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Efficiency of hot smoke layer cooling techniques: investigation of an experimental setup

Masterproject

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Summary

Firefighters in the Netherlands use smoke layer cooling techniques (SCT) to lower the temperature of the smoke layer in an adjacent room to the fire room. Due to lowering the smoke layer temperature, the risk of this smoke layer is reduced and an offensive fire attack can be started. However, until now, the efficiency of these techniques is not known. Throughout a discussion with the Fire Service Academy, an experiment is initialised and designed. The goal of this experiment was to determine the efficiency of different smoke layer cooling techniques. In addition, a possible definition of the efficiency is found.

The initialised experiment consists of two rooms in which room one contains the fire and some openings. In the wall between the rooms, openings are applied that can be closed manually if enough smoke has entered room two. The reference situation is when enough smoke has entered the room and the doors are closed. After that a SCT is applied and several needed measurements can be done through which the efficiency can be calculated. However, this study showed that the experimental setup is not useful because the smoke temperature is still too low (between 30-60°C) when the desired smoke layer height is accomplished. At this temperature, water will not vaporise and an attack with a SCT will be useless. Therefore, a few recommendations are given for which more research is necessary before implementation.

List of definitions and quantities

A list of used quantities, indices and definitions in this study is given below.

List of quantities

A [m²]	area
b [-]	proportion of water that vaporises in the smoke
c [J/kgK]	specific heat
$c_{p,g}$ [J/molK]	specific heat capacity of smoke
$c_{p,w}$ [J/molK]	specific heat capacity of steam
Δheight [m]	change in height
HRR [kW]	Heat Release Rate
$L_{V,w}$ [J/g]	vaporisation heat of water
m [kg]	mass
M_w [g/mol]	molecular weight of water
n [-]	fraction
n [mol]	number of molecules
P [pa]	pressure
Q [J]	energy
R [J/molK]	general gas constant
t [s]	time
T [°C], [K]	temperature
V [m³]	volume
Y_s [-]	soot yield
ε [-]	emissivity
ρ [kg/m³]	density
λ [W/mK]	conductivity

List of indices

0	reference situation of the smoke layer
1	situation of the smoke layer after a SCT is applied
c	content smoke layer after a SCT is applied
o	content smoke layer in reference situation

List of definitions

CFBT	Compartment Fire Behaviour Training
CFAST	Consolidated Model of Fire and Smoke Transport *(multi-zone model)*
FDS	Fire Dynamics Simulator *(Computational Fluid Dynamics model)*
RHR	Rate of Heat Release
RHRc	Heat (RHR) drain by cooling
RHRo	Heat (RHR) flow by fire
SCT	Smoke layer Cooling Technique(s)
FSA	Fire Service Academy

Content

Appendices

1 Introduction and goals

The number of fires is decreased in the last 10 years with about 30%. However, residential fires in living and sleeping rooms are still a big issue for firefighters (1). Therefore, the Fires Service Academy (FSA) in Arnhem performed experiments with residential fires in Zutphen to study the fire development in small fire compartments (resident). One major conclusion of this study was that a small change in the assumptions and configurations, like a change in type or place of furniture and the ventilation rate, influences the fire development significantly (2). The fire development in dwellings is also changed due to the change of materials that are used for furniture or to insulate the building envelop, which can result in unwanted effects during a fire (2). Due to the change in materials, the development of a fire becomes faster by couches, mattresses, sources of plastics etc.. These products are made from synthetic polymers (like polyurethane foams) that has a high amount of energy which is released during a fire in a short period of time (3,4). Another conclusion from this experiment and also of other studies was that a typical (Dutch) dwelling does not exist due to the amount of varieties in compartment sizes, used furniture, style of living and type of ventilation (1,5). Compartment sizes in the Netherlands are diverse but approximately 50% of the one-family dwellings in the Netherlands range from 100-150 m². So most dwellings can be considered as a small enclosed area (6,7). The third important conclusion was that the amount of ventilation by open/closed doors or broken windows has a large effect on the development of the fire (2). Furthermore, when firefighters arrive in a dwelling, often the fire has been fuel controlled and begun smouldering in the meantime by a lack of oxygen (2,7). Also, by low air supply, the smoke layer in an enclosed compartment becomes filled with unburnt products, formed by incomplete combustion, which can lead to ignition under certain circumstances (4,7).

The organisation Compartment Fire Behaviour Training (CFBT) provides firefighters trainings that focus on indoor fires. One of the instructors/firefighters of CBT had noticed that the lower smoke layer, near the fire, ignites; as shown in figure 1. This observation was the starting point of this research.

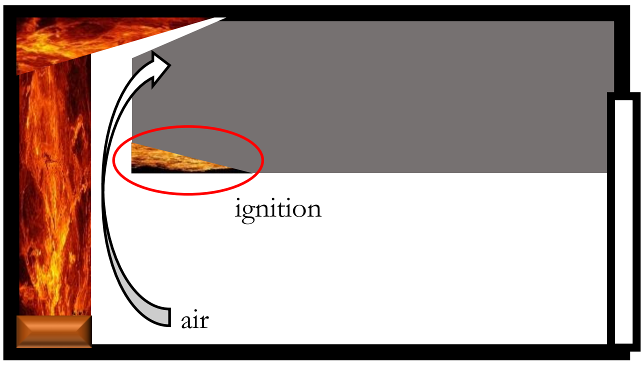


Figure 1 – Schematic view of the observed effect by a firefighter. A part of the smoke layer, close to the flame, ignites.

After some discussions about this phenomenon, there seemed to be an underlying question about the efficiency of the current Smoke layer Cooling Techniques (SCT). The main idea is that cooling the smoke layer by an offensive attack leads to a decreased risk for firefighters when they attack the fire compartment. Examples of SCT's are: 'drukluchtschuim' and 'low pressure' (8). However, the efficiency of a SCT is not investigated in detail until now. Therefore, a study is initiated to gain knowledge about the efficiency of each of these SCT's. In more detail, the relation between the impact of the attack with one of these SCT's on the smoke layer and a fire is of interest. To determine the efficiency of SCT's it is important to know the circumstances in which the firefighter enters a dwelling. Based on the mean response time of 7.5 minutes in the Netherlands the fire in a dwelling has temperatures > 600 °C (based on the standard fire curve) clarifying a sizable fire after a flashover or about to flashover (9,10). Considering the safety of firefighters this means that unsafe fire conditions are formed and a fire attack close to the fire is not possible (10,11).

(3D) SCT's are widely used nowadays to ensure a safer environment in the attack route (adjacent rooms to the fire room) and furthermore to reduce the risk of flashover or backdraft (12,13). Past experiments showed that the attack with a SCT could reduce the temperature of the smoke layer by 200 – 250 °C. Nevertheless, the temperature drop by a straight stream tactic will quickly return to its original temperature (14). Taking into account the concerns about the possible disruption of the thermal balance in a fire compartment, extensive training is necessary to apply these techniques (14). However, the following effects are needed to be taken into account. A SCT has a direct and indirect effect on the smoke layer. The direct effect is from water that vaporises and extract a lot of energy from the smoke layer. Approximately, 35% to 60% will vaporise in the smoke layer (15). The indirect effects come from water that cools the construction, approximately 30% - 50% hits the floor and 10% - 15% the ceiling, and from water that warms up (15). However, the energy that is taken out of the smoke layer due to water droplets that warm up can be considered small. Furthermore, the effect of water that cools the construction is slow and hard to measure. Both indirect effects are for that reason not taken into account in this study.

The goal of the experiment is to determine the efficiency of several SCT's in an enclosed fire compartment, comparable to a living- or sleeping room, in order to understand the impact on a smoke layer, smoke development and fire. The main issue is that the influence of a fire to the smoke layer needs to be eliminated. One of the in this research investigated ideas, is to compile two rooms with a door or opening in between which can be closed from the outside in order to separate the two rooms . Room one includes the fire source and room two is a closed room in which an attack with a SCT can be performed.
Computer simulations were used to predict the fire development in the experimental setup to know on forehand what could be expected (16).

Adjacent to the investigation of the experimental setup, a study is done to the factor 'efficiency' and how it can be defined. It is suggested by the supervisor that data of simple measurements like the temperatures, oxygen availability or the volume of the smoke layer can be used.

The research questions are as follows:

1. To which extent is it possible to determine the efficiency of a smoke layer cooling technique based on data from simple measurements like the height and temperature of the smoke layer?
2. Which combination of the variants: place-, heat release rate of the fire, opening in the facades and between both rooms gives the best reference situation in which the efficiency of a smoke layer cooling can be determined?

2 Method

This study is separated into three sub studies. First, research is done to define a definition of the smoke layer cooling efficiency. Second, to ensure a fuel controlled fire in a room, the minimum opening size of the windows and the fire characteristics are investigated with a parametric study with CFAST. Thirdly, a parametric study is performed with FDS-simulations to analyse the possible fire and smoke development in the experiment (see paragraph 2.1).

The first parametric study is, as already mentioned, performed with a multi-zone fire model. A multi-zone fire model is easy in use and give results very quickly. The needed simulations for the first parametric study were a lot due to the combinations of several variables. It was not possible to do all these calculations with FDS-simulations. FDS-simulations are Computatinal Fluid Dynamics simulations, which are specially designed to simulate fires. However, because of the limitations with CFAST in simulating the flow of smoke in more detail, FDS-simulations are used to investigate the final design of the experiment.

On forehand, the experiment of the main study, the room characteristics and the fire characteristics are described.

2.1 Experiment of the primary study

Beyond the scope of this research, but meaningful for this prior examination, is the primary study. The goal of the primary study is to analyse several SCT's and assess the efficiency of each technique. Considering the 'efficiency', a zero-situation is needed in which all parameters, which are temperature and energy of the smoke layer, are constant over time. Therefore, an experimental set-up is designed with two separate rooms in which room two performs as an adiabatic room to gain a zero-situation. Figure 2 shows the setup in which room one includes the fire source and room two the measurement area. Through the doors in the front an attack by firefighters can be performed.

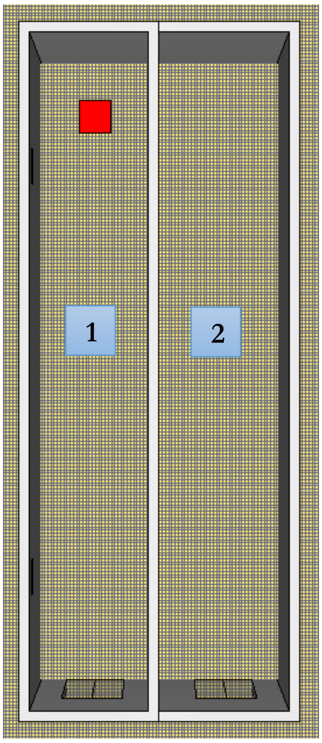


Figure 2 - Set-up experiment (PyroSim 2016).

2.2 Room characteristics

The characteristics of both rooms are:

- width of 4 meter, length of 20 meter and a height of 3 meter;
- room one includes the fire source and room 2 the measurement devices (see paragraph 2.5);
- room one includes several openings to ensure that enough oxygen is

available for the fire to ensure the fire will become a fuel controlled fire. The minimum opening sizes are determined by use of computer simulations (see paragraph 2.5);

- between room one and two, one (or more doors, see paragraph 2.6) are placed to allow smoke going from room one to room two. These doors can be closed to separate room one from room two. Dimension of the doors are 0.9 x 2.1 meter.

The wall, floor and ceiling are assumed adiabatic to exclude energy losses to the environment and to obtain a 'zero situation'. Based on a discussion with the FSA, the construction properties as mentioned in table 1 are taken into account.

Table 1 - Construction properties[1] wall, floor and ceiling.

	thickness [m]	Density [kg/m³]	Specific heat [J/kgK]	Conductivity [W/mK]	Emissivity [-]	Absorption coefficient
Concrete	0.150	2280	1040	1.8	0.9	50000
Insulation (Rockwool)	0.080	37	840	0.033	0.9	50000
Steel	0.0012	7850	460	45.8	0.95	50000

2.3 Fire characteristics

The FSA preferably want to use the already investigated woodpile consisting of chipboard, foam and pallets with a maximum Rate of Heat Release (RHR) of 3890 kW and a total mass of 170 kg. Details about the power and mass over time of the investigated woodpile are included in appendix 1. The RHR according to the time of the measured woodpile is shown in figure 3. As the expectation was that the woodpile contains too much energy in relation the volume of room one, the parametric study is done with several different fire characteristics (see paragraph 2.5). Therefore, four other theoretical formed woodpiles based on various maximum RHR (1500, 200, 2500, 3000 kW), are investigated (see figure 3). The fire curves of the theoretical formed woodpiles are based on the fire curve of the given woodpile.

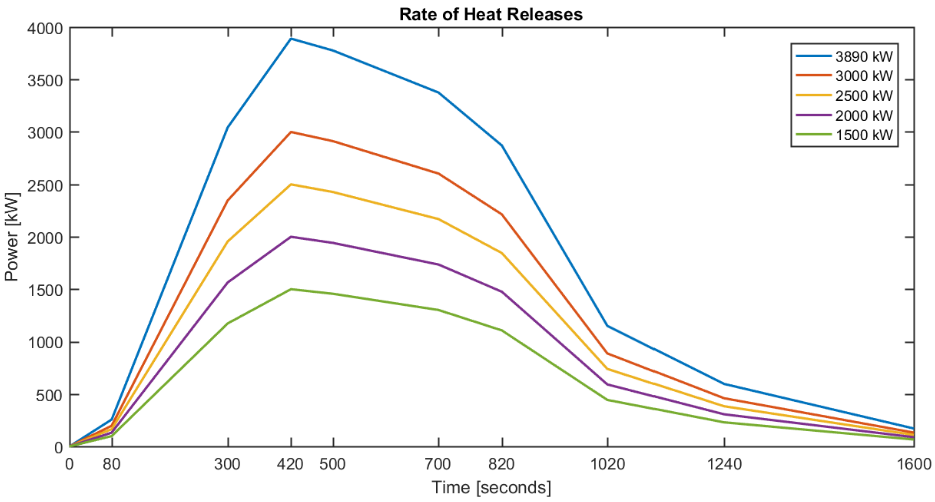


Figure 3 - Rate of Heat Release of the investigated woodpiles.

[1] Properties are based on the available materials in the library of PyroSim 2016 and (21,22)

2.4 Determination of the definition of the smoke layer cooling techniques efficiencies

As already mentioned in the introduction, one of the contents of this study is to determine the efficiency of different SCT's. In more detail, the efficiency needs to be based on common measurements like the temperature, mass or the volume of the smoke layer in the measurement room. The formula of the efficiency of SCT's is composed based on available literature like the comparison study done by M. van der Veire (17).

An important criterion of the formula is that it is based on a non-changing situation concerning the energy interchange with the environment (energy balance). Only the interaction from the attack with a SCT may affect the energy balance in room two. Furthermore, a representative smoke layer is needed in room two (see paragraph 2.2). The requirements for a representative smoke layer are defined as follows:

- The smoke layer has a height of approximately 0.8 meter, resulting in a height of approximately 0.1 meter between the top of the door and the bottom of the smoke layer. A door between both rooms needs to be closed when the correct height of the smoke layer is achieved;
- The smoke layer in the second room needs to be equally distributed over the ceiling with a maximum Δ_{Height} of 0.2 meter;
- The smoke layer has a temperature in which water can vaporize (> 100 °C).

The basic principle of the formula can be based on the mass-energy equivalence $E = mcT$. Measurements need to be done on two moments, namely: after the doors are closed (reference situation) and after a SCT is applied. A starting point of the efficiency definition can be formula 1.

$$efficiency = \frac{Ec}{Eo} \tag{1}$$

With:

Ec	[J]	energy content of the smoke layer in the reference situation (without cooling)
Eo	[J]	energy content of the smoke layer after the SCT is applied

2.5 Parametric study to the window size and fire characteristics

A parametric study is performed with different fire characteristics and different sizes of openings to gain a fuel controlled and safe experiment for firefighters. There are five different RHR (see figure 3) examined related to five different openings sizes, namely: 1, 2, 3, 4 and 5 m². The five different used RHR are shown in table 2 using the same fraction of the maximum RHR of the already measured woodpile (see appendix 1) to get the same fire curve. The simulations are performed with the software program CFAST7 which is a multi-zone fire model (18,19). In this report, the performed simulations with CFAST are mentioned as CFAST calculations.

The parameters for the CFAST simulations are as follows:

- the composition $C_4H_6O_3$ (normal cellulose fuel) and the already given fraction of the maximum RHR are used for the chemical reaction of the fire;
- Height of smoke layer according to the set-points as described in paragraph 2.4;
- Distribution of the smoke layer in room two according to the set-points as described in paragraph 2.4;

Table 2 - RHR releases that are investigated using multi-zone modelling.

Time	Fraction [-]	RHR [kW] (3890.7 kW)	RHR [kW] (3000 kW)	RHR [kW] (2500 kW)	RHR [kW] (1500 kW)
0	0.0000	0	0	0	0
80	0.06590	256	198	132	99
300	0.7821	3043	2346	1564	1173
420	1.0000	3891	3000	2000	1500
500	0.9707	3777	2912	1941	1456
700	0.8676	3376	2603	1735	1301
820	0.7379	2871	2214	1476	1107
1020	0.2958	1151	887	592	444
1240	0.1533	596	460	307	230
1600	0.0439	171	132	88	66

2.6 Parametric study to a representative smoke layer

The results from the aforementioned parametric study are included in the assumptions for the parametric study to a representative smoke layer. Therefore, FDS-simulations are performed using the commercial software program Pyrosim 2016 (20). With the FDS-simulation the smoke spread in both rooms is investigated. In total five variants are simulated whereafter one calculation was made with the most suitable parameters to analyse the effect after closing the door between both rooms. Table 3 shows the number of simulations related to the investigated variables, which are: Rate of Heat Release (RHR), place of fire, construction and the amount of doors between the rooms.

Table 3 - Number of simulation related to the investigated variables.

Simulation	Rate of Heat release		Place of fire		Construction		Door between room 1 and 2	
	Given	CFAST	middle	top	real	adiabatic	One	Two
1	X			X		X	X	
2		X		X		X	X	
3		X		X	X		X	
4		X	X			X		X
5		X	X			X		X (2,3 m)
6[2]		X	X			X		X (2,3 m)

[2] Simulation six includes the closed door after 140 seconds, based on the multi-zone modelling to determine the effect on the smoke layer in room 2 for a period of 20 seconds. Total calculation time is 300 seconds.

First, simulation 1 and 2 were comparted to investigate the advised RHR in order to get a fuel-controlled fire. Simulation 1 include the suggested woodpile with a RHR of 3890 kW and simulation 2 the recommended RHR (see paragraph 2.5). The temperatures of the different layers in both rooms are analysed to verify the safety for an offensive attack by firefighters to cool the smoke layer. Thereafter, simulation 2 and 3 are compared to investigate the differences between an adiabatic construction and a construction based on the real properties (see Table 1). All other simulation variants include adiabatic constructions to make the simulation results more comparable. Thirdly, simulation 2, 4 and 5 are compared to investigate the flow of smoke between room one and two by changing the amount of doors and place of fire. At last, simulation six is performed based on the results of simulations 1 to 5. In contrast to the five simulations which have a simulation time of 200 seconds, simulation six had a simulation time of 300 seconds.

The parameters for the FDS-simulations are as follows:

- the composition $C_4H_6O_3$ and the already given fraction of the maximum RHR are used for the chemical reaction of the fire;
- a mesh with dimensions of 0.1 m x 0.1 m x 0.1 m was used, fitting with the construction dimensions;
- Height of smoke layer according to the set-points as described in paragraph 2.4;
- Distribution of the smoke layer in room two according to the set-points as described in paragraph 2.4;
- Energy reduction of the zero-situation after the door between room one and two is closed using thermocouples on four vertical lines in room two which are equally distributed in the room. Each vertical line contains six thermocouples on 0.5, 1.0, 1.5, 1.75, 2.0, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8 and 2.9 meter above floor level.

The height of the smoke layer is determined by use of slides over the rooms to assess the smoke development in room two.

3. Results

3.1 Determination of the definition of the smoke layer cooling techniques efficiencies

The efficiency of a SCT depends on the nozzle characteristics and application technique which are described in detail in the study of Van de veire M (17). From this research it is known that the cooling efficiency of water is already determined, although the efficiency of a certain SCT on the smoke layer is not known (14). Therefore, a definition of the efficiency is determined.

A SCT inserts small water droplets into a smoke layer to extract energy resulting in a temperature drop. This temperature drop is due to several factors. First, when a water droplet contacts a hot smoke layer it vaporises as a result of which a lot of energy is extracted. Second, these water droplets can also fall to the ground and take away some smoke particles. Furthermore, because of the vaporisation the volume of water, which sublimate to gas, increase resulting in a pressure rise. The water can also cool the construction (walls, floor or ceiling) of a compartment when water meets it. The last factor is the created turbulence due to the flow rate of the water droplets. These factors all influences the conditions of a smoke layer and to some extend influence the efficiency of a SCT.

In order to determine the efficiency it is necessary to establish the different terms affecting the mass and energy balances. Because it is suggested that room two, conform the prescribed experiment (see paragraph 2.1), has a steady mass and energy balance after closing the door(s) between both rooms. However, a zero-situation can only be accomplished when the effects of the environment are excluded. Therefore a fundamental assumption is that the room's envelop is adiabatic which is guaranteed by the use of insulation material on the inside of the construction also to exclude the effect of thermal mass.

Formula 2 and 3 shows the mass and energy balance in room two based on the fact that the room is divided in two zones, namely: upper zone containing the smoke and the lower zone containing normal air.

Mass balance (lower and upper layer):

mass loss	+	mass stored	=	mass gains	+	auxiliary mass	(2)
$\dot{m}_{loss}$		$\dot{m}_{stored}$		$\dot{m}_{stored}$		$\dot{m}_{auxiliary}$	

Energy balance (lower and upper layer):

energy loss	+	energy stored	=	energy gains	+	auxiliary energy	(3)
Q_{loss}		Q_{stored}		Q_{gains}		$Q_{auxiliary}$	

Furthermore, the behaviour of a gas due to changes in the gas temperature can be based on the ideal gas law conform formula 4.

$$PV = n \cdot R \cdot T \tag{4}$$

With:

P	Pressure	[pa]
V	Volume	[m³]
n	Number of molecules	[mol]
R	General gas constant	[J/molK]
T	Temperature	[K]

As already mentioned the water droplets can mainly do two things: vaporise and extracting energy from a hot smoke layer or cooling the construction. To calculate the proportion of water that is vaporised a formula from the study of Särdqvist S can be used, see formula 5 (11).

$$\frac{V_1}{V_0} = \left(\frac{C_{p,g} \cdot (T_0 - T_1)}{b \cdot M_w \cdot L_{V,w} + C_{p,w} \cdot (T_1 - 373)}\right) \cdot \frac{T_1}{T_0} \tag{5}$$

With:

V	volume of the smoke layer	[m³]	*(use measurements)*
$C_{p,g}$	specific heat capacity of smoke	[J/molK]	*33.2 J/molK at 1000 K* (11)
T	temperature of smoke layer	[K]	*(use measurements)*
b	proportion of water which vaporises in the smoke	[-]	
M_w	molecular weight of water	[g/mol]	*18.0 g/mol* (11)
$L_{V,w}$	vaporisation heat of water	[J/g]	*2260 J/g* (11)
$C_{p,w}$	specific heat capacity of steam	[J/molK]	*41.2 at 1000 K* (11)
0	reference situation of the smoke layer		
1	situation of the smoke layer after applying SCT		

Most values in the formula are known constants. The volume and temperature of the smoke layer can be based on the calculations performed in the experiment. Because the temperature in the smoke layer is not constant over the height, it is needed to take the average temperature of the whole volume. To calculate the proportion of water that vaporises in the smoke, formula 5 is rewritten to formula 6.

$$b = \frac{\left(\frac{C_{p,g} \cdot (T_0 - T_1)}{\left(\frac{V_1}{V_0} \middle/ \frac{T_1}{T_0}\right)} - C_{p,w} \cdot (T_1 - 373)\right)}{M_w \cdot L_{V,w}} \tag{6}$$

3.2 Parametric study to the window size and fire characteristics

To determine the right properties for the FDS-simulations a parametric study is done to determine the effect of different opening sizes in room one. Figures 4 – 8 shows a strong relation between the total opening sizes of the windows in room one and the present oxygen in the layer below the smoke layer. It can be derived that the fire with a RHR of 3,980 kW uses a lot of oxygen compared to the smaller fires.

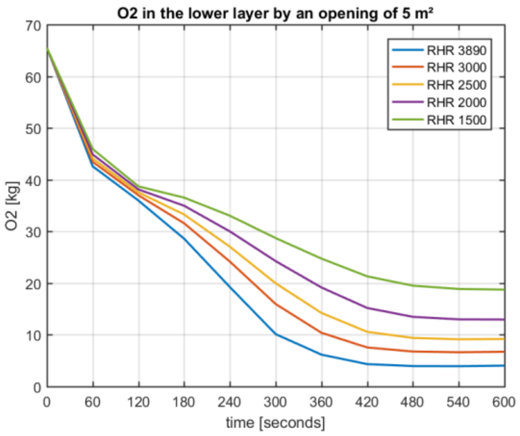


Figure 6 - O2 in lower layer by an opening of 5 m²

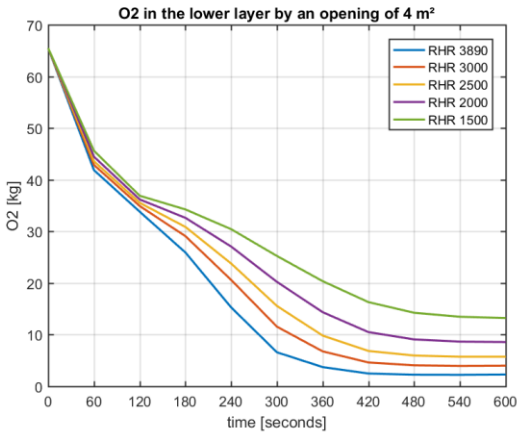


Figure 7 - O2 in the lower layer by an opening of 4 m²

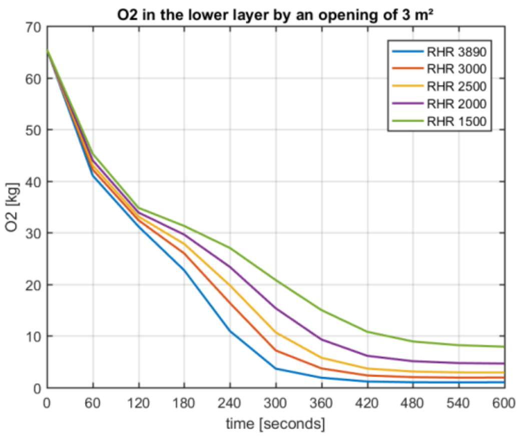


Figure 8 - O2 in the lower layer by an opening of 3 m²

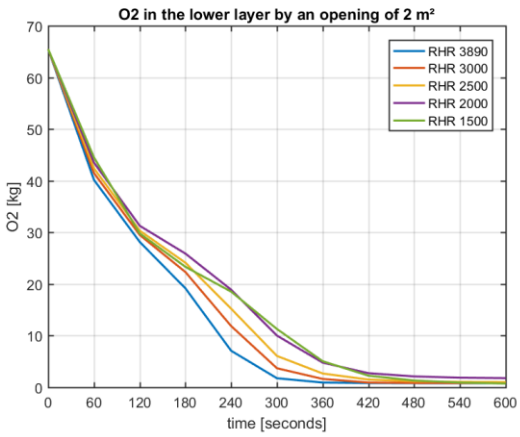


Figure 9 - O2 in the lower layer by an opening of 2 m²

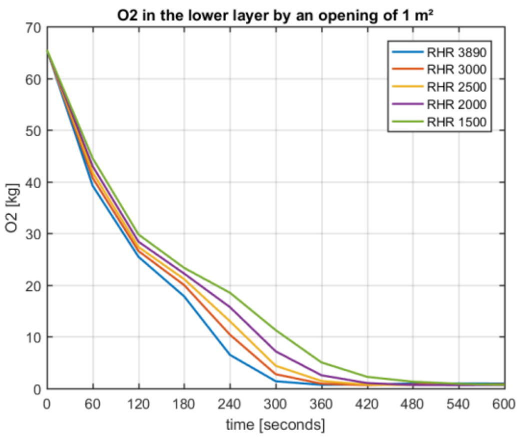


Figure 4 - O2 in the lower layer by an opening of 1 m²

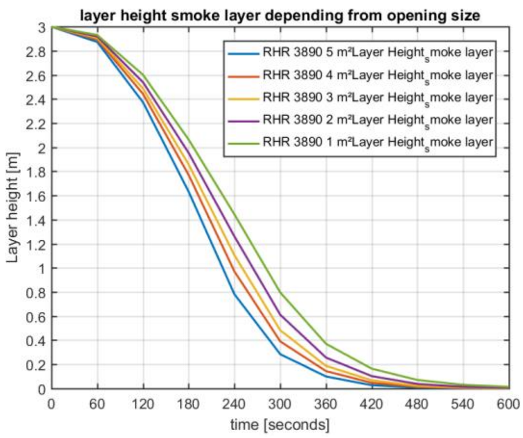


Figure 5 - smoke layer height in room 2 depending from opening size

By an opening size smaller than 3 m², all the investigated fires become fuel controlled due to the availability of zero oxygen. When the total opening area is more than 4 m², none of the investigated fires become fuel controlled.

To gain an equal smoke layer with a smaller fire, it takes approximately one minute; see figure 5. Moreover, the time that is needed to gain a smoke layer height of 0.8 meter is for a 3,890 kW fire accomplished after approximately 140 seconds and for a 2,000 kW fire after approximately 180 seconds. These values are used as the time after which the door between the rooms needs to be closed.

According to the experiment of the primary study a woodpile with a maximum RHR of 3,890 kW can be used based on the criteria that it stays fuel controlled. However, the temperature of the smoke layer in room one become 1,500 °C what results in a smoke layer temperature of 1,000 °C in room two. The temperatures in room one exceeds by 500 °C compared to the temperatures of the natural fire concept as defined in the NEN 6055. A FDS-simulation is needed to determine the right temperatures of the smoke layer formed in room two after closing the door in between. Considering the results with a woodpile of 2,000 kW, the smoke layer temperature is approximately 200 - 250 °C as shown in figure 10.

For the safety of the firefighters the smoke layer may not exceed temperatures of 250-300 °C (10). The maximum smoke layer temperature in room one, which include the fire, may become higher because the firefighter do not need to enter this room during the experiment. However, very high temperatures are unwanted because during a fail the firefighters need the option to extinguish the fire. Based on the simulations that were made with CFAST, the 2,000 kW fire appears to give the wanted temperatures as shown in figure 10. For the smoke layer (upper layer) in room one the maximum temperature is approximately 678 °C and for the smoke layer (upper layer) in room two approximately 54 °C based on the intersection point of 180 seconds.

With the use of CFAST calculations the O_2 availability, smoke layer height and the temperatures of the different layers are investigated. Concluded, the fire with a maximum RHR of 3,890 kW compared to a fire with a maximum RHR of 2,000 kW reaches temperatures of respectively 1460 °C to 670 °C for the smoke layer in room one. However, the smoke layer in room two is, taking into account the wanted smoke layer of 0.8 meter, in accordance with each other, achieving approximately 55 °C.

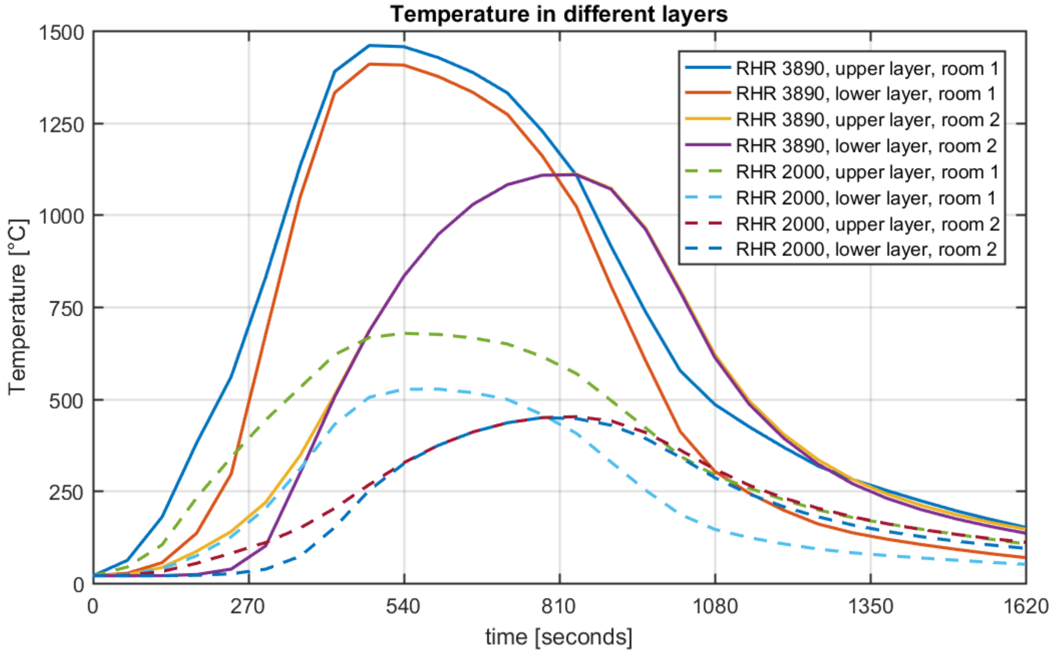


Figure 10 - Temperatures in the different layers. Comparison between a fire of 3,890 or 2,000 kW

3.3 Parametric study to a representative smoke layer

Another parametric study is performed to investigate the development of the smoke layer in the experimental set-up including the expected temperatures taken into account several variants. The development of the smoke layer is due to the fact that the same fire curve and the same Ysoot is employed more or less the same in both rooms. This conclusion can be drawn from the slices of the soot visibility, which can be found in appendix 2. However, differences were found for the temperatures of the smoke layer and the energy flow through the door(s) between the rooms. For all the simulations, except of the last, a calculation time of 200 seconds is used based on the given point of 140 and 180 seconds in which a representative smoke layer in room 2, according to the mentioned set points, should be formed.

3.3.1 Comparison between a 3,890 kW and 2,000 kW fire (simulation 1 and 2)

As mentioned in paragraph 3.2, the given woodpile of 3,890 kW results in high temperatures in room one as a result of which the 2,000 kW woodpile is investigated. Because the temperature of the smoke layer is lower with a 2,000 kW fire, the experiment is considered safer for the firefighters. The lower temperatures found with the parametric study to the window size and fire characteristics were also found with the FDS-simulations. The results between variant 1 and 2 shows temperatures of 300 °C after 140 seconds for the 3,890 kW fire and 160-200 °C after 180 seconds for the 2,000 kW fire in room one. Furthermore, the measured temperatures by the thermocouples in room two were approximately 30 °C lower in variant 2 (see figure 11). To determine the efficiency of a SCT a smoke layer with such low temperatures can make it hard to calculate the efficiency due to the fact that water will not vaporise (which is one of the main factors for the efficiency).

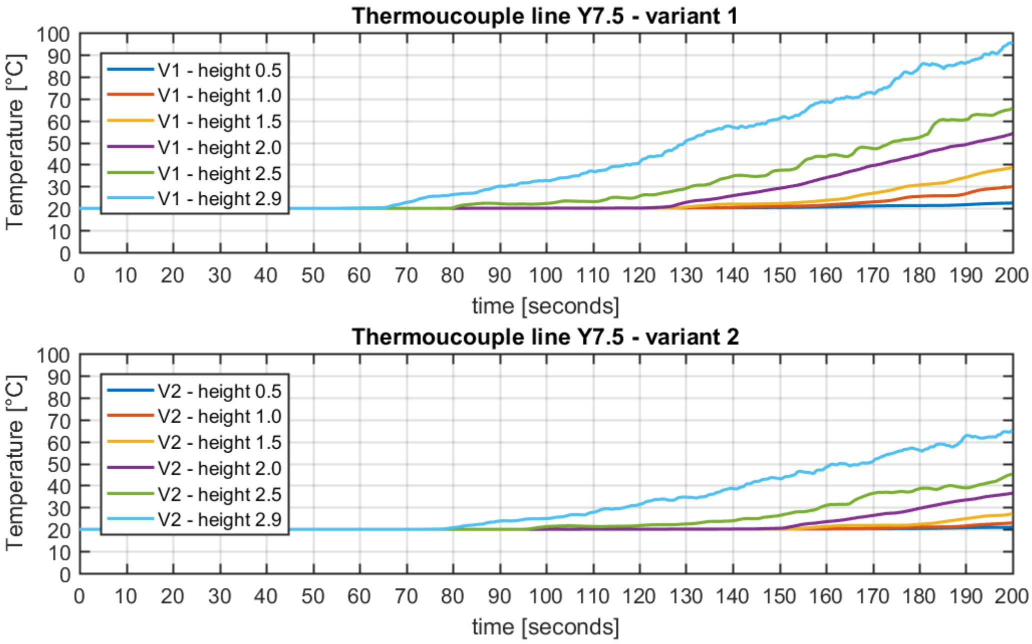


Figure 11 - Temperatures of the thermocouples in room 2 for variant 1 and variant 2

Furthermore, when a fire source with less power is used it will take longer to gain an equal smoke layer (based on the soot visibility) than using a fire source with more power (see appendix 2 and 3).

The expected temperatures with a 3,890 kW fire are, taken into account the safety of the firefighters, too high. The other calculations are therefore performed with a 2,000 kW fire.

3.3.2 Comparison between a real or adiabatic construction (simulation 2 and 3)

It is suggested that simulating with the real construction properties results in a colder smoke layer and a lower flow of smoke from room one to room two compared to an adiabatic room. The advantage of an adiabatic room is the fact that the energy exchange through the construction is zero. This assumption is needed to determine the efficiency otherwise, it is also needed to take the energy loss through the construction into account. Considering the experiment the goal is to gain a nearly adiabatic room with the given properties in table 1.

Calculating with the real construction information lead to more energy losses. This can be derived from figure 12. First, the temperature differences are respectively 131 °C and 110 ° C. Second, the integrated flow through the door, taking into account the real situation, is approximately 27.3% less than in the situation with an adiabatic room (results are based on the trend lines). At last, the maximum temperature is for both variants almost the same.

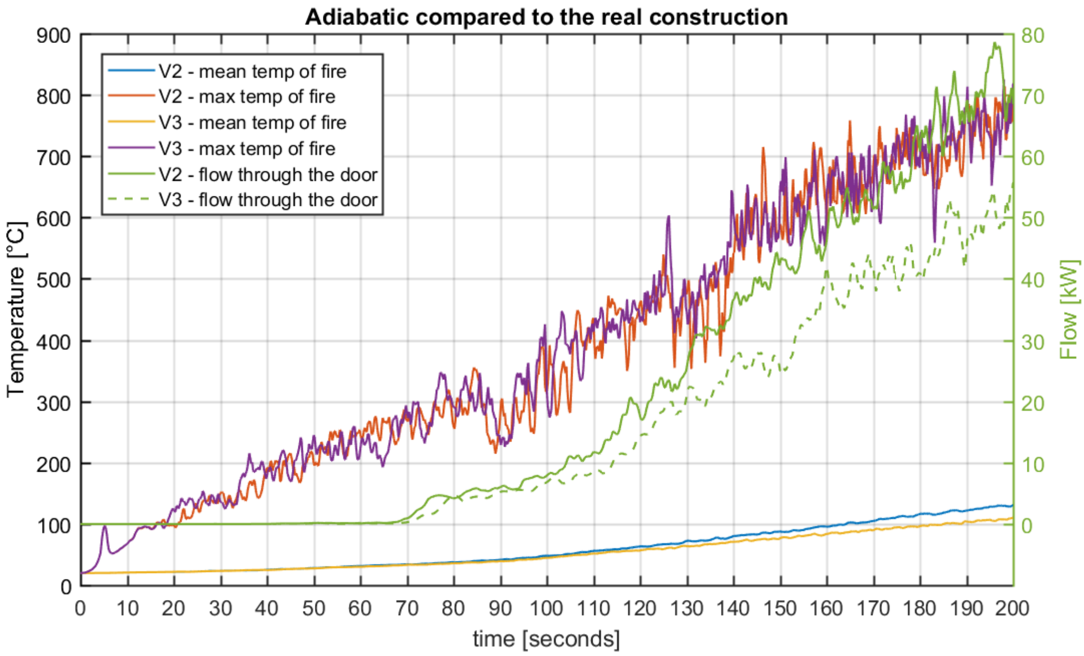


Figure 12 - Temperature of the in room 1 and the energy of the flow through the door in between

3.3.3 Influence of an extra door between both rooms (simulation 2, 4 and 5)

To increase the flow of smoke to room two, a variant with two doors is investigated. The place of fire is changed from the top of the room to the middle of room one to enhance an evenly distributed smoke layer in room two.

The results shown in figure 13 and figure 14 to figure 16 shows that due to an extra door, the flow of smoke to room two increases, resulting in a flow containing approximately 231% of the energy compared to the situation with one door. When the doors are made 0.2 meter higher, the flow contains approximately 283% of the energy. A similar result is found for the temperature of the smoke layer. Compared to variant 1 (3,890 kW fire), the same temperatures can be obtained when applying two doors with a height of 2.3 meter.

However, the given point of 140 second gives only a smoke layer temperature of 35 – 40 °C what is not enough to determine the efficiency of the a SCT because water will not vaporise at that temperature. Therefore, a FDS-simulation is made including the basic assumptions of simulation 5 taken into account a closing time of 180 seconds for the two doors between the rooms. Because trial simulations showed that the smoke layer need some time to stabilize so the calculation time was fixed to 300 seconds.

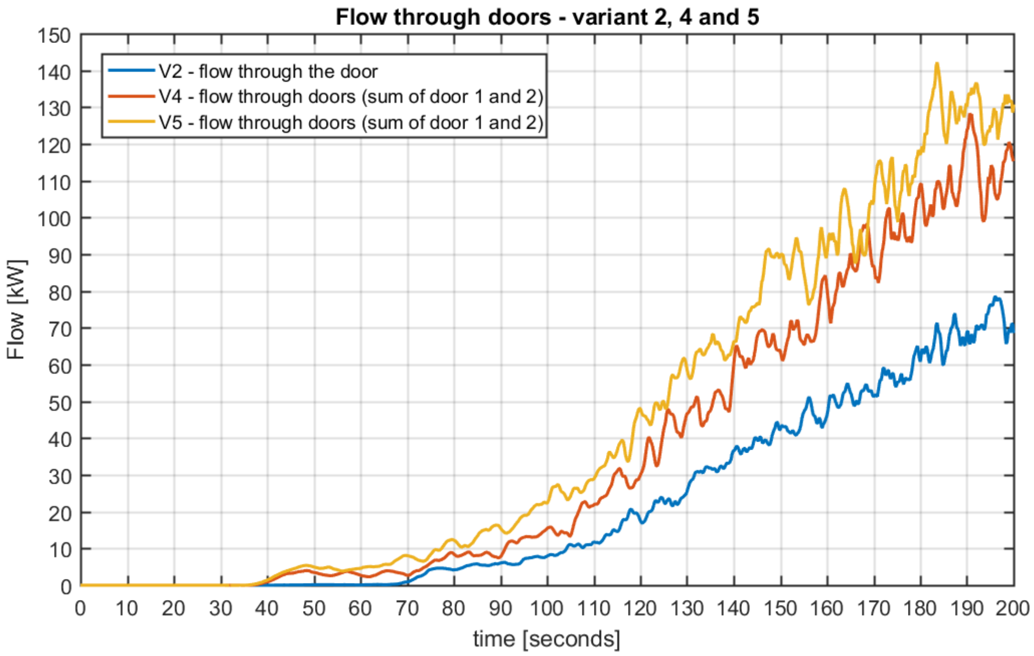


Figure 13 - Flow through the door(s) between room 1 and room 2 in kW for variant 2, 4 and 5.

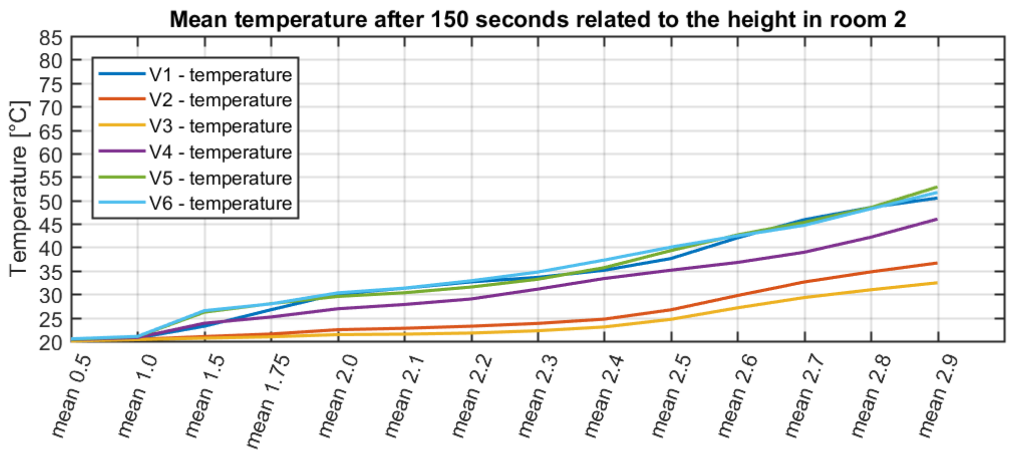


Figure 14 - Mean temperature after 150 seconds in room 2. The x-as represents the height of the thermocouple

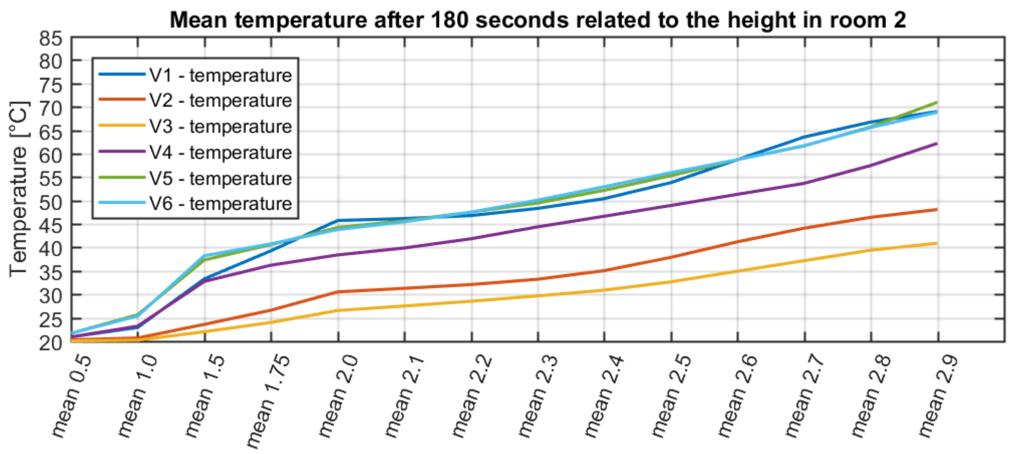


Figure 15 - Mean temperature after 180 seconds in room 2. The x-as represents the height of the thermocouple

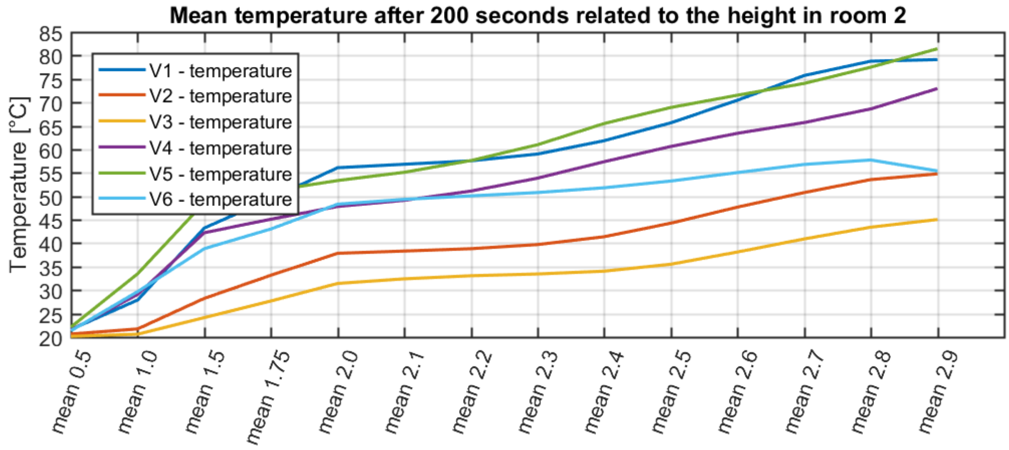


Figure 16 - Mean temperature after 200 seconds in room 2. The x-as represents the height of the thermocouple

3.3.4 Smoke layer after the door are closed (variant 6)

At 180 seconds, both doors were closed which result in a quick decrease of the smoke temperature (see figure 17). The simulation does not run long enough to see of the temperature goes to an equilibrium.

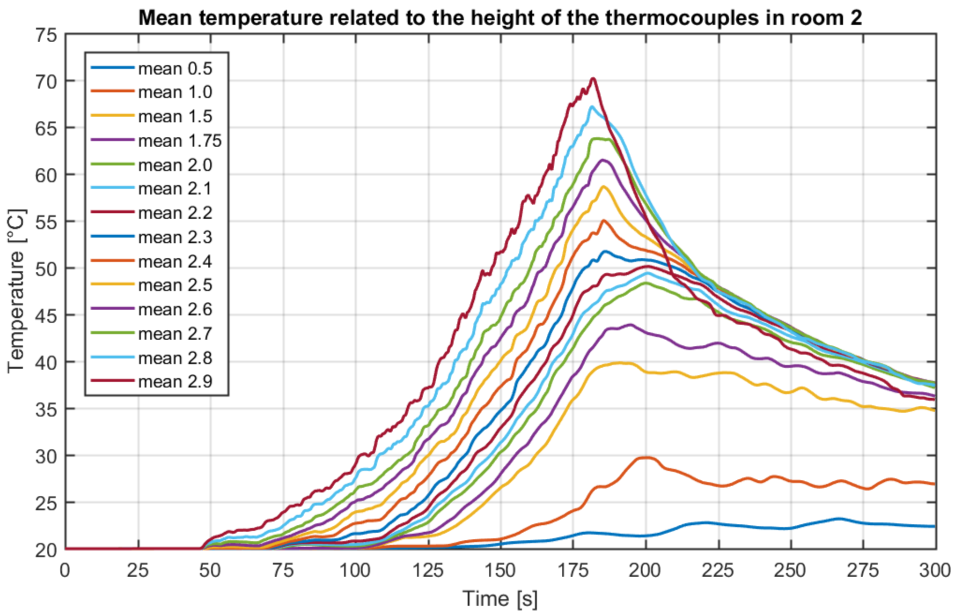


Figure 17 - Mean temperature over the height of the room related over the total depth of the room

Furthermore, figure 18 shows that the minimum and mean visibility after 180 seconds stays constant. So the amount of smoke particles does not decrease. Based on this calculation the smoke temperature will approximately be lower than 40 °C. When the smoke layer has such a low temperature, water from a SCT will not vaporise.

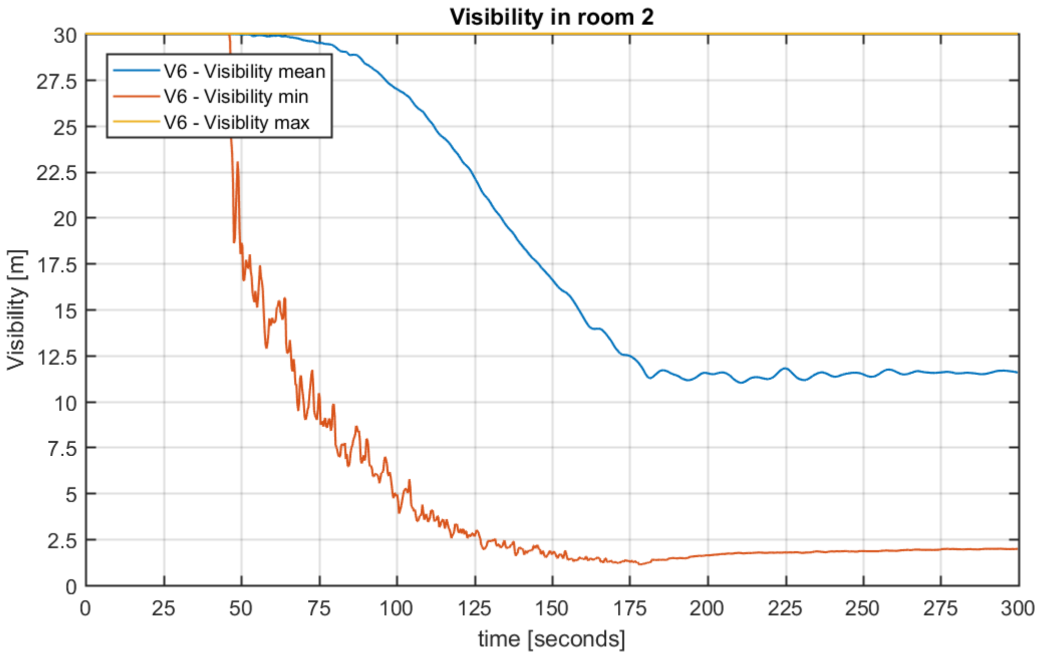


Figure 18 - Visibility in room 2 (variant 6)

4 Discussion and conclusion

To determine the efficiency of a SCT an experimental set-up is investigated consisting of two rooms. In addition, a formula is found through which the efficiency can be calculated based on vaporising water.

Considering the results of the study, particularly from the computational simulations, there are several discussion points. First, the critical conditions for firefighters in a fire compartment are temperatures > 235 °C and thermal fluxes > 10 kW/m² which means that the chosen set-point of a maximum temperature of 200-250 °C is in the range of the critical conditions (10). The conditions in room one however, rise above 1,000 °C, so the wanted woodpile was considered too dangerous (4). Results showed that a woodpile with a RHR of 2,000 kW could be used for the experiments. However, the FDS-simulations (Computational Fluid Dynamics simulations) showed that the smoke layer temperature in room two is in a range of 30 – 60 °C when the wanted smoke layer height is accomplished. This temperature is much lower than found in a normal fire, namely 900 – 1100 °C (4). The water from a SCT will not vaporise. From the results it can be concluded that the considered experimental setup do not work properly due to too low temperatures of the smoke layer. The reason is that the lower parts of the smoke layer in room one flows to room two but this part does not have high temperatures in the beginning of the experiment. In the study of Alarifi AA et. al, a smoke layer temperature of 500°C and 600 °C was reached after 155 seconds (10). It is therefore recommended to reconsider the experimental setup.

A possible option that can be investigated is the effect of running the simulations longer. When the smoke has more time to flow from room one to room two the temperature of the smoke will become higher. However, it is then needed to open the doors to the outside in room two to let a part of the smoke out. Otherwise, the smoke from room one will fully fill room two. When the firefighters than enters the reference situation, a part of the smoke will automatically flow out. This will affect the efficiency calculation. Another option is to close the door(s) between the rooms at the beginning, wait until the smokelayer in room 1 is hot enough and then open the door(s). It is also possible to redesign the experimental setup. An idea can be to place room one in the extension of room two with in between a movable wall. Then the smoke can flow to room two more easily.

When a SCT is applied, the water will vaporise and create steam. So the total volume of the gasses in room two will become larger by the steam. One of the side effects of using SCT is that a temperature decrease will go with a lower smoke free zone.

On forehand two questions were defined, which were:

1. To which extent is it possible to determine the efficiency of a smoke layer cooling technique based on data from simple measurements like the height and temperature of the smoke layer?

2. Which combination of the variants: place-, heat release rate of fire, opening in the facades and between both rooms gives the best reference situation in which the efficiency of a smoke layer cooling can be determined?

Based on the literature study, it is possible to determine the efficiency of a SCT using data from temperature and measurements of the height of the smoke layer with which the total volume of the smoke layer can be calculated. Based on a rewritten formula of Särdqvist S (11), the proportion of water vaporisation can be determined. The impact of moment and turbulence by the water spray has not been taken into account in this study.

Zooming into the experiment, computational simulations showed that the wanted woodpile resulted in too high temperatures through which the experiment becomes unsafe for firefighters. It is advised to use a less powerful woodpile with approximately 2,000 kW. In more detail, the results showed that to improve the flow of smoke and heat, more openings between room 1 and room 2 need to be applied. Including two doors instead of one increases the flow. It is advised to place the opening as close as possible to the ceiling to extract hotter smoke from room one. To gain a fuel-controlled fire the simulations proves that a total opening of at least 4 m^2 is needed.
However, as already mentioned it is advised to reconsider the experimental setup or to reconsider some parameters in order to make the flow of smoke between both rooms easier. This can be done by extending the openings to the ceiling or to redesign the experimental setup by placing room one in extension of room two with a movable wall in between.

5 References

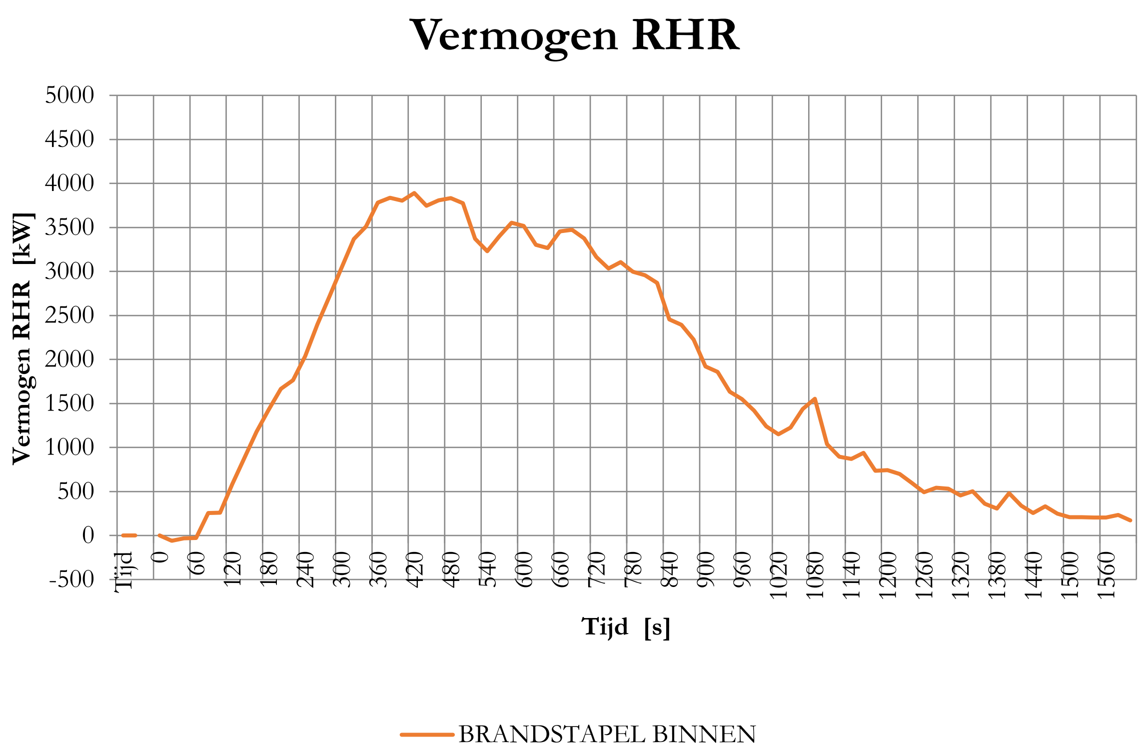
1. Brandweer; binnenbranden (totaal; naar object) [Internet]. Centraal Bureau voor de Statistiek. 2015 [cited 2016 Feb 10]. Available from: http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=37511&D1=21,24,27,30,33,36,39,42,45,48,51,54,57,60&D2=0&D3=a&HDR=T&STB=G1,G2&CHARTTYPE=1&VW=T
2. Hazebroek MCPm drs. JC, Greven dr. FE, Groenewegen-Ter Morssche drs. K, van den Dikkenberg MCDM ing. R. " Het kan verkeren " Beschrijvend onderzoek naar brandontwikkeling en overleefbaarheid bij woningbranden.
3. Stec A, Hull R, Hull TR, Stec AA. Fire Toxicity [Internet]. Fire Toxicity. Elsevier; 2010 [cited 2016 Feb 19]. 3-25 p. Available from: http://www.sciencedirect.com/science/article/pii/B9781845695026500014
4. Quintiere JG. An introduction to fire dynamics. Fire Safety Journal. 1986. 161-162 p.
5. Matellini DB, Wall AD, Jenkinson ID, Wang J, Pritchard R. Modelling dwelling fire development and occupancy escape using Bayesian network. Reliab Eng Syst Saf [Internet]. 2013 Jun [cited 2016 Feb 17];114:75–91. Available from: http://www.sciencedirect.com/science/article/pii/S0951832013000124
6. CBS. Voorraad woningen; periode 2014 [Internet]. Centraal Bureau voor de Statistiek. 2014. Available from: http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=82550NED&D1=1&D2=13-21&D3=0&D4=l&HDR=T,G3&STB=G2,G1&CHARTTYPE=1&VW=T
7. Bengtsson L-G. Enclosure fires. Göransson, Anna-Lena, Svensson B, editor. NRS Tryckeri, Huskvarna, Sweden; 2001.
8. Dikkenberg R van den, Groenewegen-ter Morsche K, Wolfs L, Vogel T. De offensieve buiteninzet: groot pand, kleine zorg? [Internet]. 2016. Available from: http://www.ifv.nl/kennisplein/Documents/20160511-BA-Offensieve-buiteninzet-groot-pand-grote-zorg.pdf
9. CBS. CBS StatLine - Branden; reactietijden van de brandweer, regio [Internet]. [cited 2017 Feb 28]. Available from: http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=83123ned&D1=4&D2=0,13-37&D3=a&HDR=T&STB=G1,G2&CHARTTYPE=3&VW=T
10. Alarifi AA, Dave J, Phylaktou HN, Aljumaiah OA, Andrews GE. Effects of fire-fighting on a fully developed compartment fire: Temperatures and emissions. Fire Saf J. 2014;68:71–80.
11. Särdqvist S. Water and other extinguishing agents. 1st ed. Göransson A-L, editor. NRS Tryckeri AB; 2002.
12. Grimwood P, Hartin E, McDoungh J, Raffel S. 3D Fire Fighting Training, Techniques and Tactics. Protection, Publications Fire; 2005.
13. Lambert K. Gas cooling : a new approach. 2012;(September):1–8.

14. Liu Z, Kashef A, Lougheed G, Benichou N. Review Of Three Dimensional Water Fog Techniques For Firefighting. 2002;(December). Available from: http://www.firetactics.com/NRC 3D.pdf
15. Chen A, Yang S, Dong X. Studies of the combined effects of some important factors on the likelihood of flashover. Fire Mater [Internet]. 2011 Mar 10 [cited 2016 Feb 19];35(2):105–14. Available from: http://doi.wiley.com/10.1002/fam.1045
16. Novozhilov V. Computational fluid dynamics modeling of compartment fires. Prog Energy Combust Sci [Internet]. 2001 Jan [cited 2016 Jan 8];27(6):611–66. Available from: http://www.sciencedirect.com/science/article/pii/S0360128501000053
17. Van de veire M. Studies on the performance of firefighter ' s gas cooling technique. 2016.
18. Peacock RD, McGrattan KB, Forney GP, Reneke PA. NIST Technical Note 1889v1 CFAST – Consolidated Fire and Smoke Transport (Version 7) Volume 1 : Technical Reference Guide. 2015;1(Version 7).
19. Peacock RD, Reneke PA, Forney GP. NIST Technical Note 1889v2 CFAST – Consolidated Model of Fire Growth and Smoke Transport (Version 7) Volume 2 : User ' s Guide. 2015;2(Version 7).
20. Thunderbird engineering. PyroSim User Manual. Building [Internet]. 2015; Available from: www.thunderheadeng.com
21. Productblad RT. Rockfit 433 PLUS Isolatie voor spouwmuren en [Internet]. [cited 2016 Nov 25]. p. 4. Available from: http://rwiumbracobn.inforce.dk/media/404870/tp_rockfit 433 plus_nl (beveiligd).pdf
22. Productblad RT. INSULATING PIPE SECTIONS [Internet]. 2004. Available from: http://www.siper-bg.com/files/products/pic136_1_en.pdf

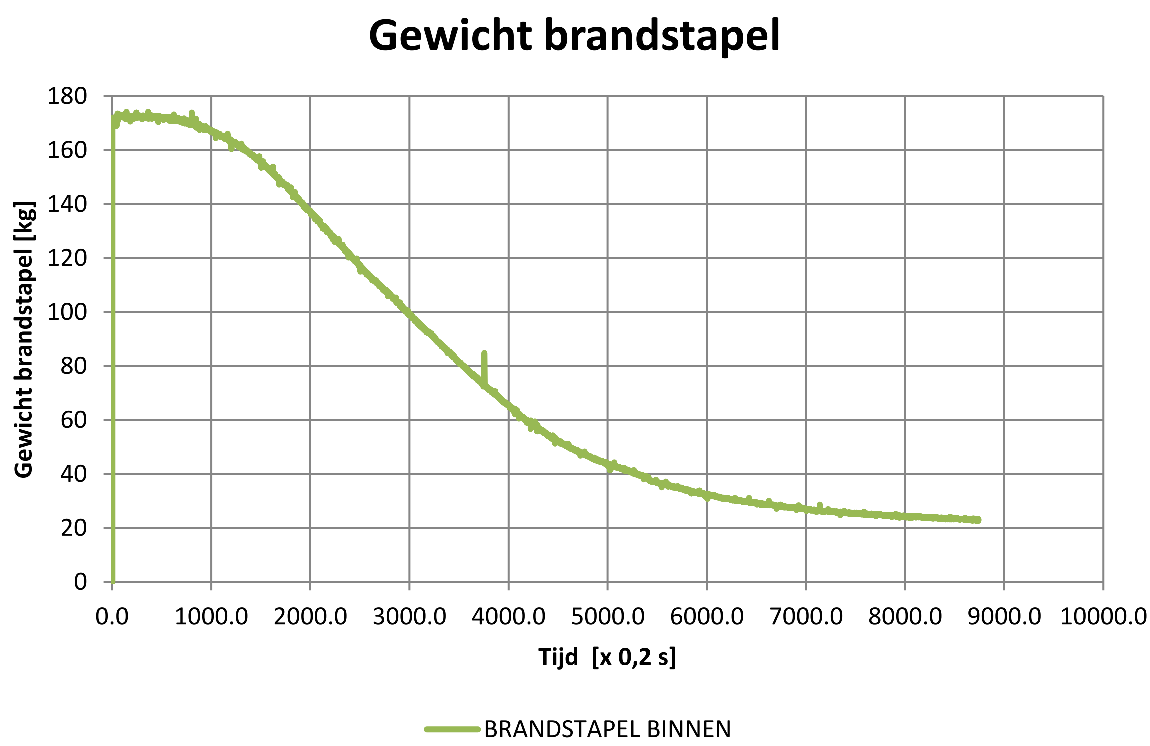
APPENDIX 1

Characteristics of the given woodpile from the 'Brandweeracademie'

Power of the given woodpile



Mass of the given woodpile



APPENDIX 2

Results of FDS-simulations

APPENDIX 2.0

List of simulations

1.1 FDS-simulation 1

RHR of 3,890 kW, place of fire in top of the room, adiabatic construction and one door between room 1 and 2

1.2 FDS-simulation 2

RHR of 2,000 kW, place of fire in top of the room, adiabatic construction and one door between room 1 and 2

1.3 FDS-simulation 3

RHR of 2,000 kW, place of fire in top of the room, real construction and one door between room 1 and 2

1.4 FDS-simulation 4

RHR of 2,000 kW, place of fire in middle of the room, adiabatic construction and two doors between room 1 and 2

1.5 FDS-simulation 5

RHR of 2,000 kW, place of fire in middle of the room, adiabatic construction and two doors (height 2.3 m) between room 1 and 2

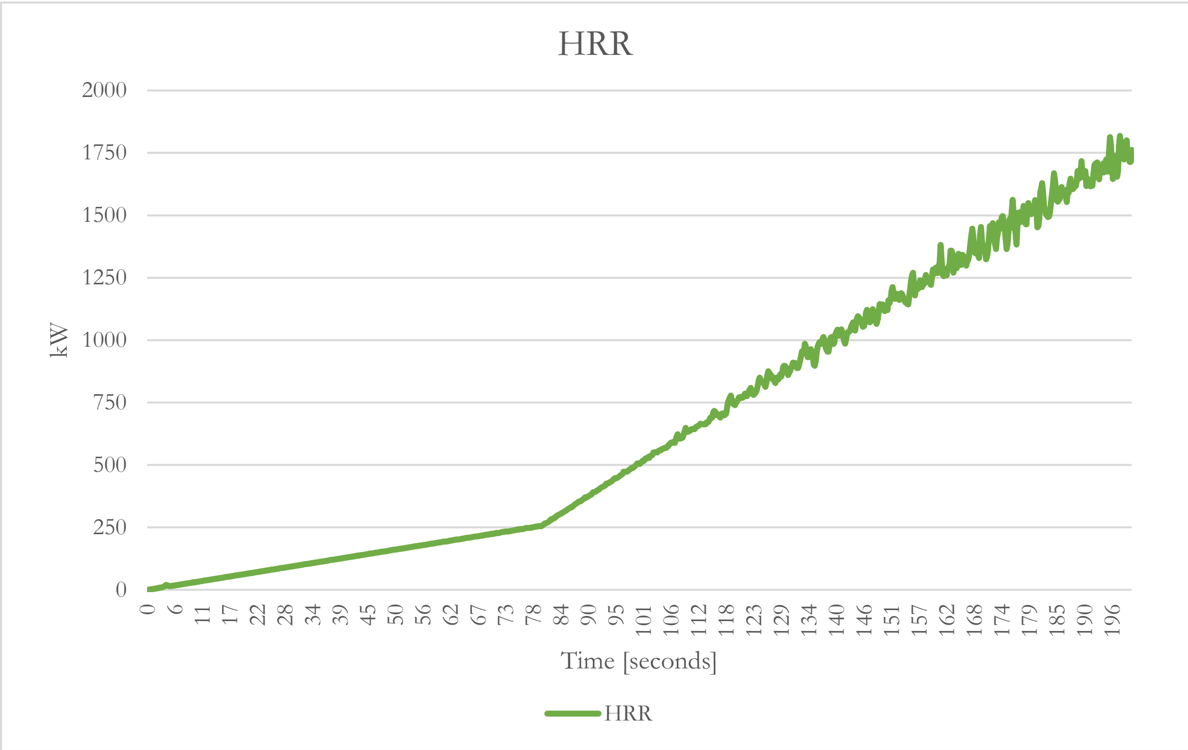
1.6 FDS-simulation 6

RHR of 2,000 kW, place of fire in middle of the room, adiabatic construction and two doors (height 2.3 m) between room 1 and 2. Including a longer running time.

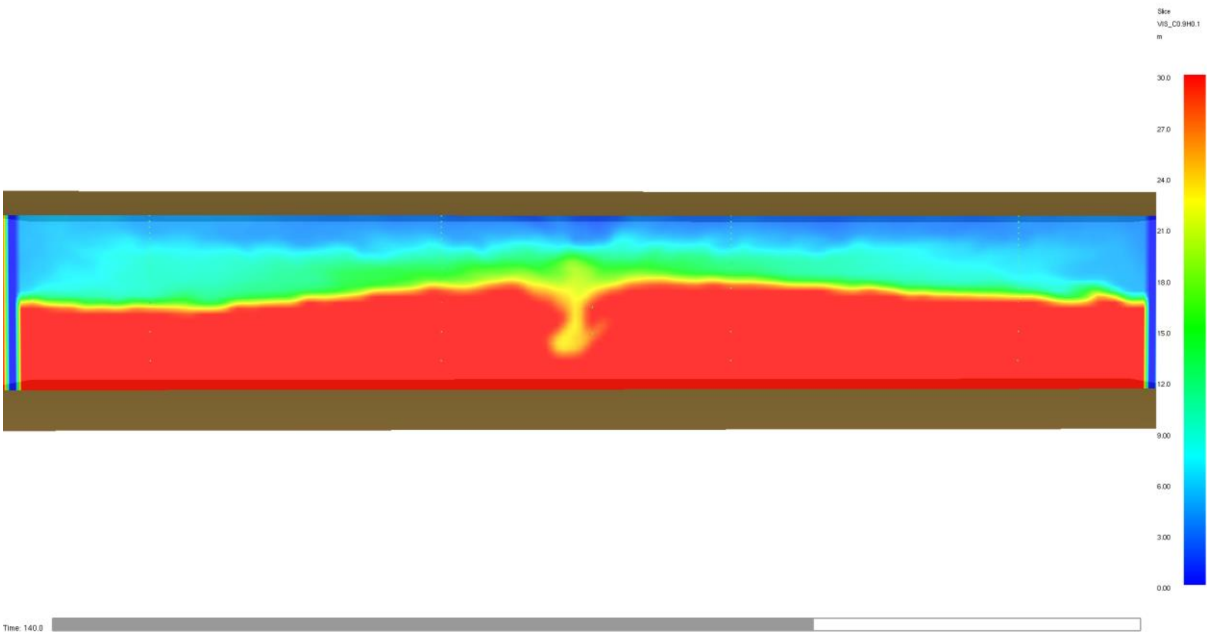
APPENDIX 2.1

Results of FDS-simulation 1

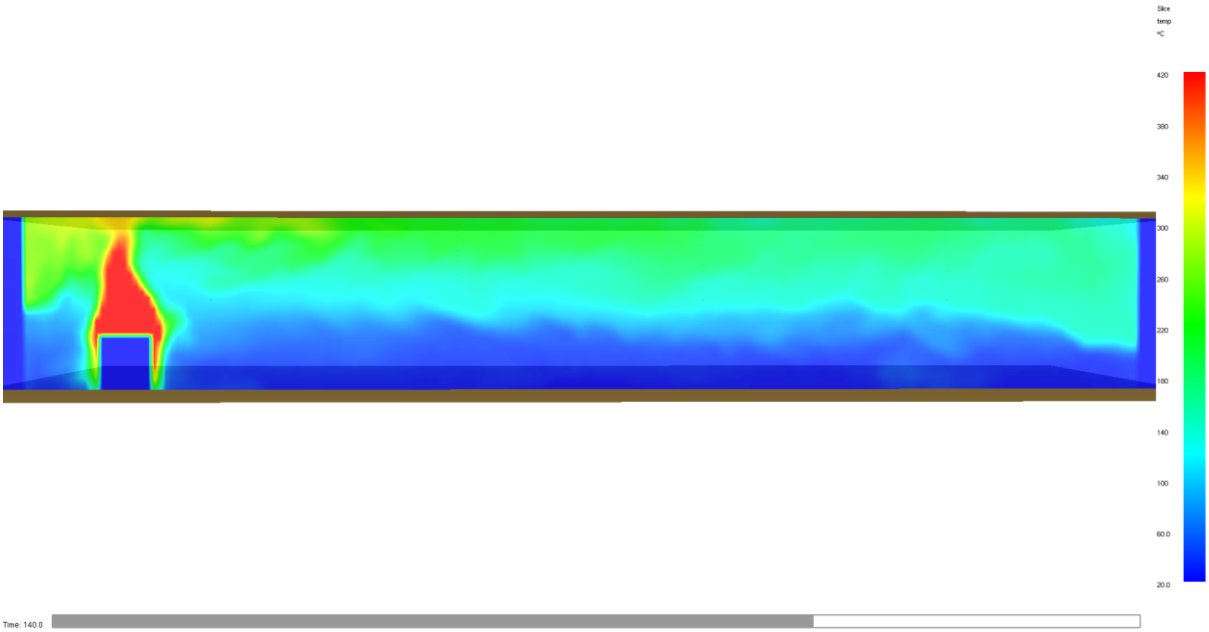
Graph of the Heat Rate Release [kW]

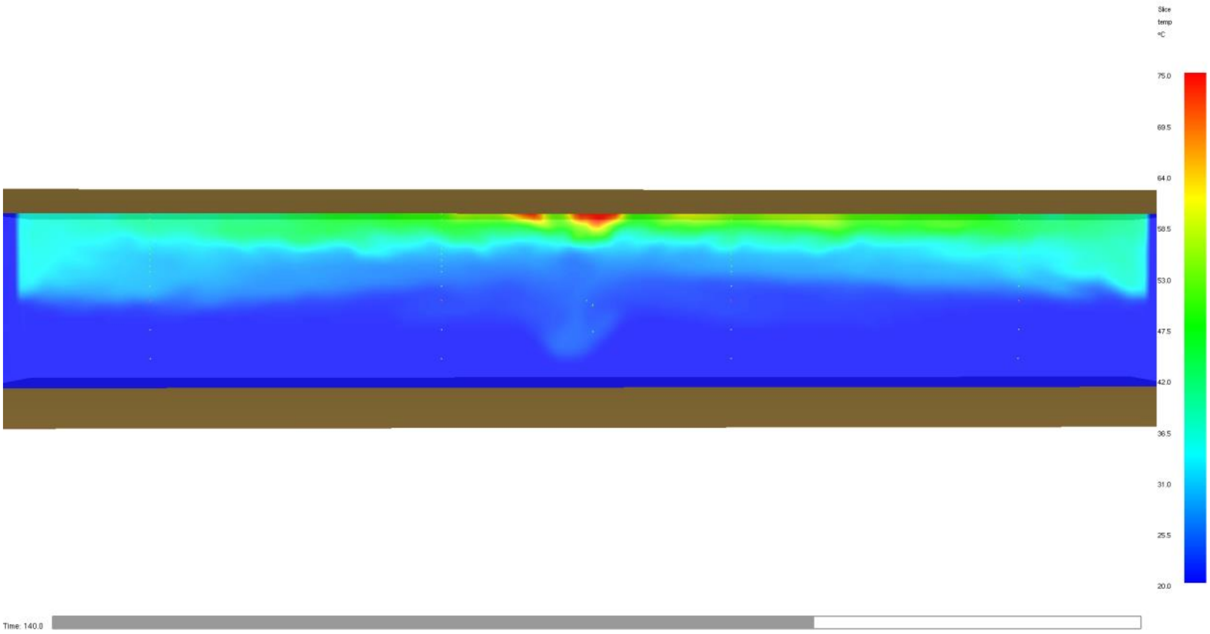


Slice of the Soot visibility after 140 seconds

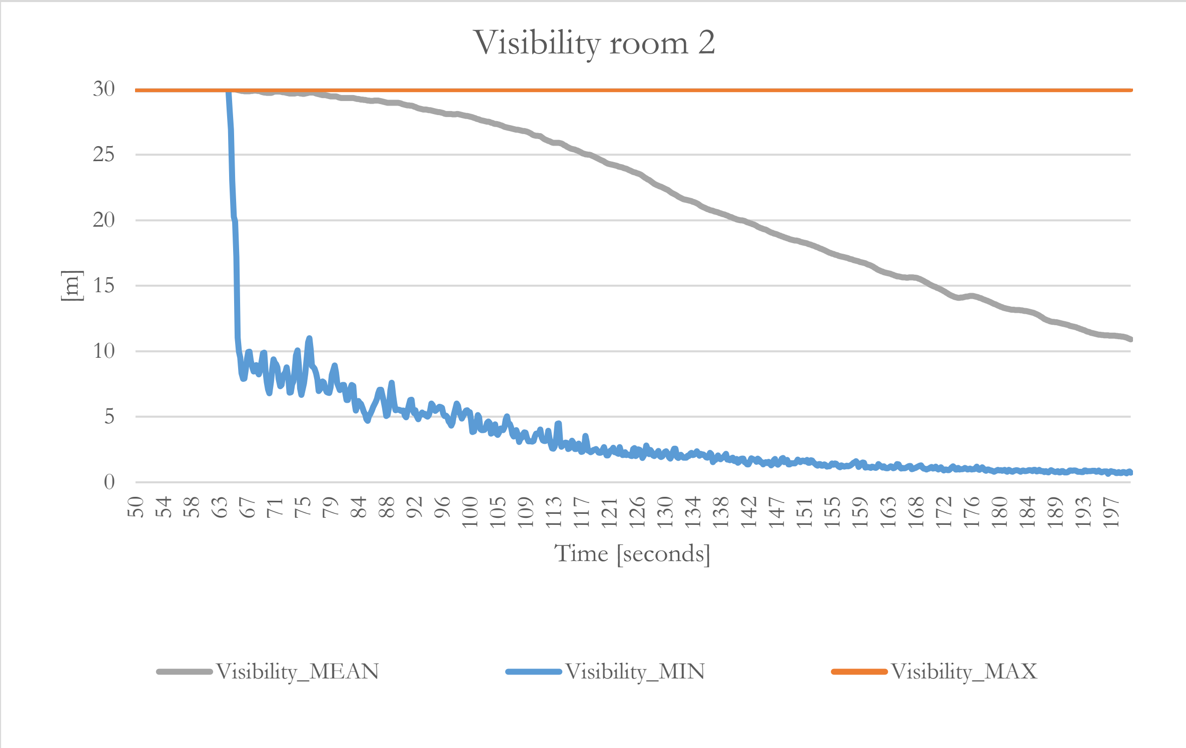


Slices of the Temperatures in room 1 and room 2 at 140 seconds

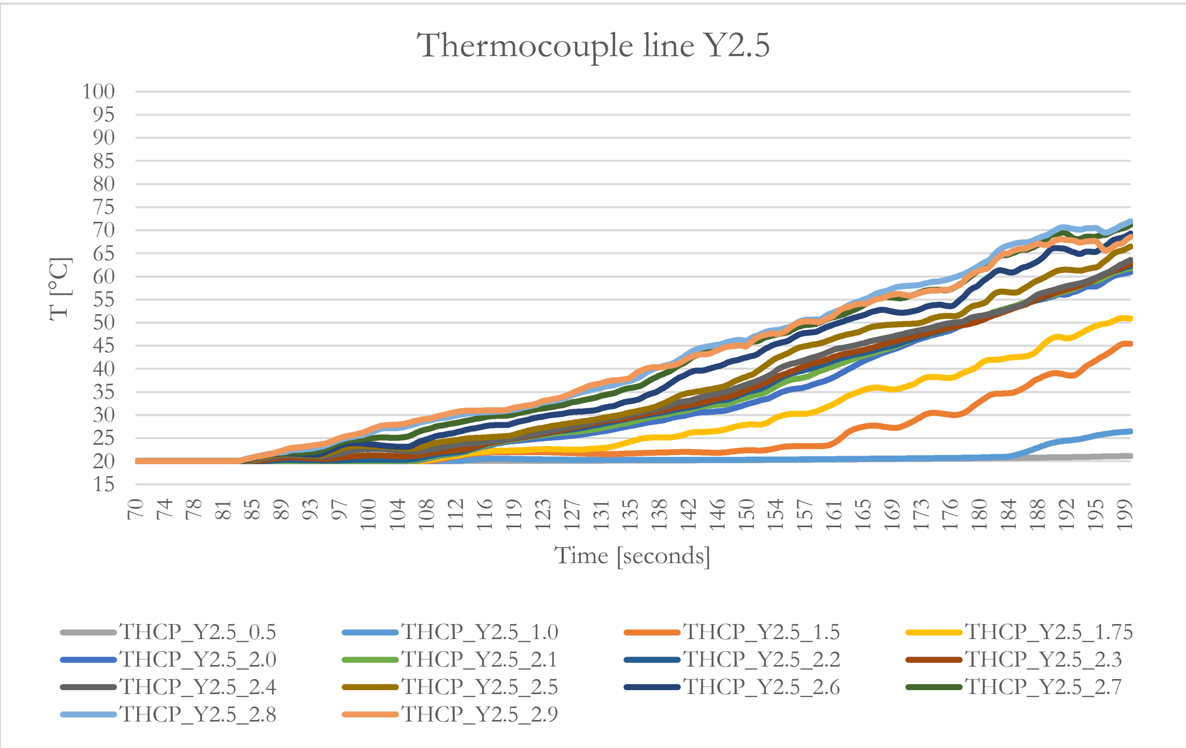




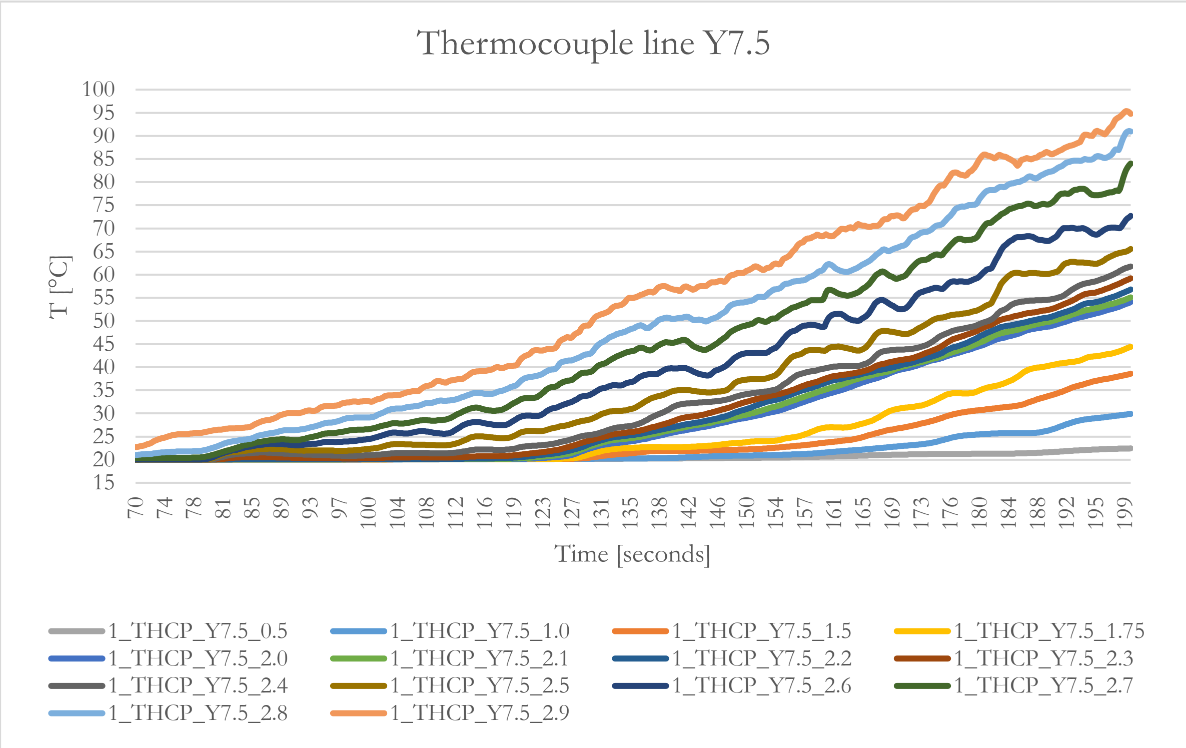
Graph of the visibility in room 2 (Max, Min and Mean)



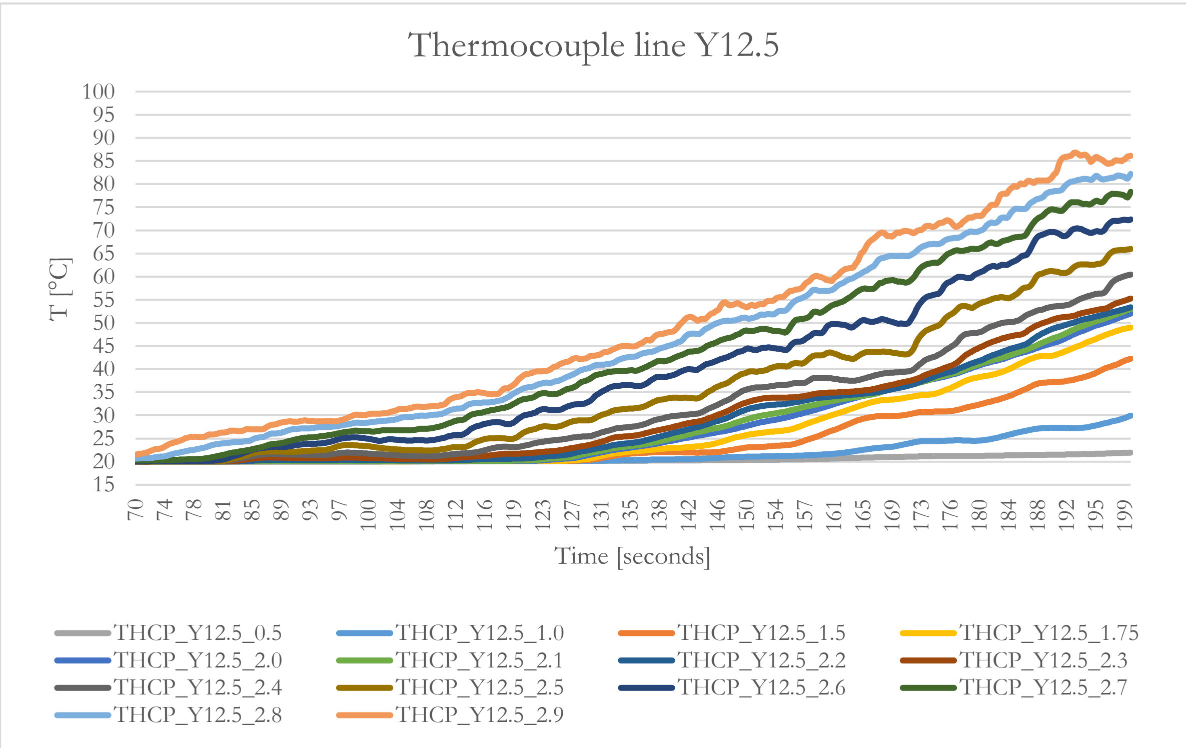
Graph of the thermocouples at Y2.5



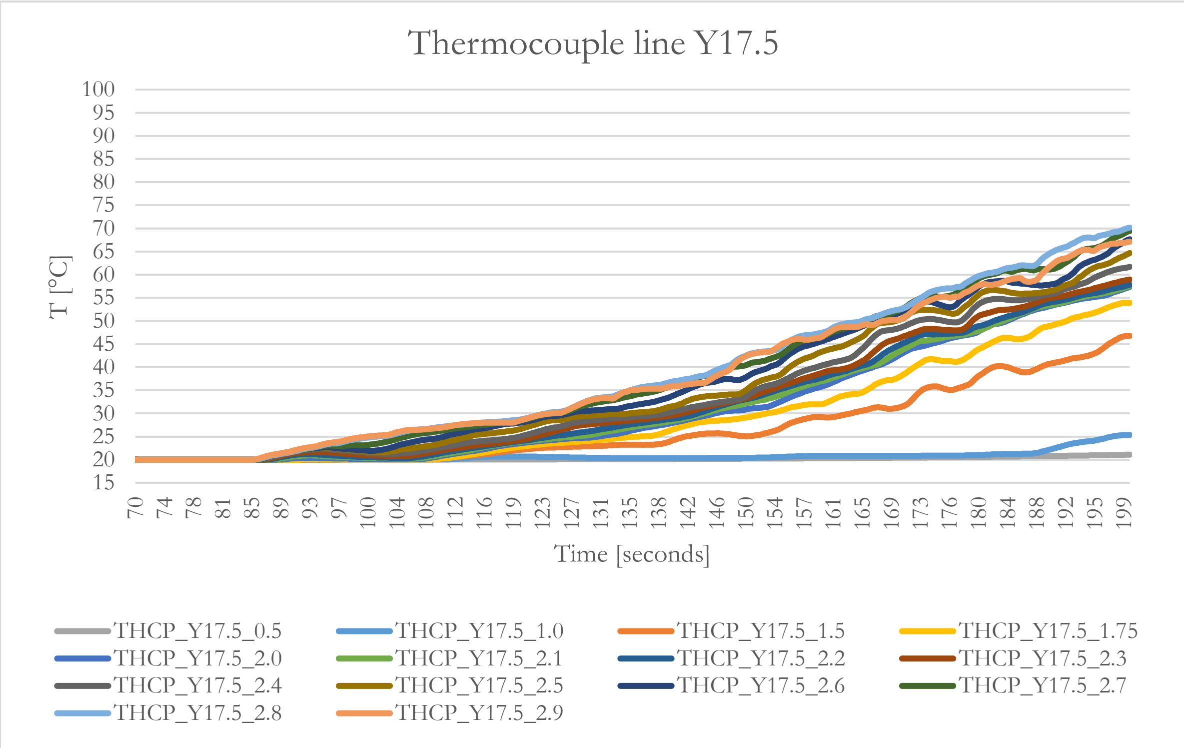
Graph of the thermocouples at Y7.5



Graph of the thermocouples at Y12.5



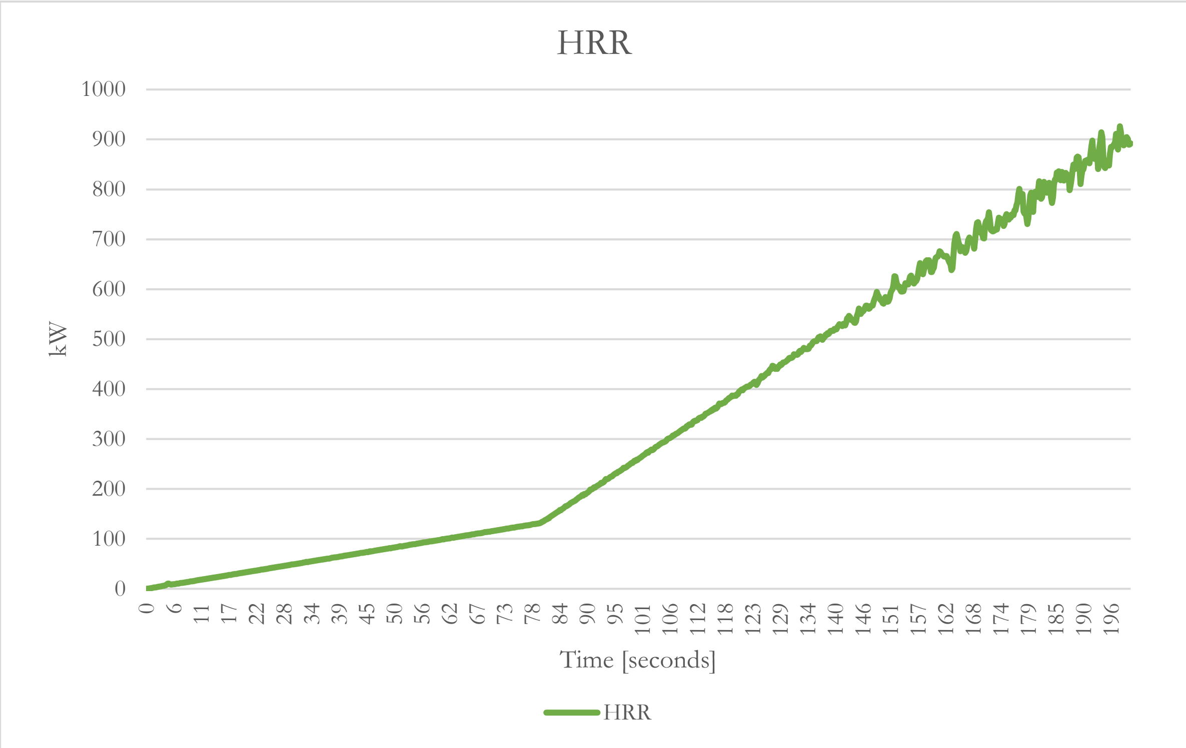
Graph of the thermocouples at Y17.5



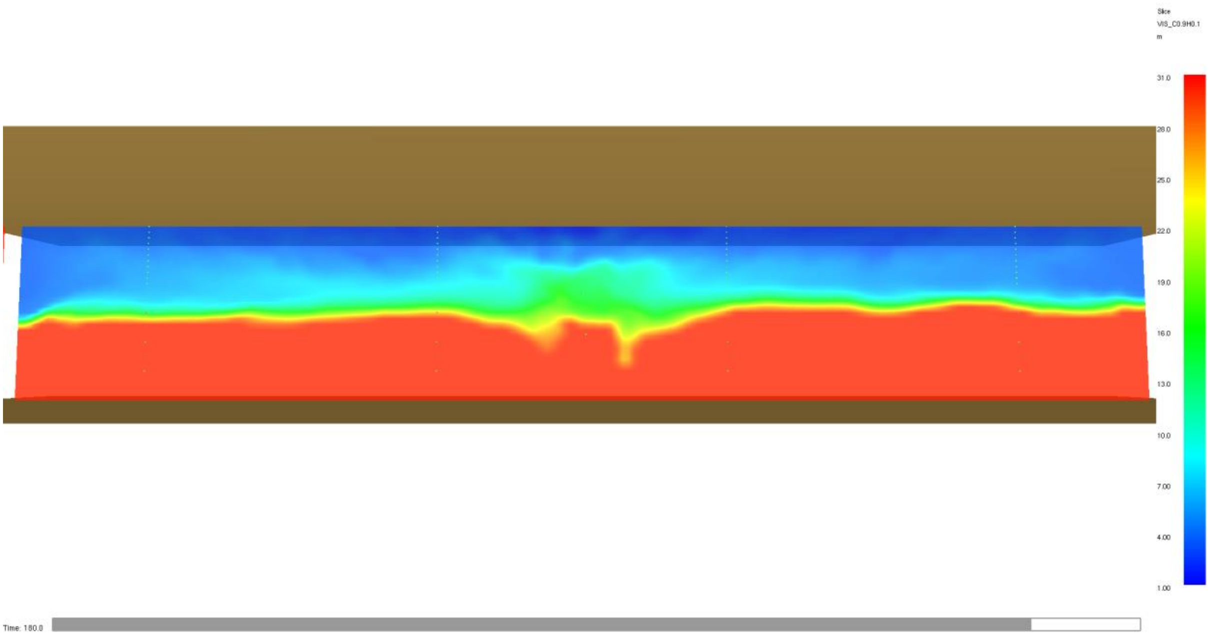
APPENDIX 2.2

Results of FDS-simulation 2

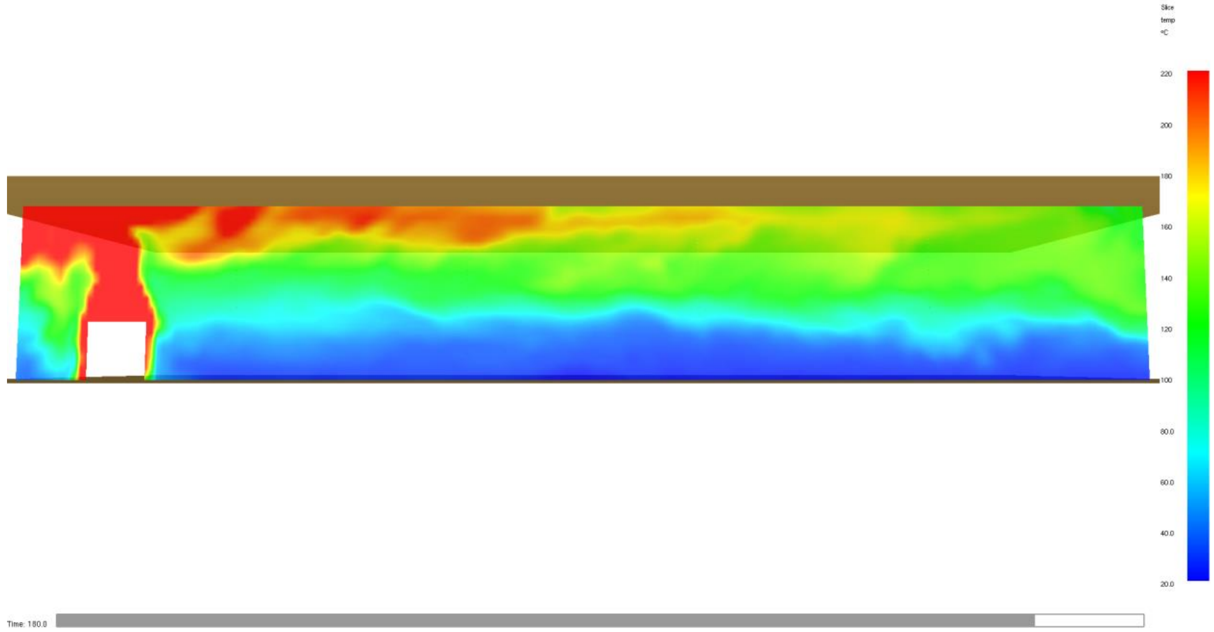
Graph of the Heat Rate Release [kW]

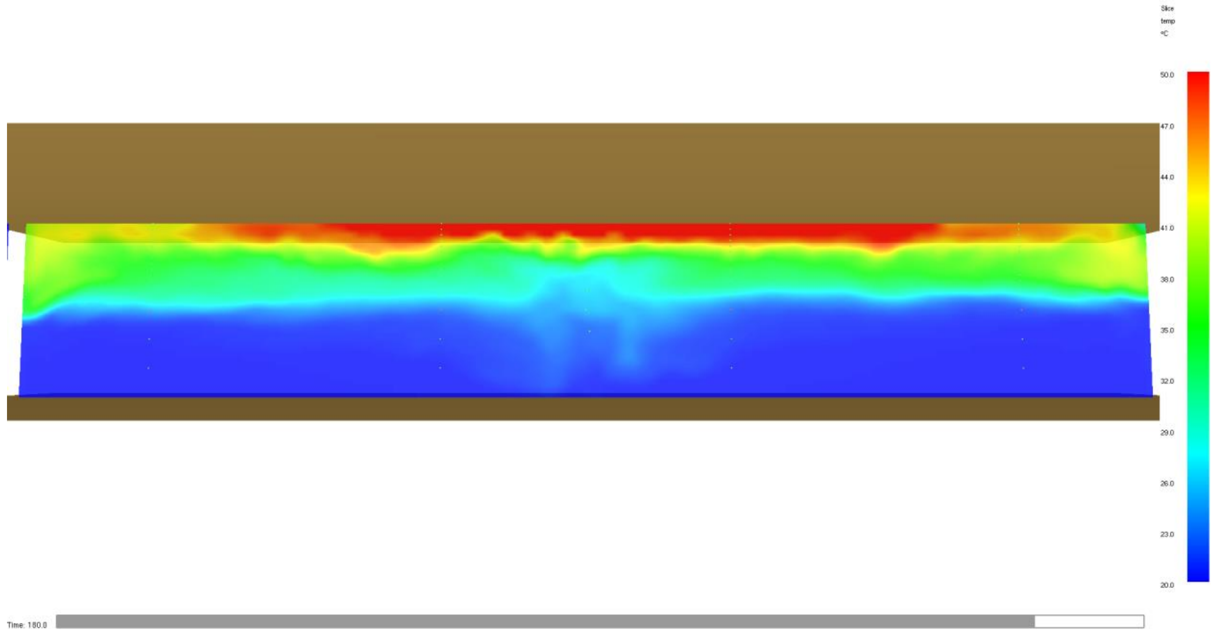


Slice of the Soot visibility after 180 seconds

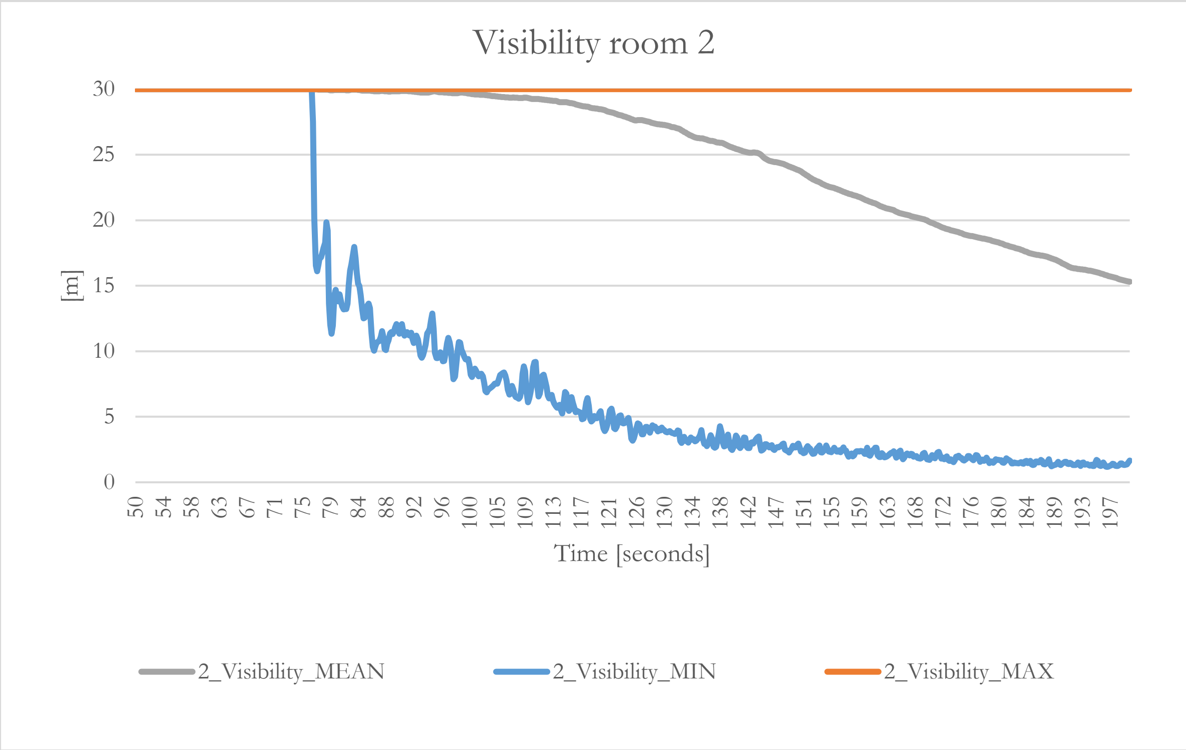


Slices of the Temperatures in room 1 and room 2 at 180 seconds

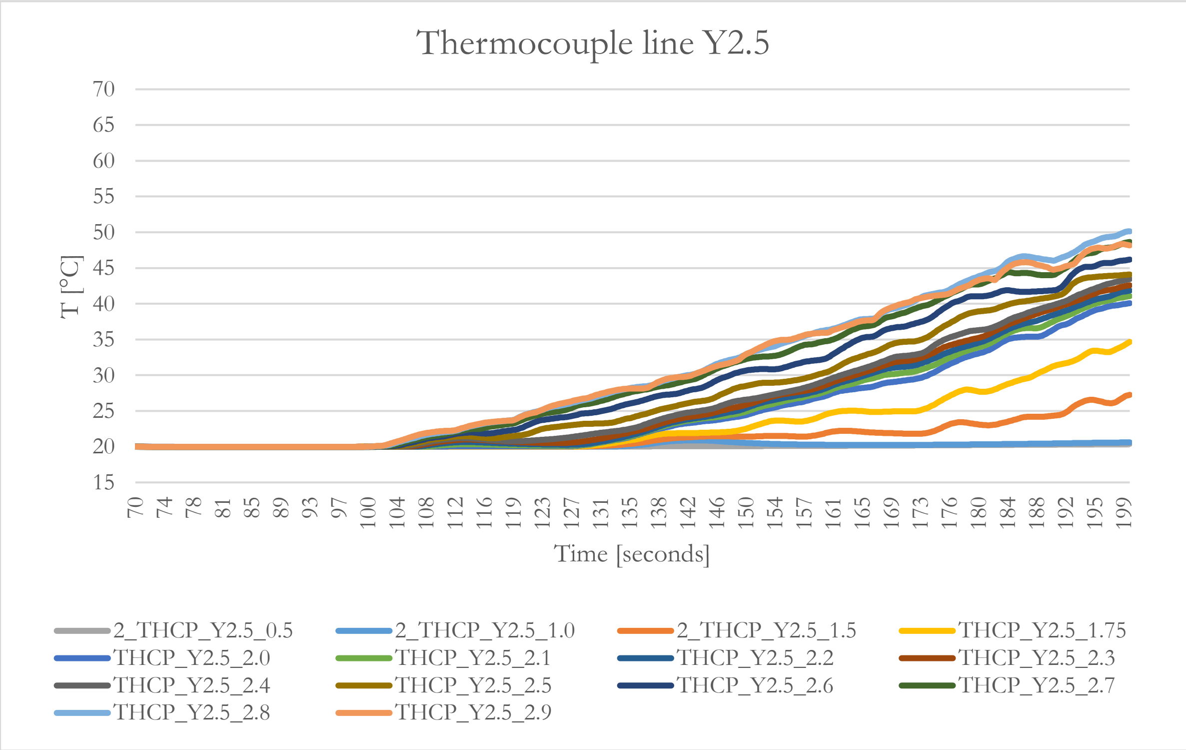




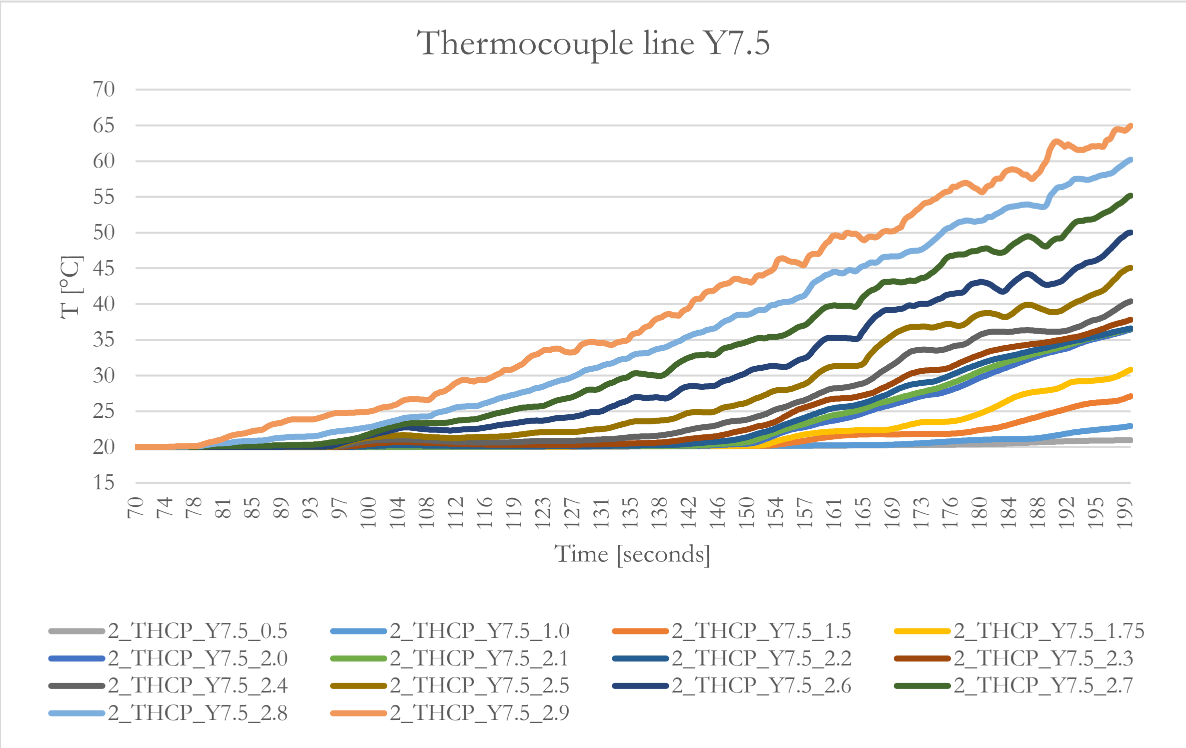
Graph of the visibility in room 2 (Max, Min and Mean)



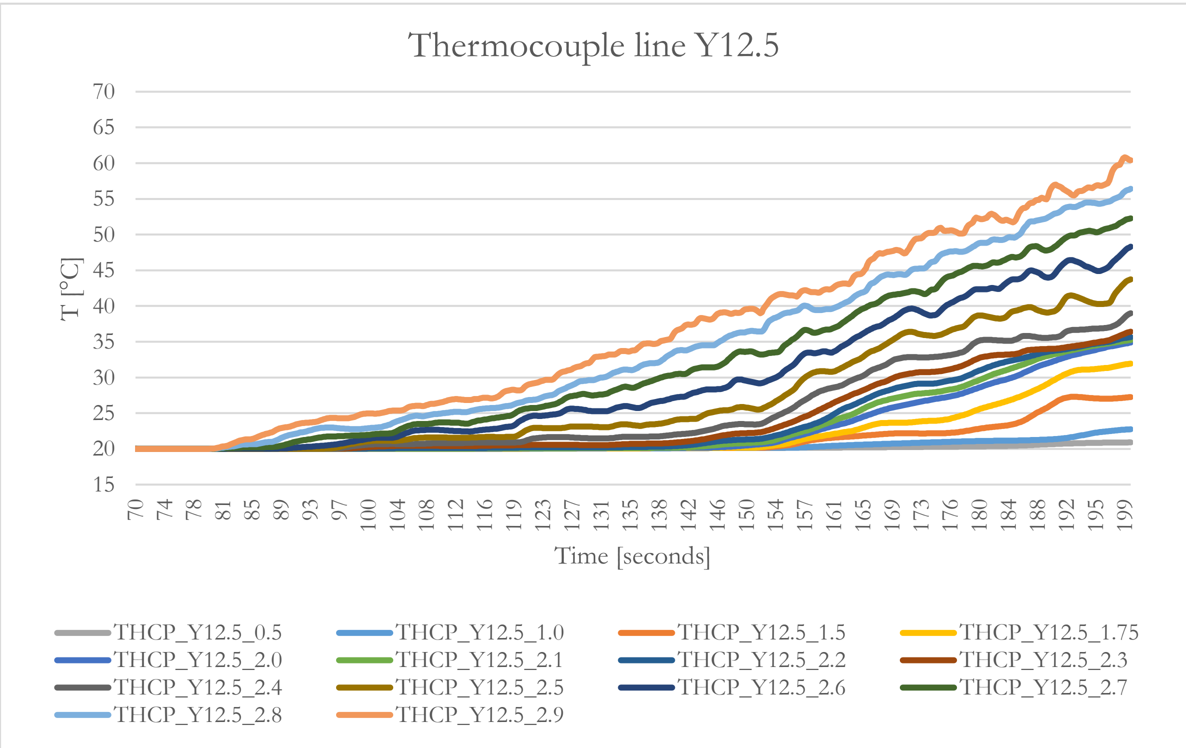
Graph of the thermocouples at Y2.5



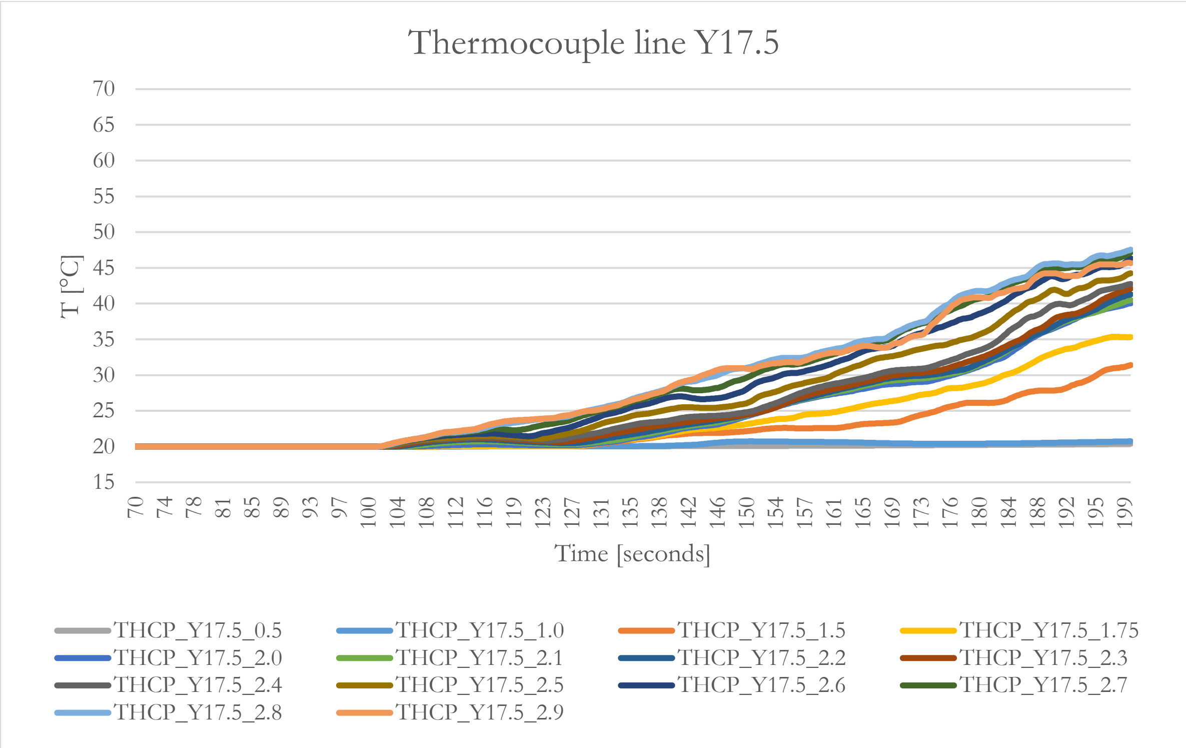
Graph of the thermocouples at Y7.5



Graph of the thermocouples at Y12.5



Graph of the thermocouples at Y17.5

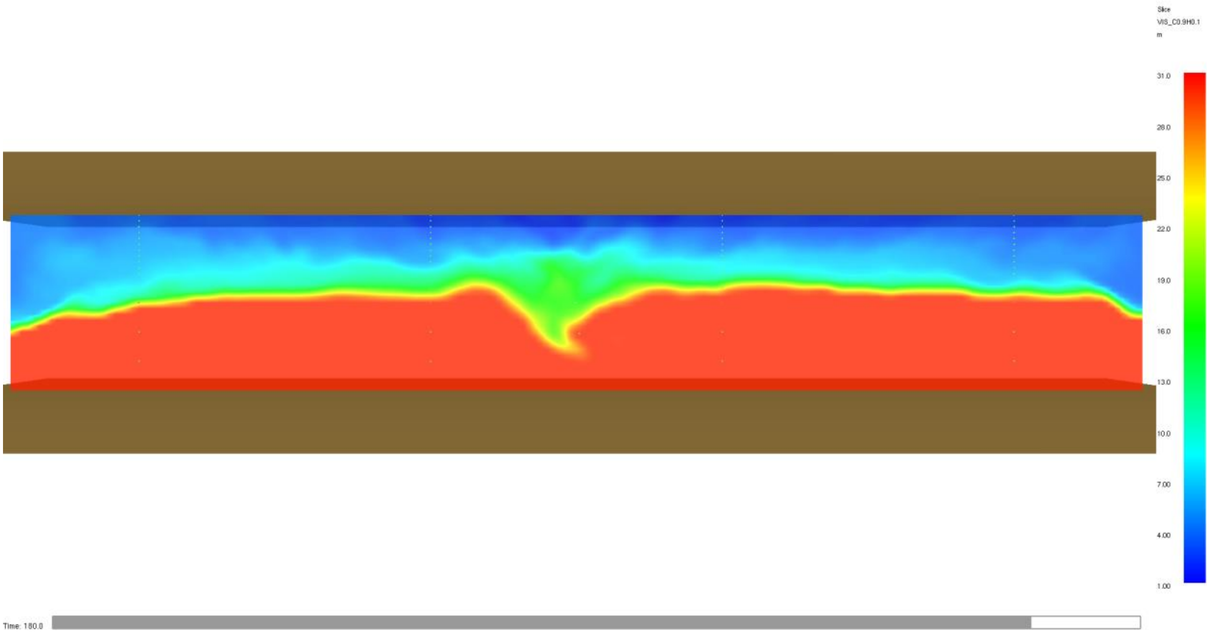


APPENDIX 2.3

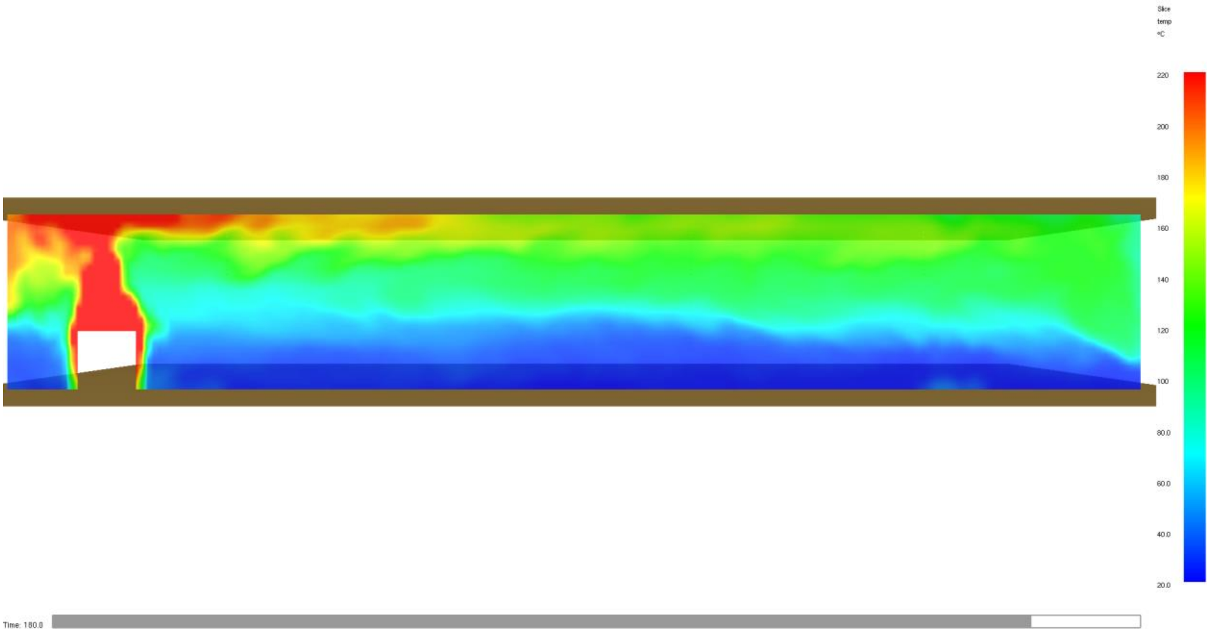
Results of FDS-simulation 3

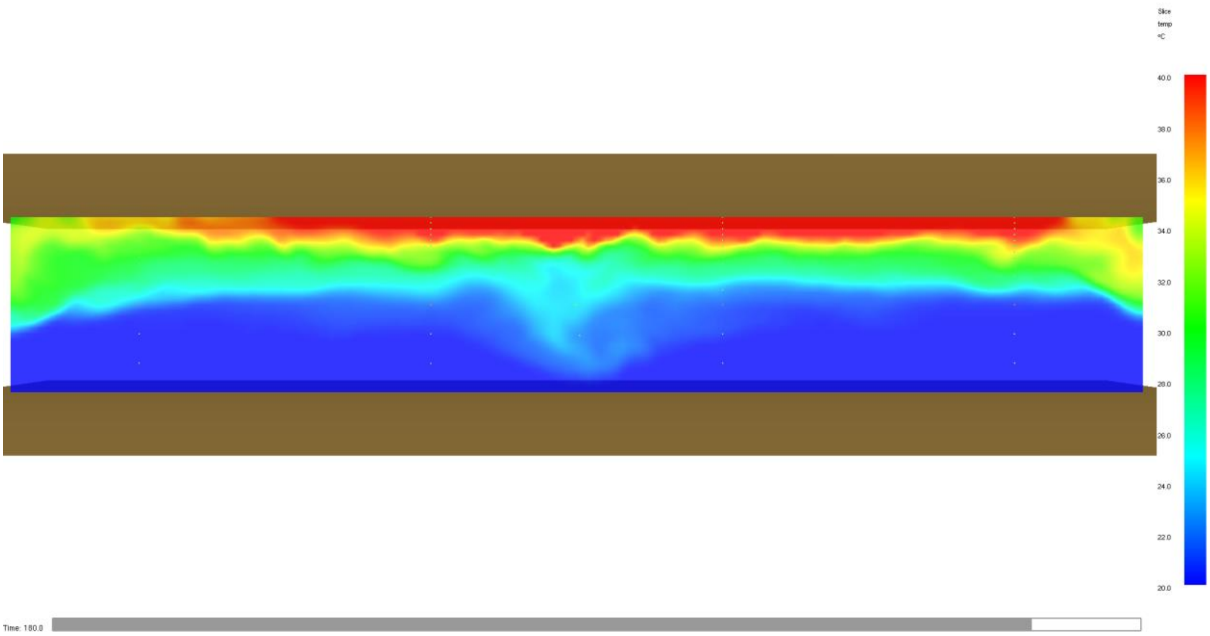
Graph of the Heat Rate Release [kW]

Slice of the Soot visibility after 180 seconds

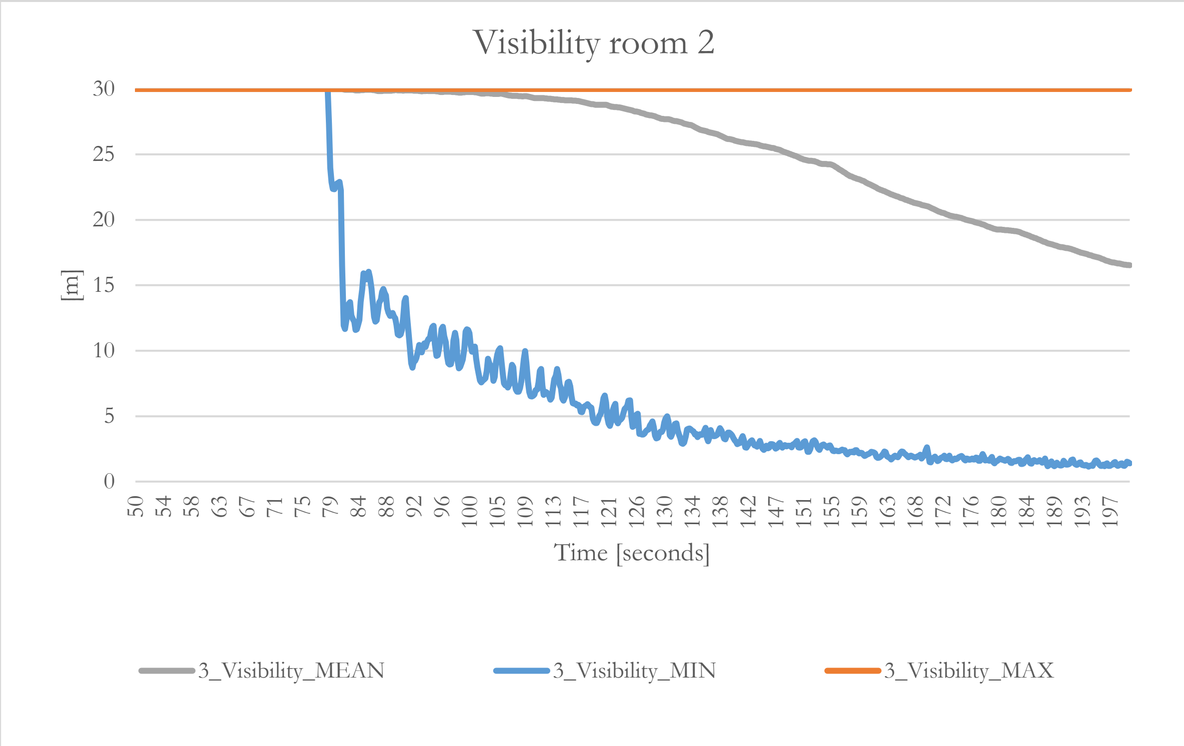


Slices of the Temperatures in room 1 and room 2 at 180 seconds

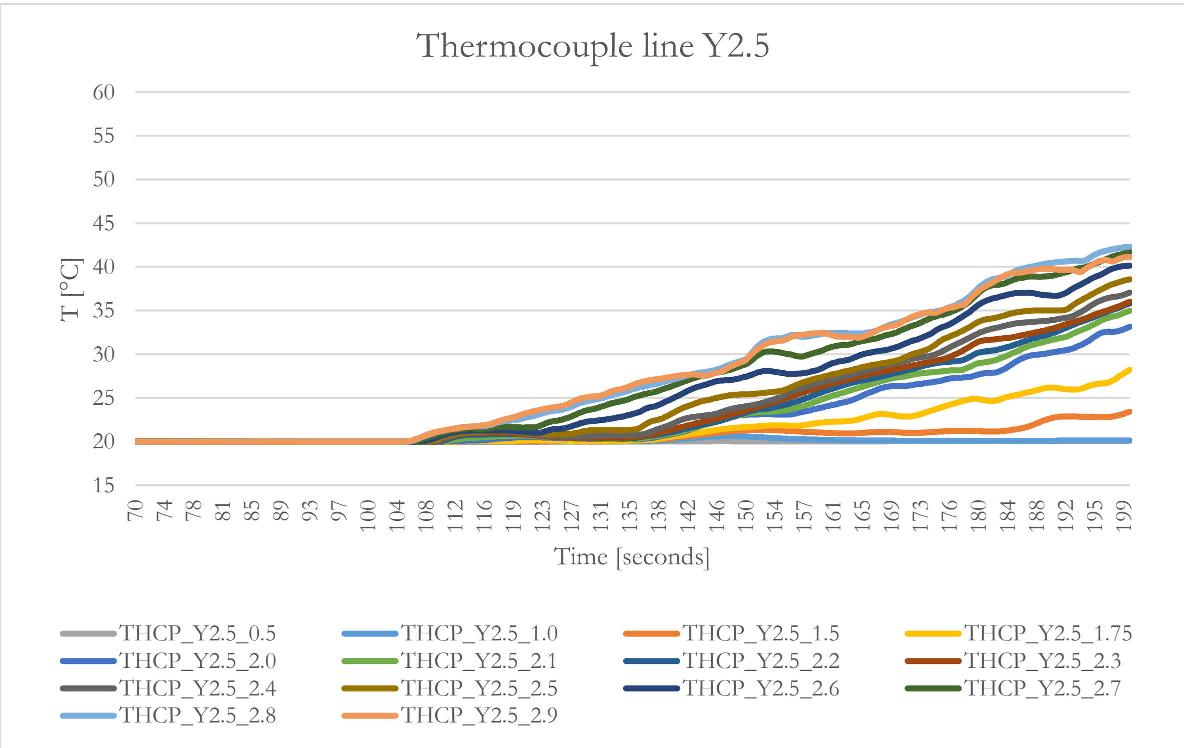




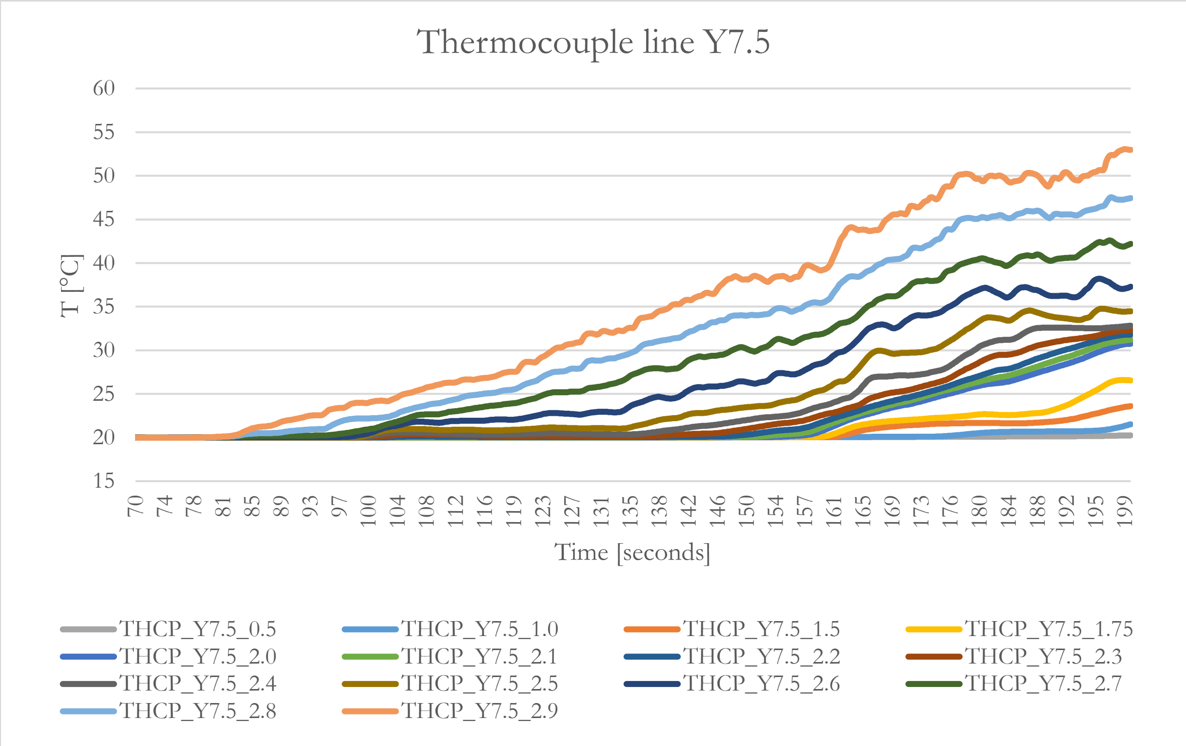
Graph of the visibility in room 2 (Max, Min and Mean)



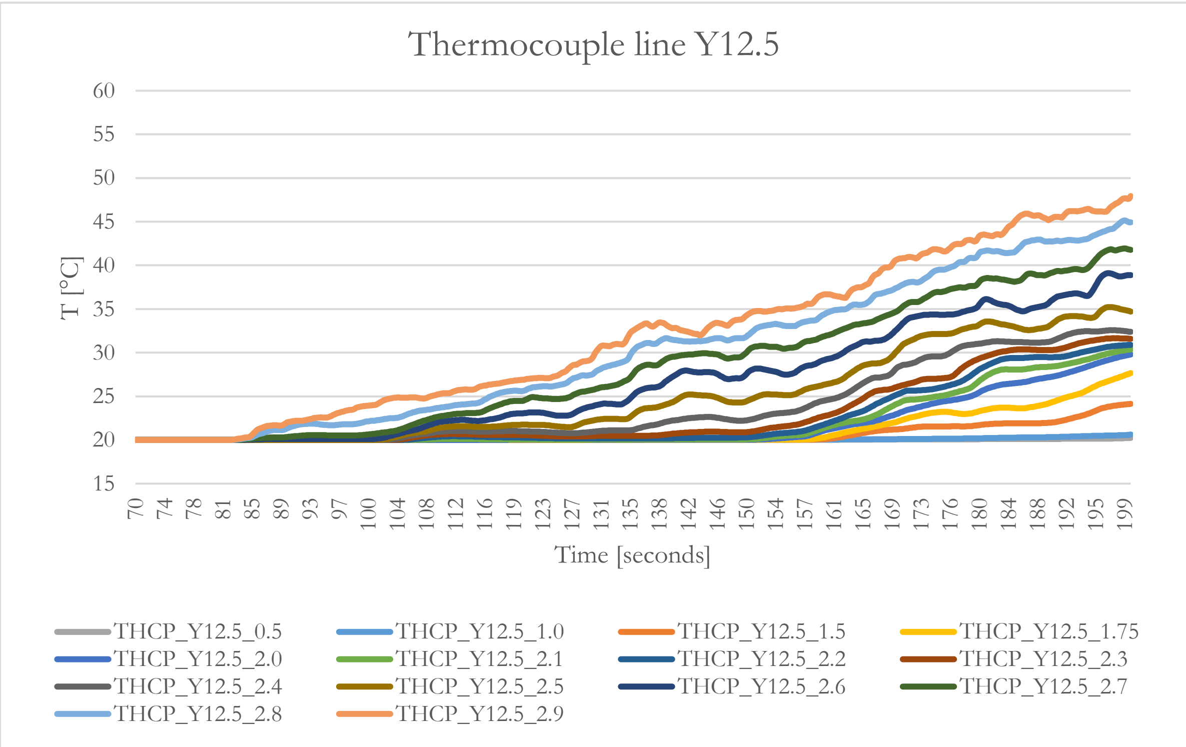
Graph of the thermocouples at Y2.5



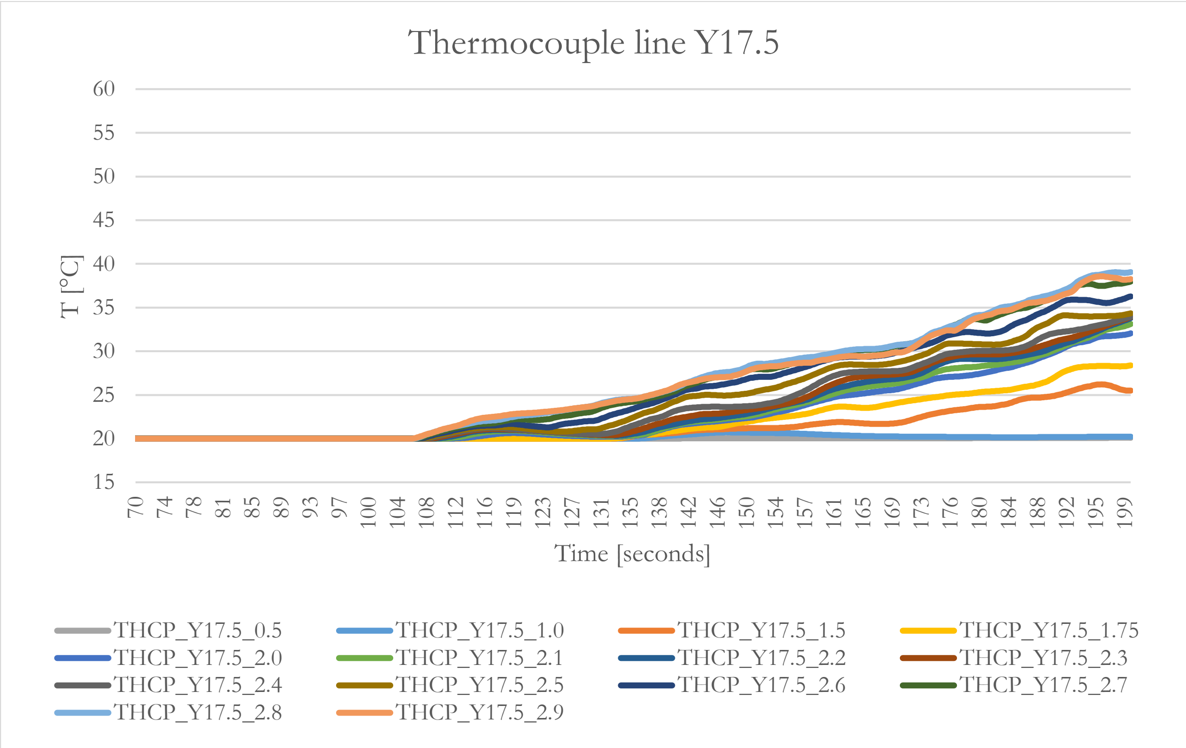
Graph of the thermocouples at Y7.5



Graph of the thermocouples at Y12.5



Graph of the thermocouples at Y17.5

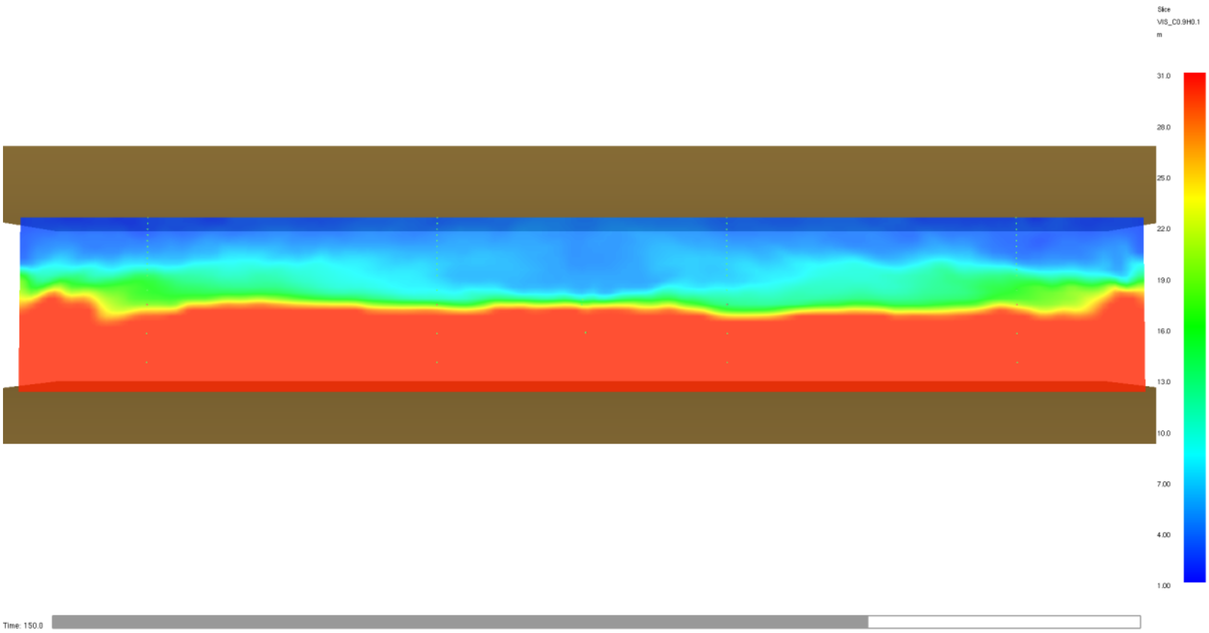


APPENDIX 2.4

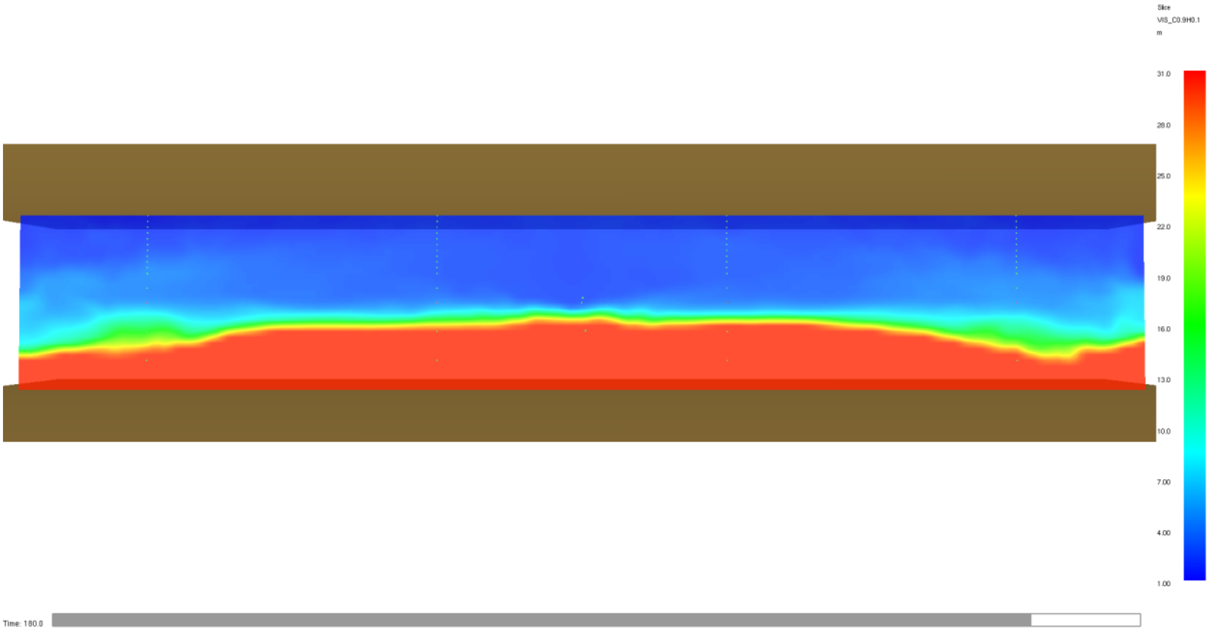
Results of FDS-simulation 4

Graph of the Heat Rate Release [kW]

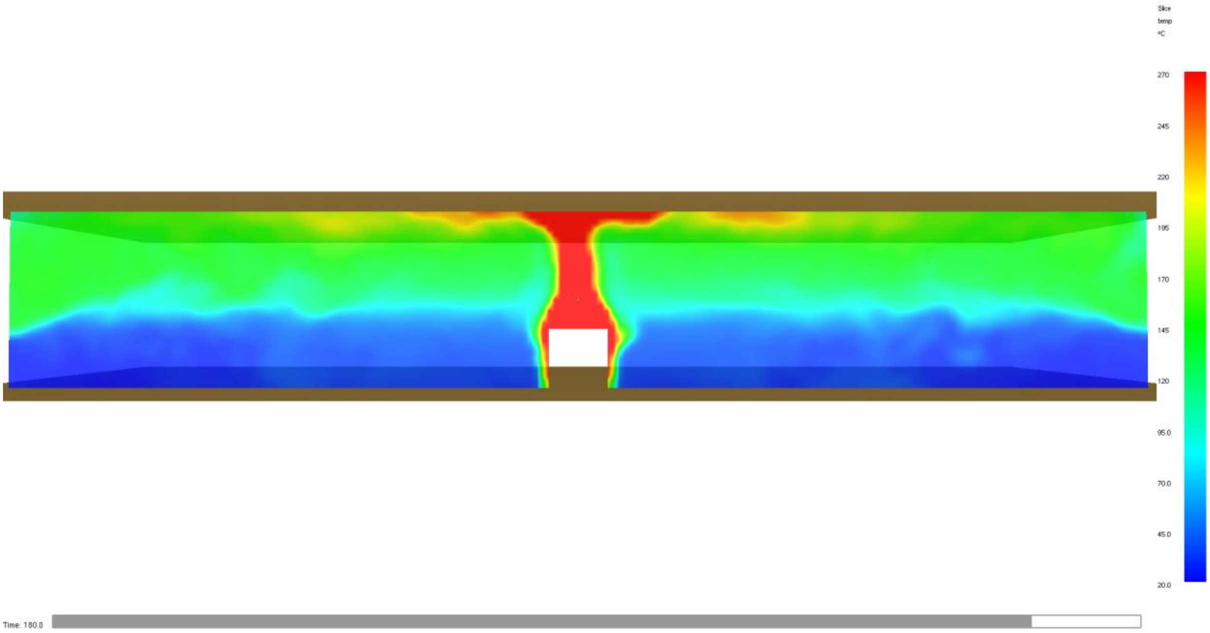
Slice of the Soot visibility after 150 seconds

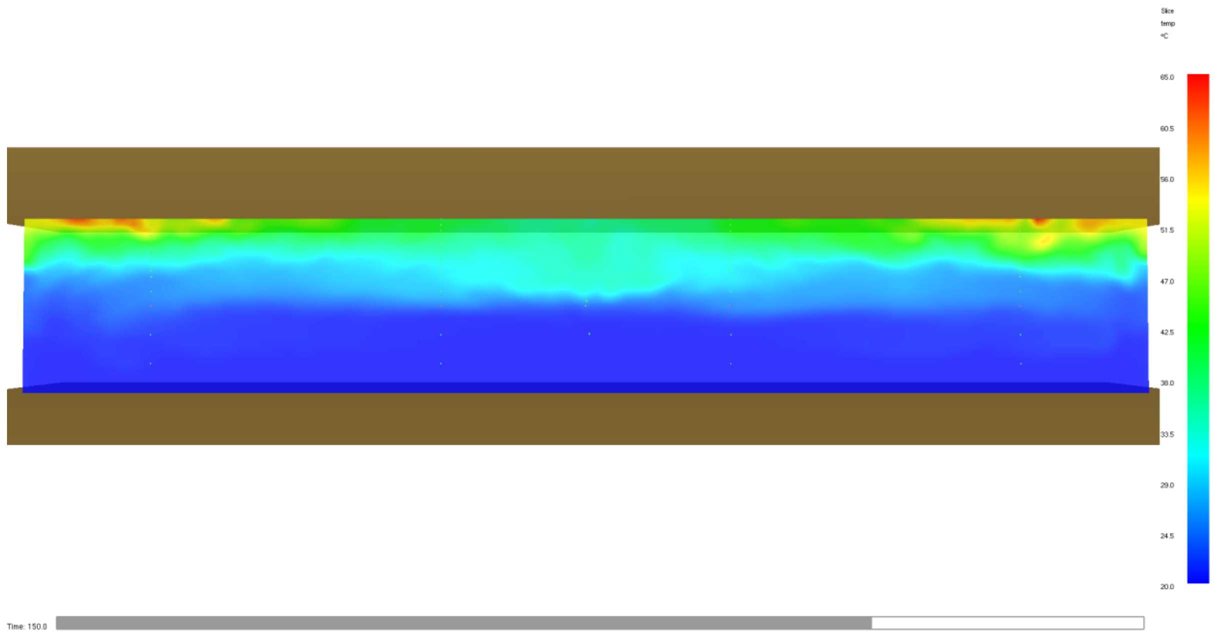


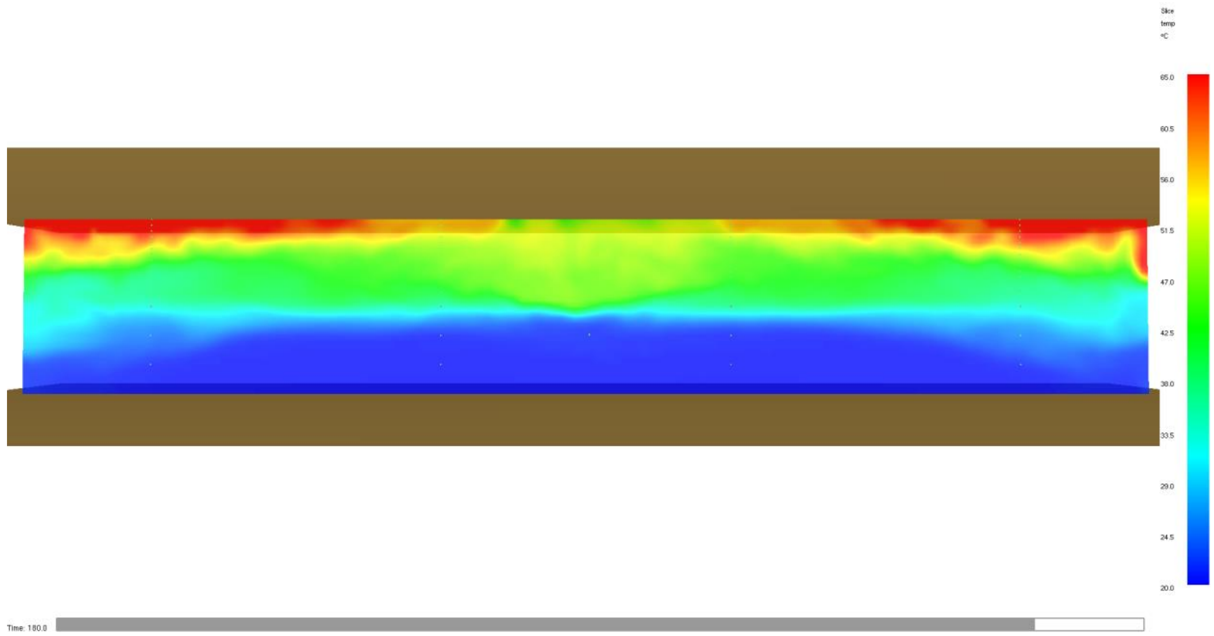
Slice of the Soot visibility after 180 seconds



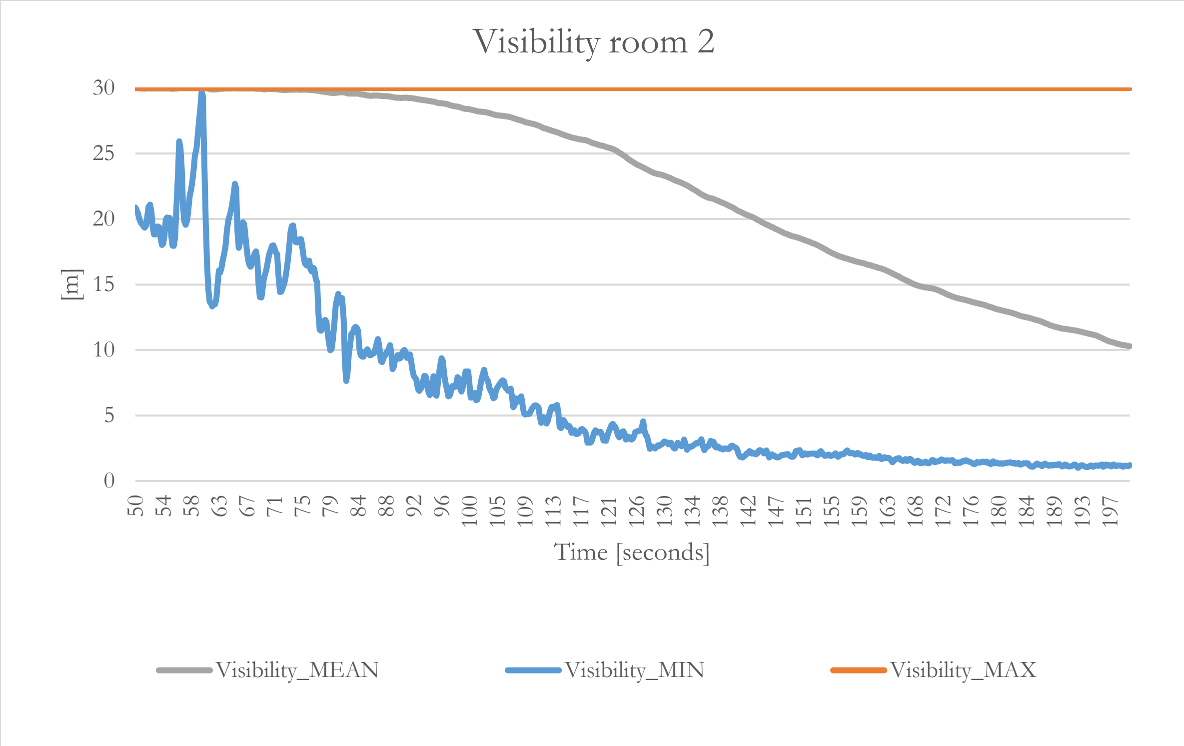
Slices of the Temperatures in room 1 at 180 seconds and room 2 at 150 and 180 seconds



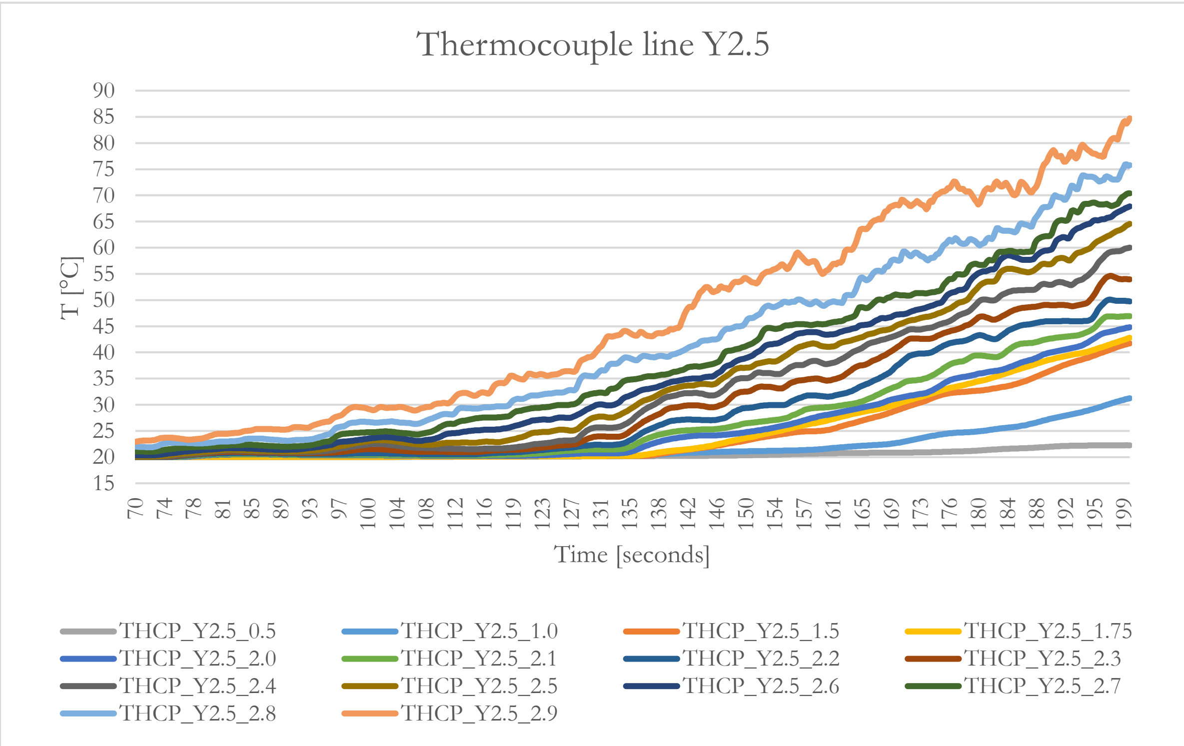

Slice
temp
°C
65.0
60.5
56.0
51.5
47.0
42.5
38.0
33.5
29.0
24.5
20.0
Time: 150.0


Slice
temp
°C
65.0
60.5
56.0
51.5
47.0
42.5
38.0
33.5
29.0
24.5
20.0
Time: 180.0

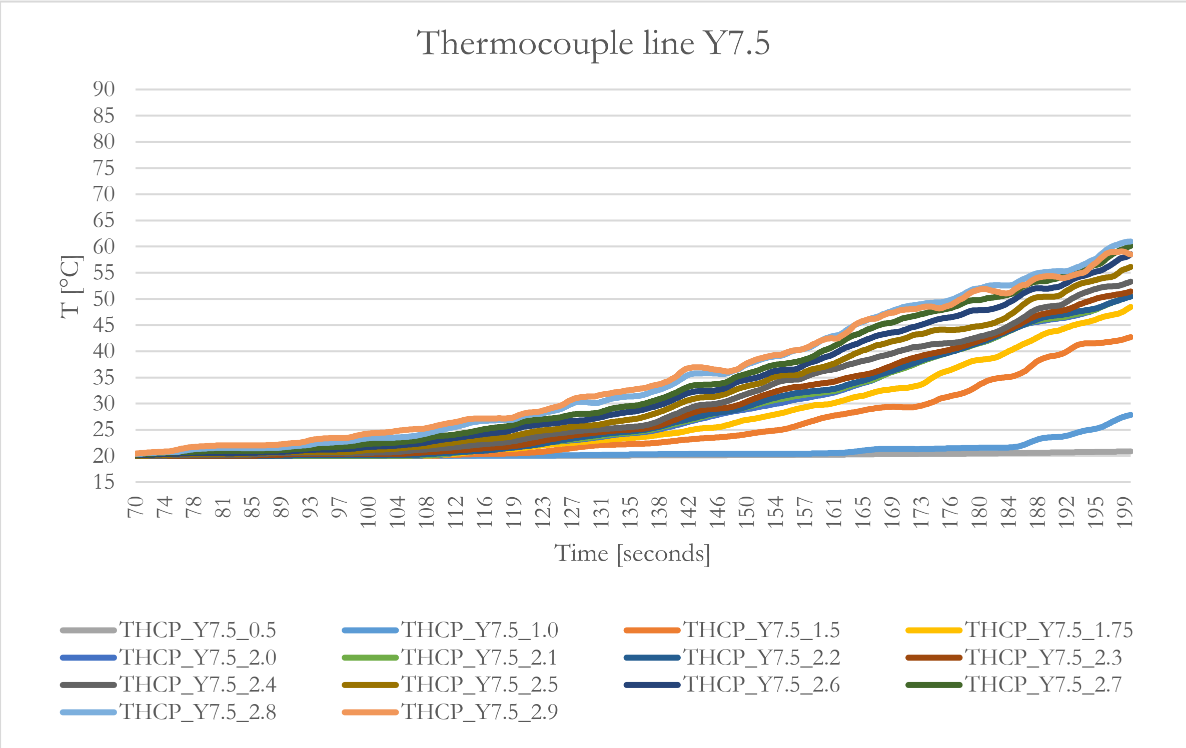
Graph of the visibility in room 2 (Max, Min and Mean)



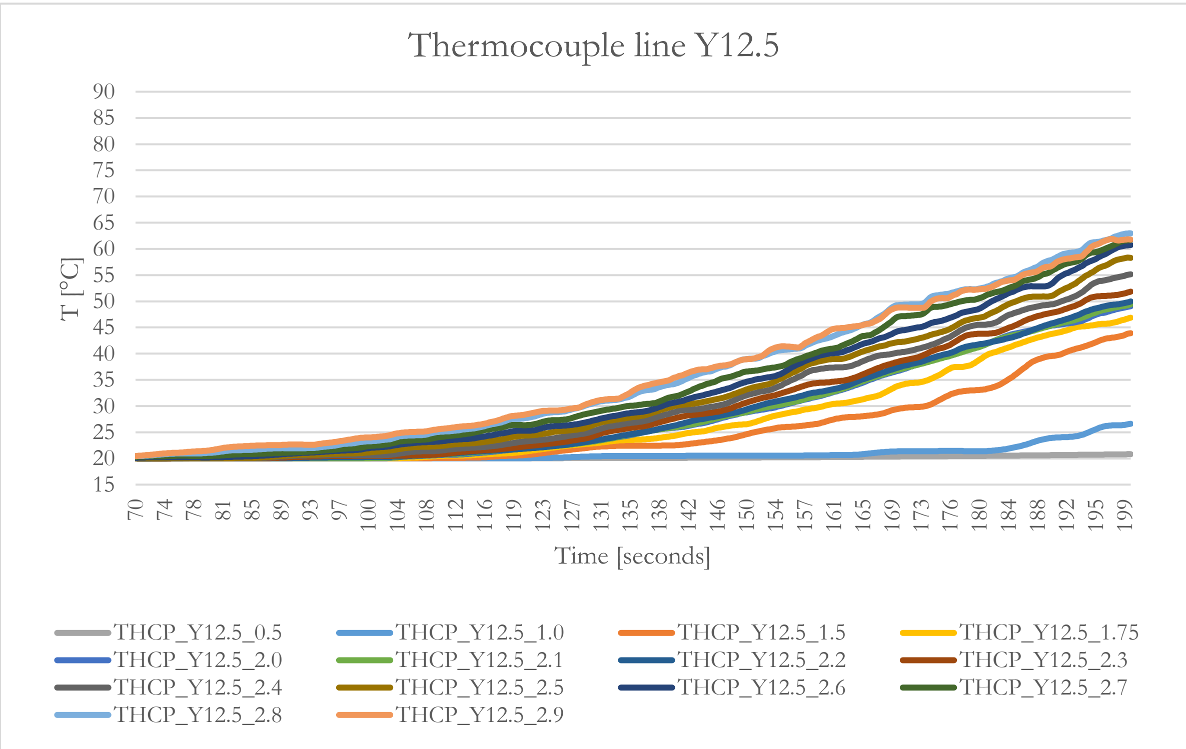
Graph of the thermocouples at Y2.5



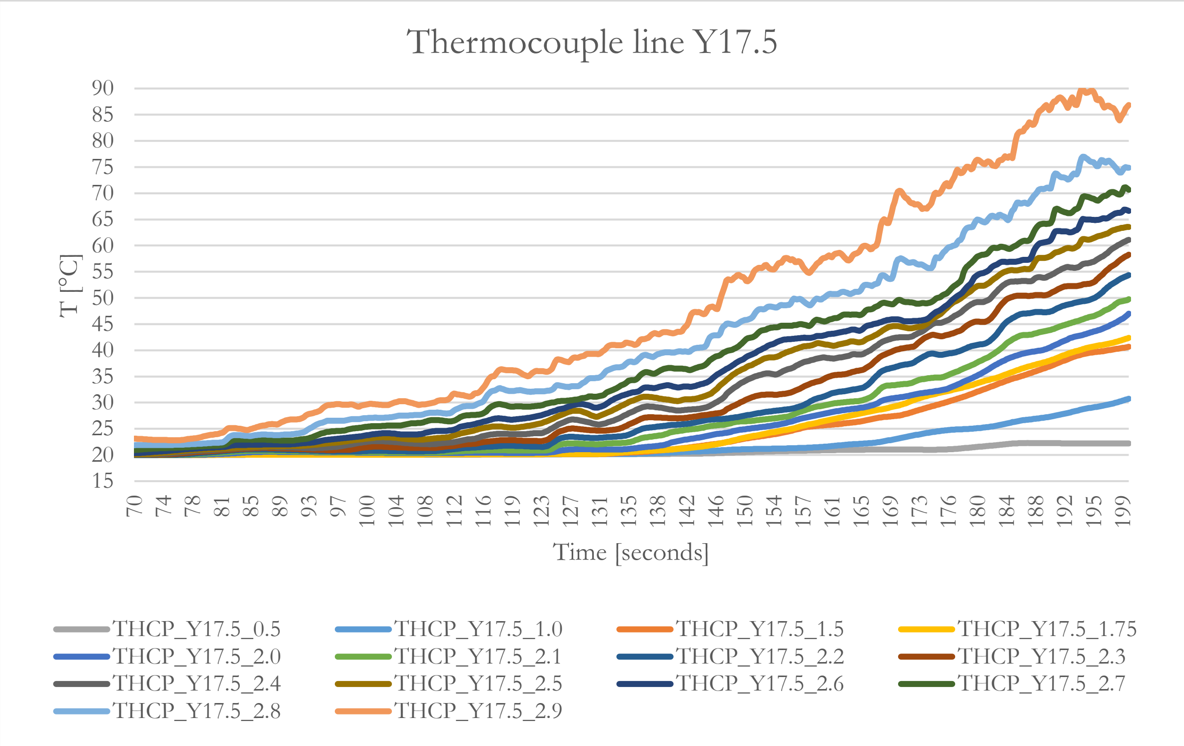
Graph of the thermocouples at Y7.5



Graph of the thermocouples at Y12.5



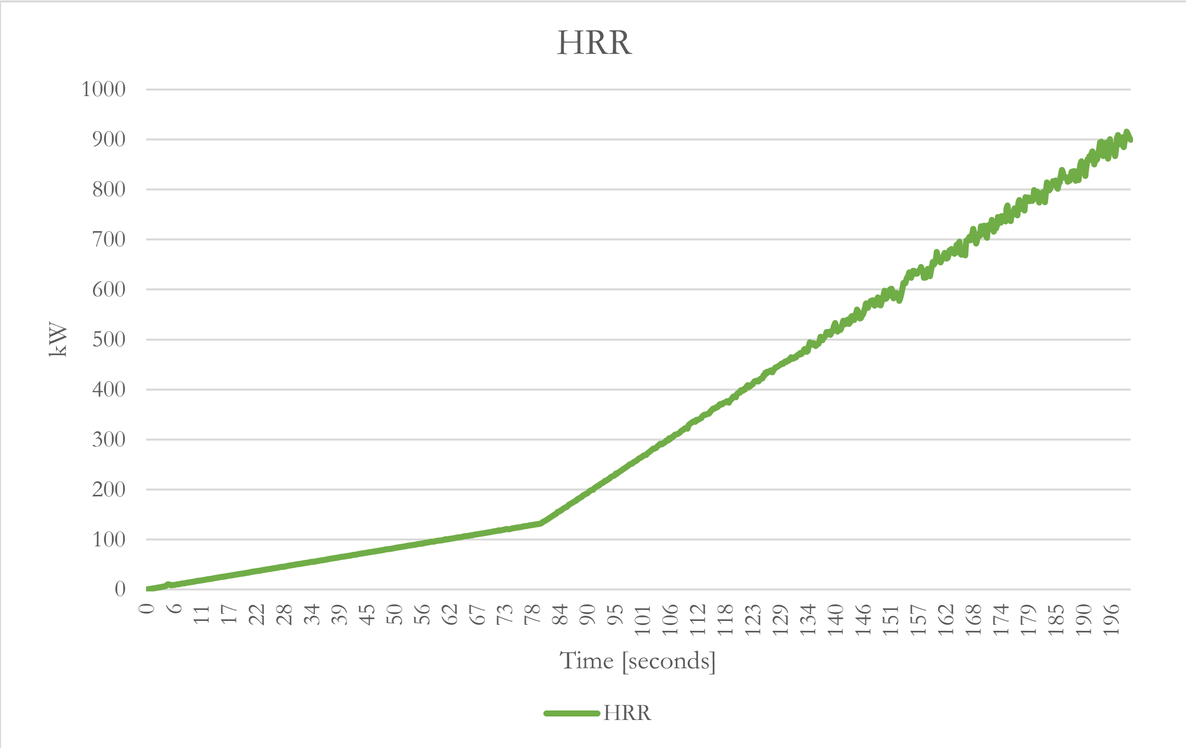
Graph of the thermocouples at Y17.5



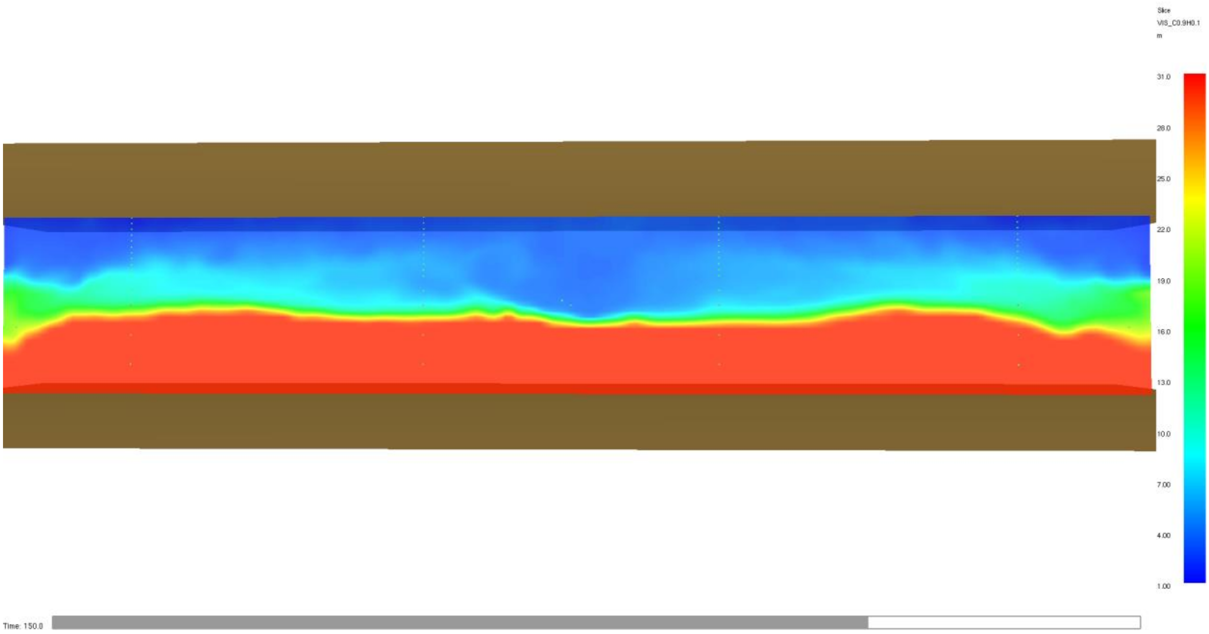
APPENDIX 2.5

Results of FDS-simulation 5

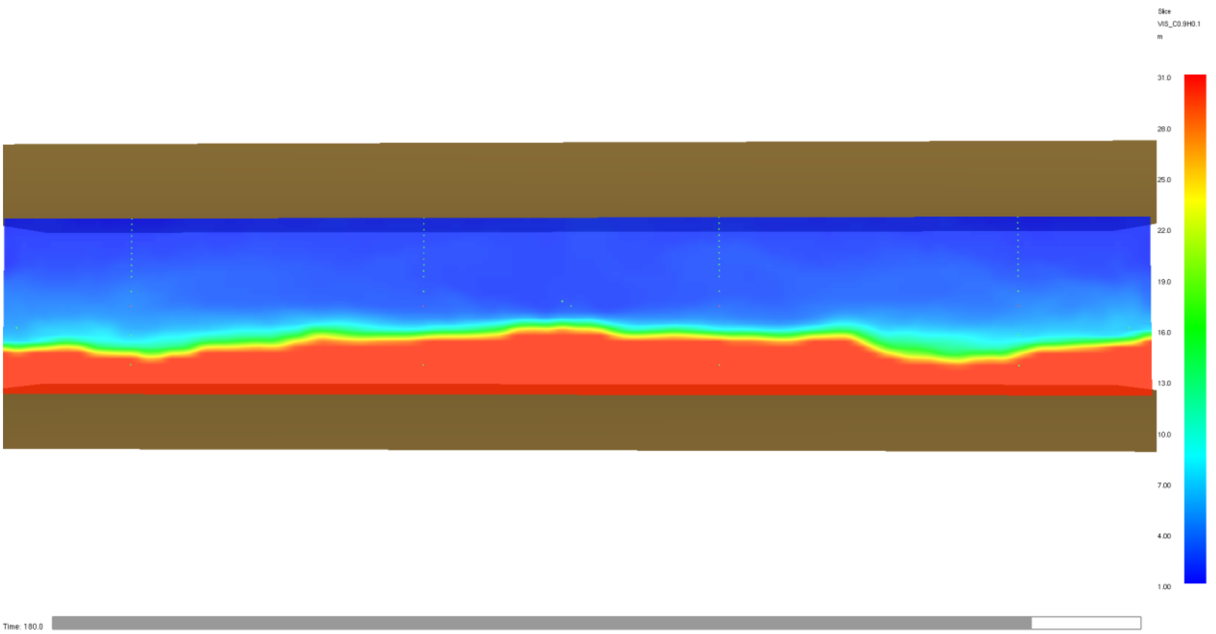
Graph of the Heat Rate Release [kW]



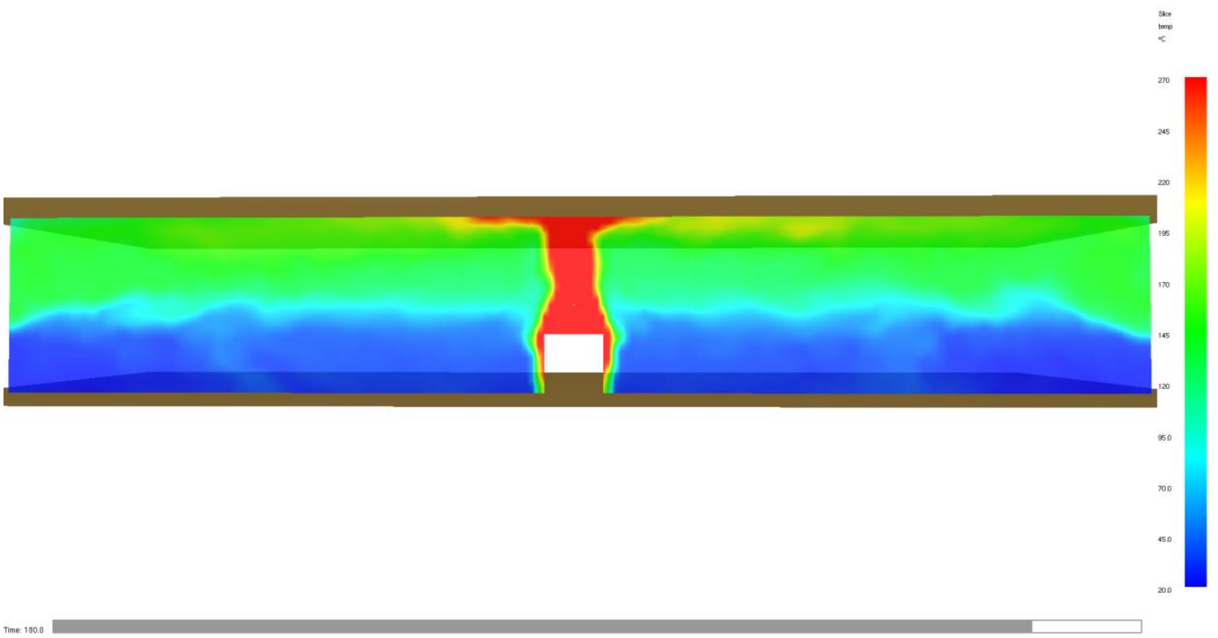
Slice of the Soot visibility after 150 seconds

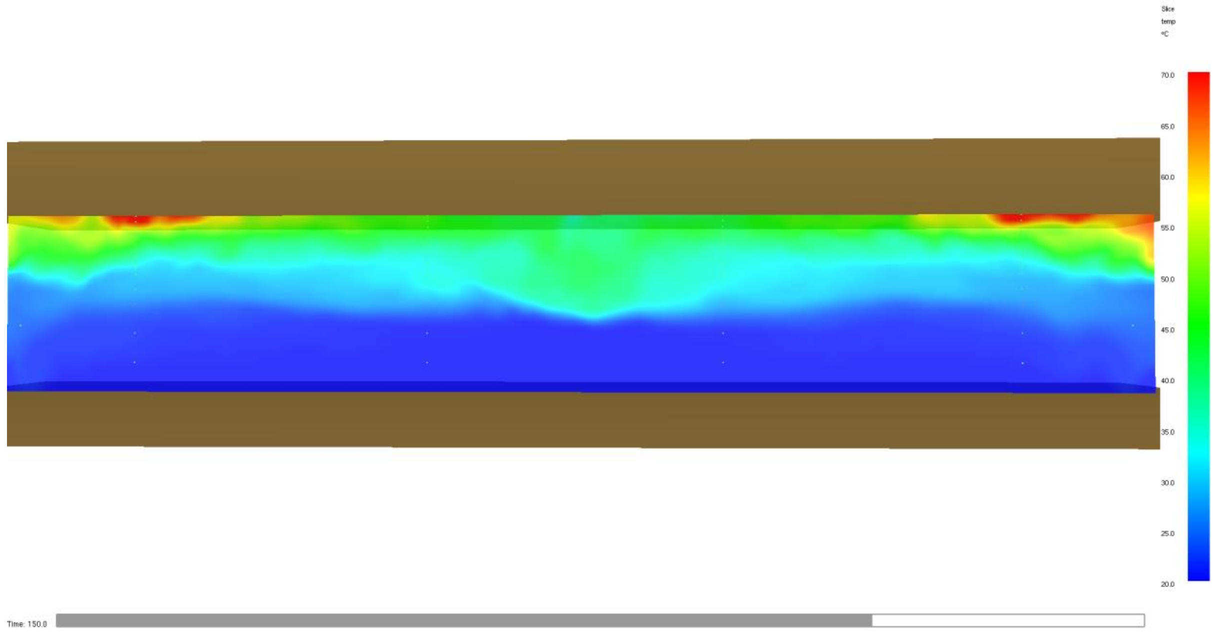


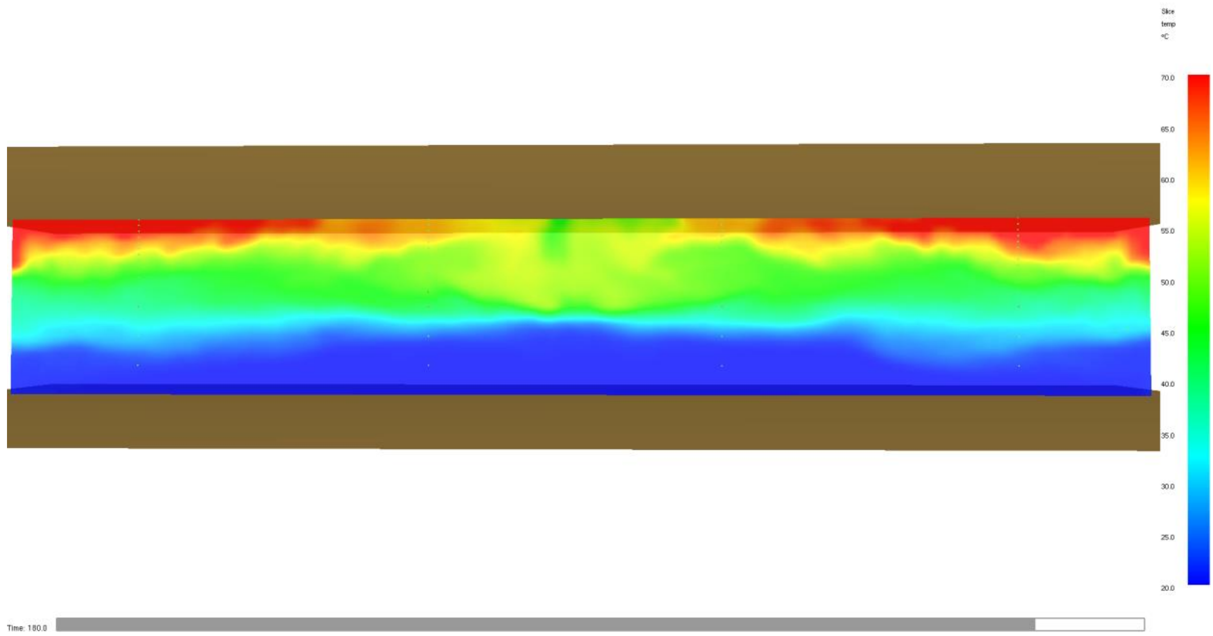
Slice of the Soot visibility after 180 seconds



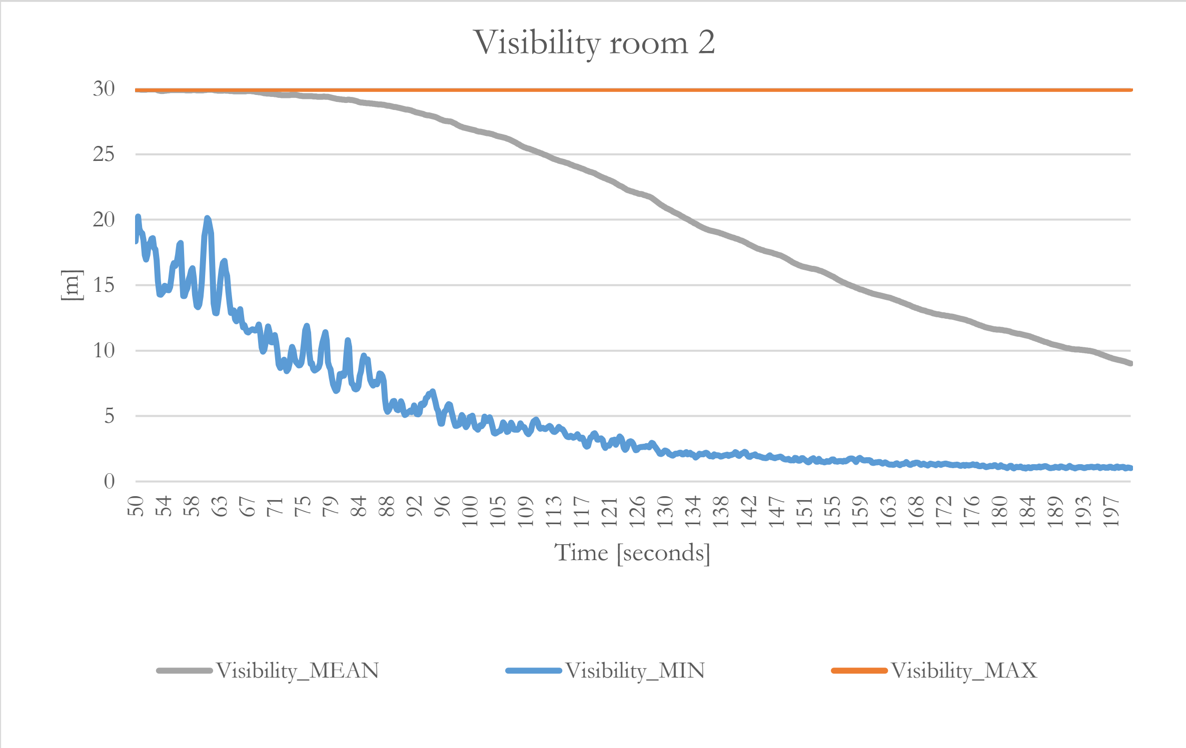
Slices of the Temperatures in room 1 at 180 seconds and room 2 at 150 and 180 seconds



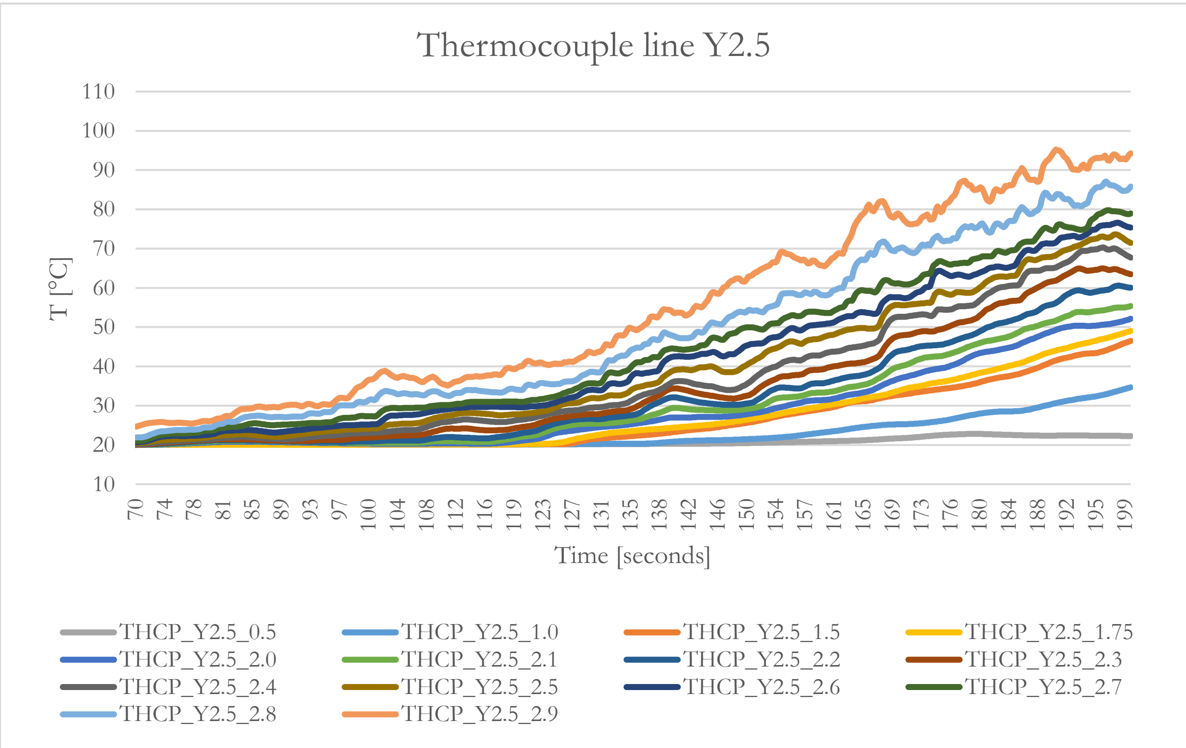

Slice
temp
°C
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
Time: 150.0


Slice
temp
°C
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
Time: 180.0

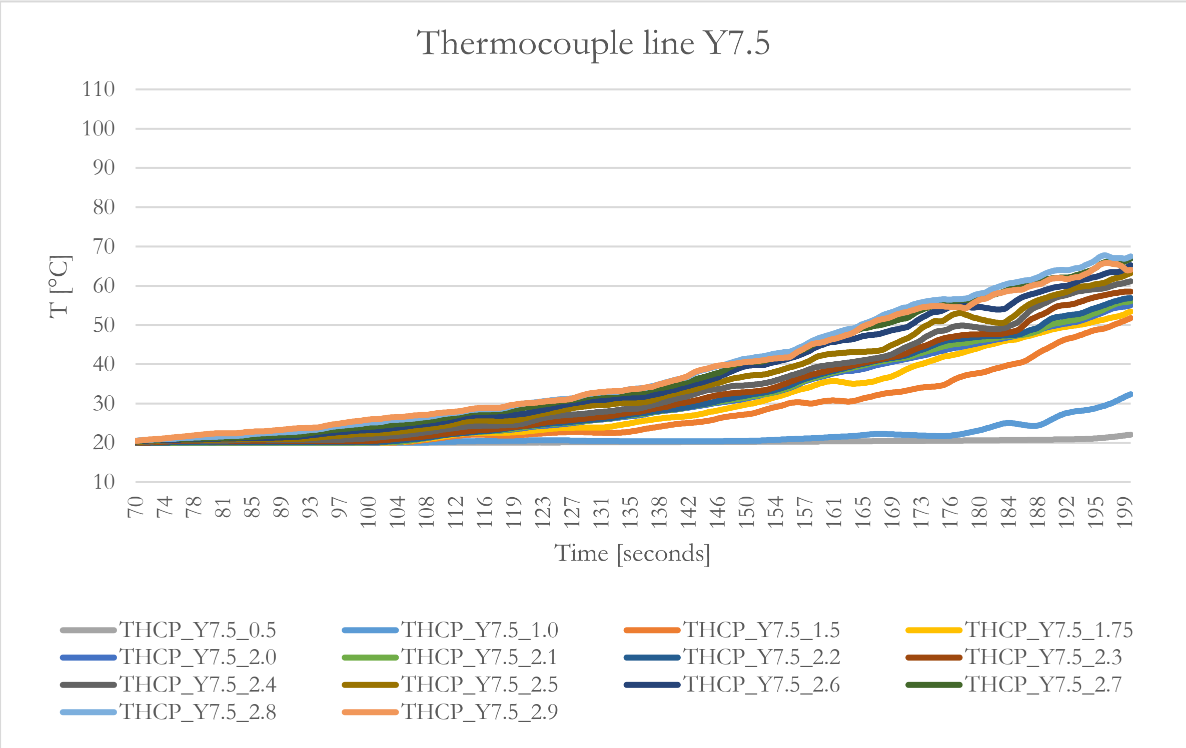
Graph of the visibility in room 2 (Max, Min and Mean)



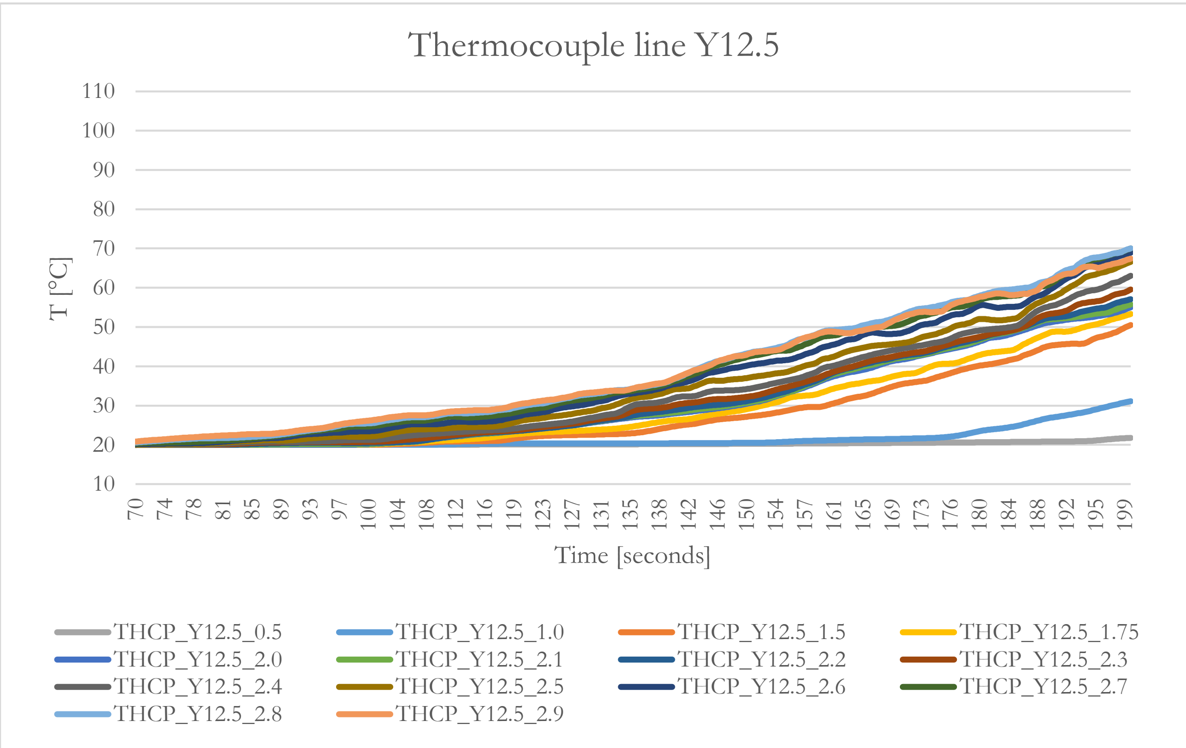
Graph of the thermocouples at Y2.5



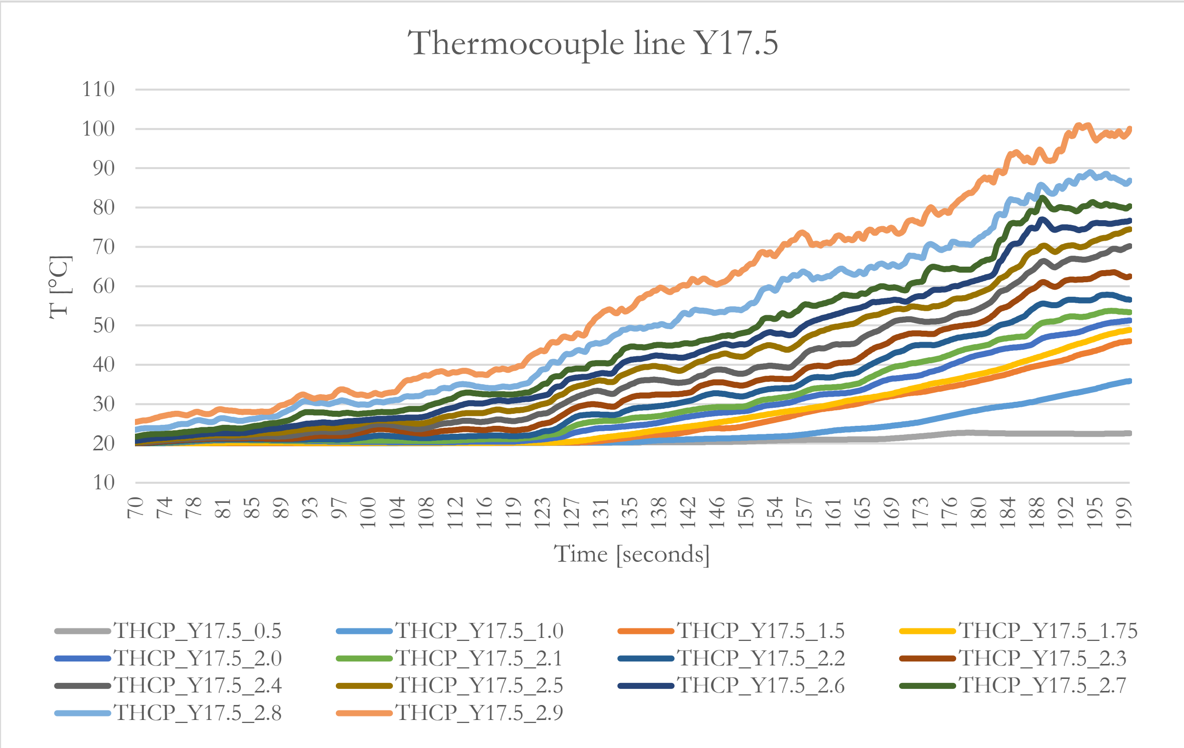
Graph of the thermocouples at Y7.5



Graph of the thermocouples at Y12.5



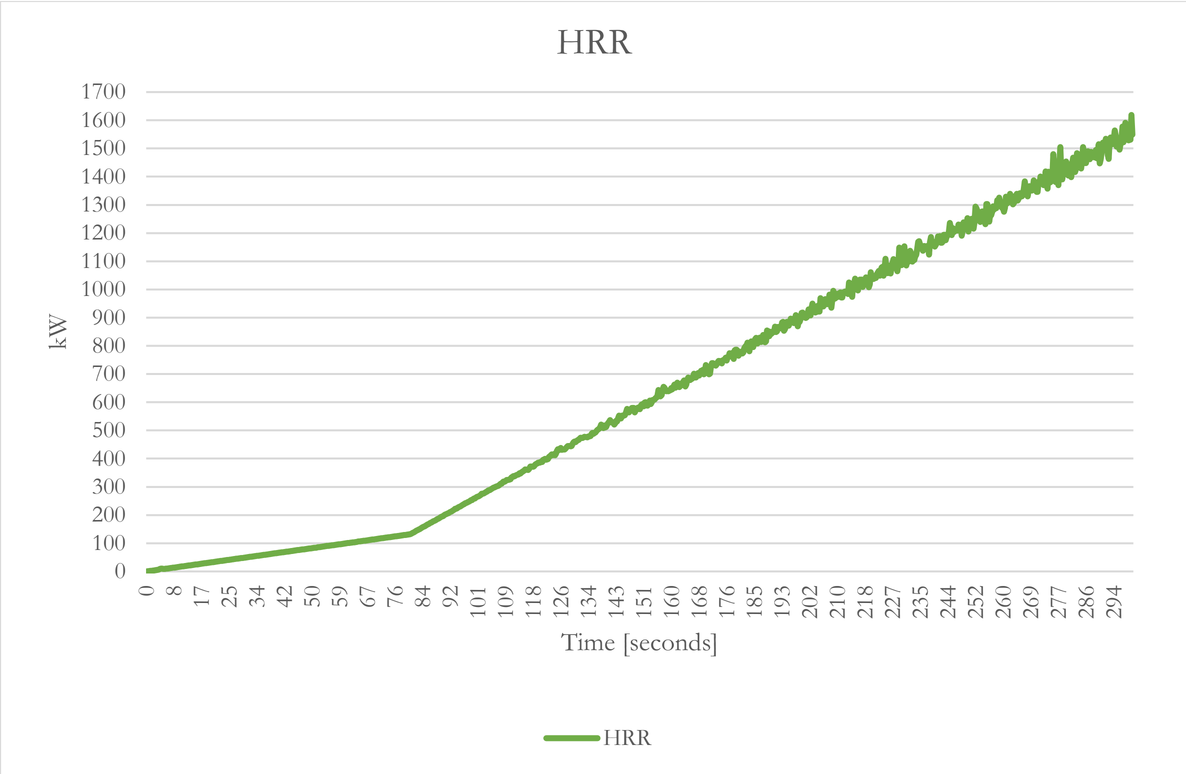
Graph of the thermocouples at Y17.5



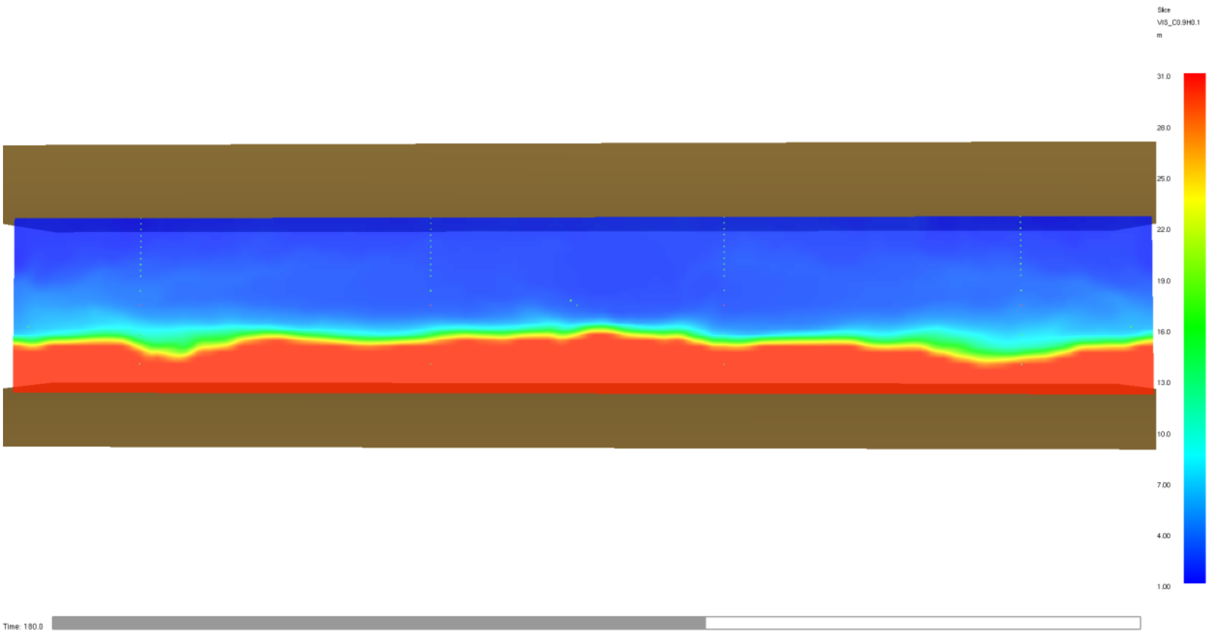
APPENDIX 2.6

Results of FDS-simulation 6

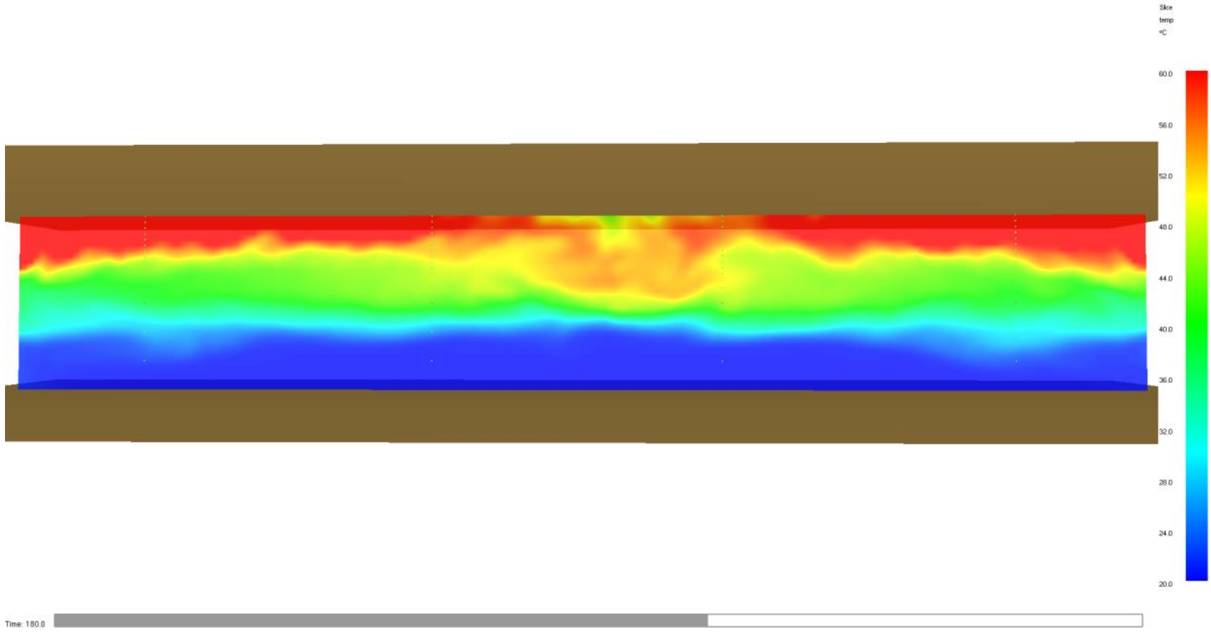
Graph of the Heat Rate Release [kW]

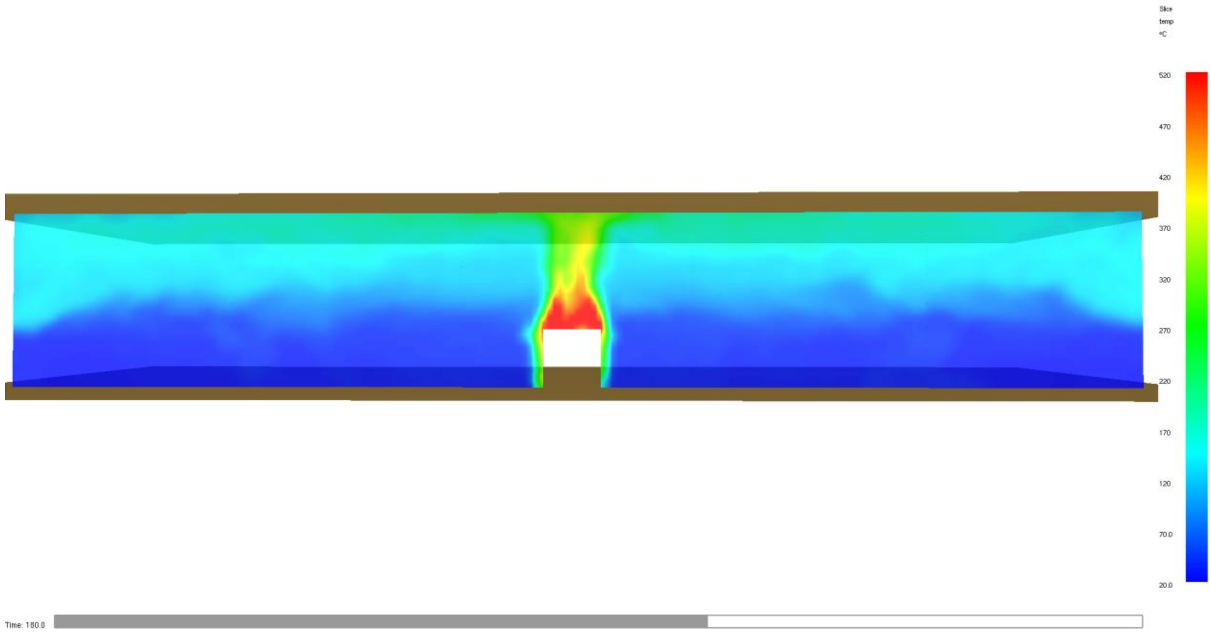


Slice of the Soot visibility after 180 seconds

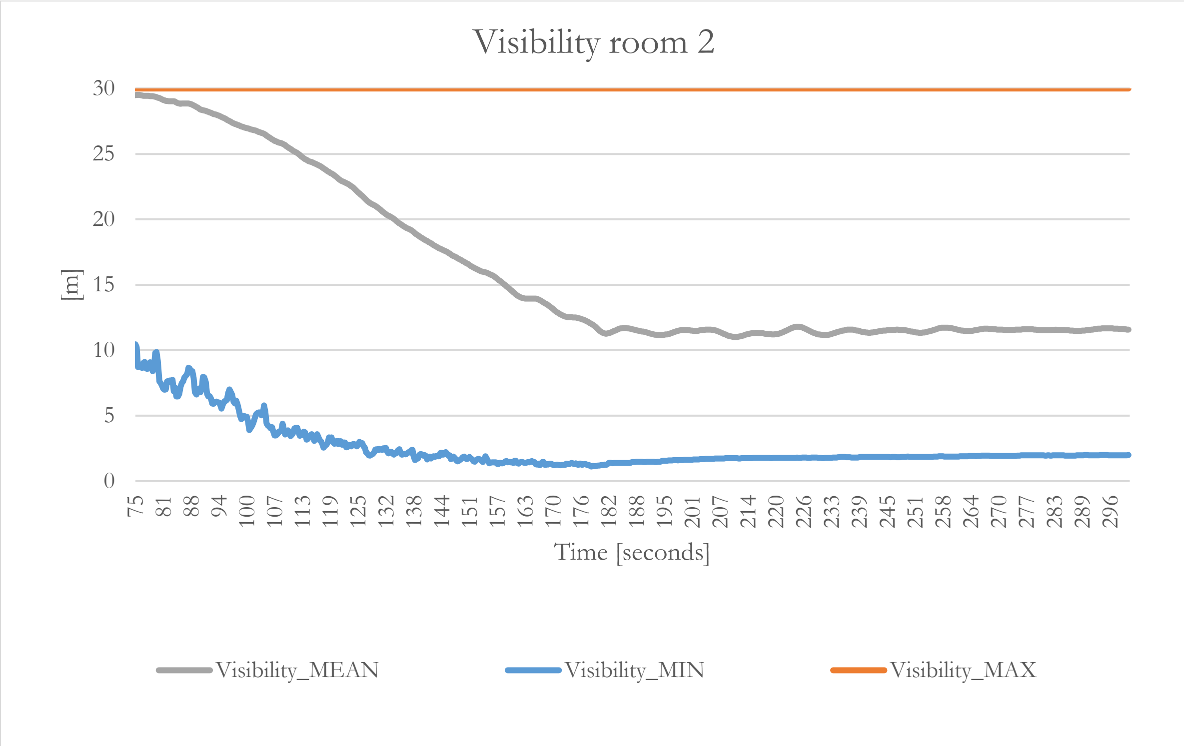


Slices of the Temperatures in room 1 and room 2 at 180 seconds

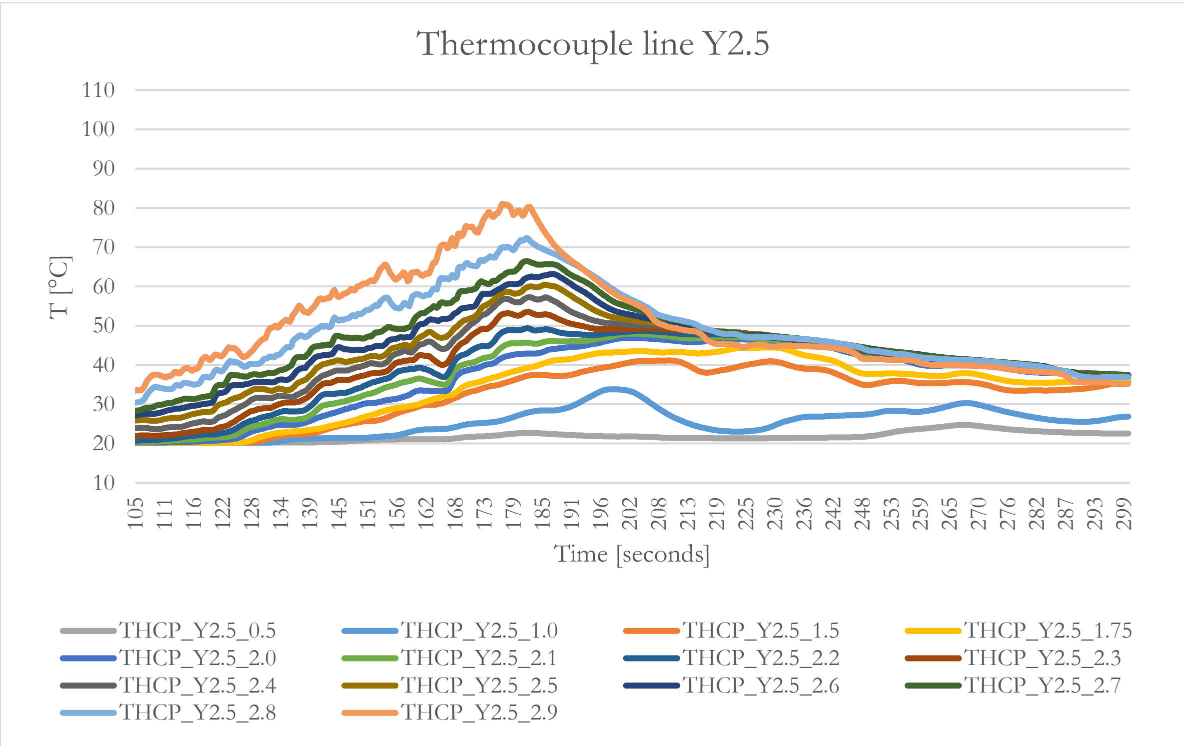




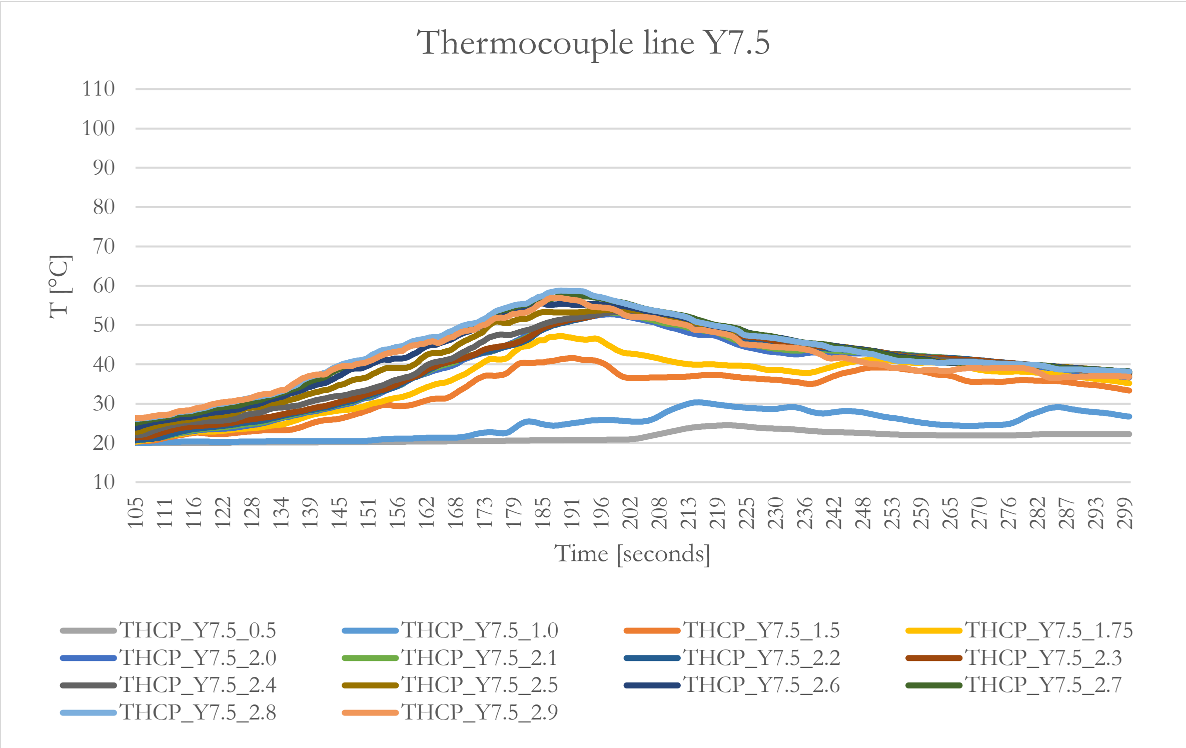
Graph of the visibility in room 2 (Max, Min and Mean)



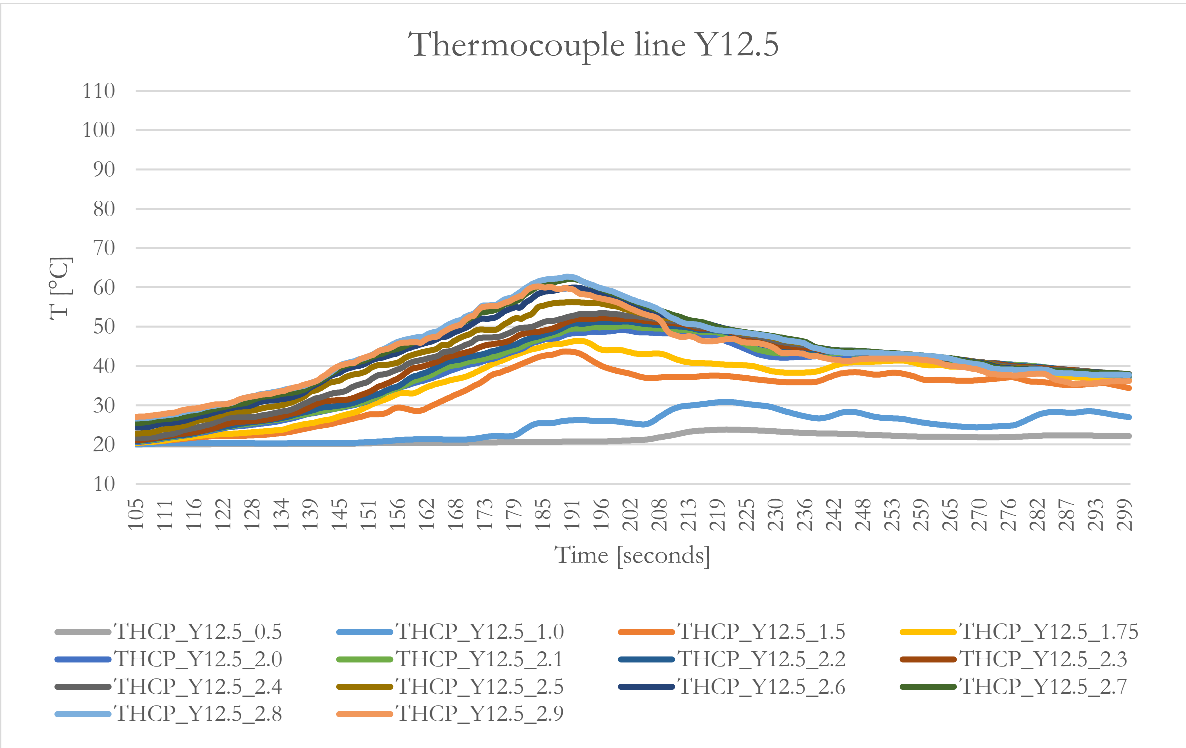
Graph of the thermocouples at Y2.5



Graph of the thermocouples at Y7.5



Graph of the thermocouples at Y12.5



Graph of the thermocouples at Y17.5