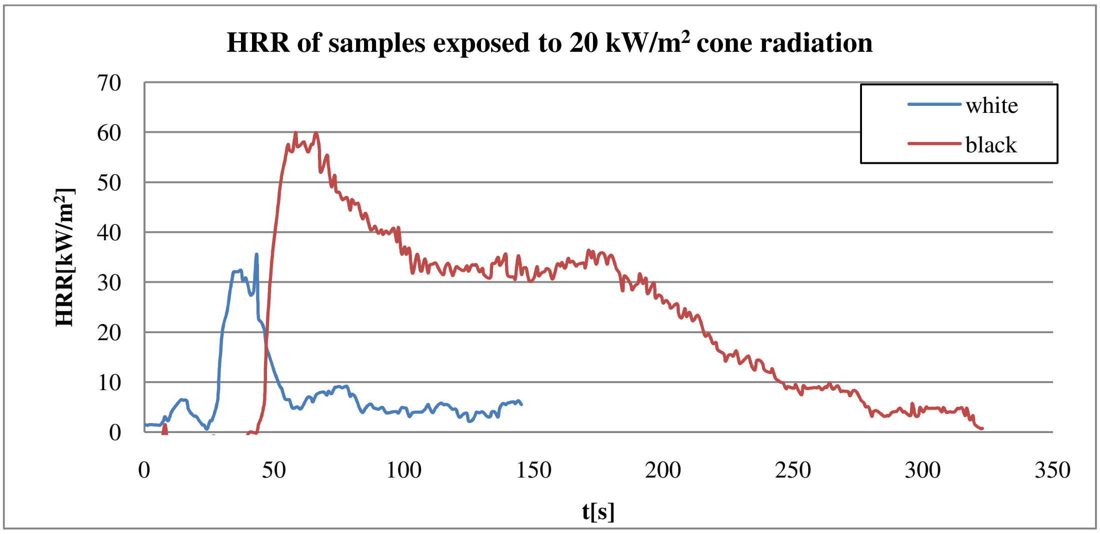
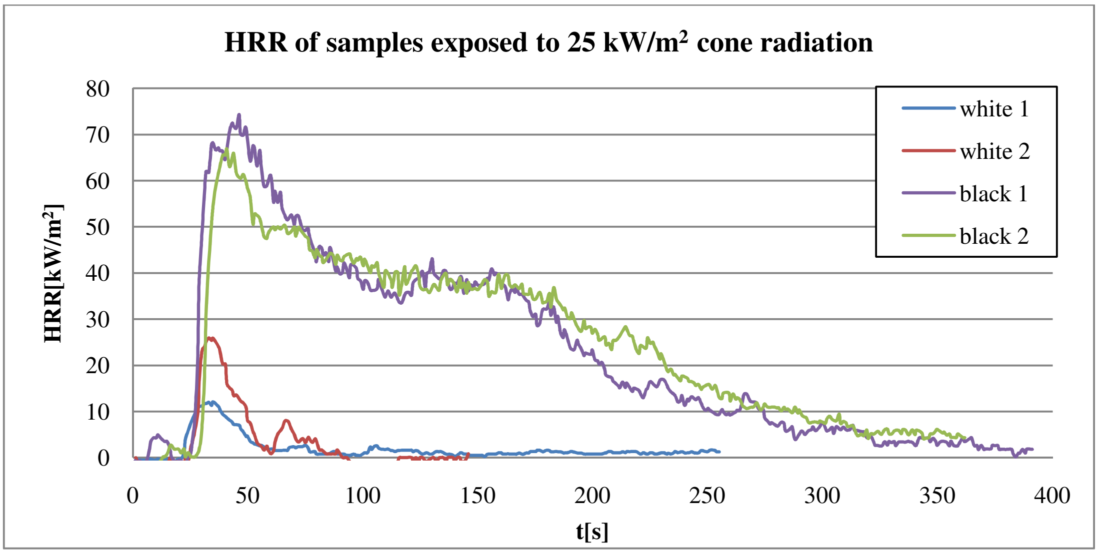
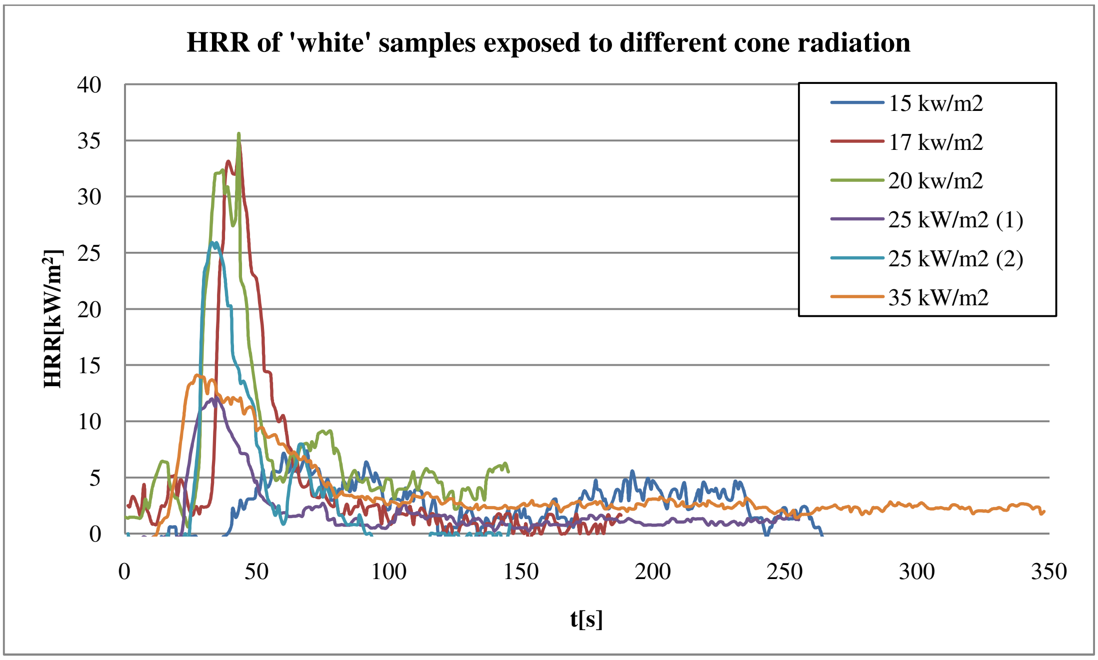
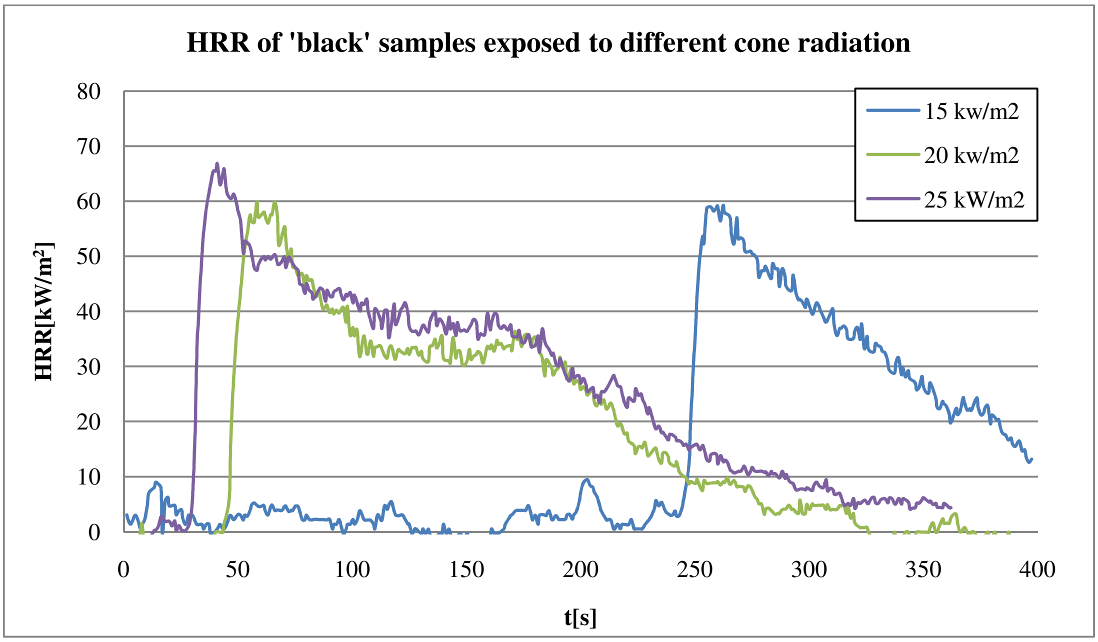
Appendix A: HRR results





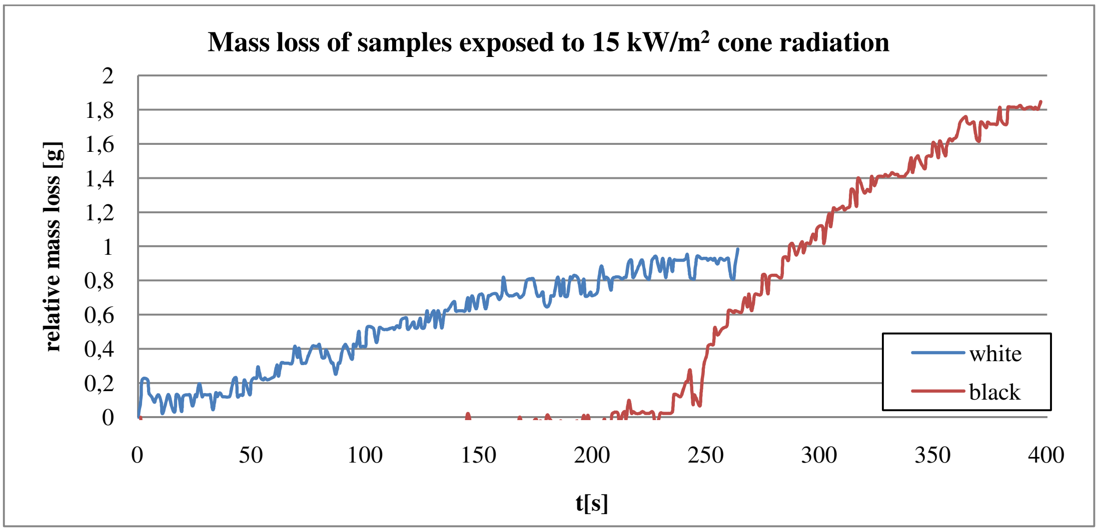


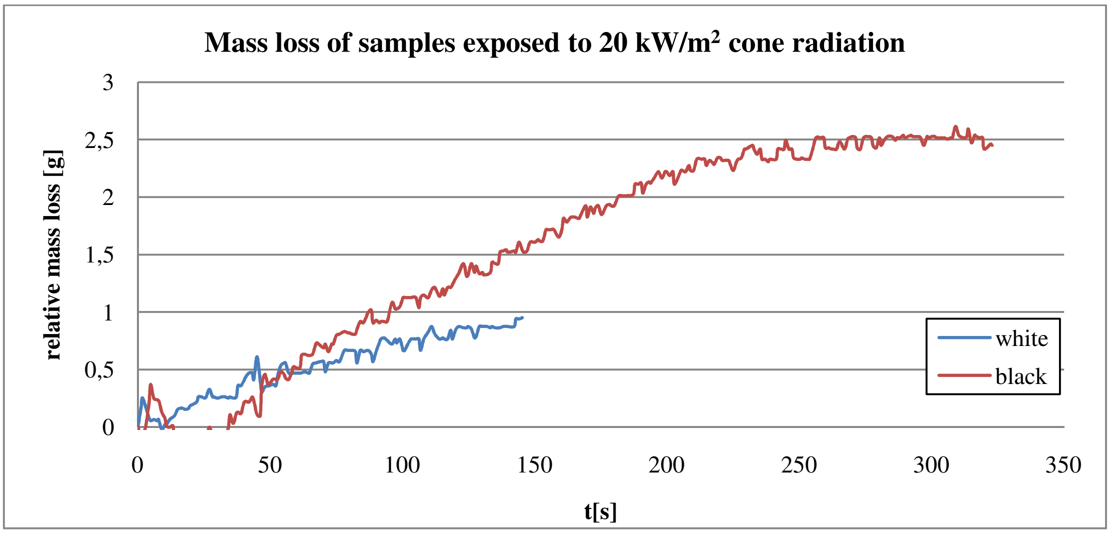

HRR of 'white' samples exposed to different cone radiation
HRR[kW/m²]
t[s]
15 kw/m2
17 kw/m2
20 kw/m2
25 kW/m2 (1)
25 kW/m2 (2)
35 kW/m2
0
5
10
15
20
25
30
35
40
0
50
100
150
200
250
300
350

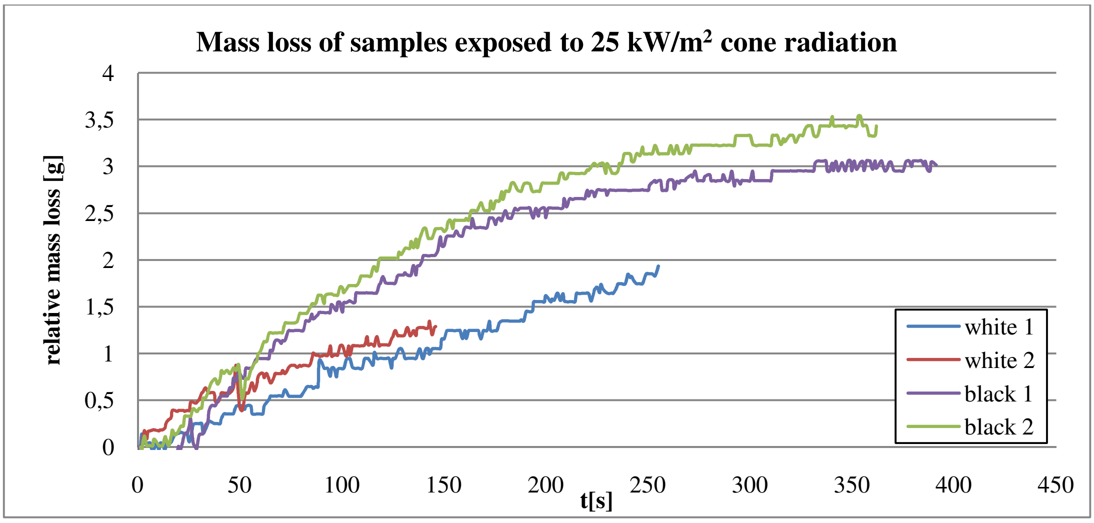

HRR of 'black' samples exposed to different cone radiation
HRR[kW/m²]
t[s]
15 kw/m2
20 kw/m2
25 kW/m2
0
10
20
30
40
50
60
70
80
0
50
100
150
200
250
300
350
400

Appendix B: Mass loss results

The mass losses of 'white' and 'black' aerogel blankets exposed to different cone radiations are presented in the following graphics. The results were too small and not very realistic because the samples had the amount of combustible material and the amount of water very similar. Because of this, it was difficult to make a difference between the combustion and the evaporation of the sample materials. Despite the above, a fast decrease of the sample weigh could be appreciated in the ignition time. Although there was some mass loss before ignition time due to evaporation, most of the mass loss was after ignition during the flaming time. Moreover, the mass loss in the 'black' aerogel blankets was higher because probably this type of material had more combustible material amount.



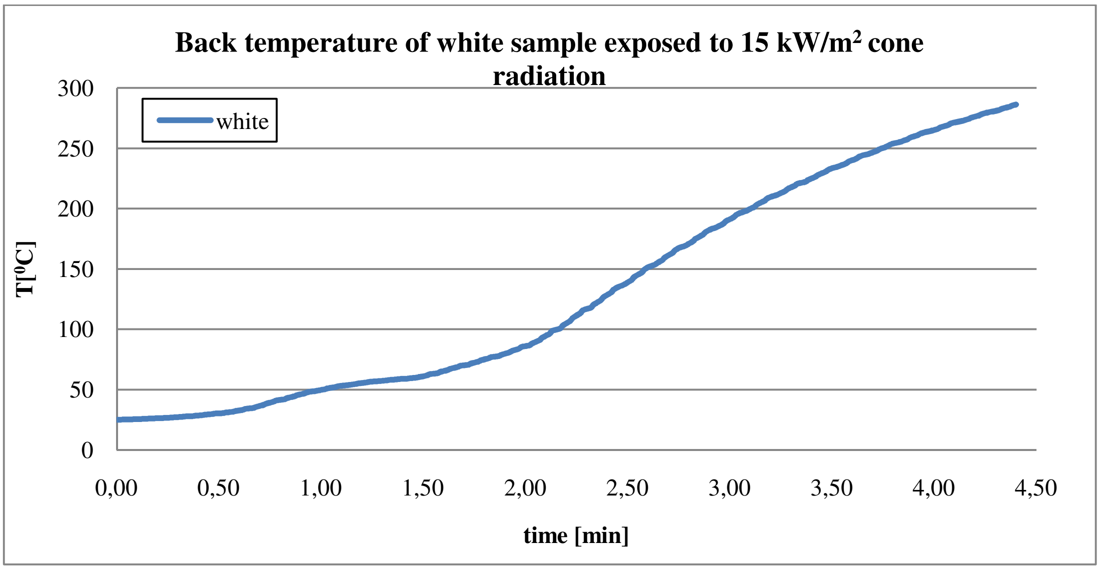


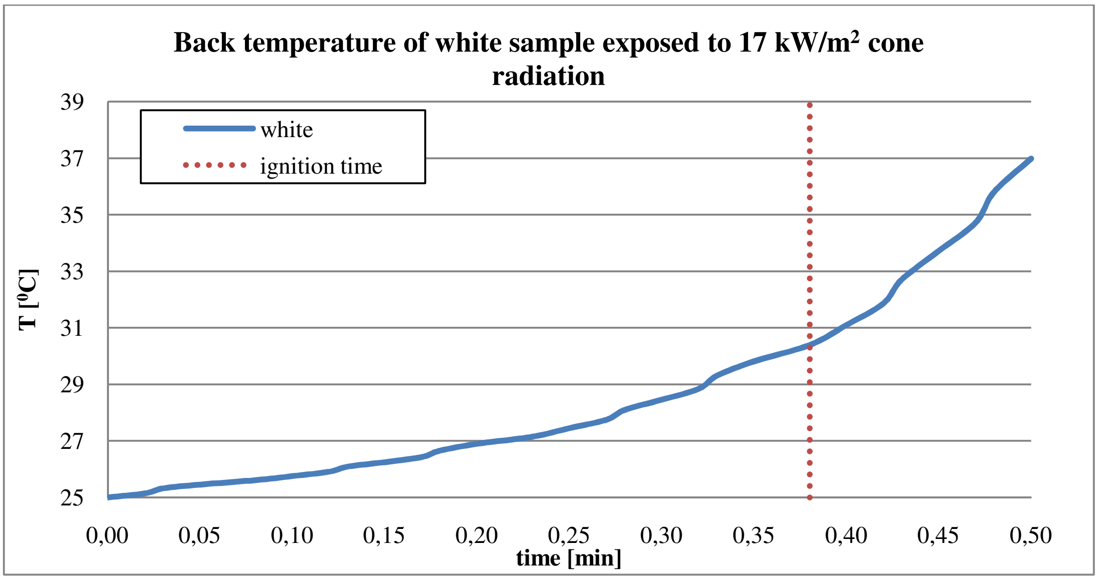


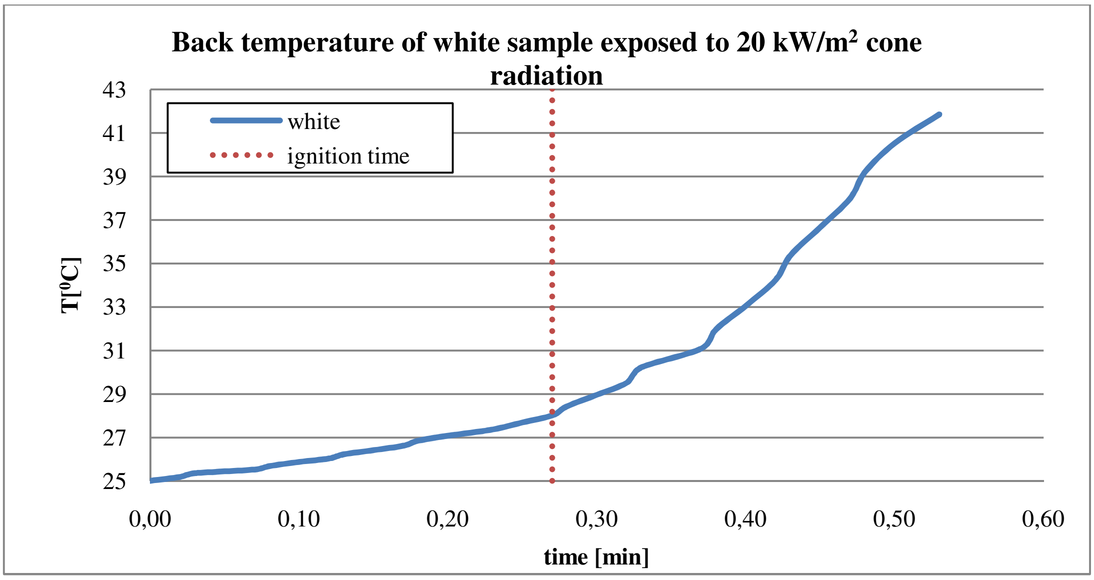
Mass loss of samples exposed to 25 kW/m² cone radiation
relative mass loss [g]
t[s]
0
0,5
1
1,5
2
2,5
3
3,5
4
0
50
100
150
200
250
300
350
400
450
white 1
white 2
black 1
black 2

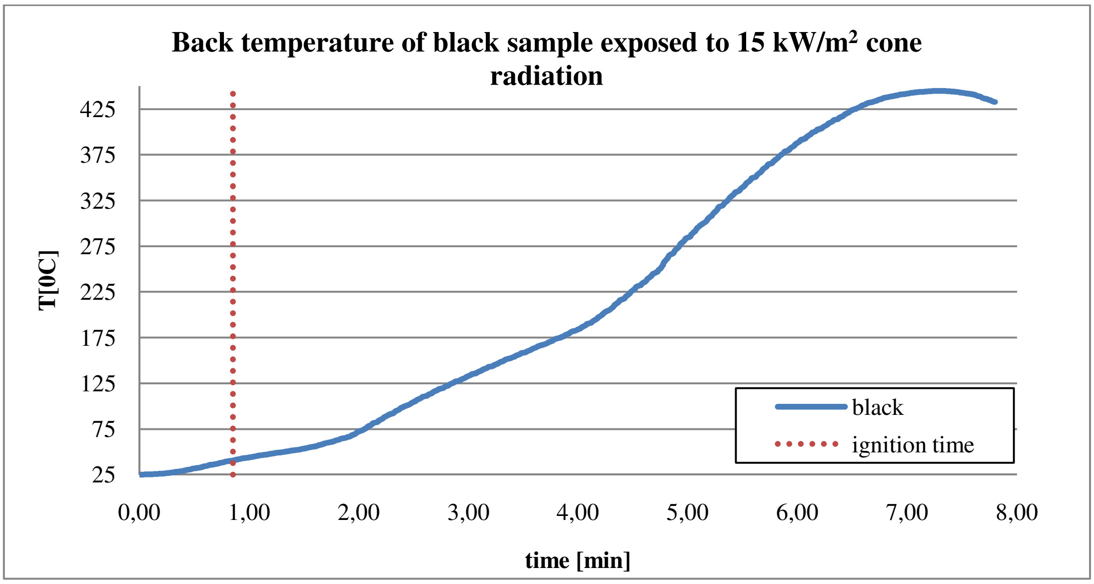
Appendix C: Back temperature results

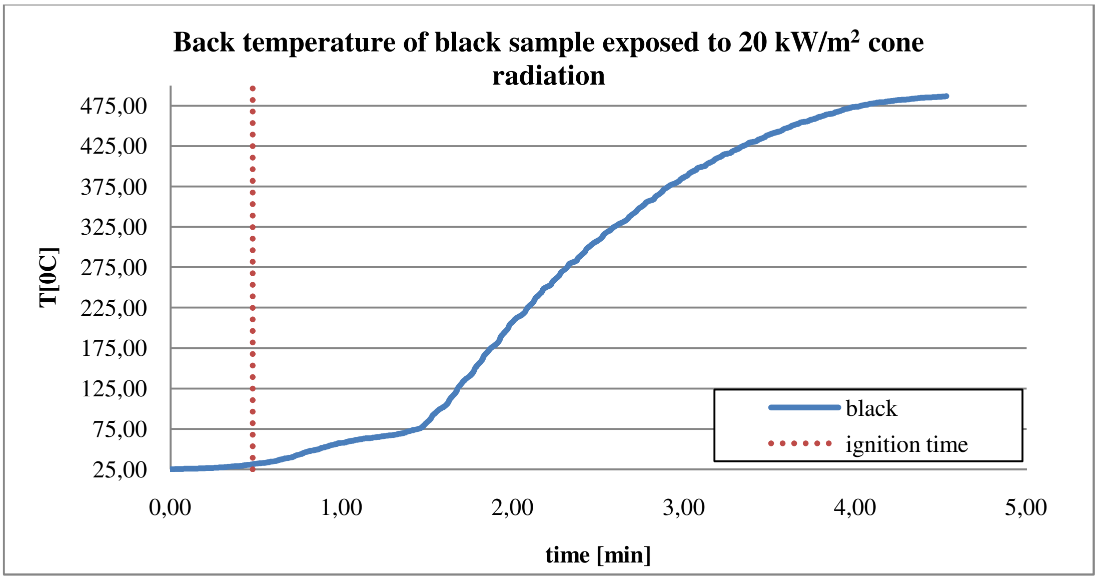
The temperatures of the back side of the samples tested in the Cone Calorimeter method are presented in the following graphics. The temperature results are from the exposure beginning to the stop flaming time of the samples.






Back temperature of white sample exposed to 20 kW/m² cone radiation
white
ignition time
T[⁰C]
43
41
39
37
35
33
31
29
27
25
0,00
0,10
0,20
0,30
0,40
0,50
0,60
time [min]


Back temperature of black sample exposed to 15 kW/m² cone radiation
T[0C]
425
375
325
275
225
175
125
75
25
black
ignition time
0,00
1,00
2,00
3,00
4,00
5,00
6,00
7,00
8,00
time [min]


Back temperature of black sample exposed to 20 kW/m² cone radiation
T[0C]
475,00
425,00
375,00
325,00
275,00
225,00
175,00
125,00
75,00
25,00
black
ignition time
0,00
1,00
2,00
3,00
4,00
5,00
time [min]