CFD simulations of the Cutting extinguisher

Robert Svensson, Johan Lindström, Raúl Ochoterena, Michael Försth

SP Technical Research Institute of Sweden

Fire Research

SP Report 2014:43

CFD simulations of the Cutting extinguisher

Robert Svensson, Johan Lindström, Raúl Ochoterena, Michael Försth

Abstract

CFD simulations of the Cutting extinguisher

Developing tactics for extinguishing fires located in structures is needed. Nowadays, the most commonly procedure employed by most fire brigades when extinguishing fires located in the interior of buildings, consists in sending a unit of firefighters inside the structure spraying high amounts of water on the surface of the burning fuels. This procedure has enormous caveats since it leads to the unavoidable necessity of exposing personal to situations where risks to their personal safety are major. Furthermore, water damage is common. An alternative to these tactics consists on using the Cutting extinguisher which in principle allows combating a fire by injecting water mist into the burning building without the necessity of entering it.

This work studies the Cutting extinguisher when used for fire-fighting activities in conventional and idealised civil structures by the aid of computerised simulations and experimental data. The simulations were done using Fire Dynamics Simulator (FDS) which is an open-source code for modelling well-ventilated fires while experimental data was obtained from idealised and controlled fires and experiments.

Findings of this study suggest that the Cutting extinguisher can be used for combating fires in confinements using less water than traditional methods. This is done by reducing both the gas temperature and relative concentration of oxygen in the room instead of cooling the surface of the fuels as traditional methods do. The high velocity of the jet induces mixing in the confinement, enhancing the interaction of droplets with hot combustion products and promoting the vaporisation of the injected water. Furthermore, the induced momentum to the gases in the room together with the vaporisation of the injected water reduces the overall gas temperature inside the structure. Generally speaking, adding water to fires reduce the possibility of fire spread and flash over.

Results from the simulated living room show that up to 80 % of the injected water vaporises when the averaged gas temperature is in the range of 200~250 °C and, for the 70 m^3 apartment, with an open window of 2.3 m^2 and a continuous heat source of 1 MW, the water vapour concentration increases by 30 % after 60 s of injecting water.

Keywords: Cutting extinguisher, FDS, Water mist, Oxygen reduction (inerting), Gas cooling.

SP Technical Research Institute of Sweden
Box 857, SE-501 15 BORÅS, SWEDEN
Telephone: +46 10 516 50 00, Telefax: +46 33 13 55 02
E-mail: info@sp.se, Internet: www.sp.se
www.sp.se

Fire Research
SP Report 2014:43
ISBN 978-91-87461-86-6
ISSN 0284-5172

Contents

Acknowledgements

The funding to this work by Vinnova is greatly acknowledged. This work has been funded within the Forska & Växa program and grant agreement 2013-03588 acting Cold Cut Systems as customer ordering the project from SP Fire research.

Special acknowledgement is given to Torwald Snickars and Patrik Söderberg at Cold Cut Systems who participated in numerous meetings giving feedback and information to the project. They also played an active role in the design and experimental execution of the project. Special acknowledgement is also given to Sven-Gunnar Gustafsson and Lars Gustavsson at SP Fire Research, Lennart Hällfors, Mauri Sköld, and Krister Palmkvist at Södra Älvsborg Fire & Rescue Services and Cold Cut Systems for conducting the experimental part of the project at Guttasjön.

1 Introduction

Developing tactics for extinguishing fires located in structures is needed. Nowadays, the most commonly procedure employed by most fire brigades when extinguishing fires located in the interior of buildings, including the Swedish rescue services, consists in sending a unit of firefighters inside the structure spraying water on the surface of the burning fuels by the aid of conventional and archaic well proven technologies. This procedure has enormous caveats since it leads to the unavoidable necessity of exposing personal to situations where risks to their personal safety are major, for instance, the unit is sent to untenable atmospheres in potentially unstable structures with very limited air supply and insufficient personal protection. Fighting fires in these fashion is clearly inefficient, furthermore; it leads to the use of large quantities of water resulting in water damaging the building. In other words, the buildings are damaged not only by the fire itself, but further weakened and affected in their structure and fundaments by the employed water. In addition, the water employed for extinguishing fires transports contaminants from the fire to the environment.

Fighting fires using systems operating at pressures ranging a few atmospheres requires of high amounts of water. This in its turn leads to, as aforementioned, property loss and environmental damages. Statistics indicate that in Sweden alone fire caused economic losses of approximately 4 000 MSEK during 2013 [1]. However; the statistics do not provide information on the extent of the reported damages caused by water damage itself and the combination of water damage and fire.

Although the Swedish Work Environment Authority indicate that the first tactical choice when fighting building fires should be to fight the fire from the exterior of the building [2], some fatalities have occurred in Sweden due to firefighters entering a burning building. A relatively novel option for fighting fires in compartments is provided by using the Cutting extinguisher [3] where the firefighters fight the fire from a safe position outside the building. The Cutting extinguisher uses high pressure water to create a water jet capable to cut a hole through building materials and allowing water mist entering the fire room without allowing fresh air to enter the building. The fine water mist produced by the system effectively cools the hot fire gases and reduces the relative oxygen concentration in the confinement and the risk of fire spread and ignition of hot fire gases. This method radically increases the safety for firefighters since fires can be combated from the exterior of the affected structure instead than from the interior.

Several reports have presented studies of the use of water mist for fire suppression [2, 3]. Research reports indicate that it is an inconsistency that the mechanisms for fire suppressing for a well-known suppressing agent such as water are complicated and difficult to describe when it is used in mist form [4]. Water has been traditionally used in very large quantities in such a way that the most important fire suppressing mechanism is cooling of the hot fuels. Water mist, on the other hand, interacts with the gas phase and not with the fuel surfaces promoting gas cooling and reducing the relative concentration of oxygen in the enclosure due to water vaporisation. This leads to reducing the amount of extinguishing water, especially if the mist is injected with a high velocity.

The exact understanding of the jet behaviour has been lacking until recently when the drop size distribution of the spray from the cutting extinguisher was measured experimentally using laser diagnostics [5]. The study shows that the spray can be characterized by a volume mean diameter d_{30} of 110 μm. This confirms previously made assumptions that the volume mean diameter is approximately d_{30} of 110 μm [6, 7]. Knowledge of droplet size distribution allows for a more analytic analysis of the effect of the cutting extinguisher, as well as for numerical simulations as will be presented in this report.

The objectives of this project are the following ones:

- Understand how variations on physical parameters such as droplet size distribution, concentrations and mean velocity affect the performance of water mist as suppressing agent.

- Understand how the parameters governing the momentum and shape of the spray such as liquid pressure and nozzle design affect the performance of the cutting extinguisher.

- Create the technical bases for further product development using a numerical model for simulating the performance of the spray in various environments.

- Create a visualisation tool for the cutting extinguisher for pedagogical purposes for Fire and Rescue Services.

It must be stated that due to computational limitations, the numerical model does not simulate the extinguishing process itself, but the interaction between the high velocity spray and the hot gases without including droplet breakup or coalescence effects. The spray is injected in the computational domain using a previously measured droplet size distribution 10 m downstream the nozzle in cold conditions [5].

This report is divided as follows: Section 2 contains background information about spray physics, Section 3 describes briefly the implementation of the spray into FDS (Fire Dynamics Simulator). Details about the implementation of FDS as well as simulation and experimental results are discussed in the Appendices.

2 Background

This section presents theory which is required for understanding the parameters used in the implementation and results from simulations of the cutting extinguisher. As a reference, a photography of the spray from the cutting extinguisher is shown in Figure 1. Much of the information in this section can also be found in reference [5].

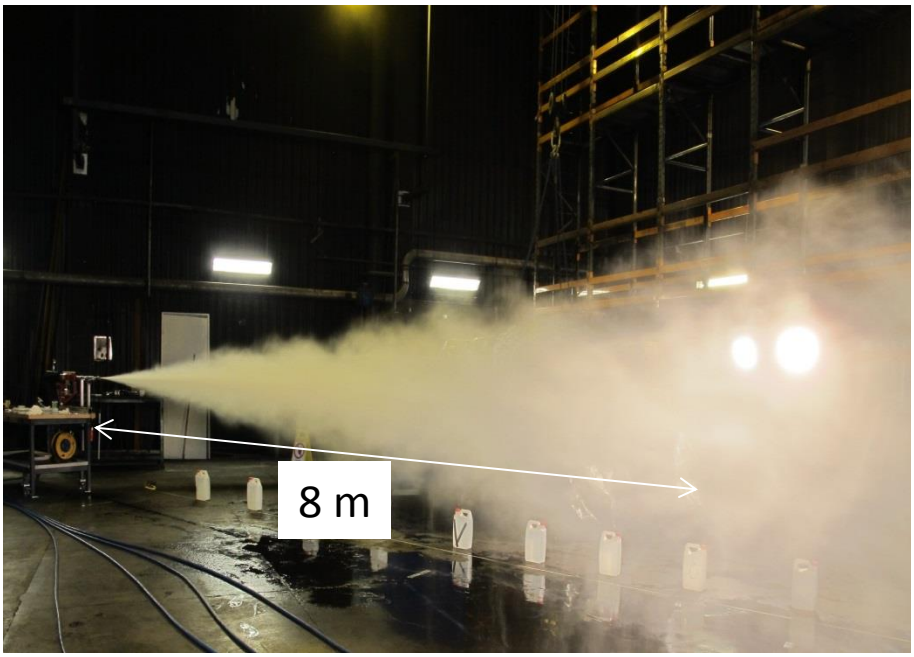

Figure 1: The cutting extinguisher. From reference [5].

2.1 Droplet size distributions

Small droplets (d < 1 mm) are in general close to spherical in shape and can therefore be physically described using their diameter. For a spray with a poly-disperse droplet size distribution different parameters are used [8] which can help in reducing the droplet size distribution to a scalar (a single value). The parameters used in this report are presented below (N is the number of droplets):

Length Mean Diameter d_{10} (arithmetic mean diameter)

$$d_{10} = \frac{\sum_{n=1}^{N} d_n}{N} \quad (1)$$

Length mean diameter, d_{10}, is what is meant by the "average diameter" in common language.

Sauter Mean Diameter d_{32}, SMD

$$d_{32} = \frac{\sum_{n=1}^{N} d_n^3}{\sum_{n=1}^{N} d_n^2} \quad (2)$$

Sauter mean diameter, d_{32}, is the diameter of a droplet whose volume to surface ratio is the same as the volume to surface ratio of the entire spray. d_{32} is particularly important when mass transfer and the active area per volume is important [8, 9]. Therefore d_{32} is an appropriate parameter for water mist since the purpose with the small droplets in water mist is to achieve large surface related effects, such as cooling and vaporization, while using small volumes of water.

Volume Mean Diameter d_{30}

$$d_{30} = \left(\frac{\sum_{n=1}^{N} d_n^3}{N} \right)^{\frac{1}{3}} \quad (3)$$

Volume mean diameter, d_{30}, is the diameter of a droplet whose volume is equal to the average volume of all droplets in the spray. d_{30} is not further used in this report but was defined here since it is mention in the Introduction chapter.

2.2 Spray droplet area

An important property of water mist is that the droplets are small and therefore their total surface is large for a given quantity of water. When a liquid of volume V is atomized into a spray the total droplet area is

$$A = \frac{6V}{d_{32}} \quad (4)$$

Figure 2 shows expression (4) in graphical form. As can be observed the spray area per volume of water increases drastically for small droplets.

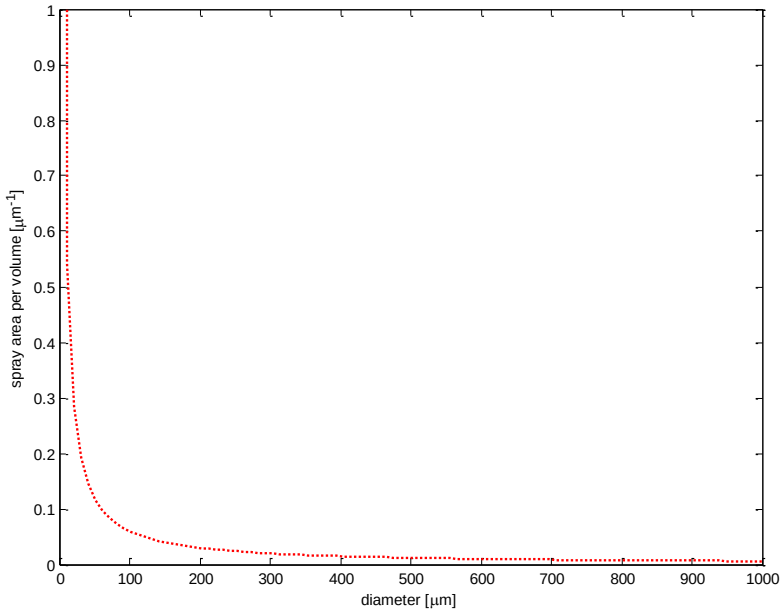

Figure 2: Spray area per volume as a function of droplet diameter (d_{32}).

2.3 Gas cooling

Water droplets extract heat from flames and hot gases. This occurs by heating the water from room temperature to 100 °C, and by vaporisation where the extracted energy is used to induce a phase change from liquid to gaseous water. The rate of transport of energy to the droplet depends on the surface area of the droplet and the relative velocity of the droplet as compared to the air [6].

A numerical example of the relative importance between heating and vaporization is as follows: The specific heat capacity of water is $c_p = 4.2 \cdot 10^3$ J kg^{-1}K^{-1}[10]. If 1 kg of water initially is at 20 °C and is heated to 100 °C this means that $80 \times 4.2 \cdot 10^3 = 330$ kJ of energy is consumed from the fire. The heat of vaporization for water is $\Delta H_{vap} = 2.3 \cdot 10^6$ Jkg^{-1} [10] which means that another 2300 kJ are consumed from the fire when the liquid water at 100 °C is vaporized to water vapour at 100 °C. Increasing the temperature of water vapour from 100 °C requires the supply of additional energy. The heat capacity of water vapour is $c_p = 1.89 \cdot 10^3$ J kg^{-1}K^{-1} at 100 °C and $c_p = 2.12 \cdot 10^3$ J kg^{-1}K^{-1} at 500 °C.

The heat transferred to the droplet per unit time is proportional to the droplet's surface. The heating rate is proportional to the transferred power per unit volume. Therefore d_{32} is useful when comparing the heating rate of the droplets since this parameter characterizes the volume to surface ratio of the spray. The relative surface to volume ratio between a low pressure systems with e.g. $d_{32} = 1000$ μm (1 mm) and the cutting extinguisher, with $d_{32} = 170$ μm is approximately $1000/170 \approx 6$. The significance of this is that the smaller water droplets from the cutting extinguisher heat up much faster and extract more power from the flames and hot gases. This in

turn will lead to an accelerated vaporisation, resulting in reducing the chemical kinetics of combustion, see Section 0.

The rate of gas cooling, which in its turn is the heating rate of droplets, and vaporization discussed above is very important since if this rate is too low the droplets will hit the floor or walls before being vaporized, which reduces that overall gas-cooling efficiency [11].

2.4 Reduction of radiative heat transfer

One of the major advantages with fine water mist is its ability to absorb heat radiation from a fire. This will reduce the radiative heat transfer, thereby reducing the fire spread, but it will also enhance the heating and vaporization of the droplets due to the absorbed heat radiation. In Figure 3 the volumetric absorption efficiency [12] for water droplets exposed to heat radiation corresponding to a 900 °C black body radiation is shown. This property, $C'''_{abs,eff}$, is a measure of how much radiation is absorbed per unit volume of water. As can be observed small droplets are superior as compared to larger droplets in absorbing heat radiation from a fire.

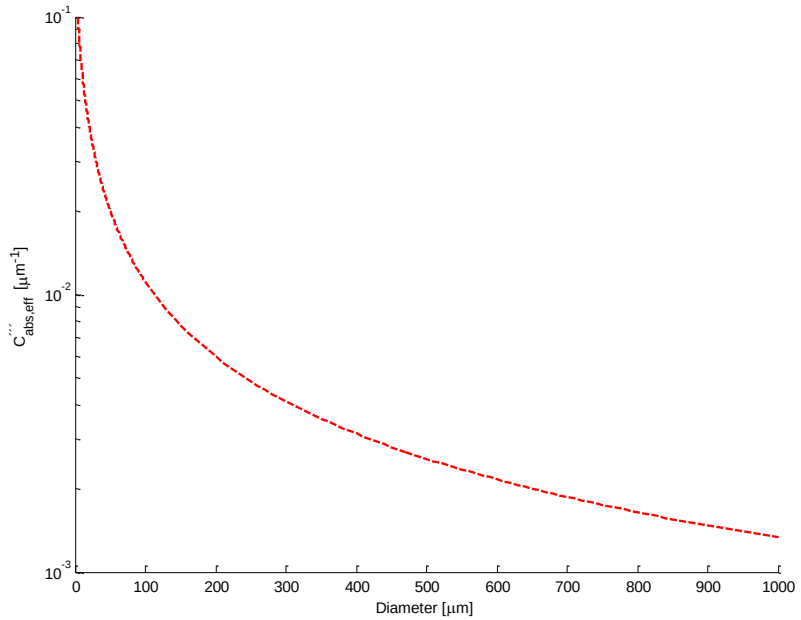

Figure 3: Volumetric absorption efficiency as a function of droplet diameter. A radiation source corresponding to 900°C black body radiation has been assumed. Adapted from reference [12].

2.5 Reduction of the oxygen concentration (*inerting*)

Fires can be extinguished by impeding the oxidising agent reacting with a given fuel. Although this is in principle impossible to achieve in fire-fighting activities, it is however possible to decrease the rate of combustion reactions or intensity of the fire by reducing the relative amount of oxygen surrounding the fuel.

Reducing the concentration of oxygen in closed compartments can be achieved by adding water vapour in the confinement until the relative amount of oxygen falls substantially and combustion can be hindered or damped. In the fire-fighting jargon reducing the relative concentration of oxygen is known as *inerting*. Nonetheless, it must be stated that since the environment of a fire is almost never inert, the term *inerting* is physically inappropriate.

As aforementioned, totally removing the oxidiser is in principle impossible to achieve. However, most of the materials used in civil constructions become almost non-ignitable at ambient conditions if the relative oxygen concentration falls under 10 %. On the other hand, this is highly dependent on the fuel and factors such as the residence time, temperature and turbulence. For instance, corn starch auto ignites at 900 °C with an oxygen concentrations as low as 5 % and at 440 °C with an oxygen concentration of 15 %. Therefore; it is impossible to define another value than 0 % of oxygen concentrations for creating an inert atmosphere for conventional materials.

It should be pointed out that the effect on fire by the reduction of the oxygen concentration can be greatly inhibited if fresh air is entrained into the confinement by the spray. Therefore, using a spray that can interact with the fire without the introduction of fresh air greatly enhances the extinguishing capacity of a system, e.g. when the extinguisher is introduced into the compartment through a minimal hole. Indeed, in such cases the system may even act to mix combustion products from the fire back into the combustion environment further enhancing its extinguishing performance. This can be accomplished by the cutting mode of the cutting extinguisher and it is therefore the scenario that is simulated and described in this report.

2.6 Transport properties

Small droplets promote fire suppression in the gas phase because, among other aspects, smaller droplets stay airborne longer than larger ones leaving more time for vaporisation.

It has been shown [13] that a droplet with 100 μm in diameter entering a gas environment at 400 °C will have a lifetime of 0.2 s and will fall 30 mm before being totally vaporised. A 1 mm droplet has a lifetime of 230 s and a falling distance of 680 m. This shows that when a large proportion of the water is carried in large droplets these droplets will fall to the floor or hit a wall before being entirely evaporated. These differences in transport properties will reduce the gas cooling and affect the vaporisation rate, as well as cause larger property losses due to water damage for conventional systems as compared to high pressure water mist systems, such as the cutting extinguisher for example.

There are typically two contradictory requirements on the spray: rapid vaporization of droplets and strong mixing induced by the spray. Smaller droplets lead to rapid vaporisation but also typically reduce the mixing. However, by using a high injection pressures, the velocity and the mass flow of the spray is increased. This clearly compensates the lower mixing potential for small droplets [6], which is part of the investigation presented in this report, but it is unclear to what degree.

Atomisation of the jet from the cutting extinguisher commences just after the liquid jet exits the nozzle and commences its interaction with the surrounding air; furthermore, the momentum of the jet induces a flow from the gas surrounding the spray into the spray itself. This can be exemplified in Figure 4 where a jet entering into the control volume induces a flow of air into the spray and transfers part of its momentum to the gas up to a point that the droplets and air leaving the control volume have almost identical velocities. This effect can promote fire suppression mechanism when vitiated air is entrained into the spray. If fresh air is entrained the fire suppression will on the contrary be inhibited. The transfer of momentum in these kinds of flows enhances the transport of droplets, transporting them much further away than if these droplets were simply ejected into a quiescent atmosphere at high velocities.

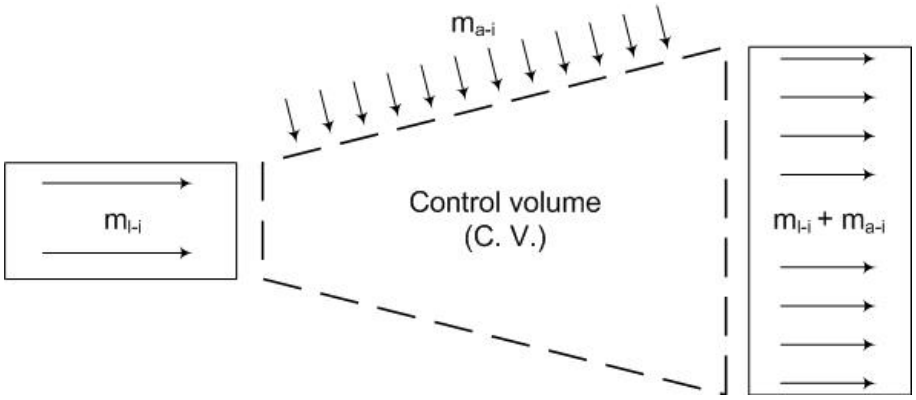

Figure 4: Control volume used for theoretical preliminary calculations.

The former discussion can be continued by contrasting the behaviour of the cutting extinguisher with the theoretical penetration of single droplets of different sizes being ejected at high velocities (200 ms^{-1}) into a quiescent atmosphere, as it is shown in Figure 5. These plots show that the penetration of droplets injected into ambient air is modest, even for very large drops as shown in the upper plot. On the other hand, experiments carried out with the cutting extinguisher [5] show that the spray produced by the cutting jet has velocities well above zero even at distances as large as fifteen metres from the nozzle. This is to a large degree a direct result of the high pressure. The high pressure, resulting in a high speed and high flow, creates a high momentum spray that pushes the water mist long distances into an enclosure fire, making it possible to act on fires distant from the nozzle despite the small droplets.

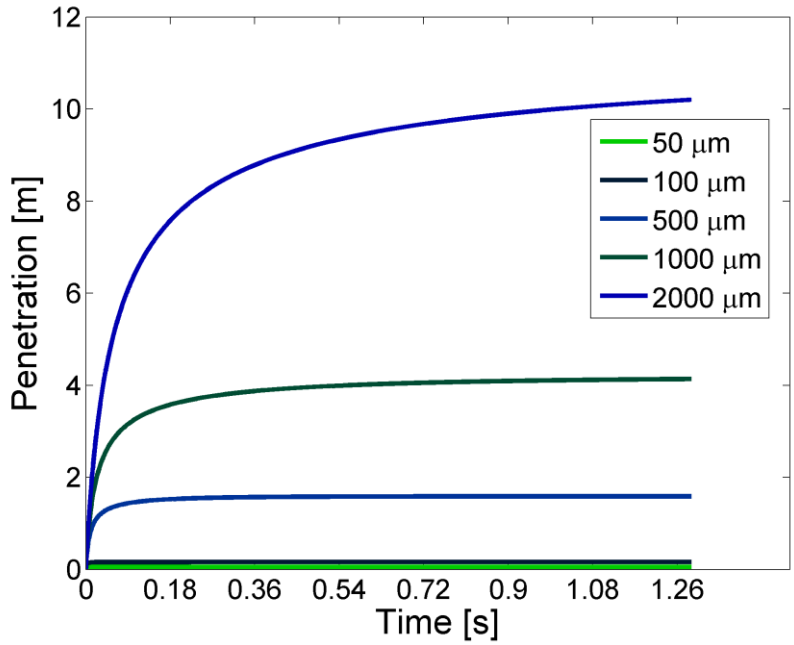

Figure 5: Theoretical penetration of single droplets into air with an initial velocity U=200 ms^{-1}.

The cone angle $\alpha/2$, see Figure 6, of the spray was determined from processing the images captured during the measuring campaign. It was found that $\alpha/2$~5.7° and it is almost constant along the spray axis.

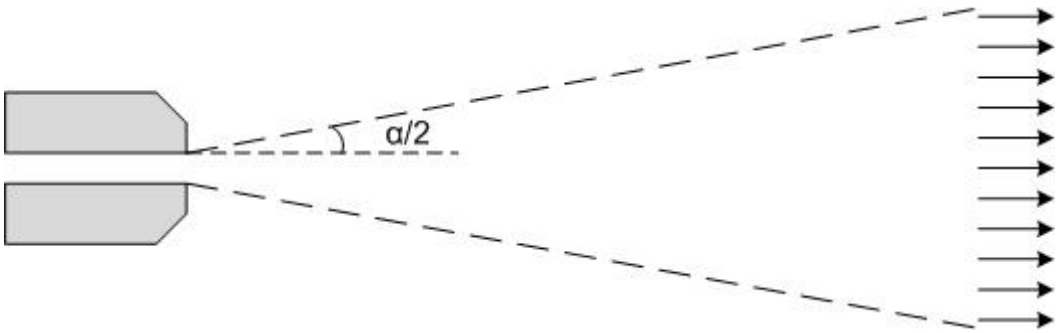

Figure 6: Sketch of the spray illustrating the cone angle.

In summary, the high pressure, entrained air, high spray momentum, and also the small cone angle of the cutting extinguisher leads to significant velocities at relatively long distances from the nozzle. This makes it possible to transport and mix the water mist much more effectively than what is indicated in Figure 5. This is of importance for the extinguishing process itself but also for the feasibility of fire fighters to enter the enclosure, although there are also negative impacts such as reduced visibility.

3 Implementation of the cutting extinguisher in FDS

Fire Dynamics Simulator (FDS) was chosen to simulate gas cooling, water vapour concentration, and stirring for the Cutting extinguisher. More about the choice of software can be found in Appendix C. This project did not aim to simulate fire dynamics. A more detailed explanation of the implementation of the spray in FDS can be found in Appendix A. Version 6.0.1 serial of FDS was used for all simulations.

3.1 Modelling fire/Choice of heat source

The heat source used in the simulations cannot be extinguished and therefore it should be considered as a heat source rather than a fire. The power of the heating source is predefined for each case.

3.2 Spray properties

For comparison, a theoretical enhanced low pressure system was simulated in the same scenarios as the Cutting extinguisher. The used parameters for the sprays are shown in Table 1.

Table 1: Spray parameters used in the simulations.

System:	Cutting extinguisher	Enhanced low pressure system
Flow rate:	60 l/min	100 l/min
Initial velocity (v_0):	220 m/s	65 m/s
Cone angle ($\alpha/2$):	6°	15°
Sauter mean diameter (d_{32}):	162 µm	1000 µm
Number of jets:	1	1
Type of jet:	Full cone	Full cone

3.3 Wall model

When a droplet impinges a wall in FDS a vertical velocity of 0.5 m/s in the downwards direction is assigned to it. Even if droplet bouncing occurs, FDS do not simulate it. Furthermore, a droplet impacting the floor will immediately disappear from the simulation environment and thereby not contribute to surface cooling or vaporisation.

3.4 Validation of the Living room simulations

To validate the ability of FDS to predict gas cooling, a series of experiments were carried out in the aforementioned testing facility. The high temperatures obtained in the simulations could not be reached in the experiments, so qualitative instead of quantitative comparisons were done. Qualitative comparisons could be made by examining the signals from one of the thermocouple trees in four experiments and

corresponding simulations that are shown in Figure 7 and Figure 8. The plots indicate that the simulated and experimental behave similarly. Figure 8 shows simulations using a surfactant added to the water (X-Fog) which results in droplets with 65% of the nominal droplet [5].

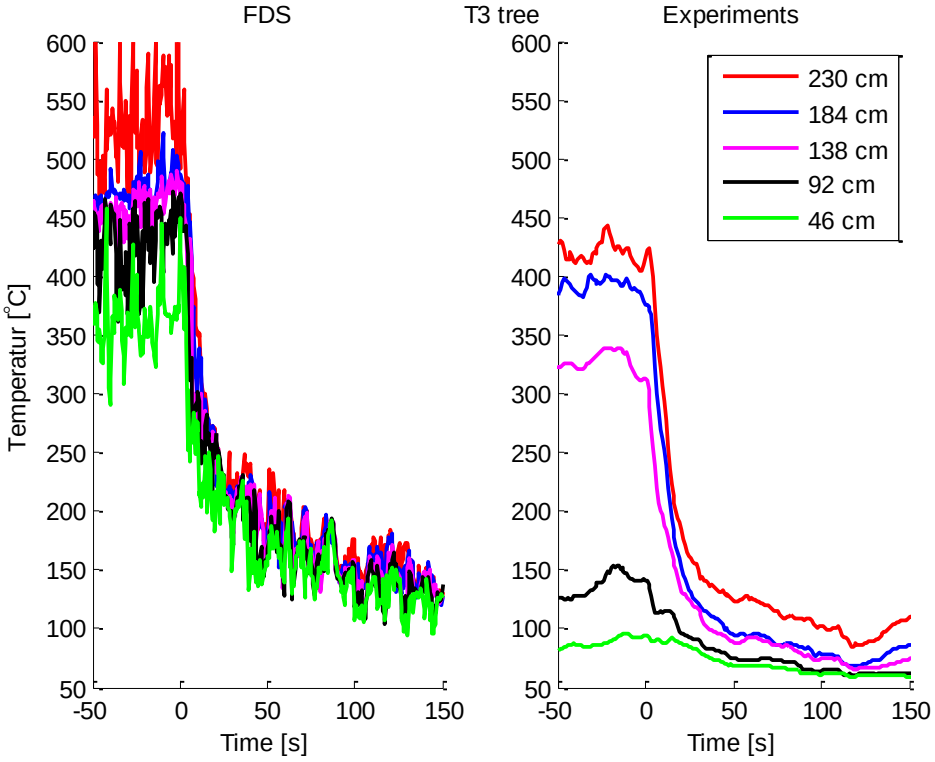

Figure 7: Temperatures from FDS compared to thermocouples in T3 (see Appendix 2).

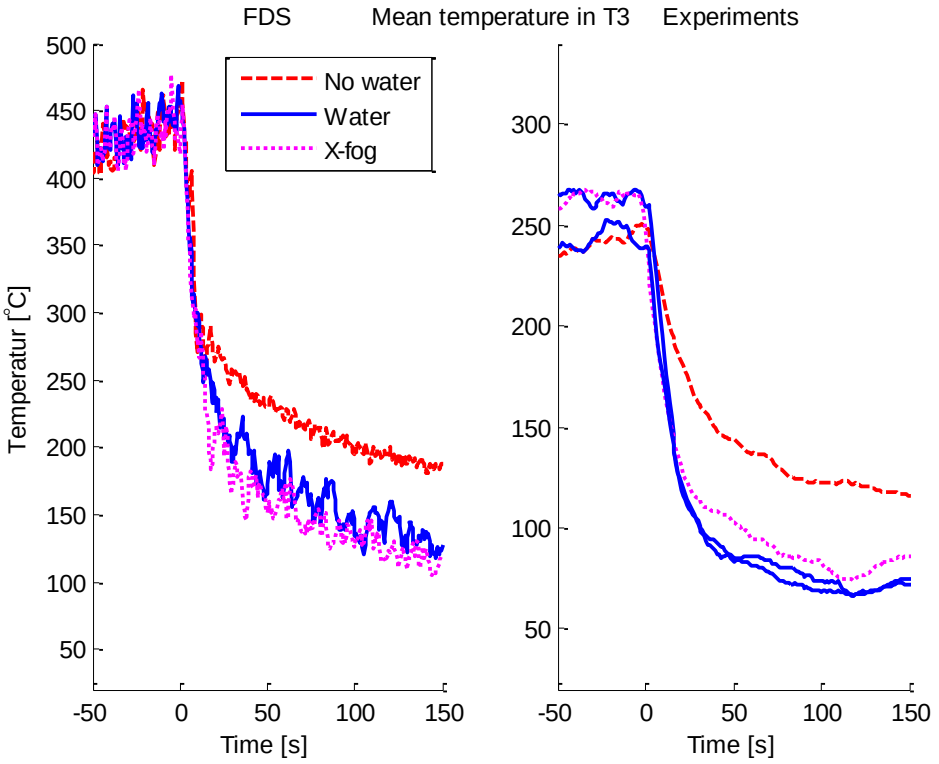

Figure 8: Mean measured values for the five thermocouples in T3 for four experiments compared to their FDS counterparts. When X-fog, water with an added surfactant, is simulated in FDS the employed water droplets have 65% of the nominal droplet size.

4 Simulation results and discussion

Three partly ventilated geometries have been simulated. An apartment, a living room, and a warehouse with a HRR (Heat Release Rate) of 1, 4, and 8 MW, respectively. In the case with the living room the HRR was turned off when the water mist was injected to the system. In the other cases the HRR was kept constant throughout the simulation. The choice to turn of the HRR in the living room simulations was made to facilitate a comparison between the simulations and the validation tests described in Appendix B.

In the living room and warehouse geometries several spray configurations have been simulated. In addition to the nominal spray of the cutting extinguisher three sprays with slightly changed momentum and three sprays with a slightly changed d_{32} have been simulated for a sensitivity analysis. All other parameters were kept constant in these simulations. Furthermore an enhanced low pressure system has simulated assuming the parameters seen in Section 3.2.

The results are presented for one geometry at a time. Each geometry is introduced by figures showing the geometrical outline. Thereafter stirring effects, gas cooling, and finally oxygen reduction effects are discussed.

Note that when water reaches the floor in FDS, the droplet will disappear from the computational domain and can therefore no longer contribute to any cooling and oxygen reduction.

4.1 Apartment

The apartment simulated is a 28 m^2 room with a ceiling height of 2.5 m. A heat source of 1 MW is placed in the kitchen area seen in Figure 9 to Figure 11. The cross sections, or planes (A, B or C), indicated are sections that will be used for visualization. All walls in the simulation are made of 10 cm thick gypsum boards. The apartment is ventilated through a 1.8 m wide and 1.3 m high open window. The apartment is heated under a period long enough for the temperature profile in the gas to reach a steady state before the Cutting extinguisher is started. The heat source continues to have the same power of 1 MW during the entire simulation. The cutting extinguisher is placed 1.7 m above the floor and perpendicular to the entry door and wall located 6.5 m downstream the nozzle exit. This configuration was chosen since firefighters will most probably commence using the Cutting extinguisher in this way when perforating a wall or surface in the field.

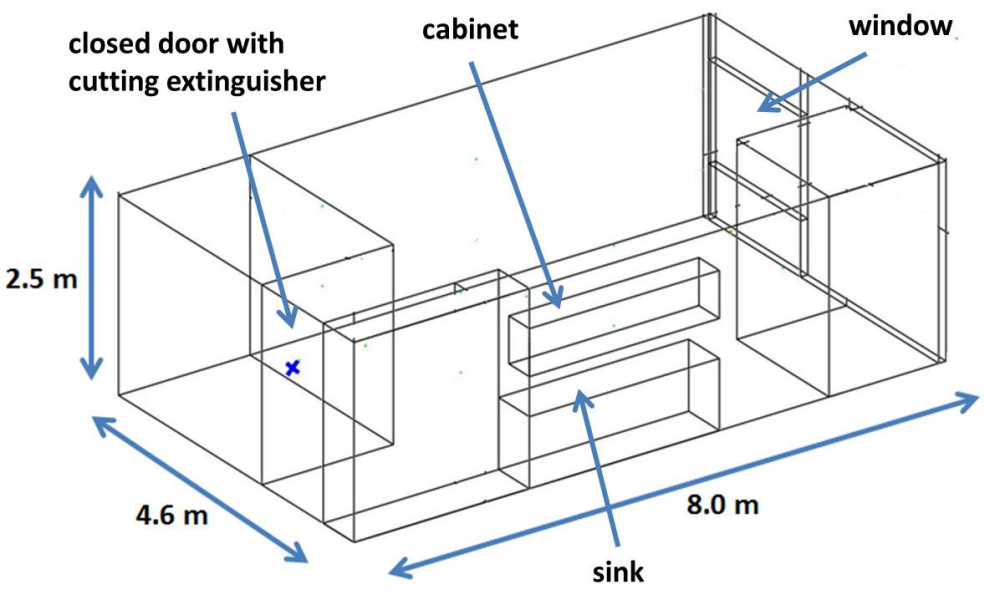

Figure 9: The geometry of the apartment in FDS. The blue cross is the position for the Cutting extinguisher.

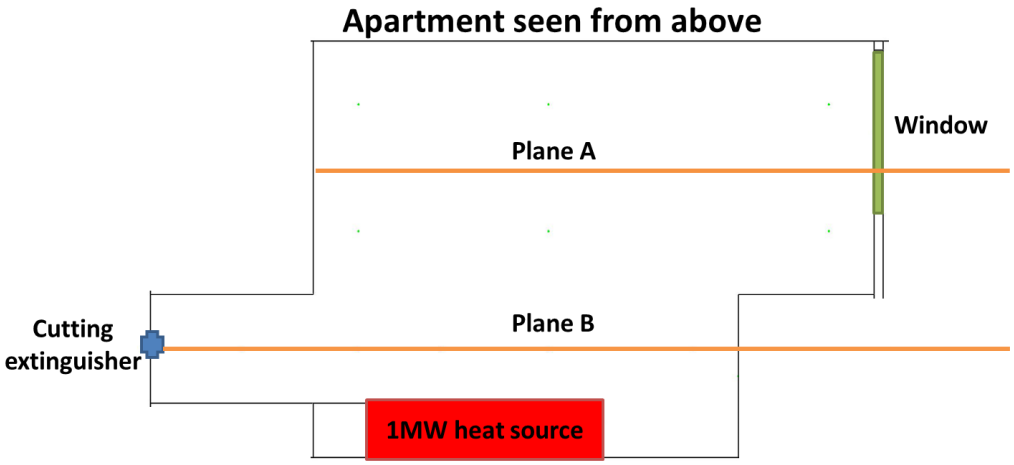

Figure 10: The geometry of the apartment in FDS seen from above.

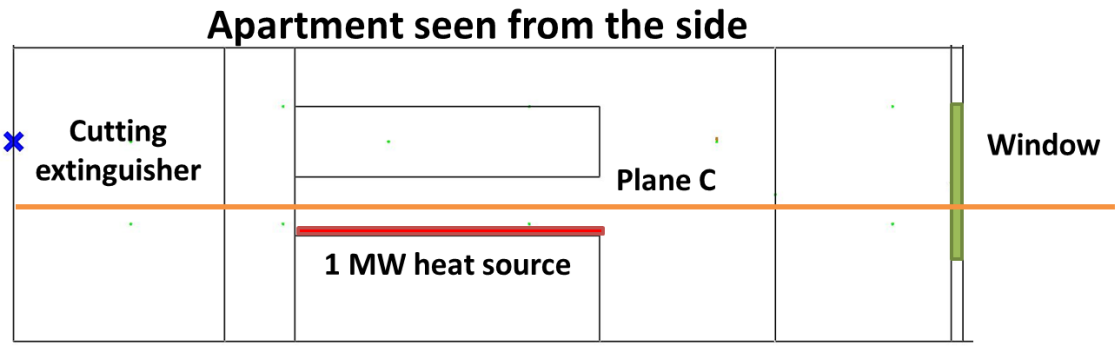

Figure 11: The geometry of the apartment in FDS seen from the side.

4.1.1 Stirring

In Figure 12 to Figure 14 vector fields are presented describing the gas transport in Plane A, B, and C from Figure 10 and Figure 11. The magnitude of the velocity is described by the colour of the vector. The vector field have been averaged over a period of 30 s in order to see the net gas transport rather than the chaotic instantaneous velocity field. The vector field is very stable during the 150 s the Cutting extinguisher is employed. By looking at the figures it can be observed that the gas velocity is at least a few meters per second everywhere in the apartment.

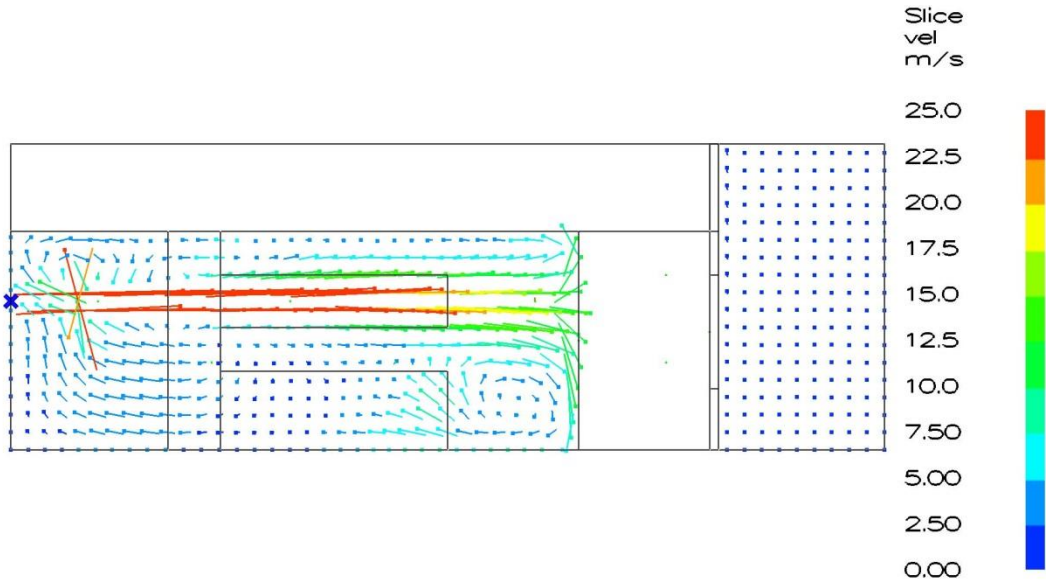

Figure 12: Velocity vectors seen in Plane B to describe the gas transport in the apartment. The vector field is averaged over 30 s.

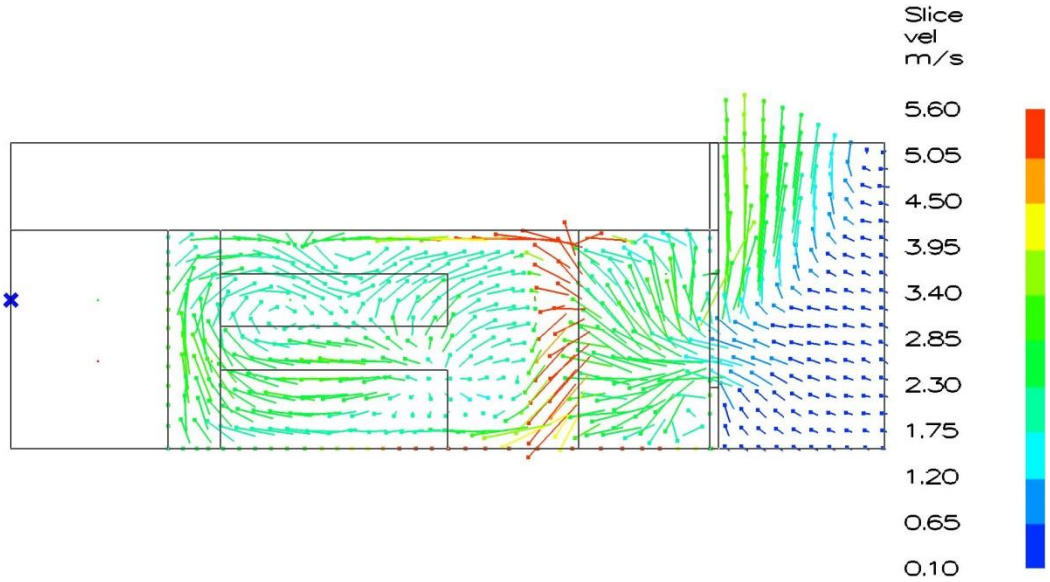

Figure 13: Velocity vectors seen in Plane A to describe the gas transport in the apartment. The vector field is averaged over 30 s.

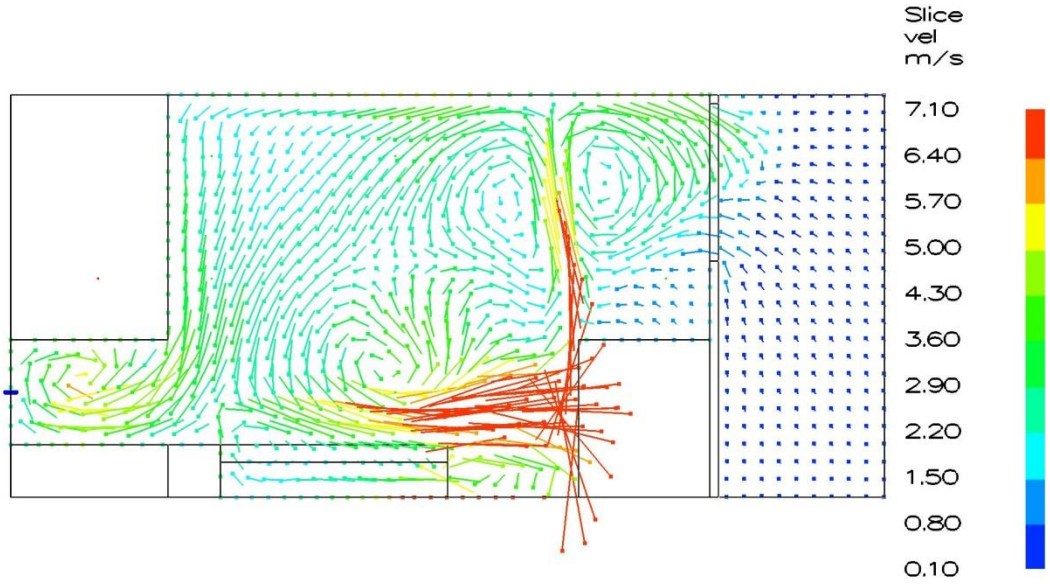

Figure 14: Velocity vectors seen in Plane C to describe the gas transport in the apartment. The vector field is averaged over a period of 30 s.

4.1.2 Gas cooling

Figure 15 and Figure 16 illustrate the temperature reduction after 60 s of action of the Cutting extinguisher. There is a homogenous temperature of approximately 200 °C in the apartment after 60 s. The temperature will continue to decrease after 60 s down to approximately 150°C after 120 s. Note that the 1 MW fire cannot be extinguished in the simulations due to the implementation of the heat source in FDS.

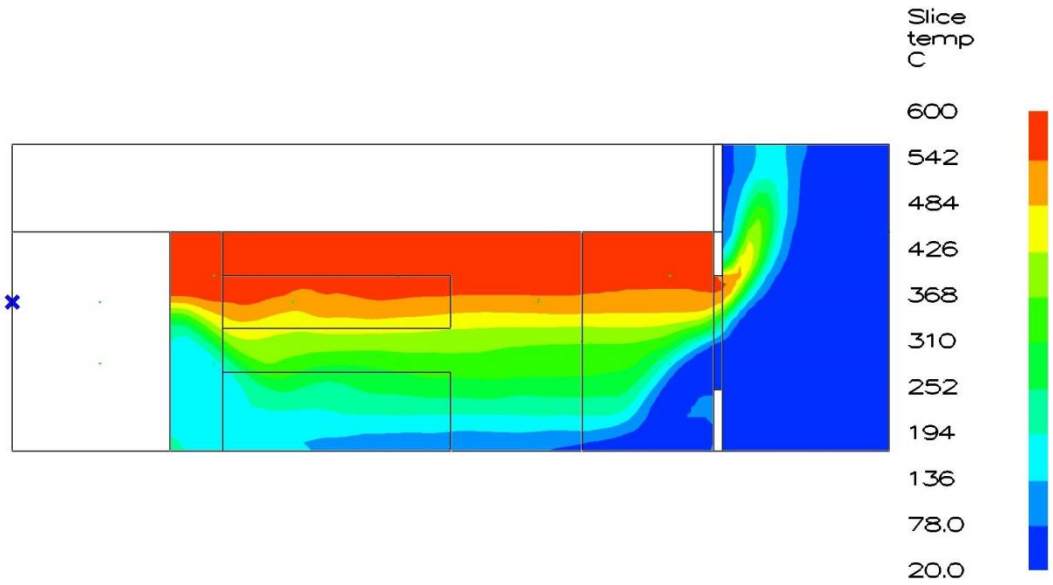

Figure 15: Temperature field in Plane A in the apartment right before the Cutting extinguisher is simulated. The field is averaged over 10 s.

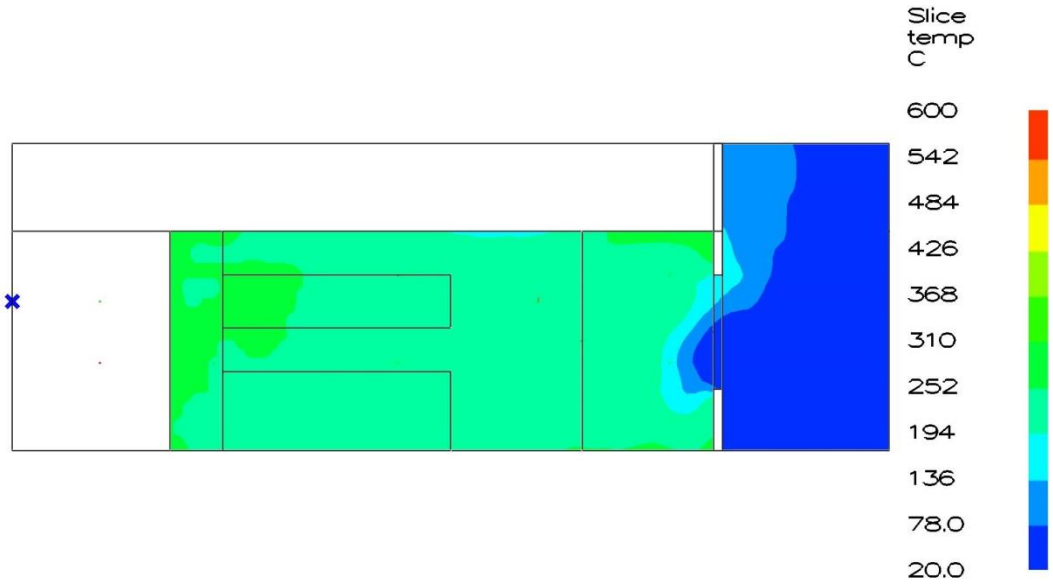

Figure 16: Temperature field in Plane A in the apartment after 60 s use of the Cutting extinguisher. The field is averaged over 10 s.

4.1.3 Oxygen reduction

Figure 17 and Figure 18 show the oxygen concentration in Plane A while Figure 19 and Figure 20 show the water vapour concentration. After 60 s the oxygen volume concentration is reduced to approximately 10 % (as compared to the ambient 21 % in the lower part of the apartment, before the cutting extinguisher was triggered) 1.5 m inside of the window. The oxygen reduction is due to the vaporization of water and

the combustion of the fire. After 60 s the water vapour volume concentration has increased from a few percent to approximately 40 %. If oxygen reduction effects of the fire itself are excluded, the oxygen concentration in the room would be less than 13 % due to the production of water vapour. The missing 3 % points can reasonable be attributed to the oxygen consumption of the fire. The gas concentrations are homogenous, which is a sign of an efficient stirring in the room due to the high velocity of the injected spray.

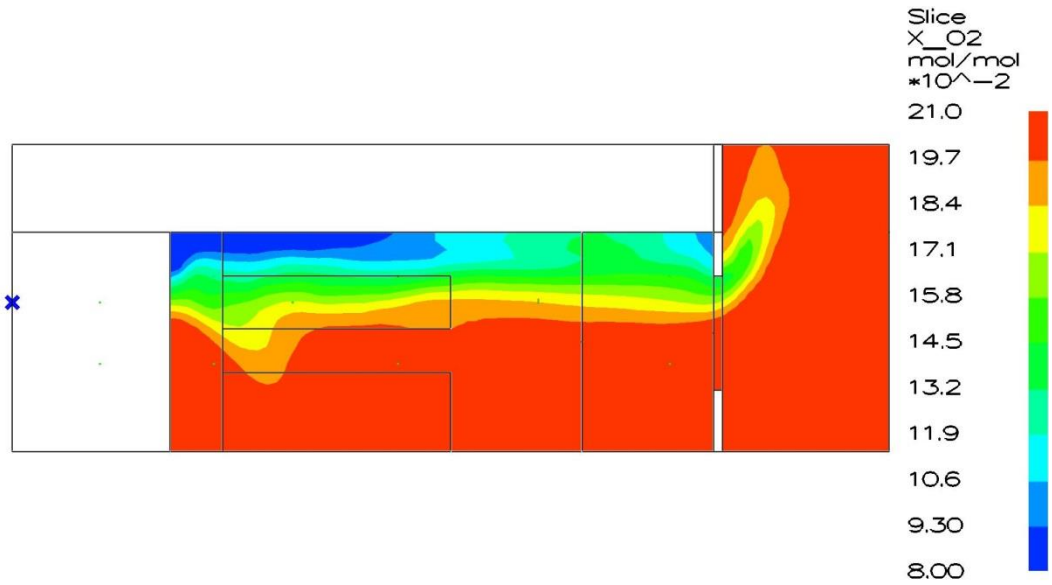

Figure 17: Oxygen volume concentration in Plane A in the apartment right before the Cutting extinguisher is simulated. The field is averaged over 10 s.

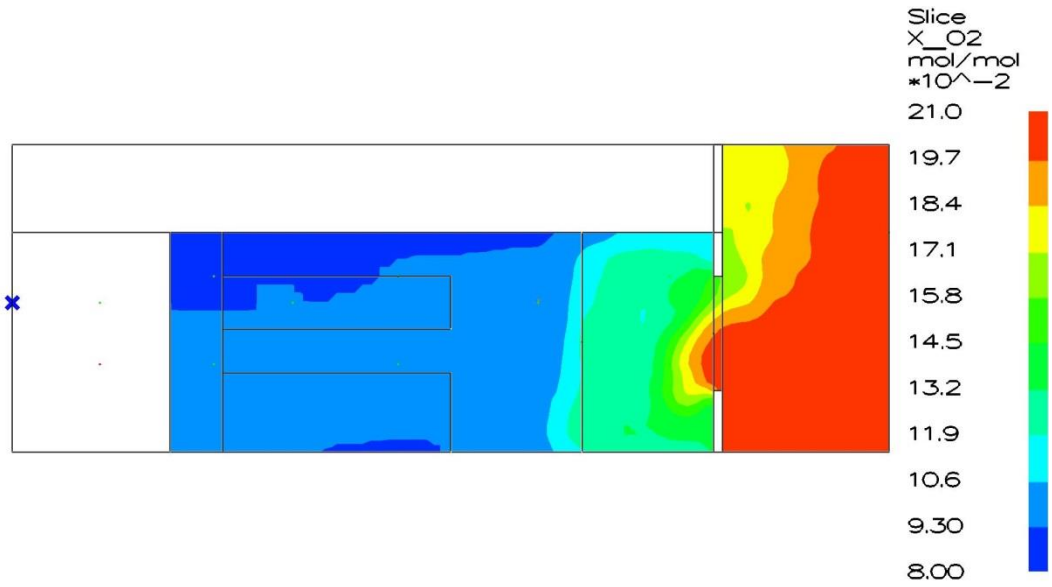

Figure 18: Oxygen volume concentration in Plane A in the apartment after 60 s use of the Cutting extinguisher. The field is averaged over 10 s.

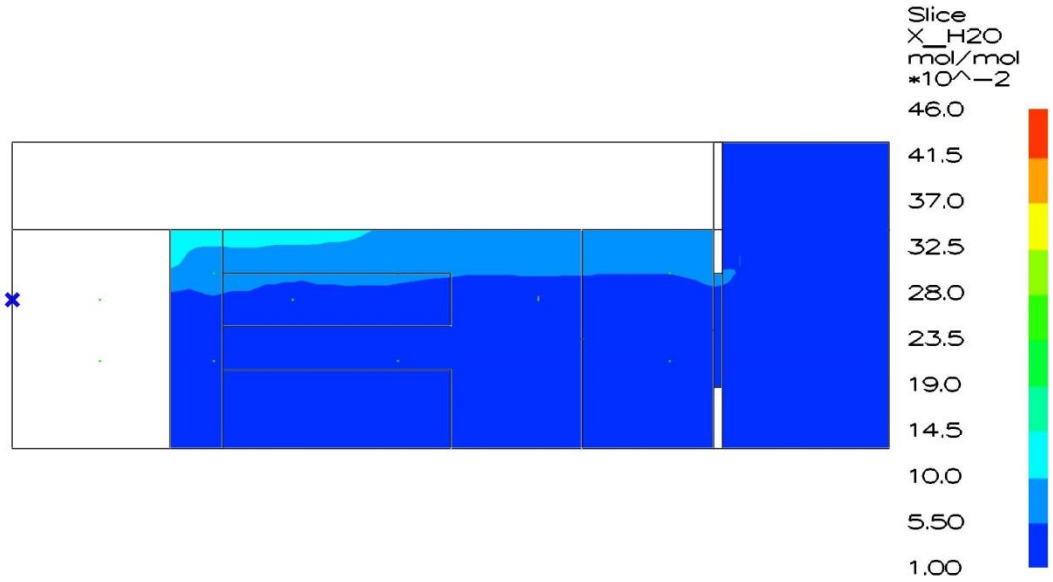

Figure 19: Water vapour volume concentration in Plane A right before the Cutting extinguisher is simulated. The field is averaged over 10 s.

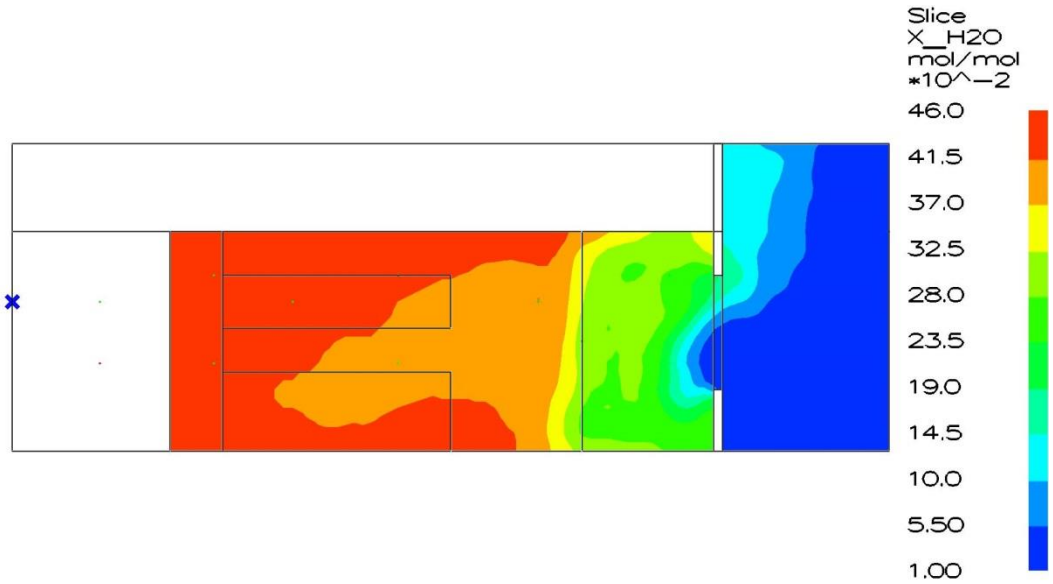

Figure 20: Water vapour volume concentration in Plane A after 60 s use of the Cutting extinguisher. The field is averaged over 10 s.

4.2 Living room

The simulated living room is a partly ventilated 54 m^2 rectangular room with no obstructions and a ceiling height of 2.8 m. All walls in the simulation are made of 3 mm steel, 50 mm isolation, and an additional 3 mm of steel. There are four ventilation holes in the living room. One 0.7 m^2 window, one 1.89 m^2 door, and two 0.55 m^2 vents close to the floor, see Figure 21. The reason for the two vents and the wall materials is to have an identical geometry to a test facility where some validation test described in Appendix B were done.

A heat source of 4 MW is placed on the floor seen in Figure 22 to Figure 23. The living room is heated long enough for the temperature profile in the gas to reach a steady state before the Cutting extinguisher is started. The heat source is turned off at the same time as the Cutting extinguisher starts in order to facilitate a comparison between the simulations and the validation tests described in Appendix B.

The cutting extinguisher is placed 1.7 m above the ground and is aimed towards the middle of the room.

Note that droplets impacting the floor disappear from the computational domain.

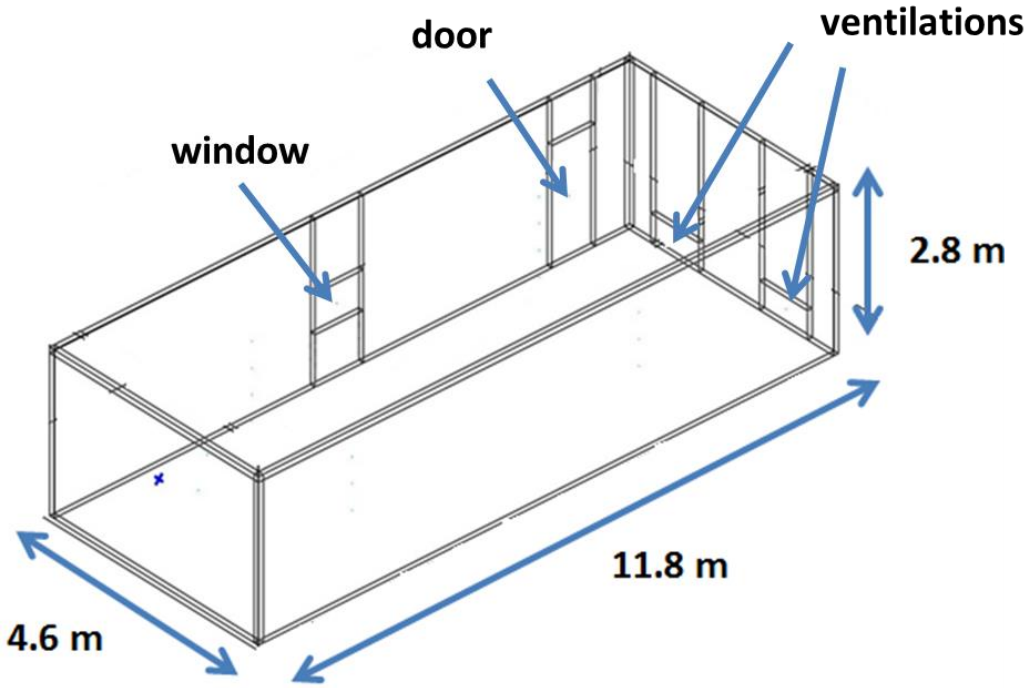

Figure 21: The geometry of the living room in FDS. The blue cross is the position for the Cutting extinguisher.

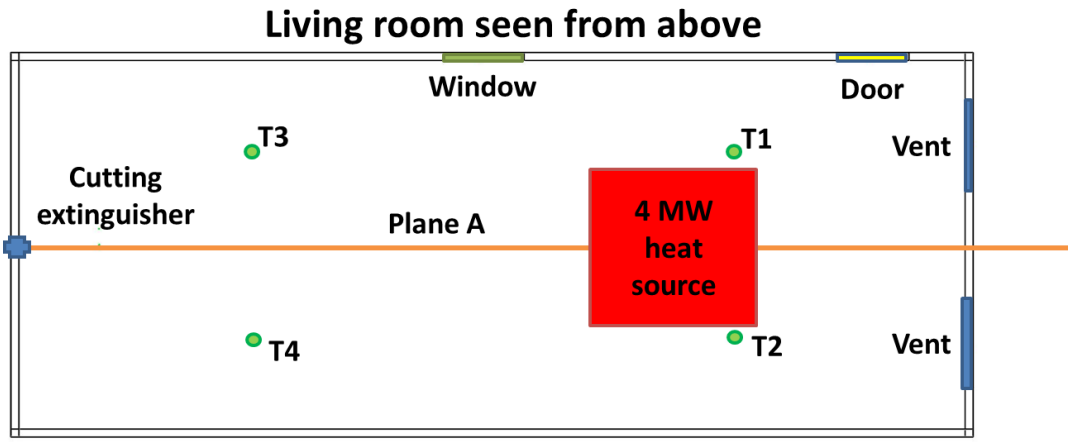

Figure 22: The geometry of the living room in FDS seen from above. T1 to T4 are thermocouple trees of five thermocouples each.

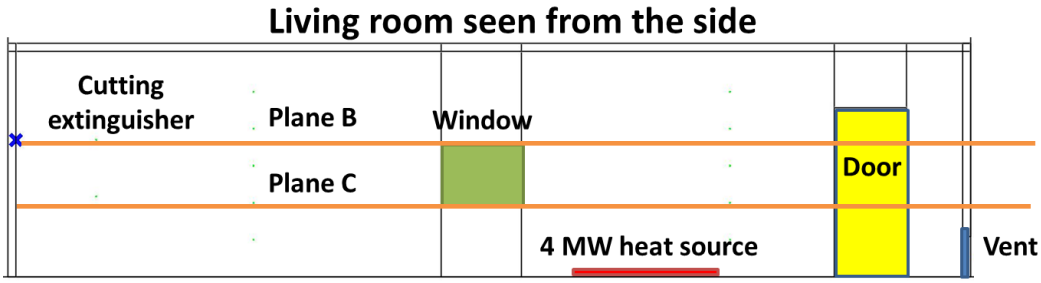

Figure 23: The geometry of the living room in FDS seen from the side.

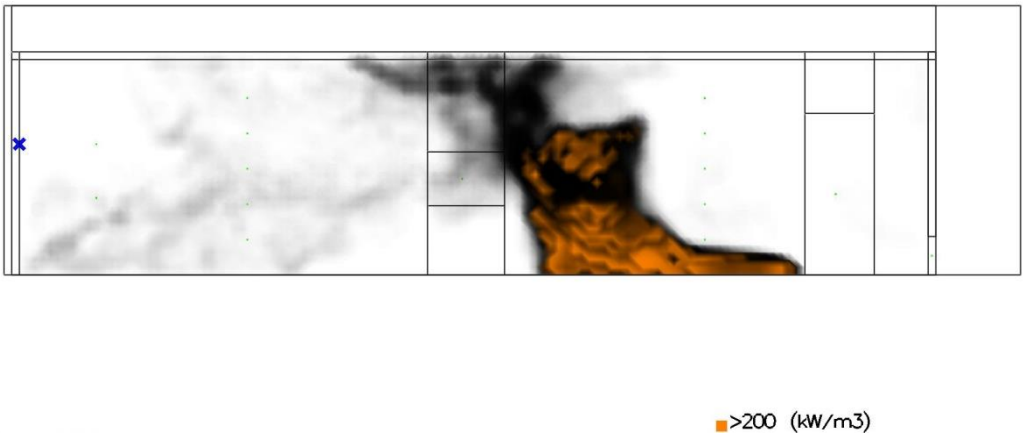

Figure 24: A picture of the heat source.

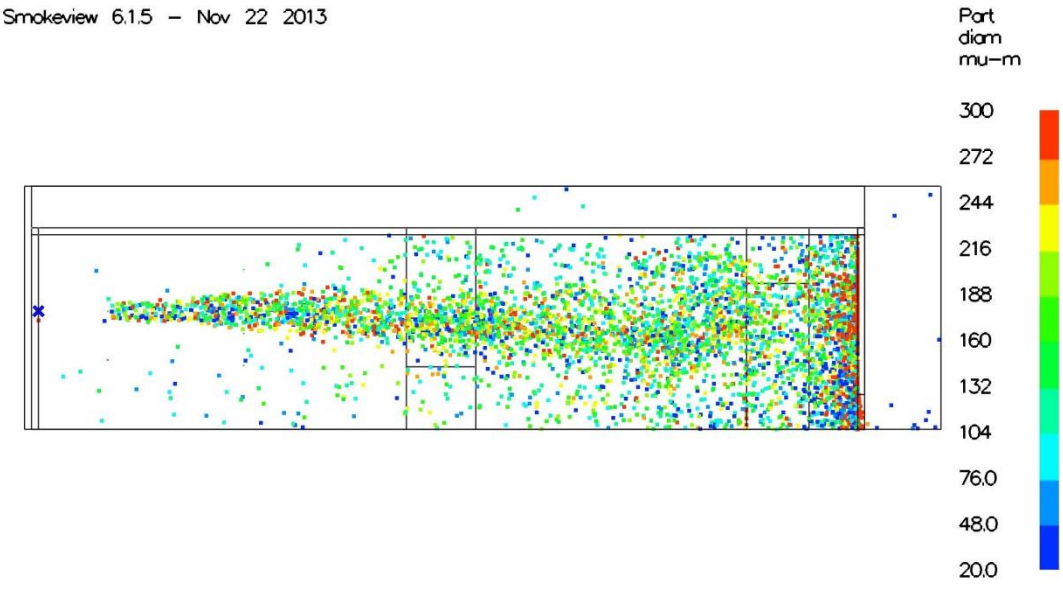

Figure 25: Spray of the nominal Cutting extinguisher with a d_{32} of 162 µm in FDS. The colour shows the particle diameter. Note that the size distribution seen in the figure is different than it would have been in a cold space since a large amount of the smaller droplets have vaporized.

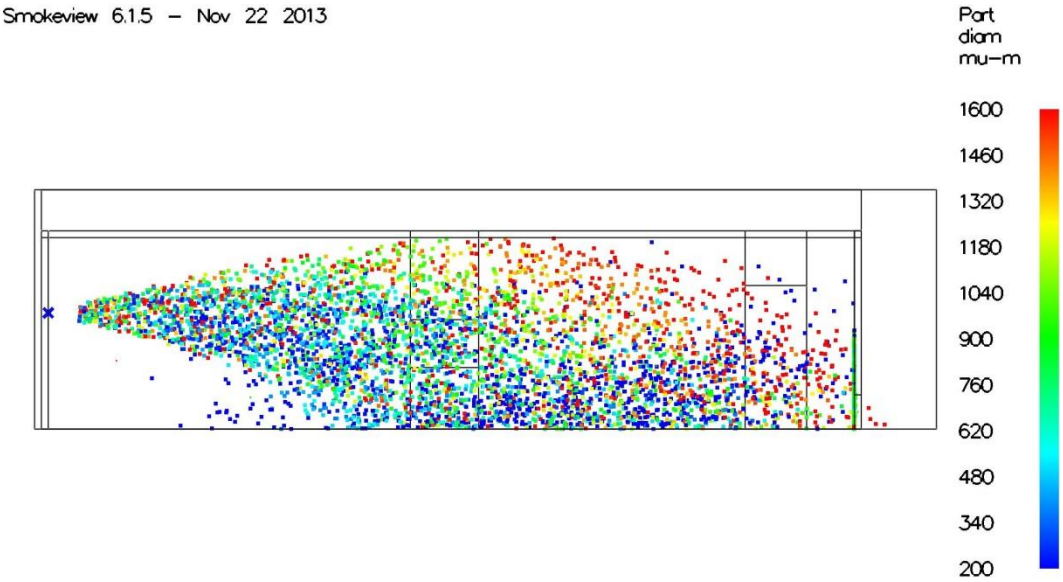

Figure 26: Spray of the enhanced low pressure system with a d_{32} of 1000 µm in FDS. The colour shows the particle diameter. Note that the size distribution seen in the figure is different than it would have been in a cold space some of the smaller droplets have vaporized

4.2.1 **Stirring**

In Figure 27 to Figure 29 vector fields are shown describing the gas transport in Plane A, B, and C for the nominal Cutting extinguisher and for the enhanced low pressure system in Figure 30 to Figure 32. The magnitude of the velocity is described by the colour of the vector. The vector field have been averaged over 30 s between 45 and 75 s after the injection of water mist started. The vector field will change slightly during the 150 s the spray was simulated, which is not presented here. The fields look similar for the two systems, but with higher gas velocities for the Cutting extinguisher.

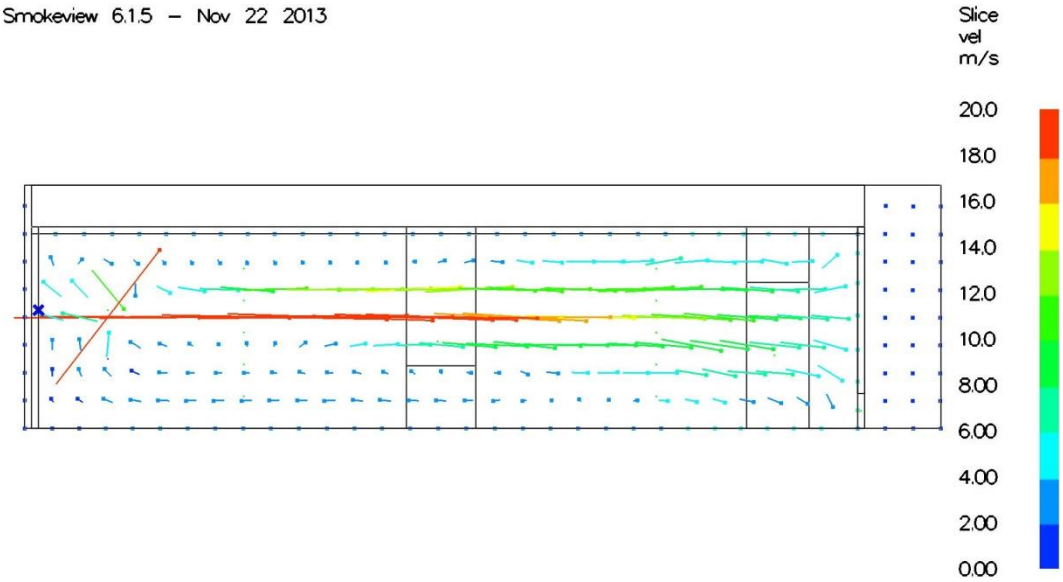

Figure 27: Velocity vectors seen in Plane A, when the Cutting extinguisher is used, to describe the gas transport in the living room. The vector field is averaged over 30 s.

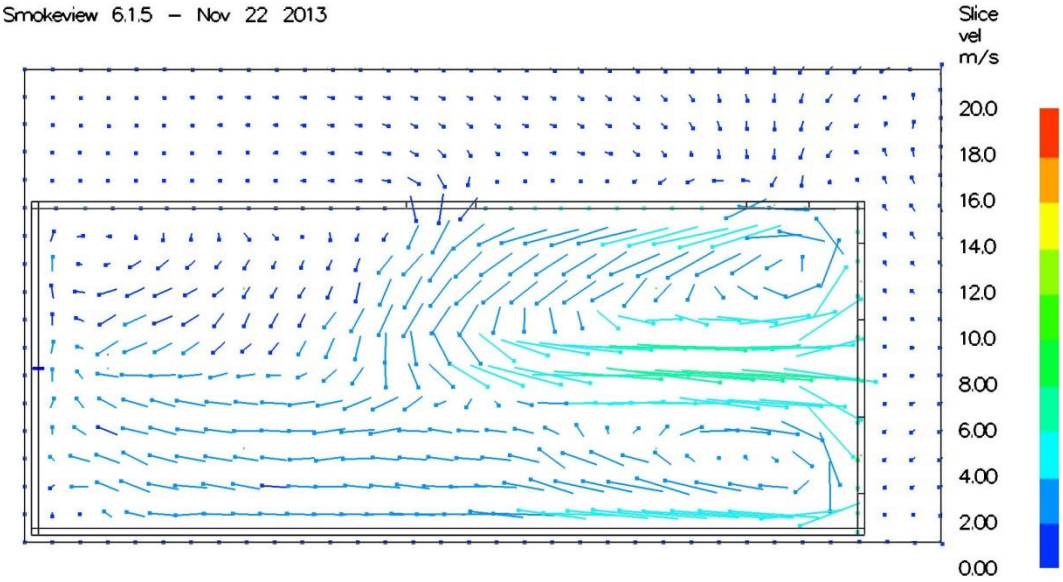

Figure 28: Velocity vectors seen in Plane C, when the Cutting extinguisher is used, to describe the gas transport in the living room. The vector field is averaged over 30 s.

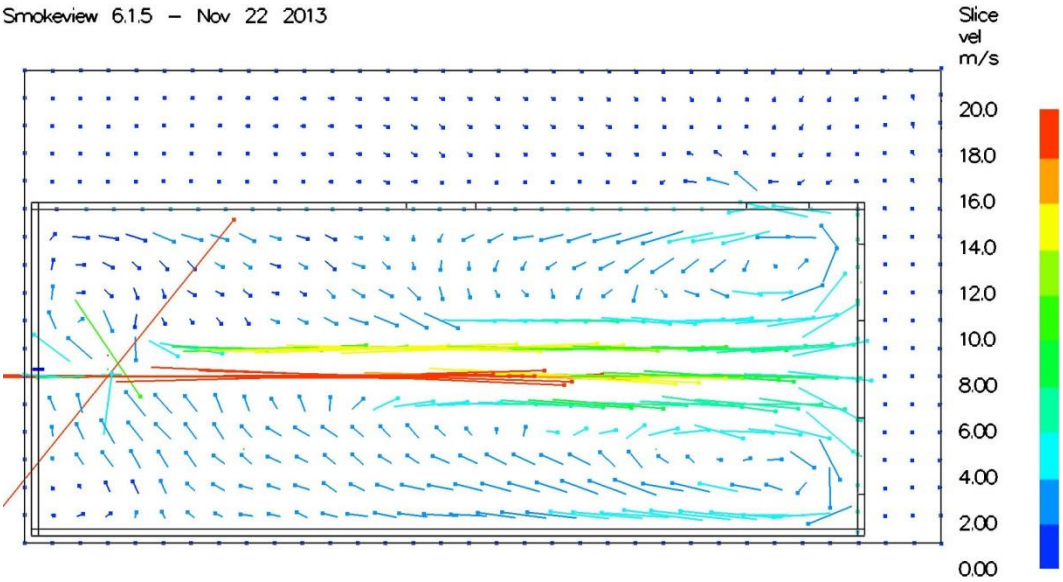

Figure 29: Velocity vectors seen in Plane B, when the Cutting extinguisher is used, to describe the gas transport in the living room. The vector field is averaged over 30 s.

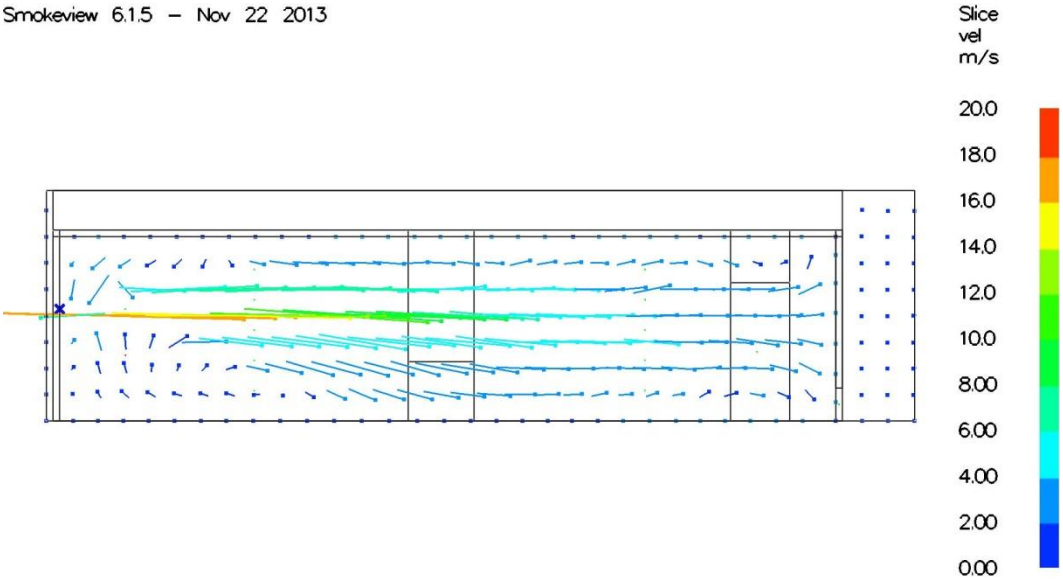

Figure 30: Velocity vectors seen in Plane A, when the enhanced low pressure system is used, to describe the gas transport in the living room. The vector field is averaged over 30 s.

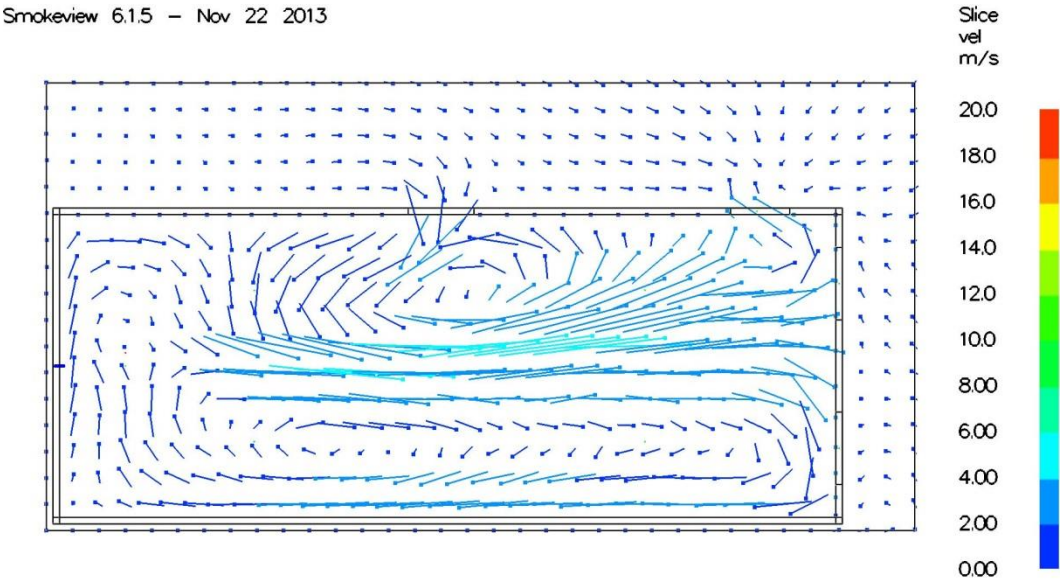

Figure 31: Velocity vectors seen in Plane C, when the enhanced low pressure system is used, to describe the gas transport in the living room. The vector field is averaged over 30 s.

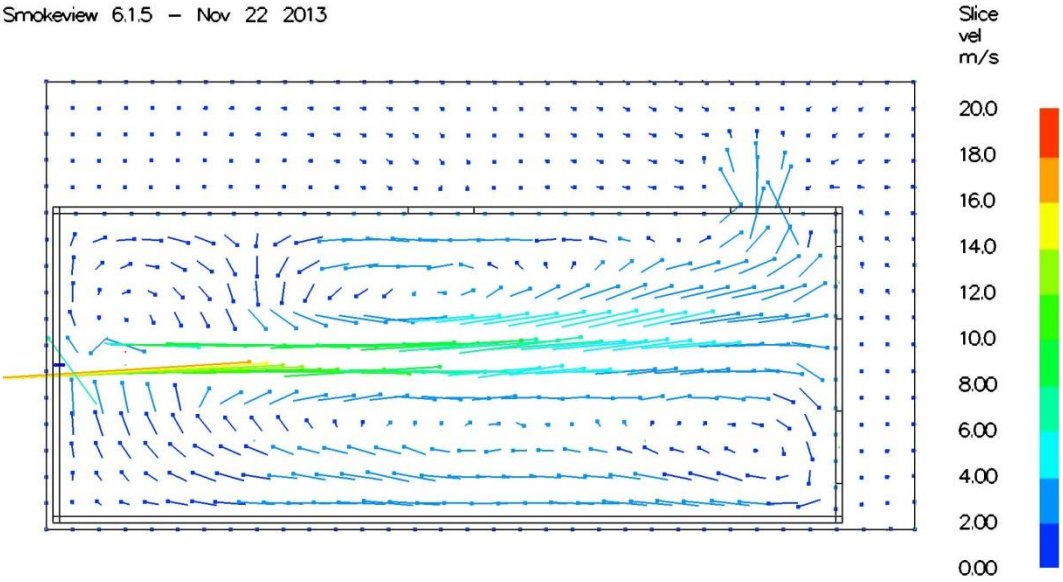

Figure 32: Velocity vectors seen in Plane B, when the enhanced low pressure system is used, to describe the gas transport in the living room. The vector field is averaged over 30 s.

4.2.2 **Gas cooling**

In these cases there are two contributing factors to the oxygen reduction of a potential fire, the oxygen consumption of the combustion process and the dilution of the gases by adding water vapour. A water mist system will affect the latter, so it is logical to study the water vapour concentrations rather than the oxygen concentrations.

Figure 33 to Figure 35 show the temperature reduction due to 10 s and 60 s use of the Cutting extinguisher in the living room. The average gas temperature of 20 positions, seen in Figure 22, drops from 470 °C to 240 °C after the first 10 s use of the Cutting extinguisher. After 60 s the average temperature had dropped further to 140 °C. For the enhanced low pressure system the average temperature was 290 °C after 10 s and 230 °C after 60 s. This should be compared to the temperatures when no water is used at all, and only the HRR is turned off. In that case the temperature drops from 470°C to 350°C after 10 s and 230 °C after 60 s. In other words the average temperature for these 20 positions after 60 s is the same for the enhanced low pressure system as if there was no water at all according to the simulations. A plausible explanation for this is that when we measure an average temperature of 230 °C, the local temperature close to the spray of the enhanced low pressure system is too low to even vaporize the smallest droplets in the spray.

In Figure 36 to Figure 38 sensitivity analyses of the average gas temperature of 10 positions in T3 and T4, seen in Figure 22, over time are presented. These positions are purposely chosen in such a way that gas cooling at these points is challenging since they are located near the injected narrow spray. Figure 36 illustrates the impact on gas cooling for different d_{32}, Figure 37 illustrates the sensitivity to the momentum of the spray, and Figure 38 finally illustrates the effect of two entirely different sprays: the Cutting extinguisher and the enhanced low pressure system.

The minor changes in temperature when the d_{32} is modified are difficult to quantify due to the relatively large fluctuations. However, the general trend in Figure 36 is that the cooling effect is more efficient with smaller droplets than with larger droplets. The simulations shows that droplets in the range from 65 – 110 % of the nominal d_{32} have the same gas cooling effect down to approximately 250 °C. It is first when the room is so cold that we measure an average temperature of 250 °C that it can be seen that smaller droplets will work more efficiently.

With minor changes of the spray momentum a quantification of differences in temperature is not straightforward although the trend seems to be that higher momentum gives a more efficient cooling of gases, as seen in Figure 37. When a more drastic change of momentum is made, down to 31 % of the nominal value, the simulation clearly shows that the cooling effect is affected negatively.

It is interesting to notice that according to the simulation results, no difference in gas temperature can be observed for T3 and T4 when the enhanced low pressure system is used as compared to no extinguishing water at all, see Figure 38.

By using data from Figure 47 and assuming that all water impinging on surfaces do not contribute to any cooling and the rest vaporises and remains at a certain temperature, it is possible to calculate the amount of energy absorbed by the vaporised sprays produced by the Cutting extinguisher and the enhanced low pressure system over a period of 60 s. Assuming that vapour remains at a temperature of 100 °C the calculated values are 1.8 and 0.44 MW, respectively, and for 300 °C the values are 2.1 MW and 0.5 MW for the cutting extinguisher and the enhanced low pressure system, respectively.

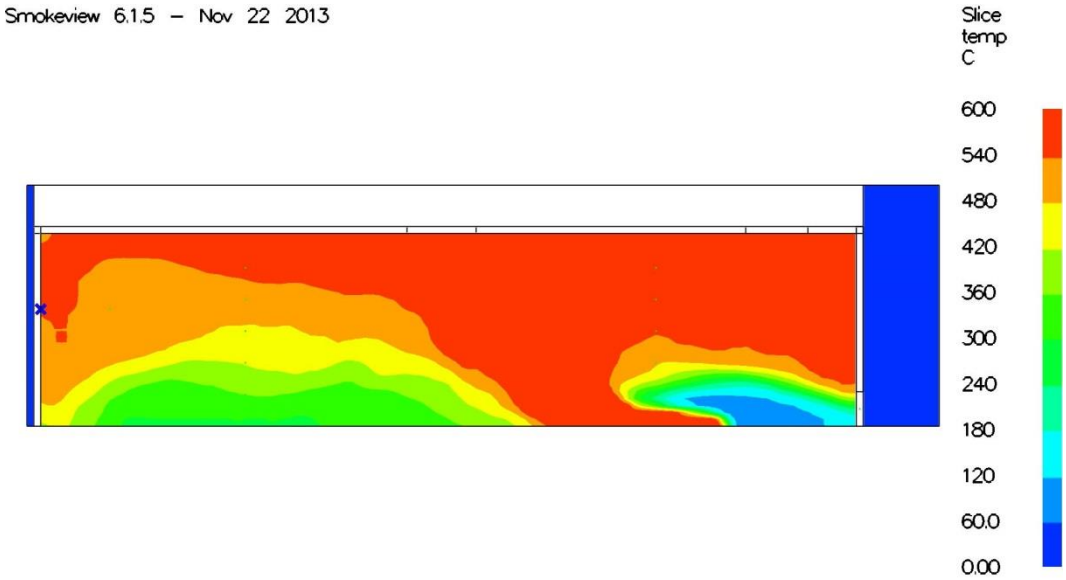

Figure 33: Temperature field in Plane A in the living room right before any spray is injected. The field is averaged over 10 s.

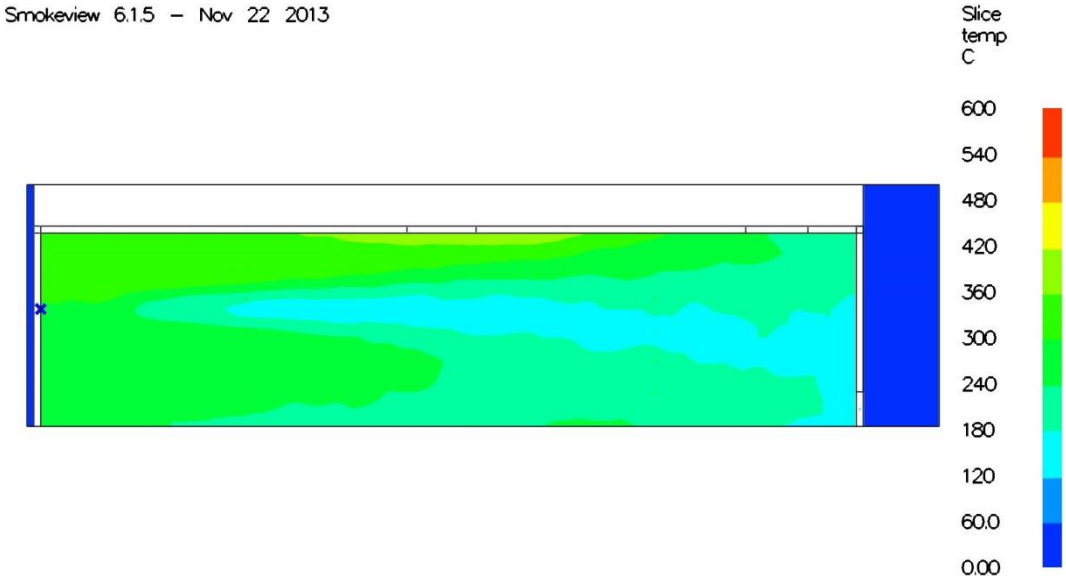

Figure 34: Temperature field in Plane A in the living room after 10 s use of the Cutting extinguisher. The field is averaged over 10 s.

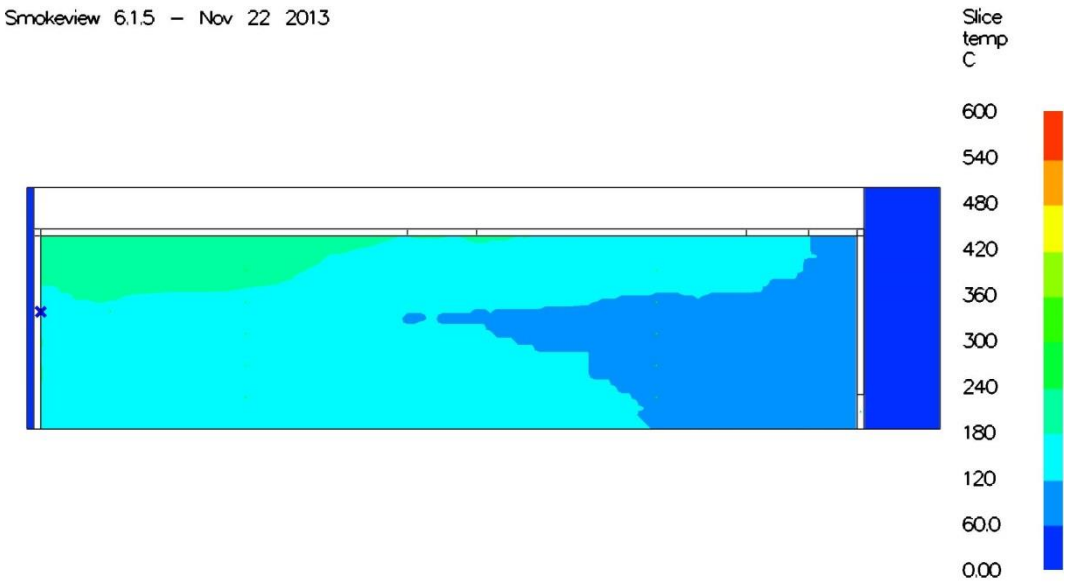

Figure 35: Temperature field in Plane A in the living room after 60 s use of the Cutting extinguisher. The field is averaged over 10 s.

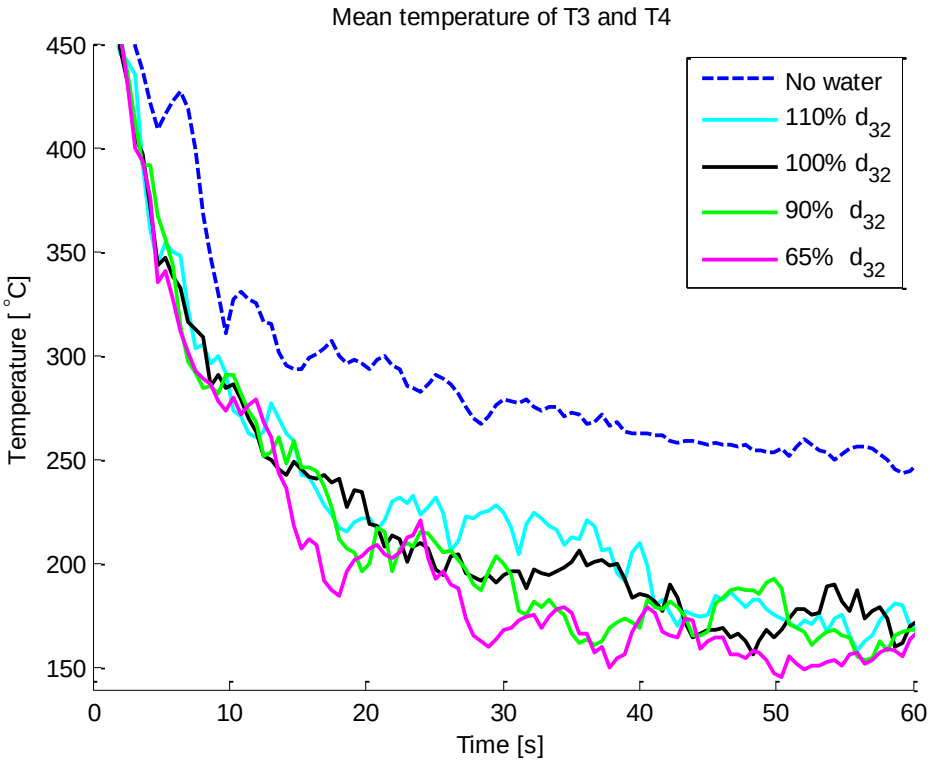

Figure 36: Sensitivity analysis of the mean temperature of T3 and T4 over time. Only d_{32} is changed while flow rate and momentum are kept constant. The sensitivity analysis is compared to a scenario where no water was used for gas cooling.

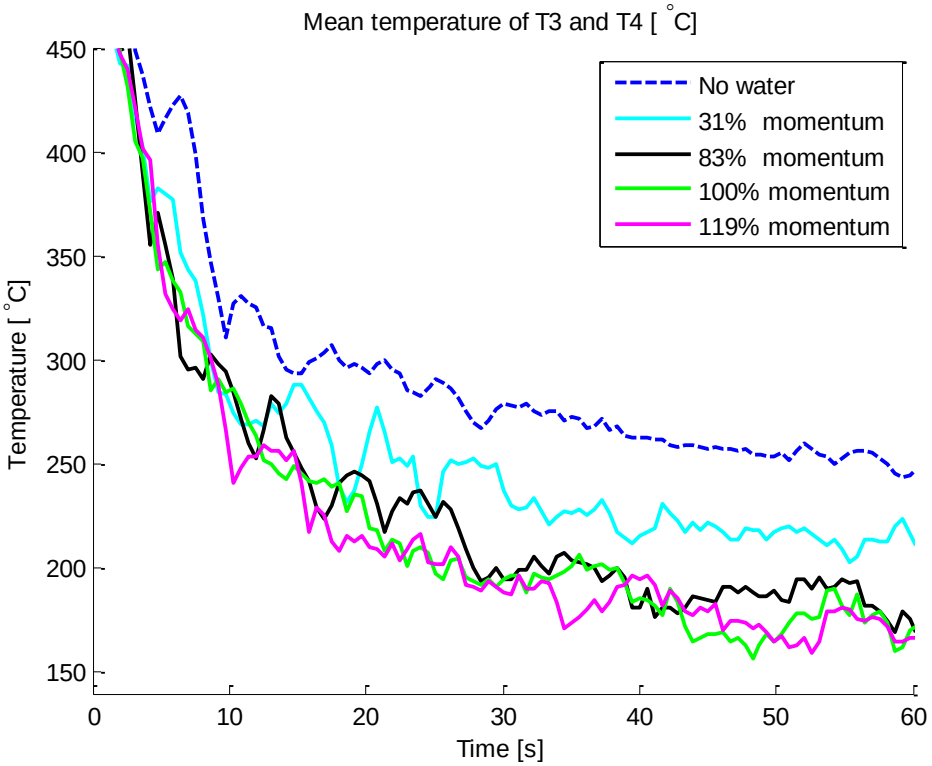

Figure 37: Sensitivity analysis of the mean temperature of T3 and T4 over time. Only the momentum if the spray is changed while flow rate and the droplet size distribution are kept constant. The sensitivity analysis is compared to a scenario where no water was used for gas cooling.

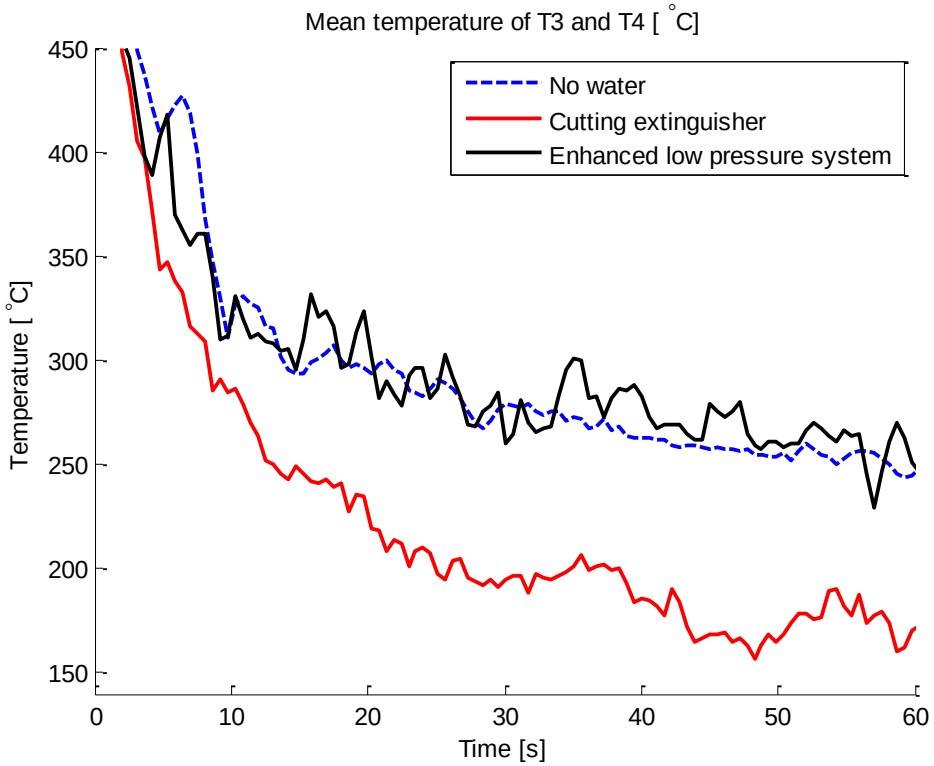

Figure 38: Comparison of gas cooling for the nominal Cutting extinguisher and the enhanced low pressure system. In T3 and T4, we cannot see any difference in gas temperature with or without the use of the enhanced low pressure system according to the simulations.

4.2.3 Oxygen reduction

In these cases there are two contributing factors to the oxygen reduction of a potential fire, the consumption of oxygen by combustion and the dilution of the surrounding air by adding water vapour. A water mist system will affect the latter, so we will look at the water vapour concentrations rather than the oxygen concentrations.

In Figure 39 to Figure 41 water vapour concentration is shown for Plane A, see Figure 22. Figure 42 illustrates how the average water vapour concentration increases from approximately 7 % to 32 % in the first 60 s after start of injection using the nominal Cutting extinguisher. If 32 % water vapour is mixed with normal air (with 21 % oxygen) the oxygen concentration would drop to 14 %. If a fire is present, additional oxygen would be consumed. It should be noted that during the 60 s of simulation the living room continuously becomes colder which makes the vaporization rate of the mist slower. Therefore, with a continued HRR, the vapour concentration would become even higher than 32 %. The oxygen concentration would be lower than 14 % both due to replacement by water vapour and due to continued oxygen consumption by the fire.

In Figure 42 a sensitivity analysis of the effect on water vapour concentration is presented with small changes the d_{32} of the nominal Cutting extinguisher. There is no change in vapour concentration if droplets vary 10 % in size. When the droplet size is

reduced to 65%, it can be seen that the vapour concentration is the same during the initial 20 s as for the nominal Cutting Extinguisher. Thereafter the vapour concentration becomes higher for the 65% droplet size as compared to the nominal cutting extinguisher. This means that the effect of smaller droplets is larger at lower temperatures since for higher temperatures the droplets are vaporized regardless of diameter, within the range of the performed sensitivity analysis After 20 s the average temperature in the living room is 200~250 °C.

Figure 43 depicts a sensitivity analysis on how changing the momentum of the spray influences the water vapour concentration. Note that the highest concentration after 60 s is reached for a jet having 83 % of the nominal momentum. A higher momentum results in an increased stirring of the gases and a more homogenous temperature, leading to a higher temperature close to the droplets and faster vaporisation. It also leads to a shorter time before the droplets will hit the wall, and thereby become ineffective in these simulations. This latter effect is first noticeable when the temperature in the room reduces to approximately 200 °C, as seen in Figure 37 and Figure 46. A further effect is that a larger momentum and increased stirring results in an enhanced air exchange through the ventilations, which results in more water vapour transferred to the adjacent environment. This can be seen by comparing Figure 43 and Figure 46.

In Figure 44 a comparison of the water vapour concentration of the nominal Cutting extinguisher with the enhanced low pressure system is shown. After 60 s the enhanced low pressure system peaks at approximately 15 % and the Cutting extinguisher at above 30 %. Note that since droplets that collide with the floor will disappear in FDS, the enhanced low pressure system will not be able to cool surfaces. If the droplets would not disappear, some of them would vaporize and probably slightly increase the water vapour concentration.

Figure 45 to Figure 47 show the accumulated mass of water on the walls and floor. This gives an indication of the vaporisation rate. For this scenario approximately 30 % of the water impinges a surface during the first minute of operation for the nominal Cutting extinguisher. It can be seen that even small changes in d_{32} will affect the vaporisation rate.

The use of the enhanced low pressure system results in larger amounts of water impacting the surfaces than the cutting extinguisher. After one minute almost 90 of 100 litres impinge the wall or the floor for the former system, whereas for the cutting extinguisher only 18 of the 60 litres impact on the aforementioned surfaces.

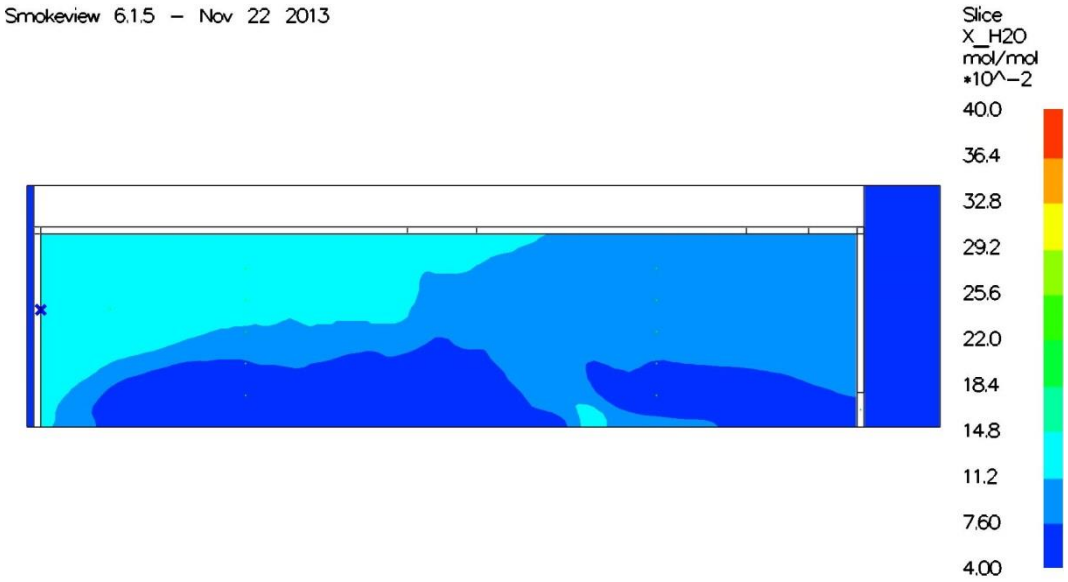

Figure 39: Water vapour volume concentration in Plane A in the living room right before the Cutting extinguisher is simulated. The field is averaged over 10 s.

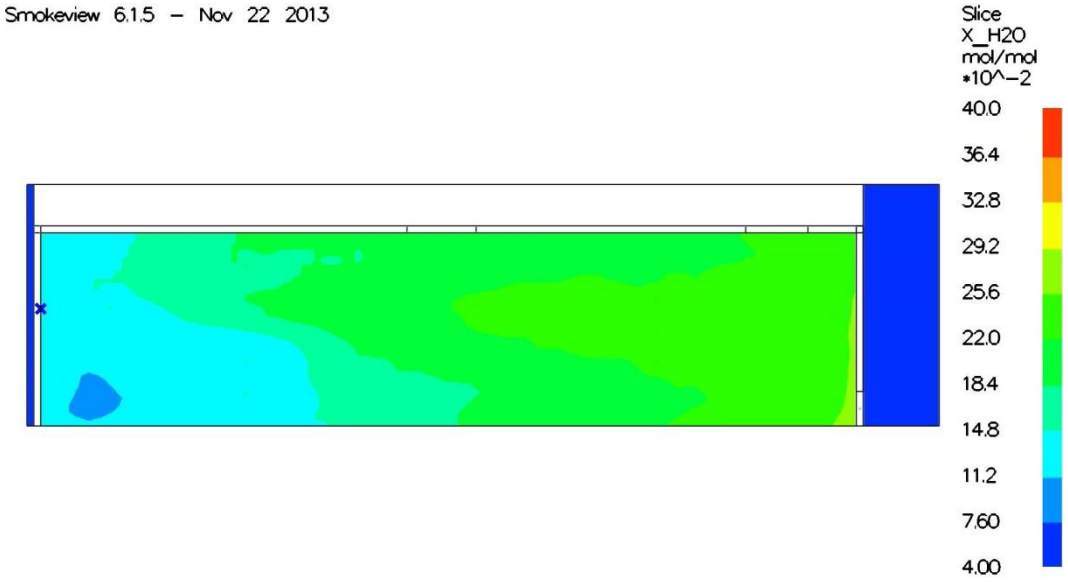

Figure 40: Oxygen volume concentration in Plane A in the living room after 10 s use of the Cutting extinguisher. The field is averaged over 10 s.

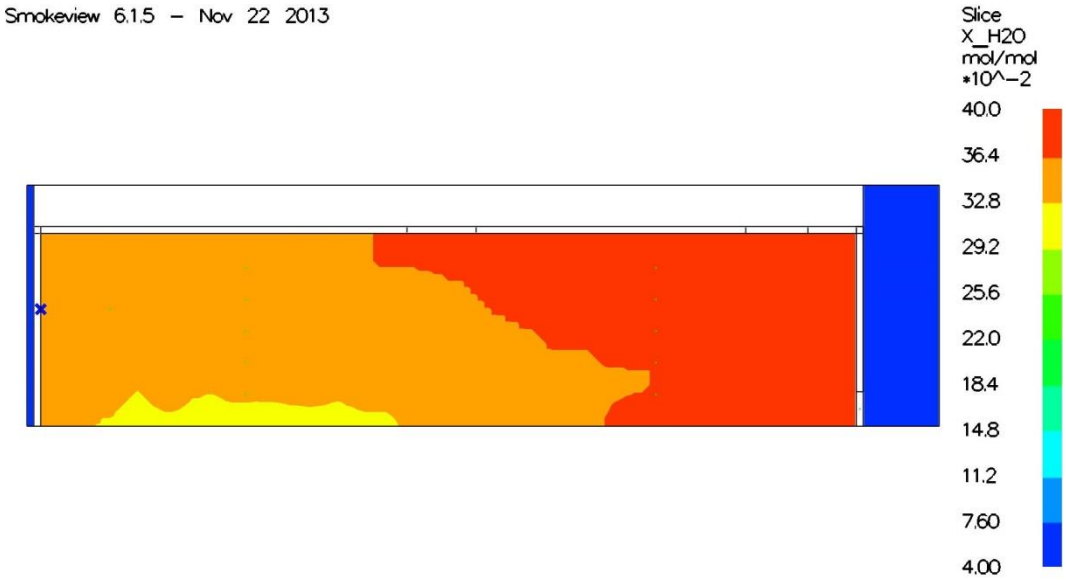

Figure 41: Oxygen volume concentration in Plane A in the living room after 60 s use of the Cutting extinguisher. The field is averaged over 10 s.

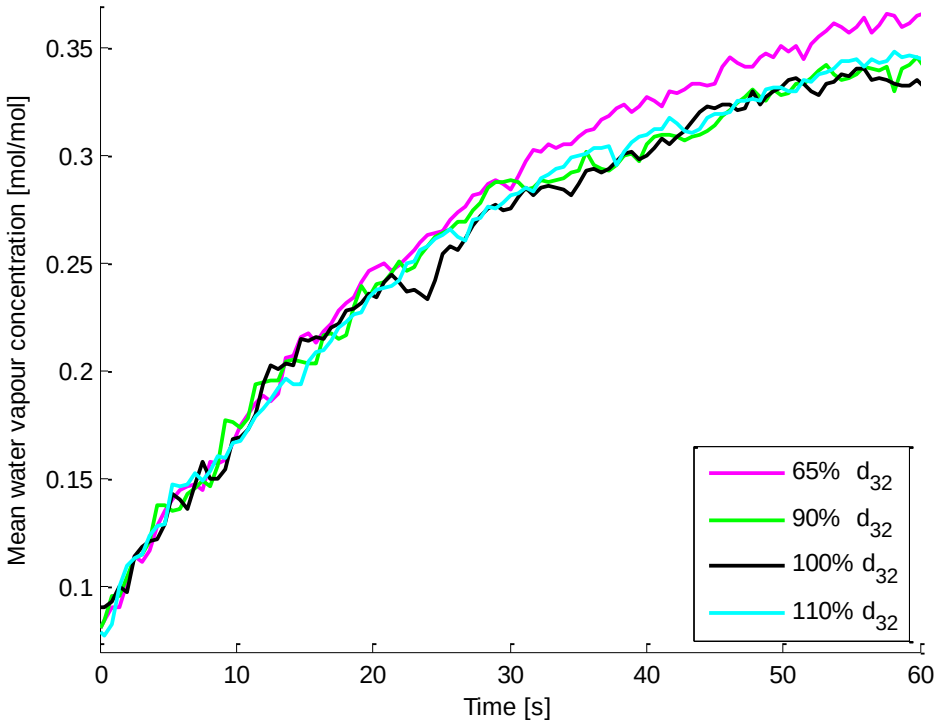

Figure 42: Sensitivity analysis of the mean water vapour concentration over time. Only d_{32} is changed while flow rate and momentum are kept constant. It is first after 20 s the 65% d_{32} starts to differ from the other results. This shows that the smaller droplets will make a larger difference at lower temperatures.

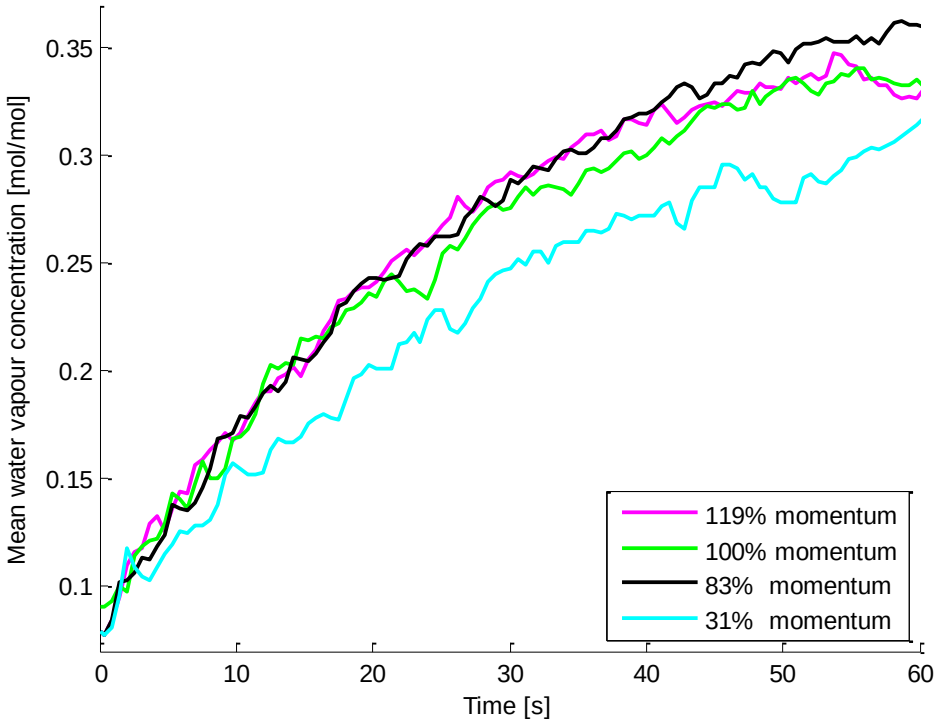

Figure 43: Sensitivity analysis of the mean water vapour concentration over time. Only the momentum of the flow is varied while flow rate and d_{32} are kept constant. After 30 s the most effective spray is the one with 83% of the nominal momentum.

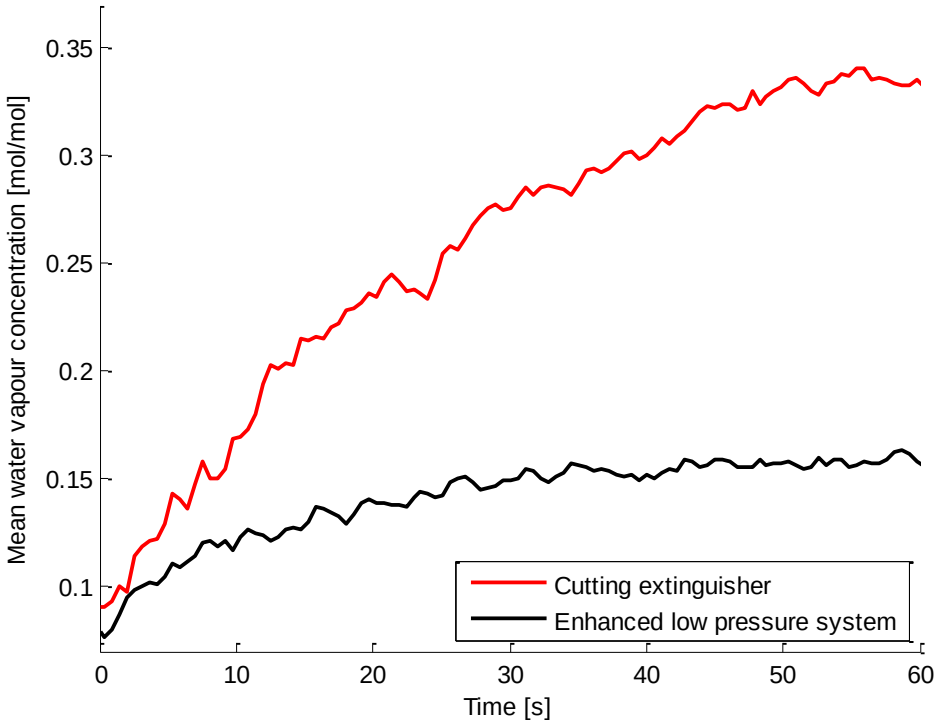

Figure 44: Comparison of water vapour concentration as function of time between the nominal Cutting extinguisher and the enhanced low pressure system.

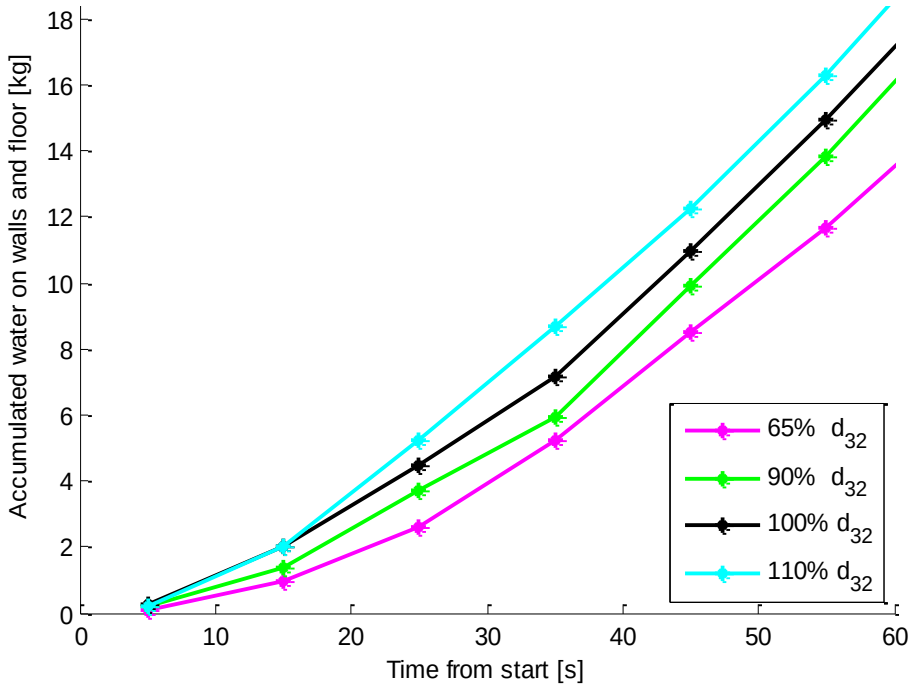

Figure 45: Accumulated water on walls and floor as a function of time. Only d_{32} is changed while flow rate and momentum are kept constant. Note that total amount of water sprayed into the living room is 60 liters during 1 minute.

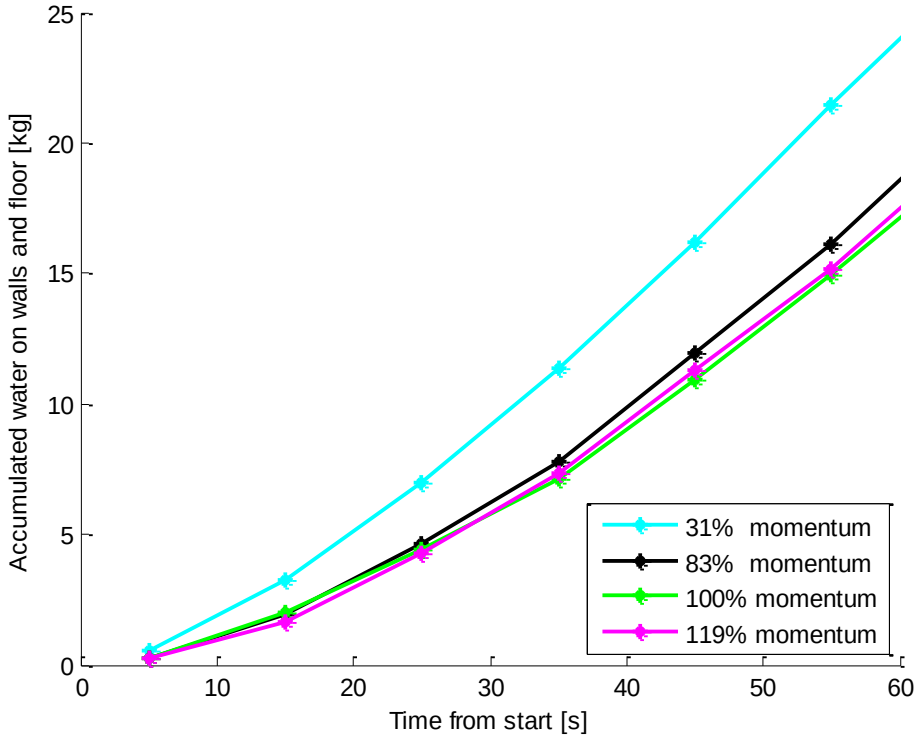

Figure 46: Accumulated water on walls and floor for sprays with different momentum. The momentum of the flow is changed while flow rate and d_{32} are kept constant. Note that total amount of water sprayed into the living room is 60 litres per minute. When the momentum is increased to 119 %, there accumulated water is more than for the nominal Cutting extinguisher after 30 s.

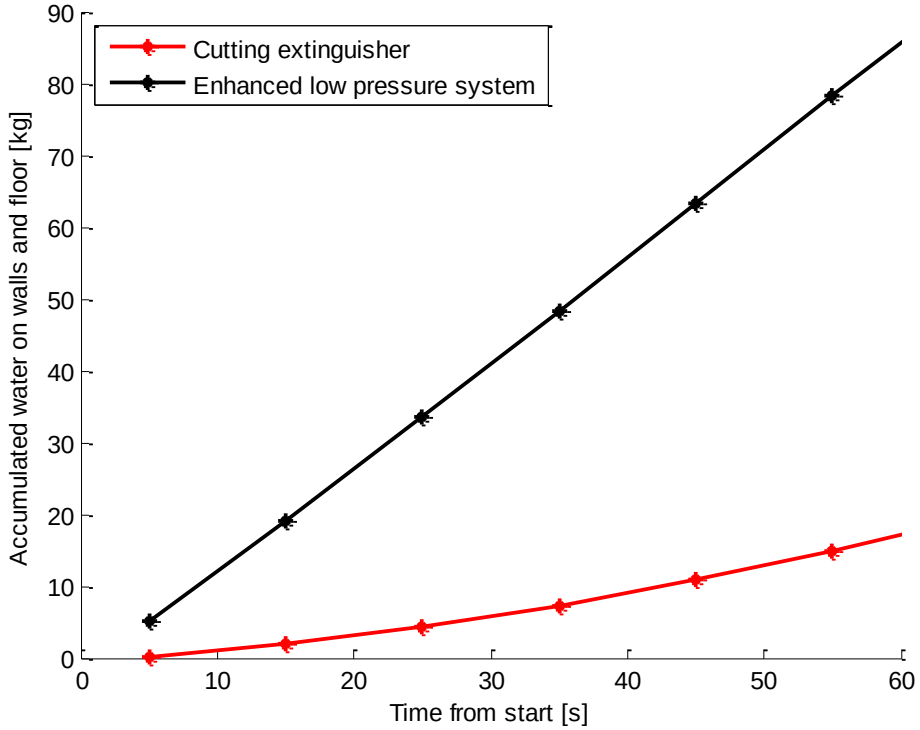

Figure 47: Accumulated water on walls and floor for the studied systems. The total amount of water sprayed into the living room is 60 and 100 litres during 1 minute for the Cutting extinguisher and the enhanced low pressure system, respectively.

4.3 Warehouse

The warehouse is a partly ventilated large room with dimensions of 17 × 6 × 5 m. The room does not have obstructions as seen in Figure 48 to Figure 50. The walls are made of 20 cm thick concrete. There is a 15 m wide and 0.5 m high window 4 m above the floor.

The warehouse is heated with an 8 MW heat source. The power is so large for this ventilation that the temperature profile is independent on where on the floor the heat source is located. Regardless of the placement of the burner, fuel is combusted only very close to the window. The power is kept constant at 8 MW during the entire simulation.

The injection location of the spray is placed 1.7 m above the ground and the axis of propagation of the spray is horizontal and placed straight forward towards the middle of the room. If the spray would have been angled slightly upwards, this would have given better effect on oxygen reduction and cooling of gases. However, the aim of this report is rather to compare different sprays and geometries than to investigate methods for firefighting.

Note that when droplets impact the floor in FDS, they will disappear from the computational domain. This will only have a small effect on the performance of the Cutting extinguisher in the simulations, since almost all water is vaporised before

impinging on a surface. For the enhanced low pressure system, however; at least 80 % of the injected water will impact the floor and have a limited contribution to oxygen reduction, surface and gas cooling.

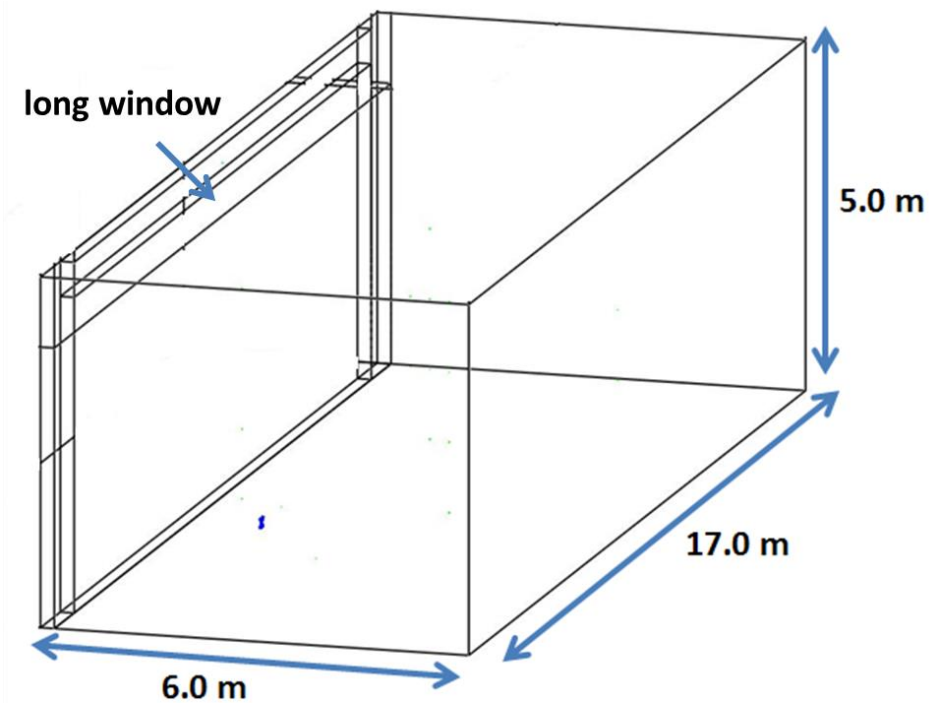

Figure 48: Geometry of the warehouse in FDS. The blue cross is the position for the Cutting extinguisher.

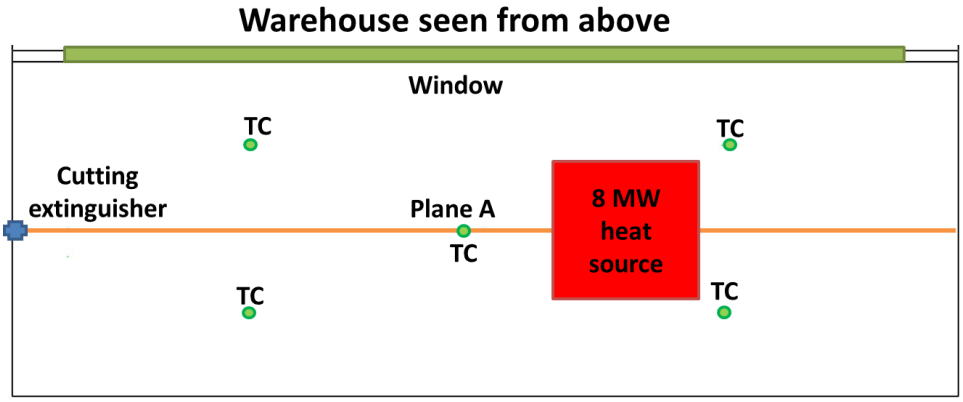

Figure 49: Geometry of the warehouse in FDS seen from above. Every TC presents a thermocouple tree with four thermocouples each at 1, 2, 3, and 4 meters above the floor.

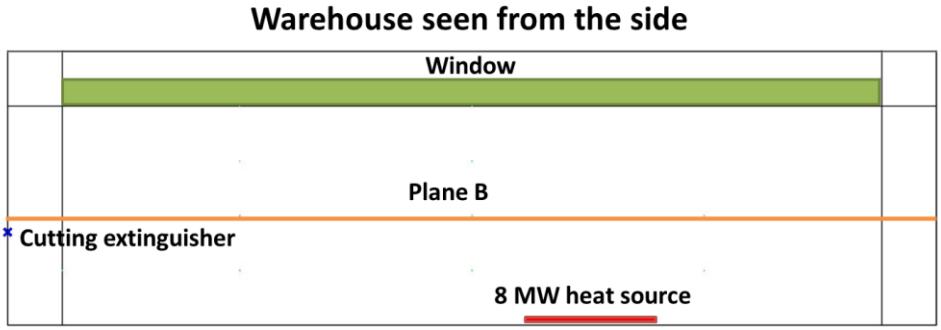

Figure 50: Geometry of the warehouse in FDS seen from the side.

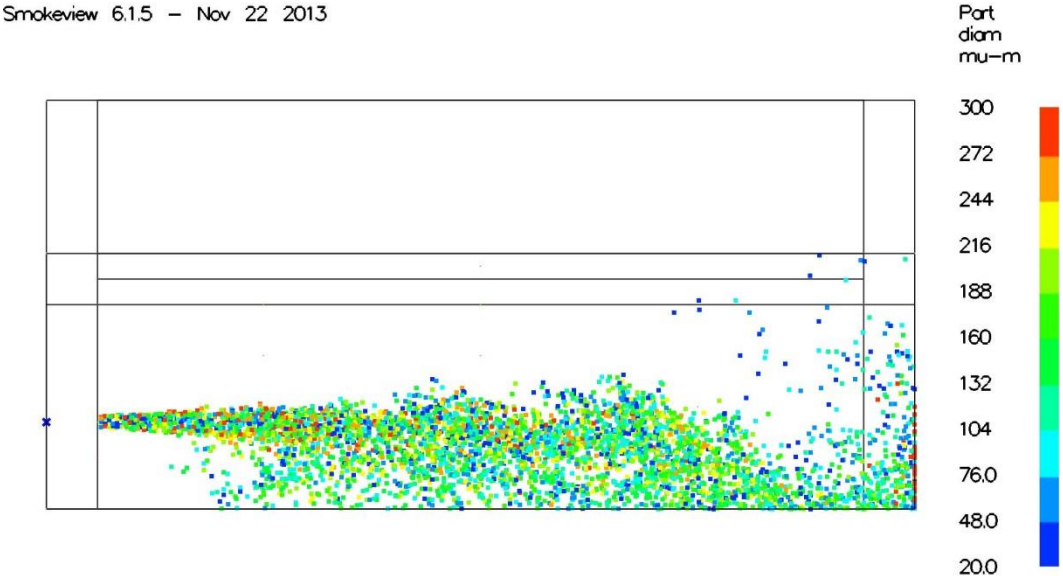

Figure 51: Spray of the nominal Cutting extinguisher with a d_{32} of 162 µm in FDS. The colour shows the particle diameter. Note that the size distribution seen in the figure is different than it would have been in a cold space since a large amount of the smaller droplets have vaporized.

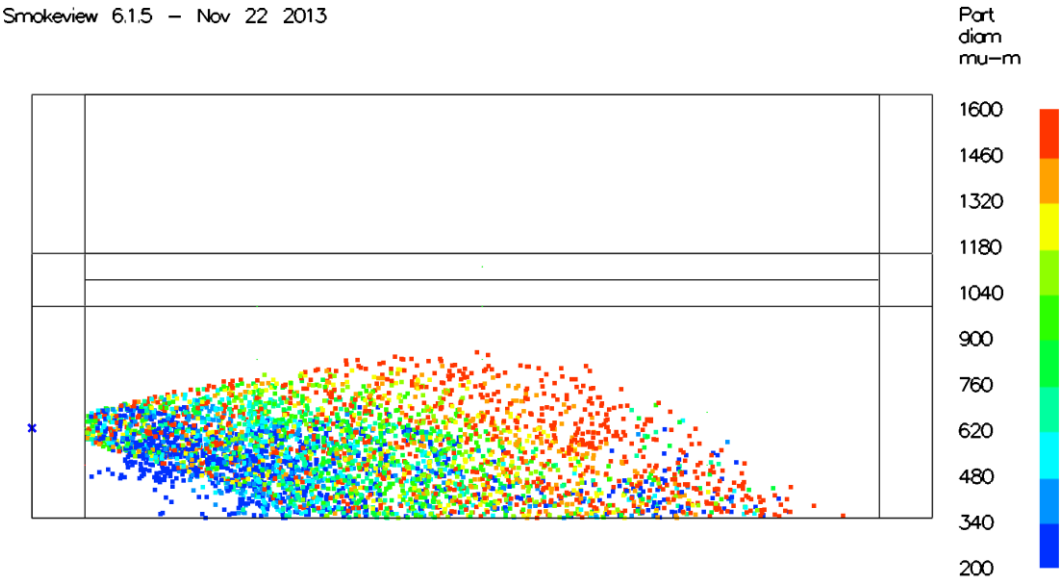

Figure 52: Spray of enhanced low pressure system in FDS. The colour shows the particle diameter. Note that the size distribution seen in the figure is different than it would have been in a cold space some of the smaller droplets have vaporized

4.3.1 **Stirring**

In Figure 53 and Figure 54 vector fields are presented describing the gas transport for the nominal Cutting extinguisher in Plane A and B, and for the enhanced low pressure system in Figure 55 and Figure 56, respectively. The magnitude of the velocity is shown in a false colour scale. The vector fields have been averaged over a period of 30 s between 100 and 130 s after the spray injection was started. The vector field will slightly change during the 150 s the spray was simulated. It can be seen that the Cutting extinguisher will have a much larger effect on the gas velocity on the opposite wall from where the spray is initialised than the enhanced low pressure system.

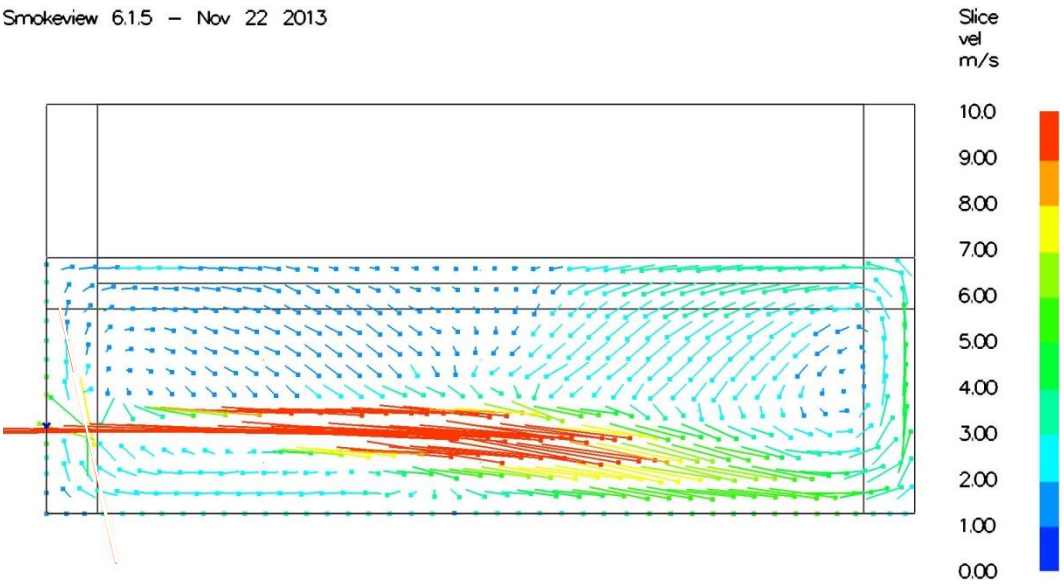

Figure 53: Velocity vectors seen in Plane A, when the Cutting extinguisher is used, to describe the gas transport in the warehouse. The vector field is averaged over 30 s.

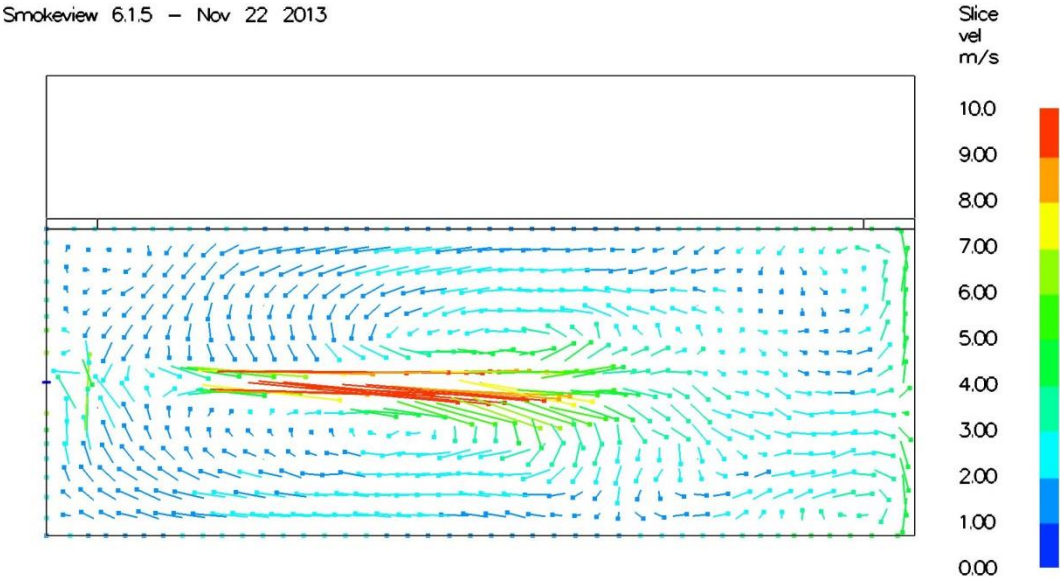

Figure 54: Velocity vectors seen in Plane B, when the Cutting extinguisher is used, to describe the gas transport in the warehouse. The vector field is averaged over 30 s.

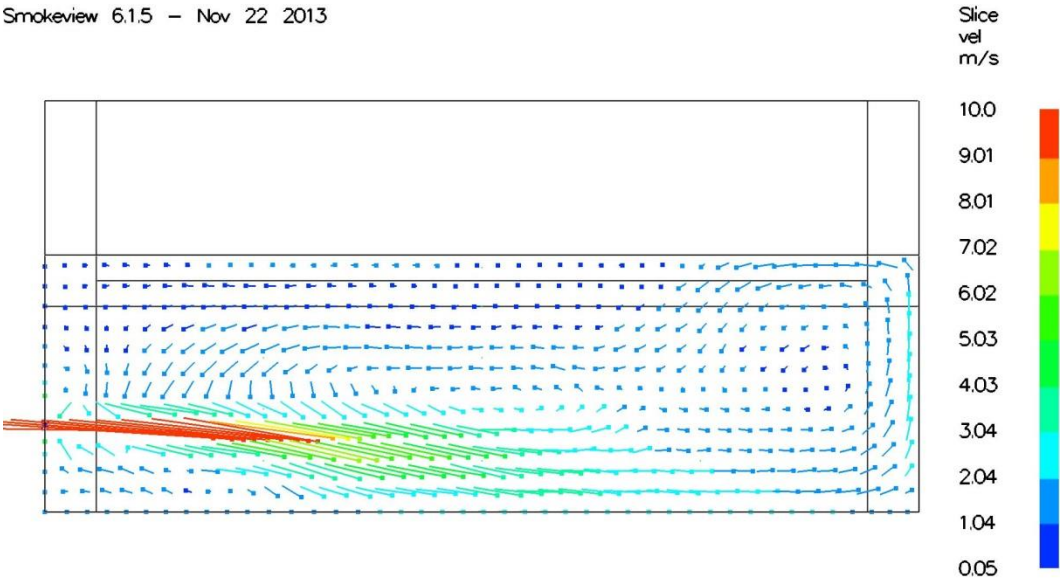

Figure 55: Velocity vectors seen in Plane A, when the enhanced low pressure system is used, to describe the gas transport in the warehouse. The vector field is averaged over 30 s.

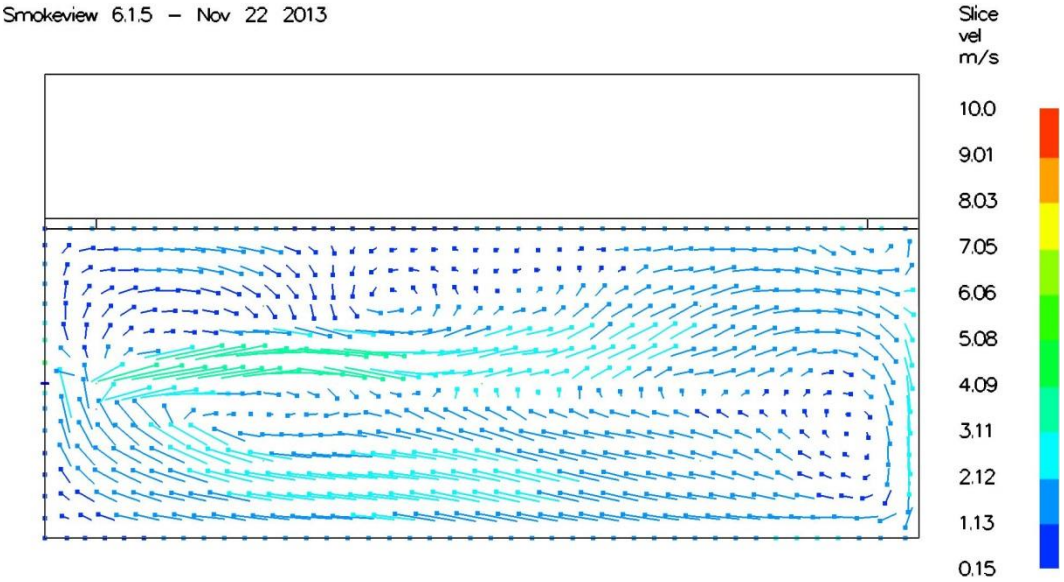

Figure 56: Velocity vectors seen in Plane B, when the enhanced low pressure system is used, to describe the gas transport in the warehouse. The vector field is averaged over 30 s.

4.3.2 **Gas cooling**

Figure 57 to Figure 59 illustrate the temperature reduction due to 0, 60, and 150 s of the action of the Cutting extinguisher, respectively. It can be observed that the length of the room makes it harder to obtain a good stirring effect and cool down the gases in the left side of the room, close to where the sprays are injected, in comparison to the room geometry. The simulated 150 s are not enough to reach a stable temperature in the warehouse.

The average gas temperature of 20 positions, seen in Figure 49, drops from 400 °C to 250 °C after 60 s, and to 210 °C after 150 s of action of the Cutting extinguisher. For the enhanced low pressure system the average temperature is 320 °C after 60 s and 300 °C after 150 s, seen in Figure 62.

Figure 60 and Figure 61 show a sensitivity analysis of the average gas temperature over time, where d_{32} and the momentum of the spray are varied separately. The small changes in temperature with the modified d_{32} are difficult to quantify due to the relatively large fluctuations. However; by observing Figure 60 there seems to be a trend with a better cooling effect for smaller droplets. Increasing the momentum of the spray, a small negative trend of the gas cooling rate is observed. This can probably be related to the stirring effect and the nature of the heat source in FDS. The sprays with higher momentum vaporise at a higher rates and do thereby extract heat from the gases faster. But since the heating power is constant throughout the simulations and the oxygen concentration is low in the room, the combustion will take place in the vicinity of the window. If the momentum of the spray is increased, stirring will increase and a flow of fresh air will be induced into the room and help in retracting the flame front from the window opening. This means that combustion will take place further into the room and thereby increase the temperature. If the scenario to be simulated would have been a well-ventilated fire, flaming combustion would occur in the interior of the room, but the use of the cutting extinguisher would have shown a simulated flame front with a position depending on the momentum of the spray.

By using data from Figure 71 and assuming that all water impinging on surfaces do not contribute to any cooling and the rest vaporises and remains at a certain temperature, it is possible to calculate the amount of energy absorbed by the vaporised sprays produced by the Cutting extinguisher and the enhanced low pressure system over a period of 150 s. Assuming that vapour remains at a temperature of 100 °C the calculated values are 2.5 and 0.88 MW, respectively, and for 300 °C the values are 2.8 MW and 1.0 MW for the cutting extinguisher and the enhanced low pressure system, respectively.

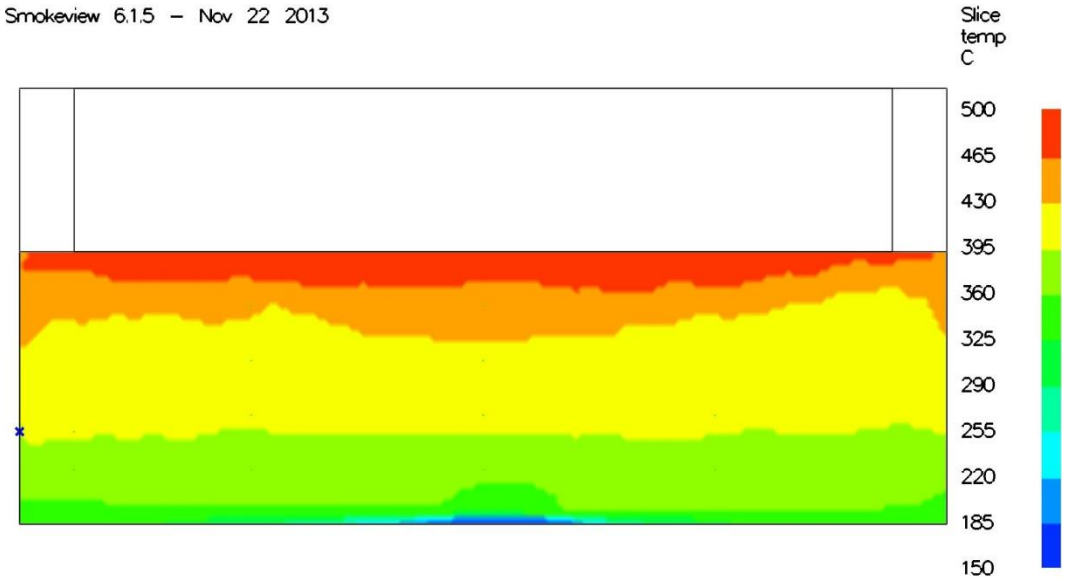

Figure 57: Temperature field in Plane A in the warehouse right before any spray is injected. The field is averaged over 10 s.

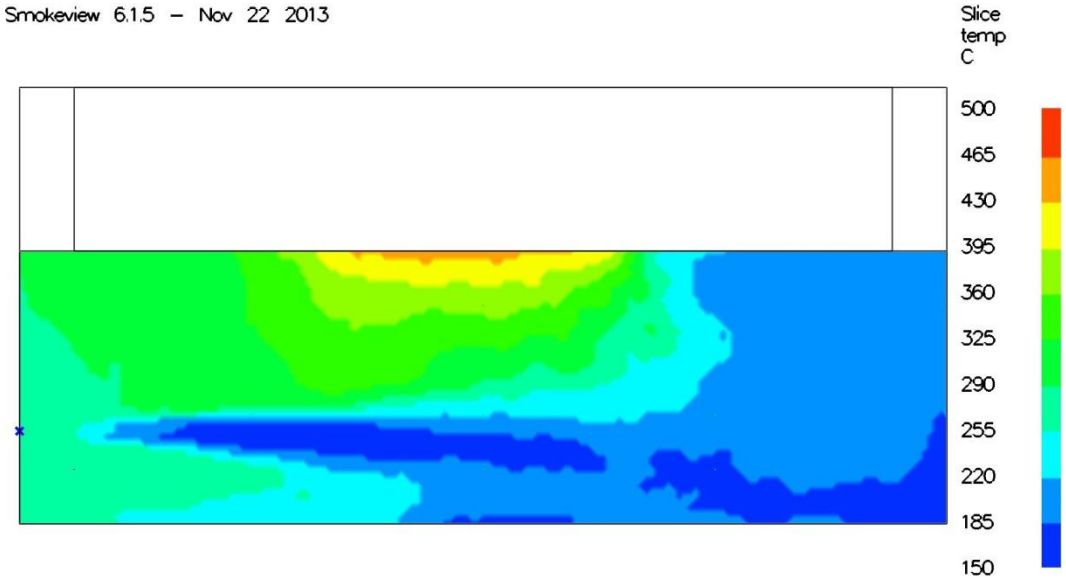

Figure 58: Temperature field in Plane A in the warehouse after 60 s use of the Cutting extinguisher. The field is averaged over 10 s.

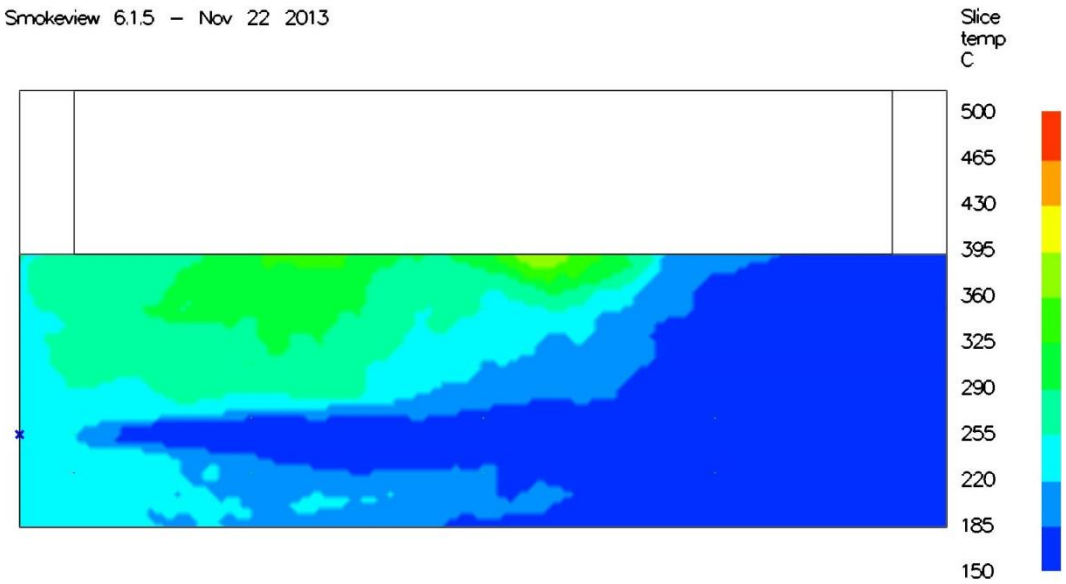

Figure 59: Temperature field in Plane A in the warehouse after 150 s use of the Cutting extinguisher. The field is averaged over 10 s.

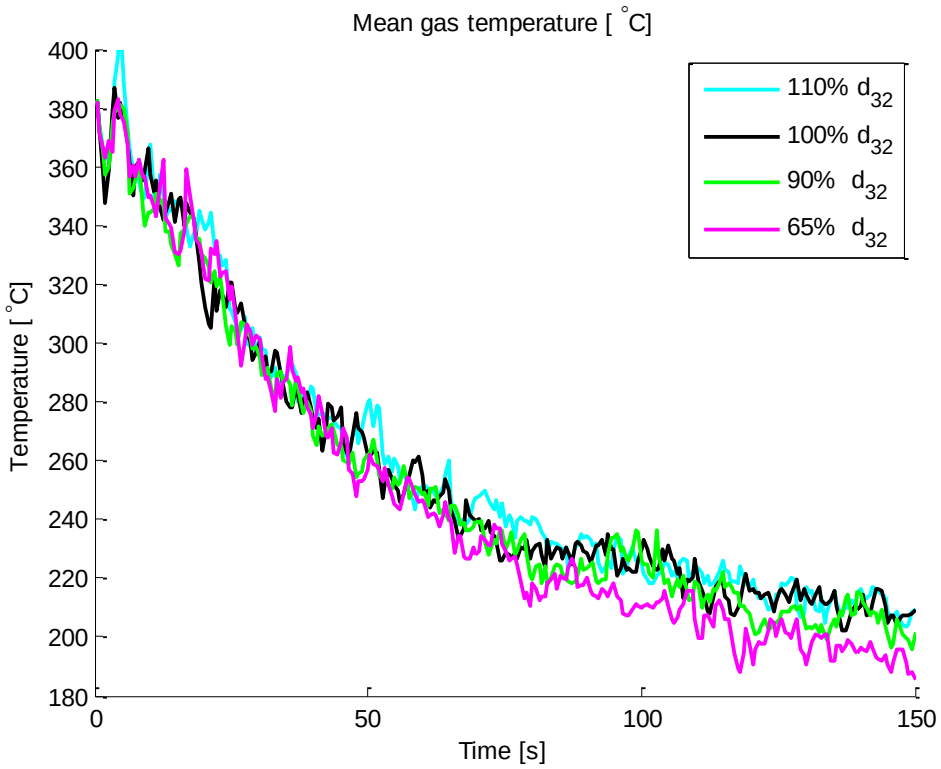

Figure 60: Sensitivity analysis of the mean temperature over time. Only d_{32} is changed while flow rate and momentum are kept constant. The power in the room are kept constant at 8 MW.

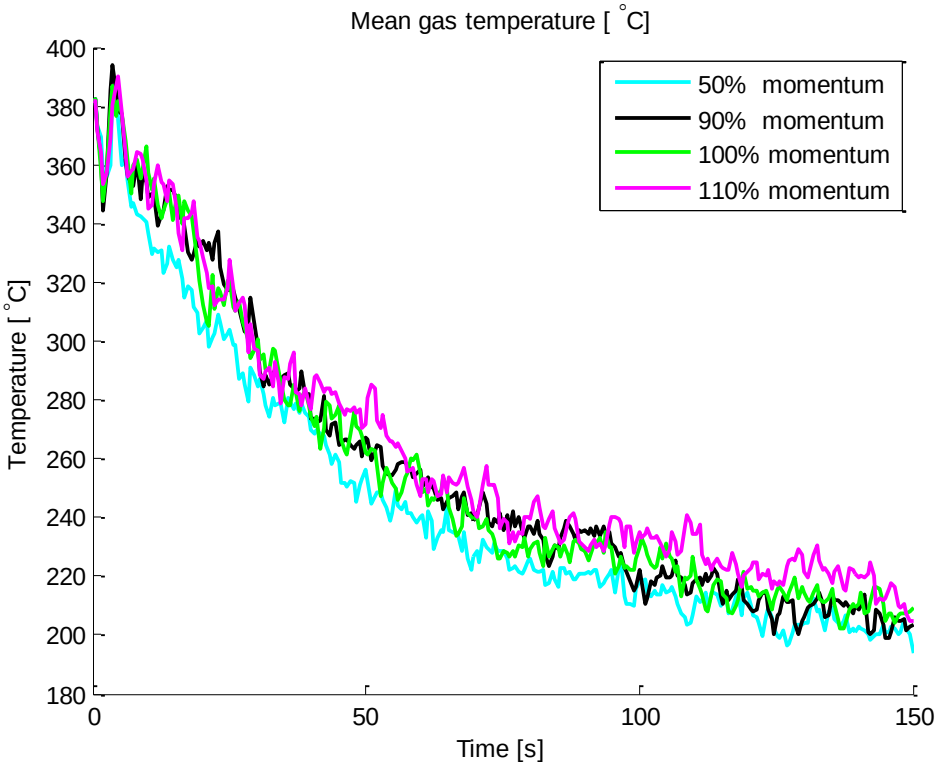

Figure 61: Sensitivity analysis of the mean temperature over time. Only the momentum of the spray is changed while d_{32} and the flow rate are kept constant. The power in the room is kept constant at 8 MW. Please read Section 4.3.2 for a plausable explanation of these results.

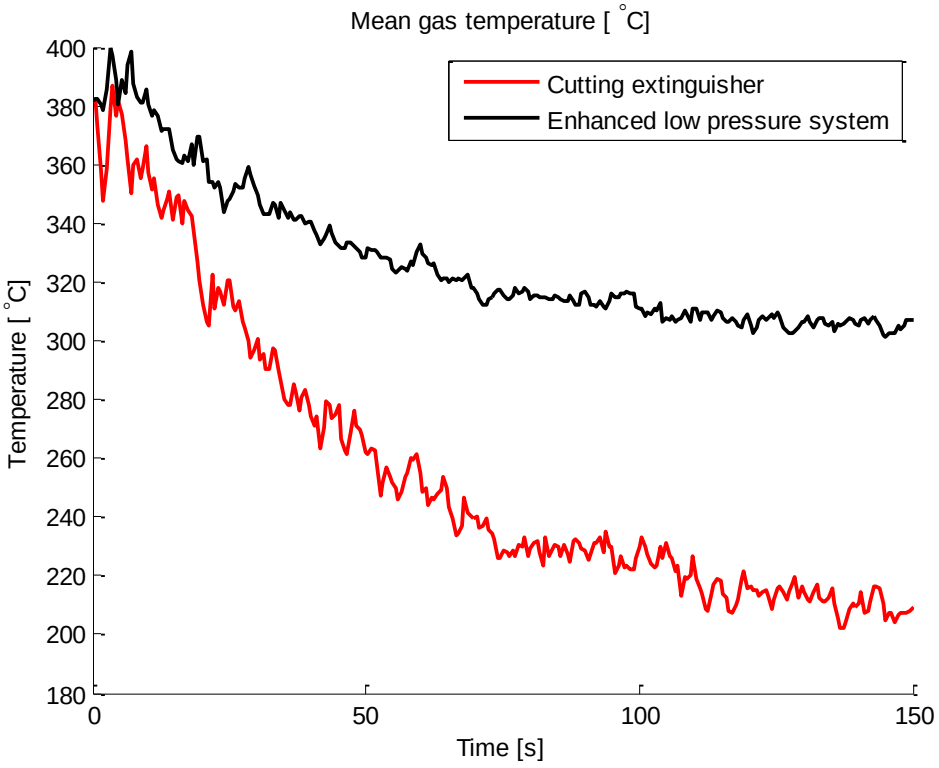

Figure 62: Comparison of gas cooling for the nominal Cutting extinguisher and enhanced low pressure system. The heating power in the room is kept constant at 8 MW.

4.3.3 **Oxygen reduction**

There are two contributing factors in reducing the oxygen concentration in a room where a fire is located, the combustion process itself and the addition of water vapour. Figure 63 to Figure 65 illustrate the water vapour concentration in Plane At 0, 60 and 150 s of using the nominal cutting extinguisher, respectively. At 60 s of use of the cutting extinguisher the average water vapour concentration reaches 30 %, and after 150 s it is as high as 45 %, leading to a maximum concentration of oxygen lower than 11.5 %.

Figure 66 and Figure 67 show a sensitivity analysis on the average water vapour concentration over time, where d_{32} and the momentum of the spray are varied separately. The differences in results are small since almost all water is vaporised for all variations of the spray. The only configuration that is slightly remarkable per se, is the one with the momentum reduced to 50 %, where less water vaporises before colliding against the floor, as seen in Figure 70.

A better way to quantify how effective the different sprays vaporise is by looking at Figure 69 and Figure 70 showing the accumulated mass of water on the floor and walls of the compartment is shown. It is also shown that higher momentum of the spray and smaller droplets result in a an enhanced rate of vaporisation. For a spray with a d_{32} of 65% of the nominal Cutting extinguisher, only 3 out of 150 litre impacts a surface. If the momentum of the spray is reduced to 50 %, 20 litres impinge the surfaces. This can be compared to 10 litres for the nominal spray.

Figure 71 compares the accumulated water mass on the floor and walls for the nominal Cutting extinguisher and the enhanced low pressure system. After 150 s, only 10 litres of the Cutting extinguishers injected 150 litres have hit a surface. For the enhanced low pressure system, over 200 of the injected 250 litres have hit a surface during 150 s. Figure 68 shows that the water vapour concentration after 150 s of use with the enhanced low pressure system reaches 22.5 %, which should be compared to the 45 % for the nominal Cutting extinguisher. It should be noted that droplets disappear in FDS when they hit the floor, which in this scenario gives a disadvantage for the low pressure spray.

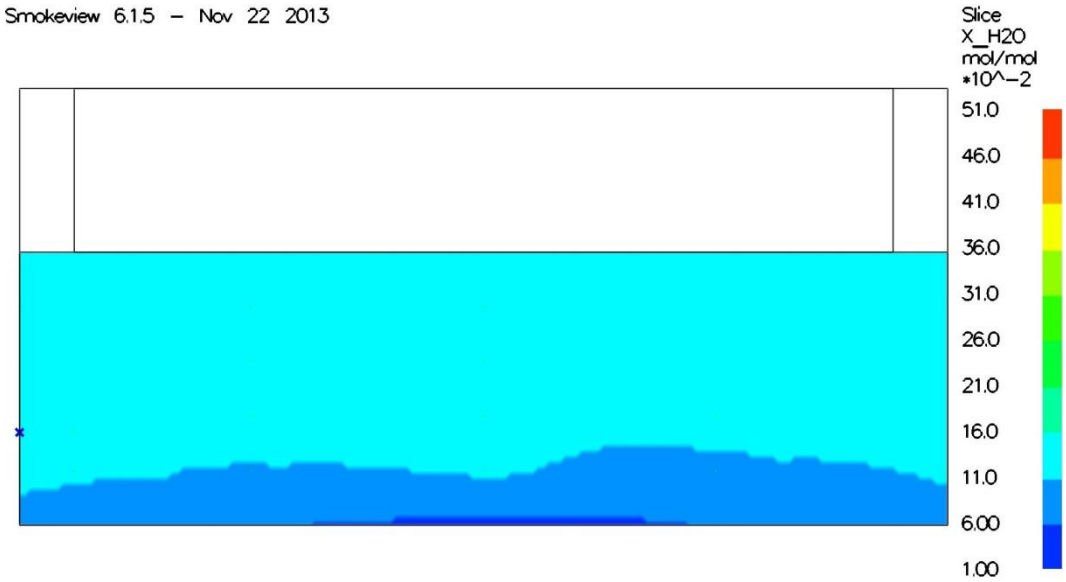

Figure 63: Water vapour volume concentration in Plane A in the warehouse right before any spray is injected. The field is averaged over 10 s.

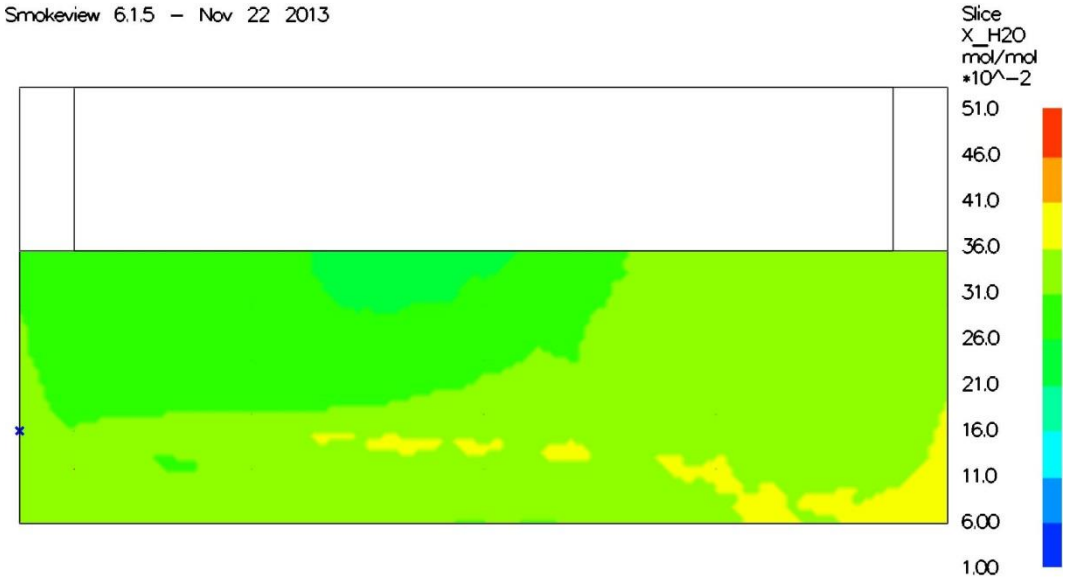

Figure 64: Water vapour volume concentration in Plane A in the warehouse after 60 s use of the Cutting extinguisher. The field is averaged over 10 s.

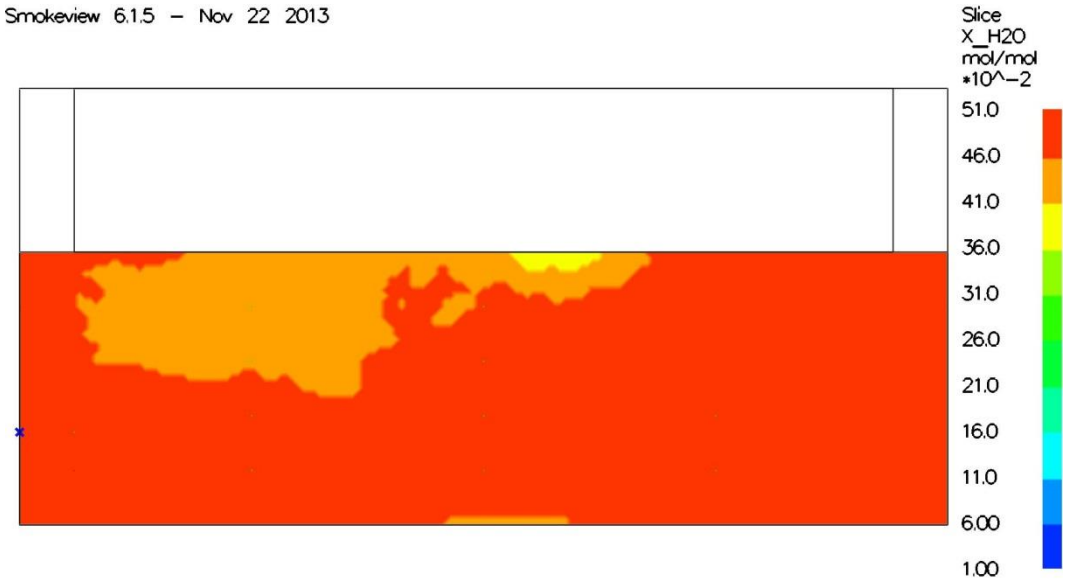

Figure 65: Water vapour volume concentration in Plane A in the warehouse after 150 s use of the Cutting extinguisher. The field is averaged over 10 s.

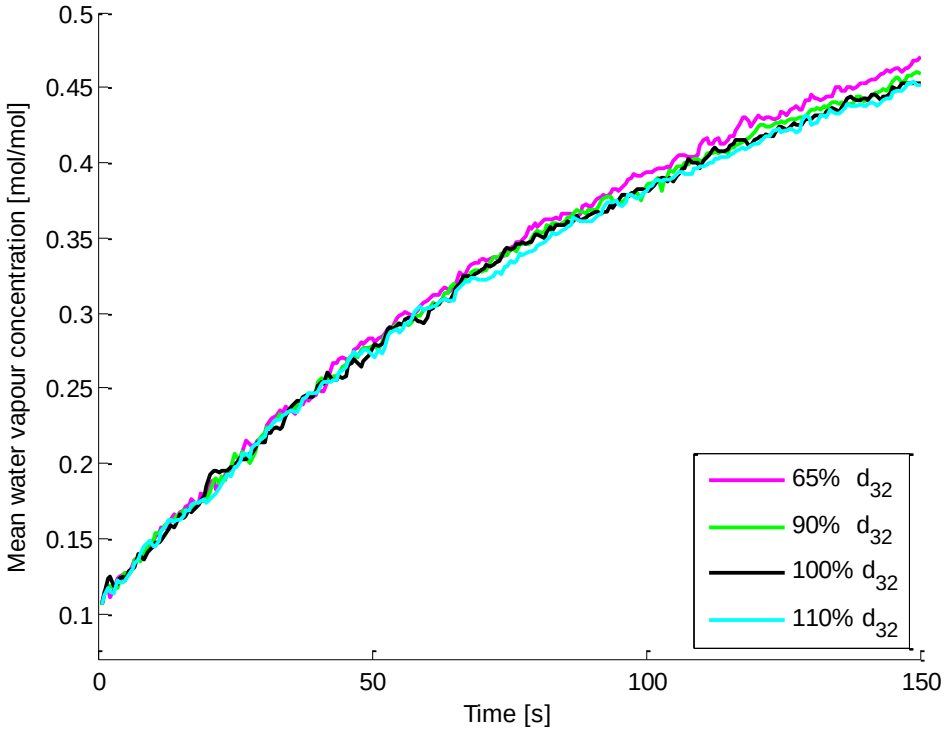

Figure 66: Sensitivity analysis of the mean water vapour concentration over time in the warehouse. d_{32} is varied while flow rate and momentum are kept constant

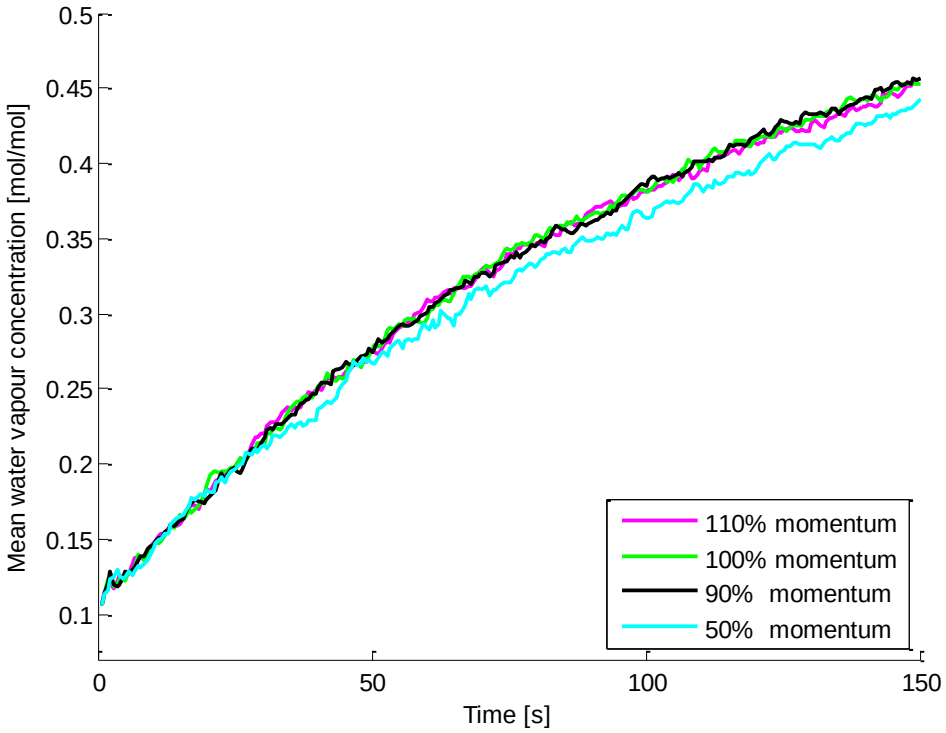

Figure 67: Sensitivity analysis of the mean water vapour concentration over time in the warehouse. Only the momentum of the spray is changed while d_{32} and the flow rate are kept constant.

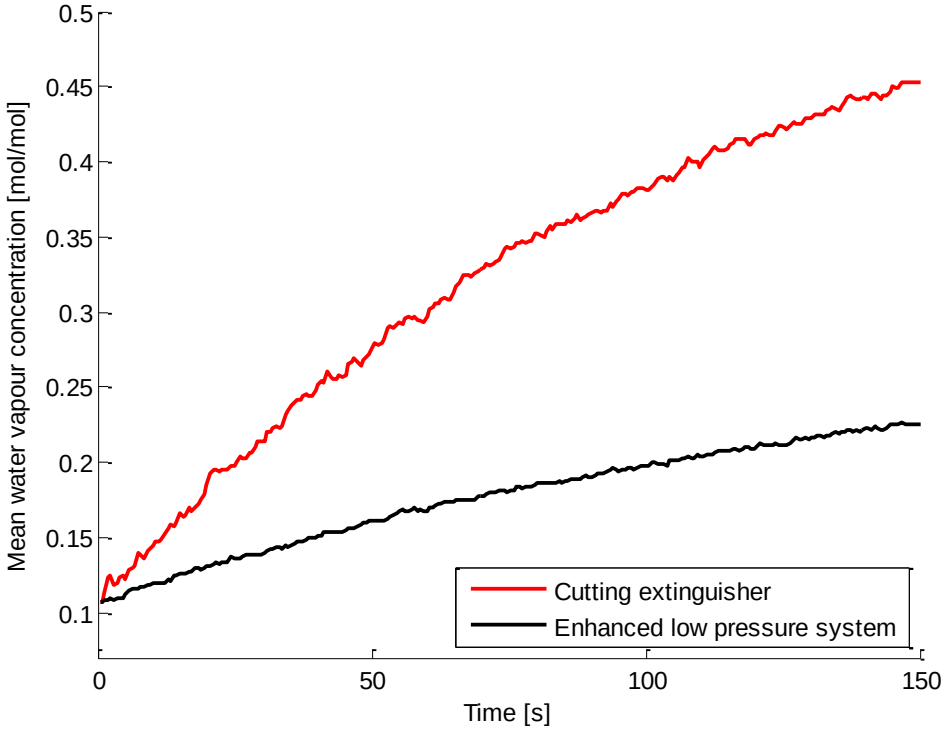

Figure 68: Comparison of water vapour concentration for the nominal Cutting extinguisher and the enhanced low pressure system in the warehouse.

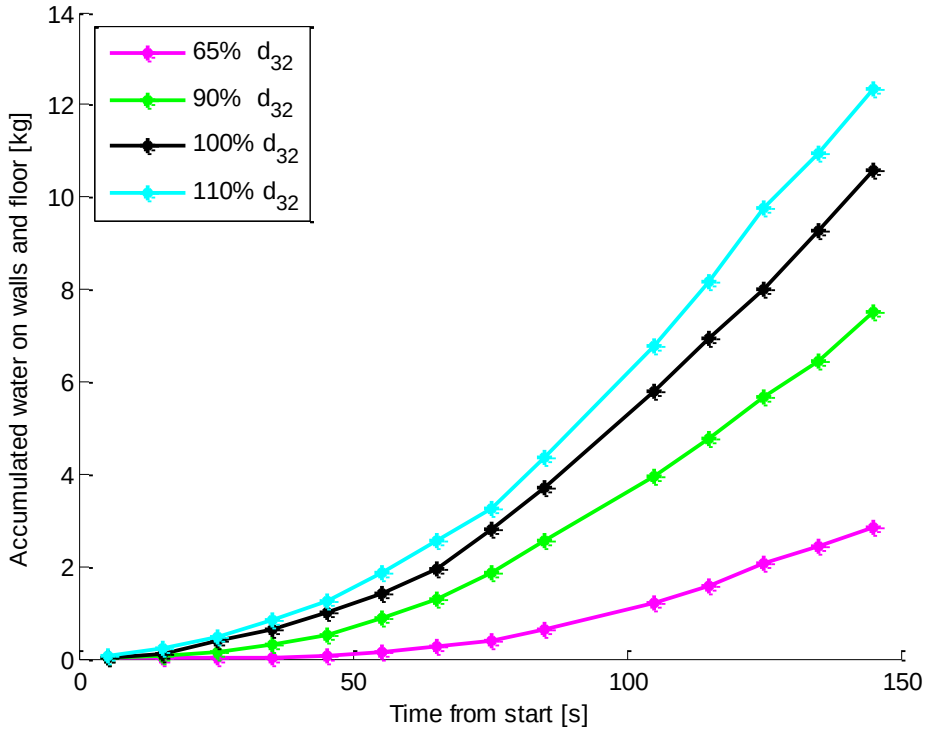

Figure 69: Accumulated water on walls and floor in the warehouse. Only d_{32} is changed while flow rate and momentum are kept constant. Note that total amount of water sprayed into the room is 150 liters during 150 s.

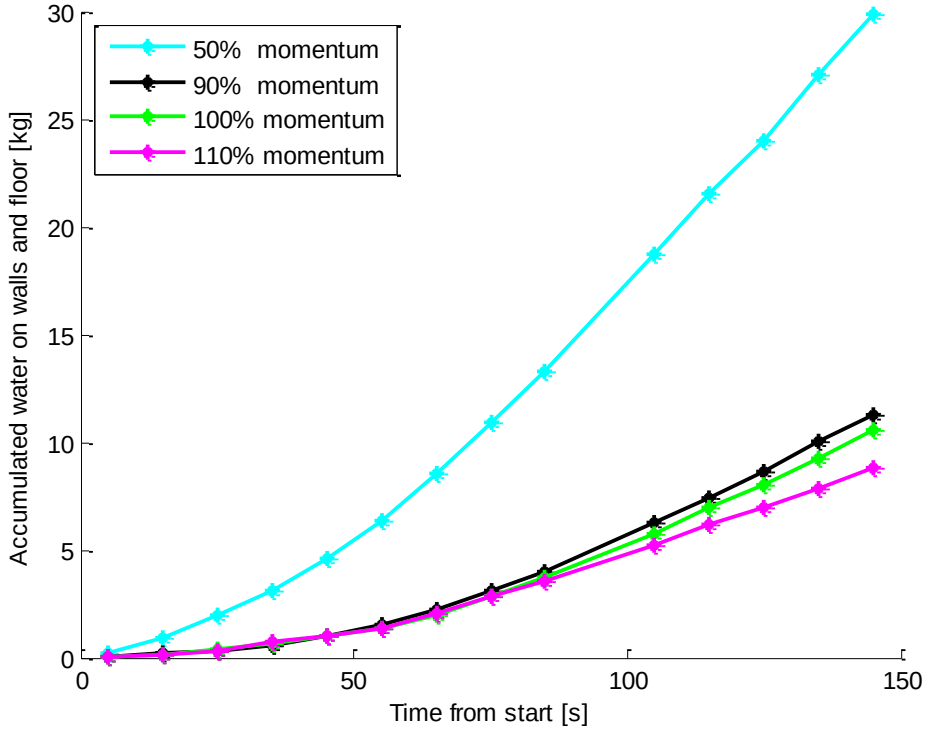

Figure 70: Accumulated water on walls and floor in the warehouse. Only the momentum of the spray is changed while d_{32} and the flow rate are kept constant. Note that total amount of water sprayed into the room is 150 liters during 150 s.

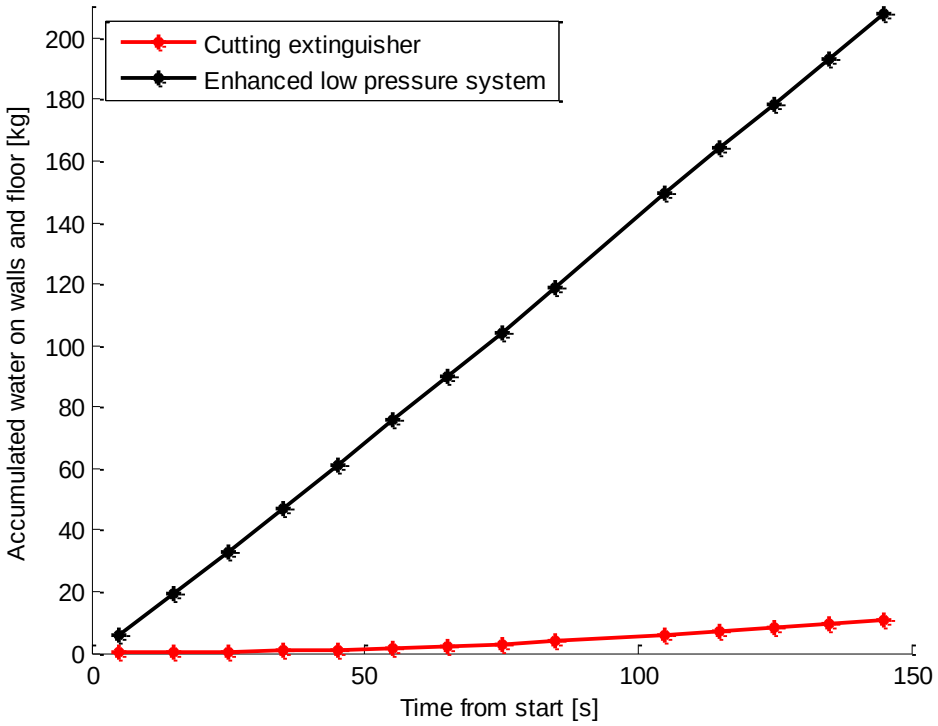

Figure 71: Accumulated water on walls and floor. The nominal Cutting extinguisher is compared to the enhanced low pressure system. Note that total amount of water sprayed into the room is 150 and 250 liters during 150 s for the Cutting extinguisher and the enhanced low pressure system, respectively.

5 Conclusions and future work

The software Fire Dynamics Simulator, FDS, was chosen as the best option available for achieving the objectives of this project. The main reasons reside in the availability to fire services around the globe and its reduced implementation price tag due to its gratuity and the in-house experience in its use.

The validation tests were partly satisfying. They showed that simulations and experiments exhibit qualitative similarities, but due to experimental difficulties and model limitations no quantitative comparison can be made. There is however, no indications that the FDS simulations should give incorrect trends under the simulated scenarios.

The results from this report could be used for further product development. Additional simulations might be needed. If used for product development, the conditions of the simulations should be well understood. Aspects such as disappearing droplets and constant power from heat sources should be carefully considered.

5.1 Change of momentum

A higher momentum results in an increased stirring of the gases, which will result in a more homogenous temperature, leading to a higher temperature close to the droplets and subsequently faster gas cooling and vaporisation of the droplets. It will also lead to a shorter time before the droplets will impinge the wall, and thereby become ineffective in these simulations. This latter effect will be noticeable as the temperature decrease. A third effect is that a larger momentum and increased stirring means that the air exchange through potential ventilations gets larger, resulting in more water vapour is lost to the adjacent environment.

These simulations suggest that the momentum of the spray is enough for cooling and vaporisation effects under the investigated scenarios. There is a temperature limit when slightly lower momentums might be preferred. For the living room simulations, where the distance to the wall is almost 12 metres, this breakpoint was when the average room temperature was as low as 200 °C. In reality, droplets bouncing of the wall would continue to have a bit more influence on the gas cooling than in these simulations.

It should be remembered that an increased momentum will often contribute to smaller droplets for a real system.

5.2 Change of droplet sizes

According to the results, there are no indications that larger droplets would have a better impact on gas cooling and oxygen reduction. The gain of a small decrease in d_{32} might however not be very clear. When studying at d_{32} from 100 to 200 µm, it is first at temperatures below 200 °C the difference start to become apparent. If we look at sprays with a d_{32} of 1000 µm compared to 200 µm, large differences can be noticed at 400 °C.

5.3 Oxygen reduction

Fires can be extinguished by impeding the oxidising agent reacting with a given fuel. Although this is in principle impossible to achieve in fire-fighting activities, it is however possible to decrease the rate of combustion reactions or intensity of the fire by reducing the relative amount of oxygen surrounding the fuel. Reducing the concentration of oxygen in closed and partially ventilated compartments can be achieved by adding water vapour in the confinement until the relative amount of oxygen falls substantially and combustion can be hindered or damped.

In the 70 m^3 apartment geometry with an open 2.3 m^2 window and a continuous heat source of 1 MW, the water vapour concentration increases by 30 % after 60 s of injecting water using the nominal Cutting extinguisher.

For the 150 m^3 living room with a 4 MW pre-heating source and a ventilation of 3.7 m^2, the Cutting extinguisher can create an average water vapour concentration of 24 % in only 20 s. The enhanced low pressure system reached 15 % after 60 s.

In the 500 m^3 warehouse with an 8 MW continuous heat source and a ventilation window of 7.5 m^2, the average water vapour concentration becomes 45 % and 22.5 % after 150 s use of the Cutting extinguisher and the enhanced low pressure system, respectively.

5.4 Gas cooling

Assuming that all water impinging on surfaces do not contribute to any cooling and the rest vaporises and remains at a certain temperature, it is possible to calculate the amount of energy absorbed by the vaporised sprays produced by the Cutting extinguisher and the enhanced low pressure system over a certain period.

Results from the simulated living room show that up to 80 % of the injected water vaporises when the averaged gas temperature in the room is about 200~250 °C. In contrast, at gas temperatures as high as 300 °C, less than 20 % of the water from enhanced low pressure systems will vaporise. This provides an indication that the Cutting extinguisher is an effective tool for gas cooling.

5.5 Future work

This work did not study the processes involved in the extinguishment of fires, but the variations in oxygen concentration and gas cooling due to water vaporisation individually. However, the combined reduction of gas temperature and oxygen concentration in limiting the intensity of a fire, require further study. Furthermore, future experiments are required for validating the simulations.

Bibliography

[1] J. Lindström, G. Appel, K. Palmkvist, K.O. Bialas, Förmåga och begränsningar av förekommande släcksystem vid brand i byggnad - fokus på miljöarbete, in, MSB Myndigheten för samhällsskydd och beredskap, 2013.
[2] AFS 2007:7 Rök- och kemdykning, Arbetsmiljöverkets föreskrifter om rök- och kemdykning samt allmänna råd om tillämpningen av föreskrifterna, in: Arbetsmiljöverket (Ed.), 2014.
[3] The Cutting Extinguisher - concept and development, in, Räddningsverket, Swedish Rescue Services Agency, 2001.
[4] T. Hertzberg, A. Hahne, C. Josefsson, G. Holmstedt, B. Husted, SP Rapport 2004:15 Vattendimma: Teori, fysik, simulering. Brandforsk projekt 514-021, in, SP Sveriges Provnings- och Forskningsinstitute, 2004.
[5] M. Försth, R.L. Ochoterena, J. Lindström, Spray characterization of the cutting extinguisher, SP Report 2012:14, in, SP Technical Research Institute of Sweden, Borås, 2012.
[6] Cutting Extinguishing Concept - practical and operational use, in, MSB, Swedish Civil Contingencies Agency, 2010.
[7] S. Särdqvist, Vatten och andra släckmedel, in, Räddningsverket, 2006.
[8] A.H. Lefebvre, Atomization and Sprays, 1 ed., Taylor & Francis, 1989.
[9] W.A. Sirignano, Fluid dynamics and transport of droplets and sprays, Cambridge University Press, Cambridge, 1999.
[10] J. Speight, Lange's Handbook of Chemistry (16th Edition), McGraw-Hill Professional Publishing, New York, NY, USA, 2005.
[11] M. Larsson, J. Westerlund, Högtrycksbrandsläckning - Ett beslutsunderlag för Räddningstjänsten, in, Department of Fire Safety Engineering, Lund University, Lund, 2006.
[12] M. Försth, K. Möller, Enhanced absorption of fire induced heat radiation in liquid droplets, Fire Safety Journal, 55 (2013) 182-196.
[13] J. Gsell, Assessment Of Fire Suppression Capabilities Of Water Mist - Fighting Compartment Fires with the Cutting Extinguisher -, in, Faculty of Art, Design and the Built Environment, University of Ulster, Belfast, 2010.

A Detailed explanation of the implementation of the cutting extinguisher in FDS

In this chapter some of the parameters and setting that were used in FDS will be explained. The version used for the simulations was FDS 6.0.1 serial.

A.1 Heat source in FDS

It is hard to properly simulate extinguishment of a fire in FDS. It has therefore never been the goal of this project to simulate any extinguishment. In the three different simulated scenarios, the heat release rate (HRR) is always predefined, and will therefore not be affected by any amount of water. In these simulations a certain amount of fuel, propanol, equivalent to a defined power will come out of a defined surface. The fuel will be transported and mixed with oxygen creating a combustible mixture which combusts independent of the gas temperature.

In the apartment and warehouse geometries, the power was set to a constant value during the whole simulations. In the room fire, the HRR was changed from 4 MW down to zero over one second at the same time the droplets are initialized to the system. The heating before the sprays were injected were ongoing long enough for the temperature profile to more or less reach a steady state.

A.2 The spray

The spray for the nominal Cutting extinguisher used in the FDS simulations have consisted of lagrangian particles with a d_{32} of 162 µm with a flow rate of 60 l/min. The force of the spray is approximately 220 N (=1 kg/s x 220 m/s). The spray is presented by 5 000 particles/second in FDS that are randomly sent in a cone with an angle of 6 degree from the centerline. The particle sizes will be randomly chosen from the size distribution described in the Section A.2.1.

A.2.1 Drop size distribution

The droplet size distribution used in the FDS simulations is a Rosin Ramler – Log normal distribution. It has been fitted with a least square method to be similar to the measured size distribution 10 m from the nozzle. In the measurements the d_{32} was found to be 170 µm with an error of 10%, in the simulations the used d_{32} is 162 µm. The distribution can be seen in Figure 72. The droplets were unable to atomize in the simulations. The same distribution have been used for the enhanced low pressure system, but with an up scaled size for every droplet.

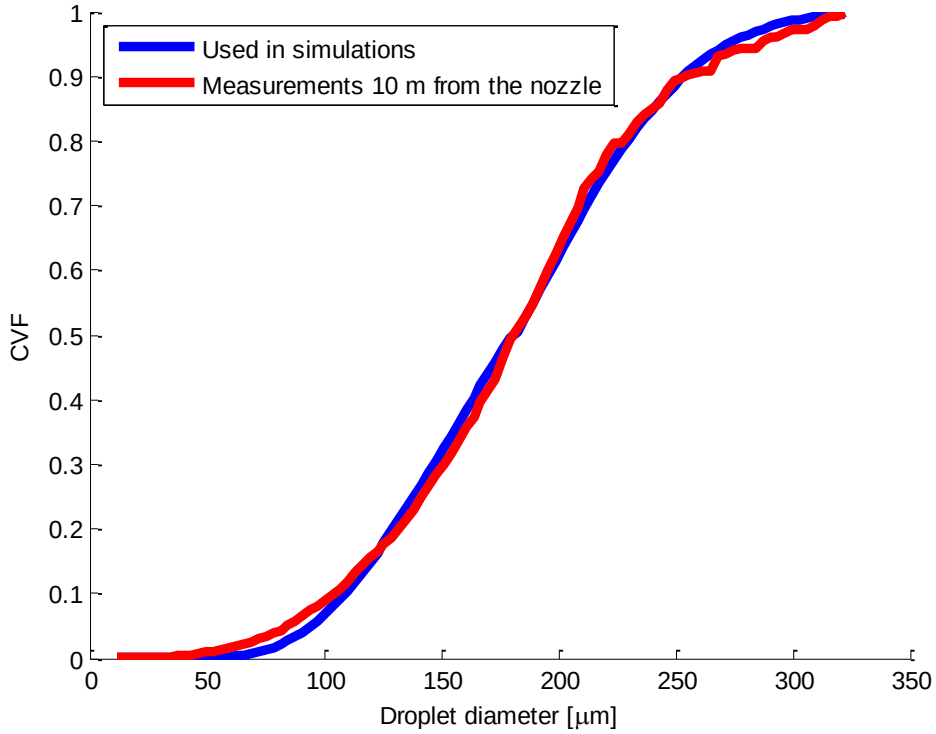

Figure 72: Cumulative volume fraction used in FDS compared to the measured distribution.

A.2.2 **Momentum and energy**

The momentum of the real spray was kept in the simulations, the kinetic energy was not. The lagrangian particles could have been initialized at the position of the nozzle with a velocity of 220 m/s. It is not however recommended to initialise the spray in a single grid cell, but rather have an offset distance from the nozzle where the particles can be initialized in more than one cell. In the simulations, the offset was set to be 1 m. At that distance the spray was initialized in 4 grid cells.

Is was assumed that 1 m downstream the nozzle, the speed of the surrounding air and droplets is equal. Comparative simulations were made initialising droplets at 220 m/s and using the velocity patch, which forces the air in a volume to a certain velocity. The patch was placed 1 m downstream the nozzle, had a size of 0.2 x 0.2 m and a velocity of 58 m/s. The droplets were added at the same area as the patch with the same velocity as the patch, but with a cone angle of 6 degrees. The two simulations gave very similar droplet velocities as seen in Figure 73. The solution with the velocity patch was used, since that solution severely reduces the simulation times. The momentum added to the system will be equal for the two solutions, the kinetic energy will however not.

The energy lost by using a *velocity patch* could be compensated in FDS by adding turbulent kinetic energy in form of large Eddies at the velocity patch. This was chosen not to be done due to the already large inaccuracies from the coarse mesh.

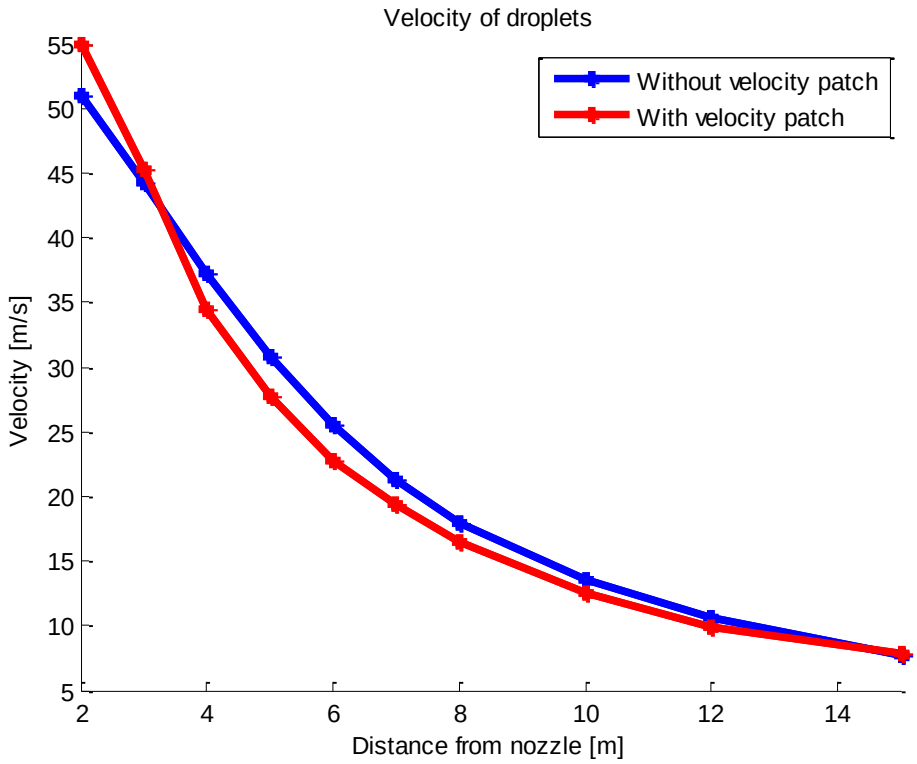

Figure 73: Average droplet velocities in the middle of the spray at different distances from the nozzle.

A.3 Grid size analysis

The grid sizes used for our simulations are far off from the recommendations for large eddy simulations (LES). To verify the results, some comparative simulations have been made in the apartment geometry described in Section 4.1. The gas temperature at 4 locations in the apartment can be seen in Figure 74. It can be seen that for cell sizes of 5, 7, and 10 cm cell the temperatures are similar, but the temperatures for cell sizes of 20 cm differ significantly. A cell size of 10 cm was used to save computation time.

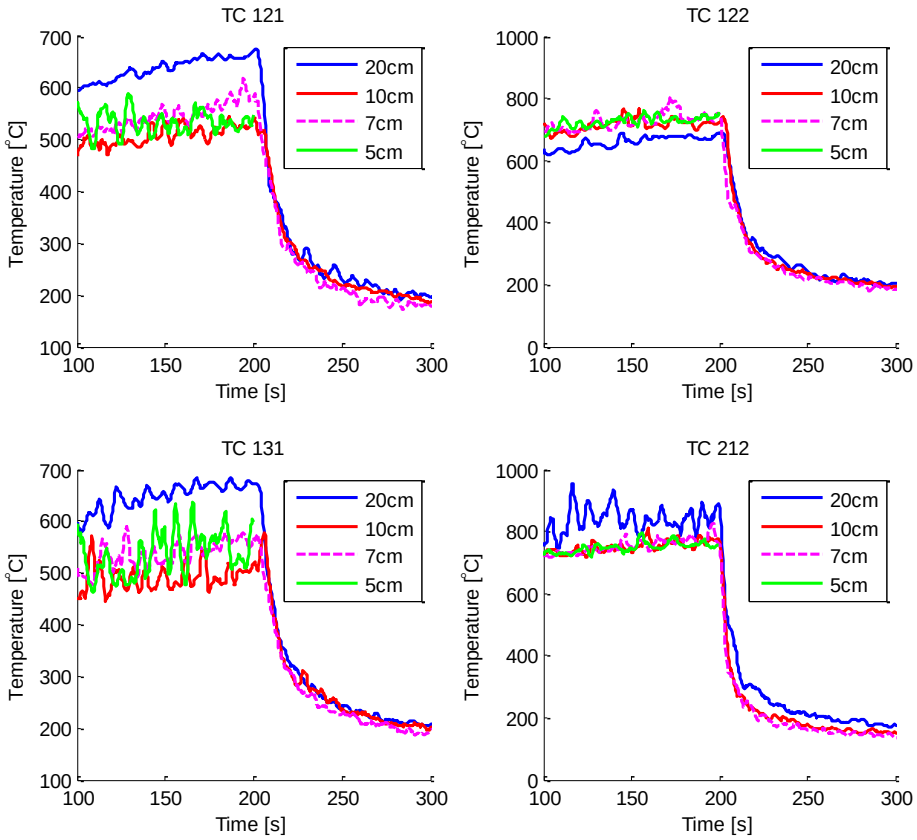

Figure 74: Temperature in 4 locations of the apartment geometry for different cell sizes. Note that the result from the 5 cm simulation is not complete. The simulation aborted due to numerical instability after 205 seconds.

A.4 Interaction between droplets and surfaces

In FDS and under this study all water impinging a vertical surface wets the surface without bouncing and every droplet is assigned with a vertical velocity downwards of 0.5 m/s. However, in reality some of the water would bounce of the surface.

In a series of tests made by CCS, buckets were placed below a vertical wall at which the Cutting extinguisher was aimed. Measurements show that approximately 50 % of the water impinging the wall would bounce off the surface. This will result in a higher cooling of the surfaces and less cooling of the gases in the simulations than if it would have been possible to make the droplets bounce. There would have been more uncertainties if we had added the bouncing effect to the simulations. Like the change of droplet sizes, which for us is unknown.

A particle impacting the floor will immediately disappear without any heat exchange with the floor.

B Experimental tests for model validation

To help validating the simulations done in FDS, real scale fire test were done at Guttasjön, Södra Älvsborg Fire & Rescue Services training centre between the 9th and 11th of June 2014. The tests described in this appendix were performed for validation purposes only and shall not be interpreted as the correct way to use the Cutting extinguisher.

B.1 Experimental setup

The tests were carried out in a container system that had the dimensions and openings as shown in Figure 79 to Figure 82. The containers were built in corrugated steel in two layers with 50 mm of Rockwool insulation between the steel layers.

Four tests were carried out in real scale to validate the conducted FDS simulations. In all tests the air inlets shown underneath the fire in Figure 75 were opened, one window and one door were also opened during the tests, se Figure 80. LPG was used as fuel to make the fire as comparable to the one in FDS as possible.

The tests were performed as follows:

a) The LPG gas burner in the container was ignited, as shown in Figure 75.
b) After 2-3 minutes of pre-heating the intensity of the fire was increased and the large port at the opposite wall, see Figure 81, was closed. The aim was to reach a temperature as high as possible, without letting the flame self-extinguish due to oxygen reduction.
c) When the temperature inside the container was stabilized, the LPG fire was turned off having only hot fire gases in the container.

The four tests were performed according to Table 2.

Test	Description
1	After the LPG burner was turned off the hot fire gases was allowed to cool down without using the Cutting Extinguisher.
2	Seconds after the LPG burner was turned off the hot fire gases was cold down with the Cutting extinguisher, se Figure 76. The Cutting extinguisher was activated in 2 minutes. With a flow of 58 l/min two minutes activation time gives a total flow of 116 litres.
3	Repetition of test 2.
4	Test 4 was conducted in the same way as described for test 2 above. The difference from test 2 was that 2% X-Fog was added in the water. Adding X-Fog to the water, the Sauter Mean Diameter, d_{32}, is reduced to 65% as compared to pure water [5].

Table 2: Description of the performed tests 1-4.

The Cutting extinguisher was used in a horizontal line 1.7 m above floor level. Due to the construction of the container system the Cutting extinguisher was directed into

the container 1.7 m from the right hand side wall, se red X marks in Figure 79 and Figure 81. In Figure 79, T1-T4 marks positions of different measurements. All four positions indicate the location where temperature was measured with 0.5 mm thermocouples. Thermocouples were positioned 0.46, 0.92, 1.38, 1.84 and 2.30 m from floor level. T3 also contained equipment for gas analysis and pressure measurements 0.46 and 2.30 m from ground level, shown in Figure 78. All thermocouples were protected from water mist and radiation from overlying hot fire gases with aluminium foil. No attempt was made to quantify how well the aluminium foil protects the thermocouples from water mist nor radiation. All temperature curves, gas levels (CO, CO_2, and O_2) and pressure are shown in Section B.2.

In addition to the four tests described in Table 2 that were conducted to validate the simulations, another five tests were conducted in the container system. These tests were conducted not for validation purposes but in order to gain more information about how the cutting extinguisher cools hot fire gases, oxygen reduction the environment and stirring effects.

Test	Description
5	Different ventilation compared to test 2. The window and door on the left side of the room was closed. Instead the large port was open during the test. After the LPG burner was turned off the hot fire gases was allowed to cool down without using the Cutting Extinguisher.
6	Same tests scenario as described for test 5. When the LPG burner was turned off the Cutting extinguisher was activated for two minutes.
7	Different ventilation compared to test 6. All ventilation openings were closed before activation of the Cutting extinguisher.
8	Instead of using LPG as the fire source 14 wooden pallets were ignited in the container, shown in Figure 77. The ventilation was the same as in test 2. When the fire had reached a size where the temperatures inside the container had been stabilized the Cutting extinguisher was activated.
9	Test 9 was conducted in the same way as described for test 8 above. The difference from test 8 was that 2% X-Fog was added in the water.

Table 3: Description of the performed tests 5-9.

The wooden pallets used in test 8 and 9 were placed on a metallic frame in piles of 7 pallets. The piles were placed 1 m above the ground level and 0.9 m from the container wall. In all tests where the cutting extinguisher was used it was activated for two minutes. After this time period very small amounts of water was observed on the floor. These small amounts indicates good vaporization and validates the data shown in Figure 45 and Figure 46. By adding X-Fog in the water the Sauter Mean diameter, d_{32}, becomes 65% of what it is for pure water using the Cutting extinguisher. X-Fog is an additive for extinguishment water that is produced by X-Fire AB. X-Fog is used both in Sweden and internationally to impregnate material to make them more fire resistant and for fire extinguishment. X-Fog is documented to be friendly to the environment.

Figure 75: Pre-heating of the container system.

Figure 76: The Cutting extinguisher in action.

Figure 77: Wooden pallets as the fire source in test 7 and 8.

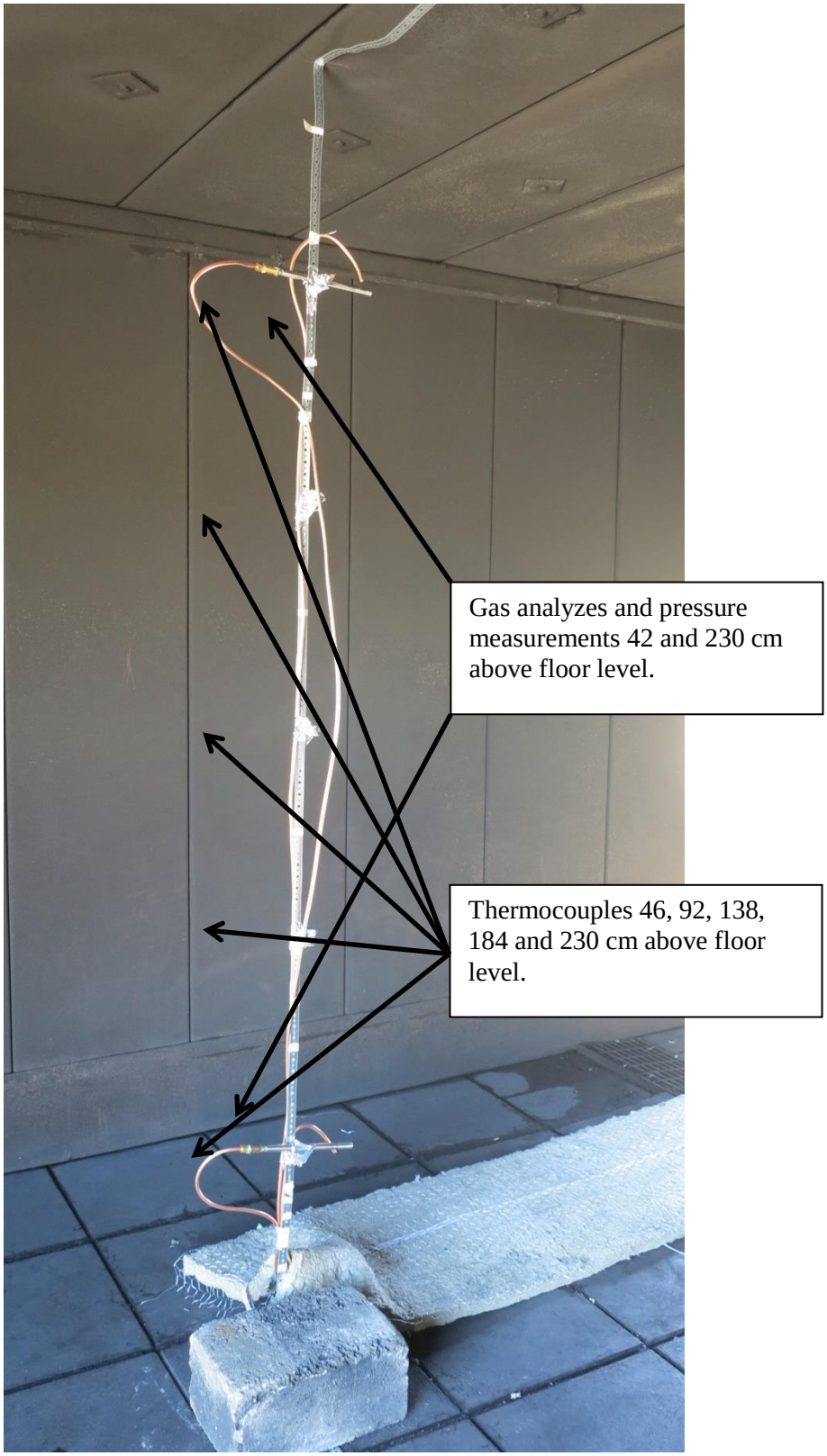

Figure 78: T3 containing thermocouples, gas analyses and pressure measurements.

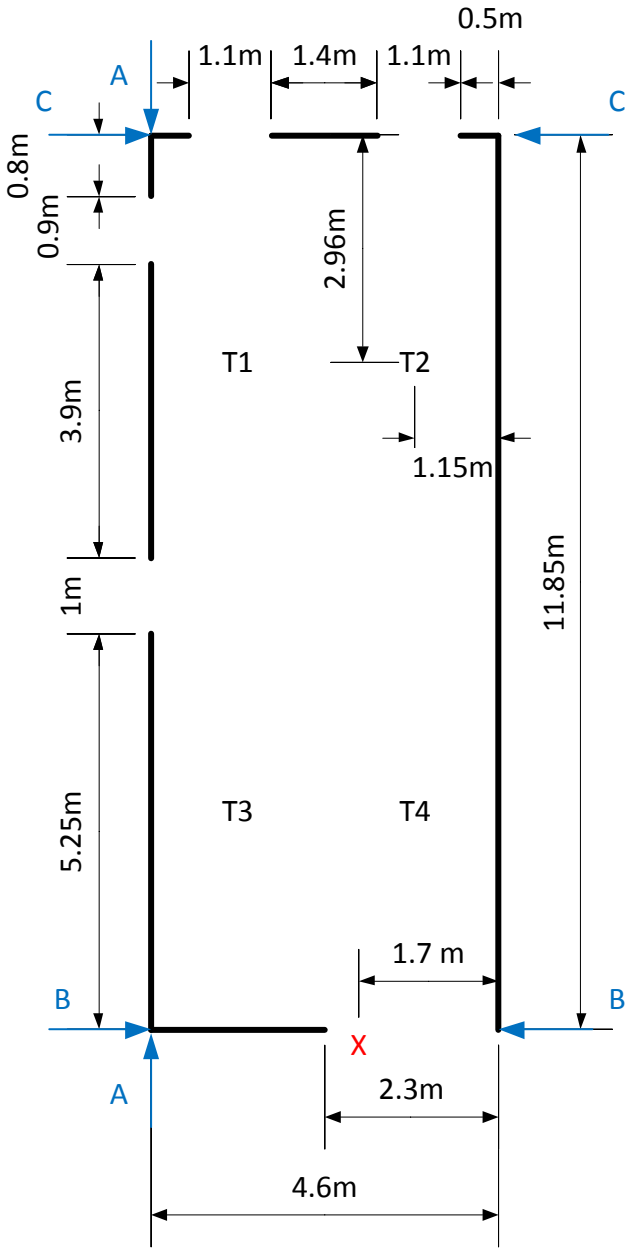

Figure 79: Top view of the container.

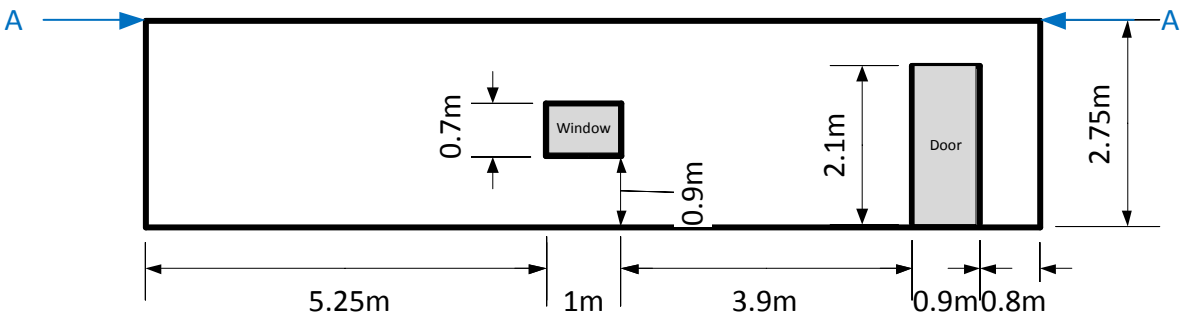

Figure 80: View A-A of the container.

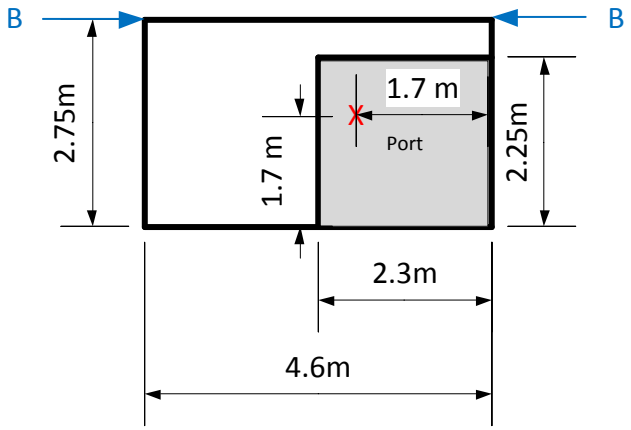

Figure 81: View B-B of the container.

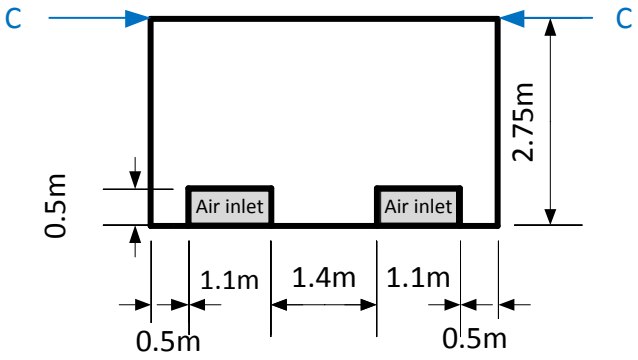

Figure 82: View C-C of the container.

B.2 Experimental results

In this section all logged temperatures, dry gas concentrations (CO, CO_2, and O_2), and relative pressure data from the experiments in Guttasjön are presented.

B.2.1 Test 1

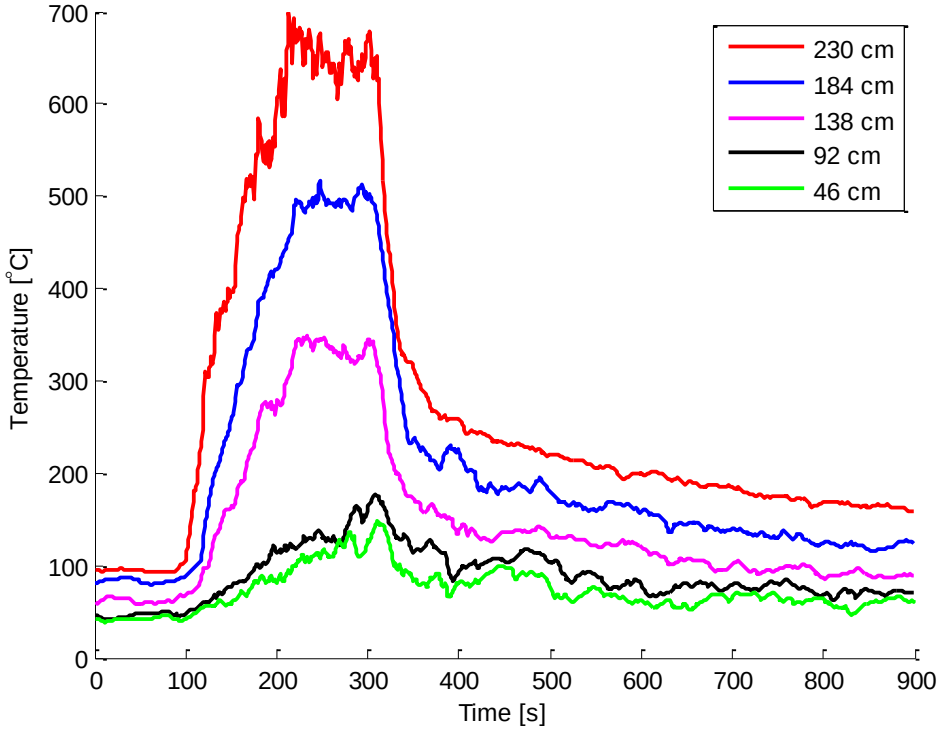

Figure 83: Temperatures, thermocouple tree T1.

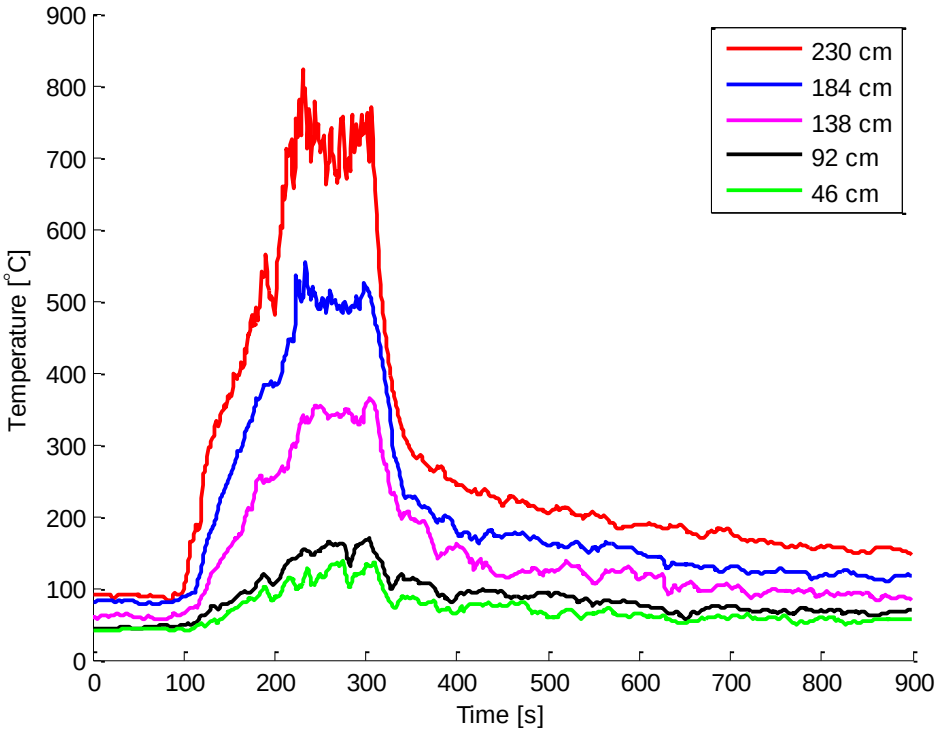

Figure 84: Temperatures, thermocouple tree T2.

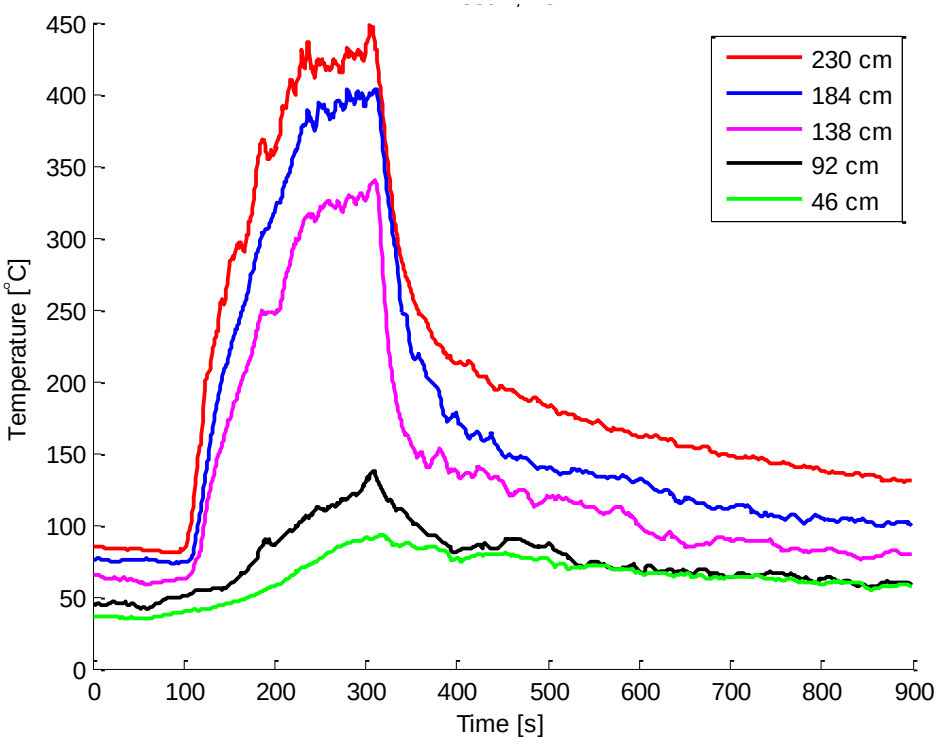

Figure 85: Temperatures, thermocouple tree T3.

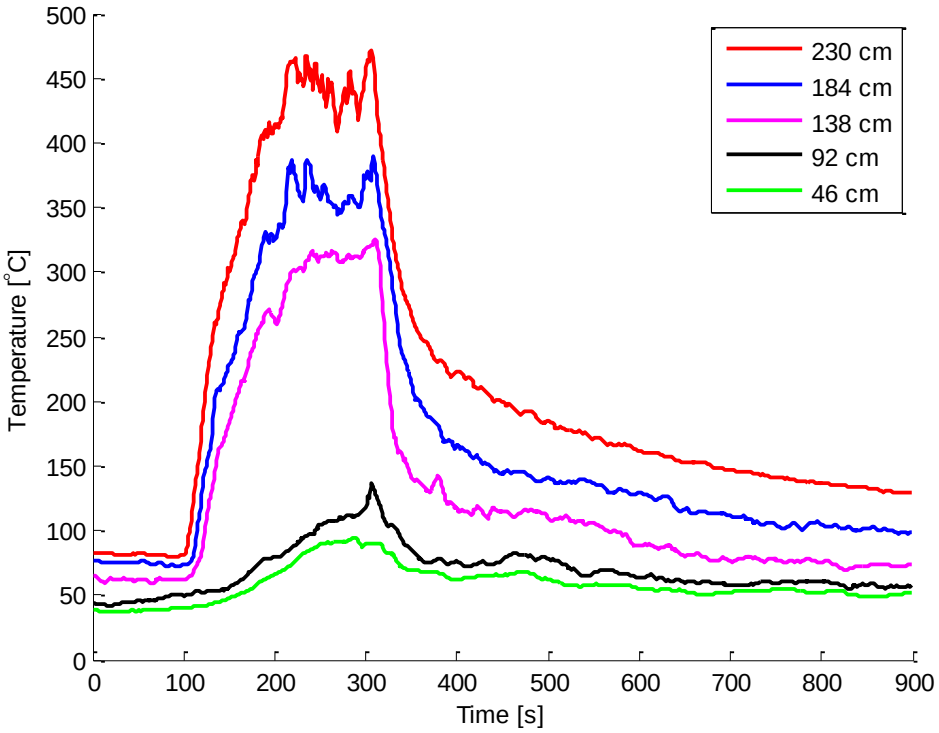

Figure 86: Temperatures, thermocouple tree T4.

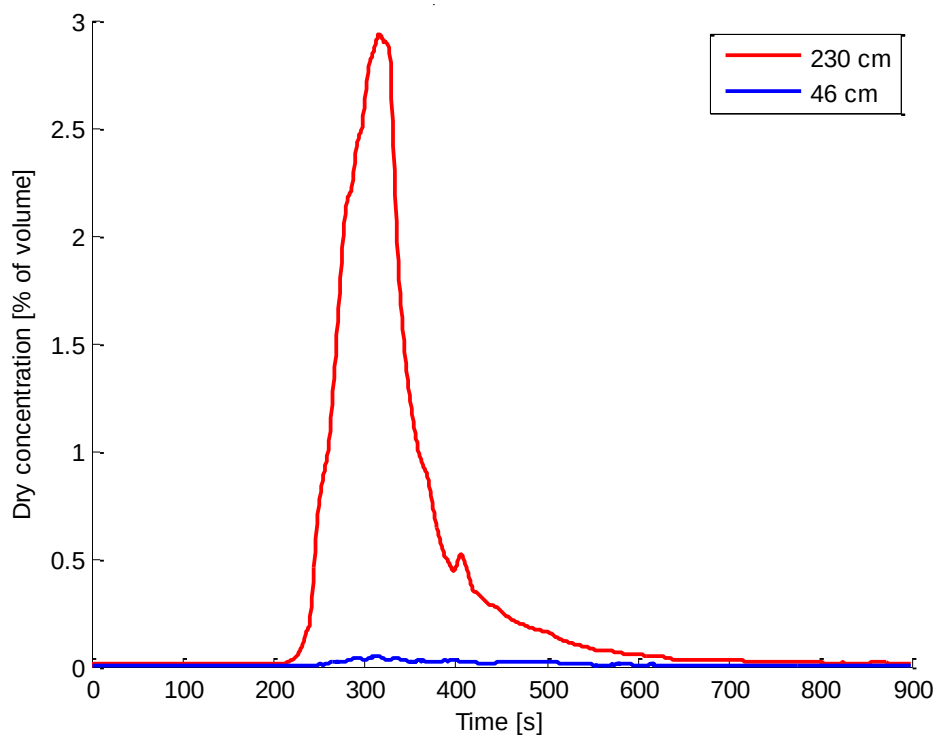

Figure 87: CO concentration.

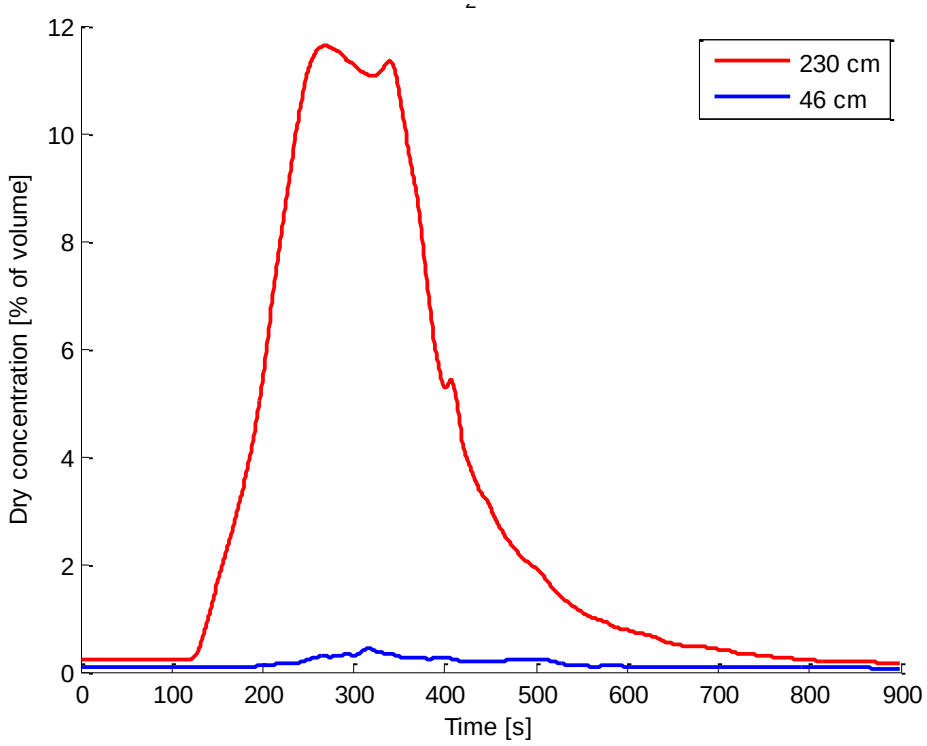

Figure 88: CO_2 concentration.

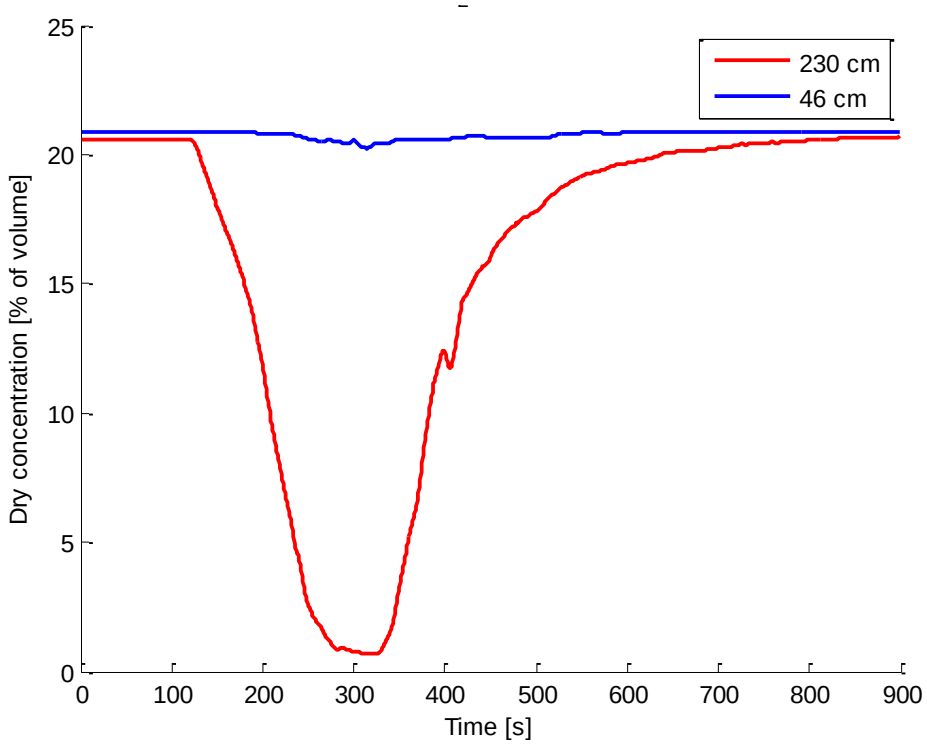

Figure 89: O_2 concentration.

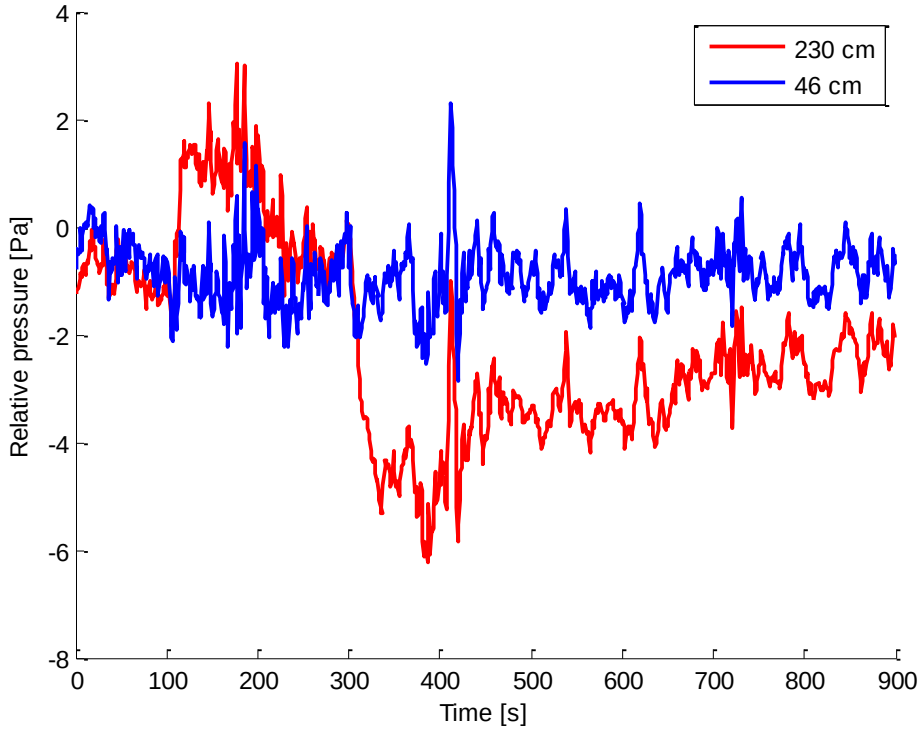

Figure 90: Relative pressure.

B.2.2 **Test 2**

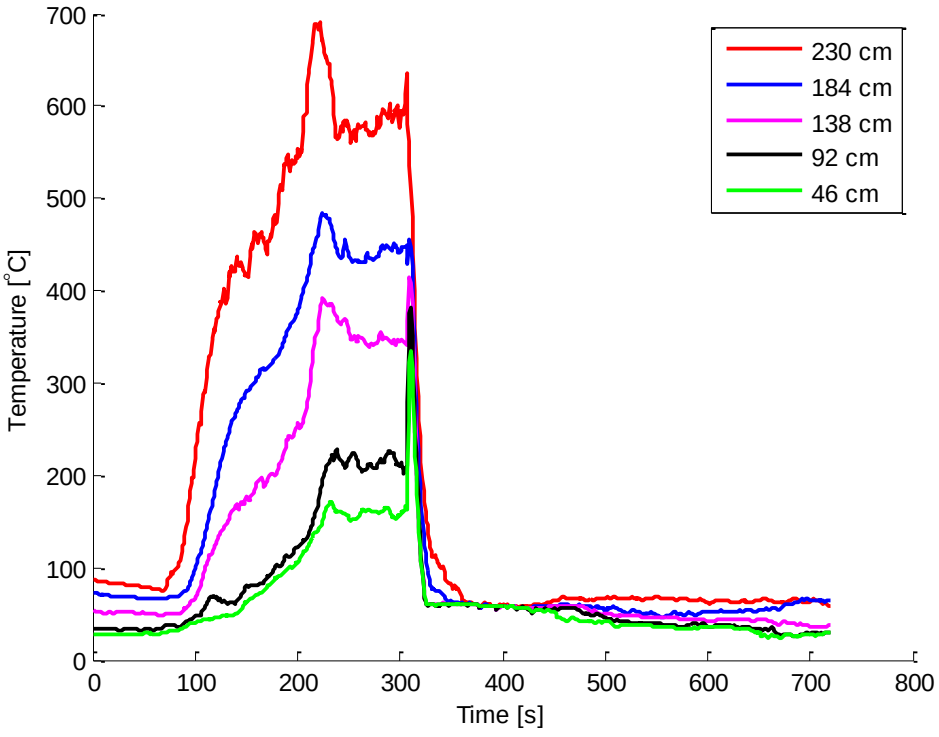

Figure 91: Temperatures, thermocouple tree T1.

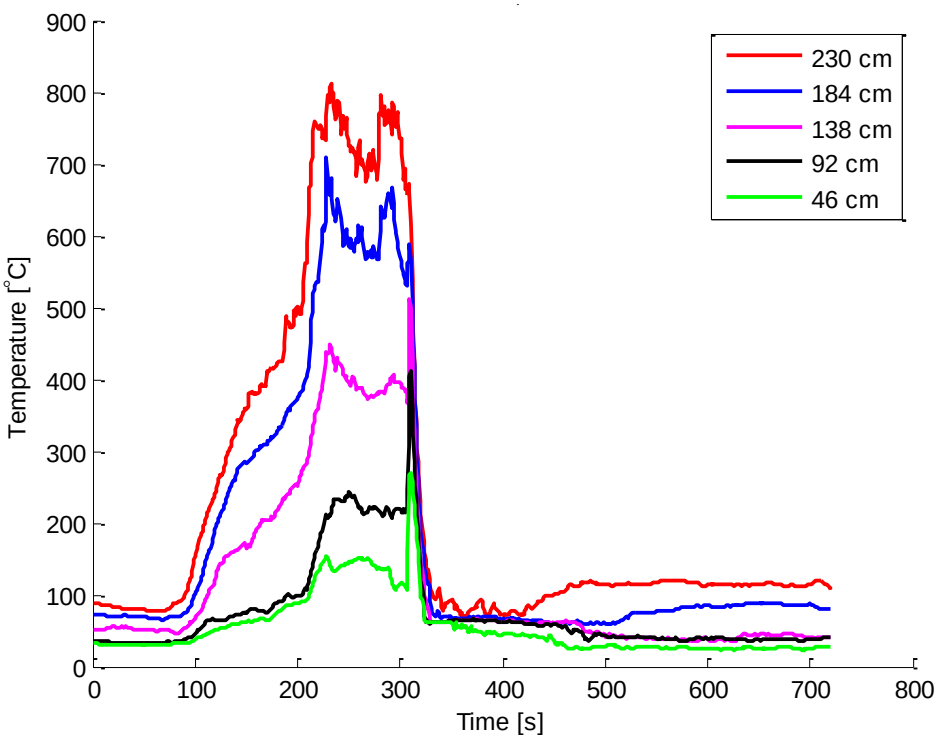

Figure 92: Temperatures, thermocouple tree T2.

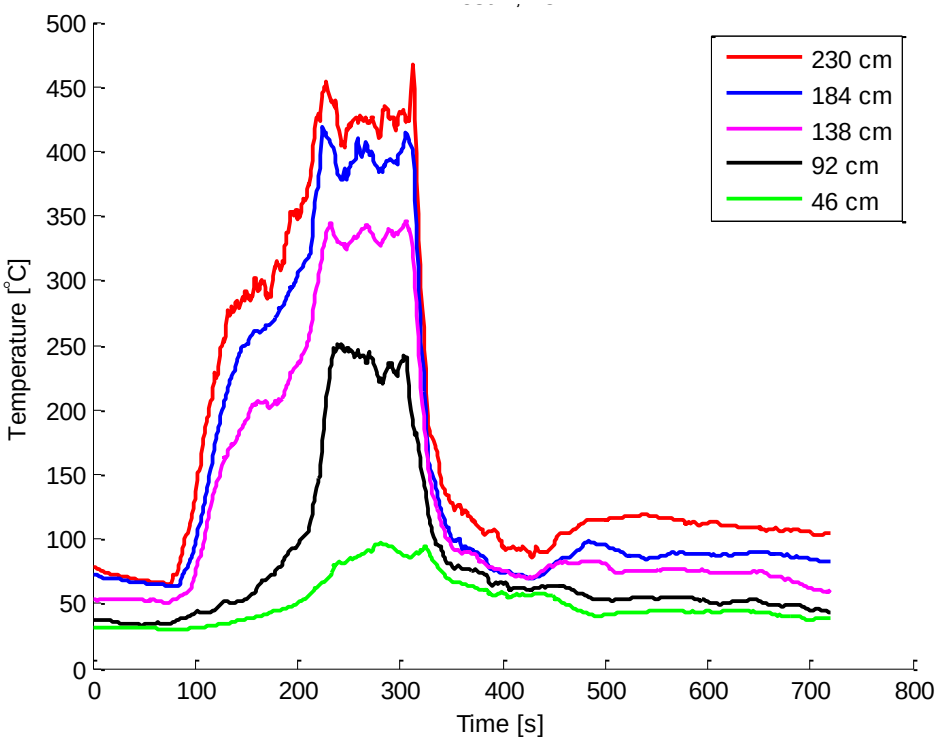

Figure 93: Temperatures, thermocouple tree T3.

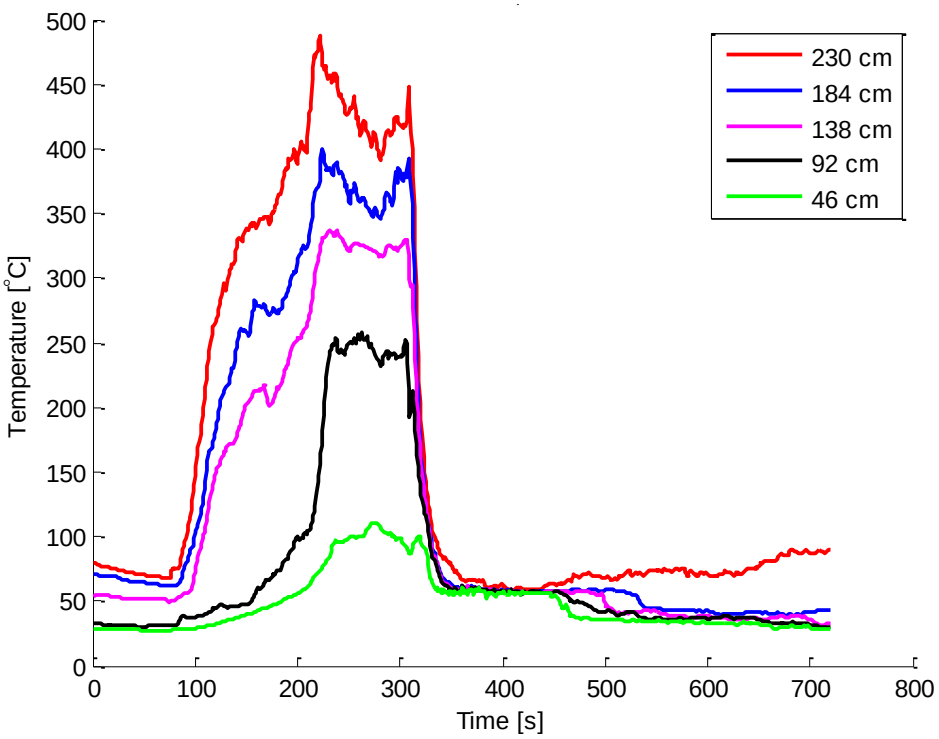

Figure 94: Temperatures, thermocouple tree T4.

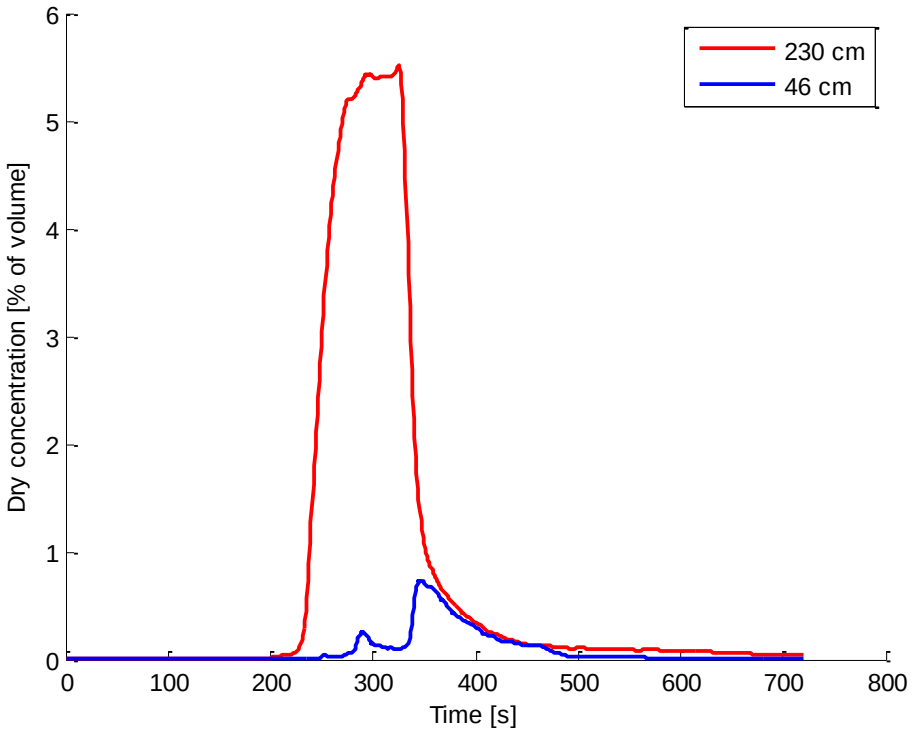

Figure 95: CO concentration.

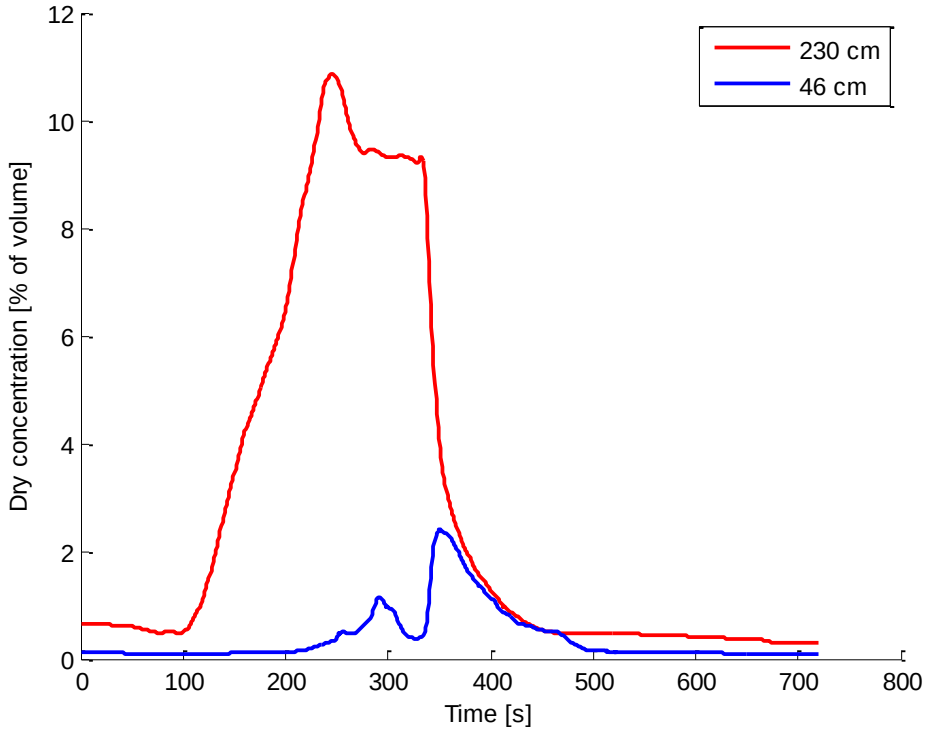

Figure 96: CO_2 concentration.

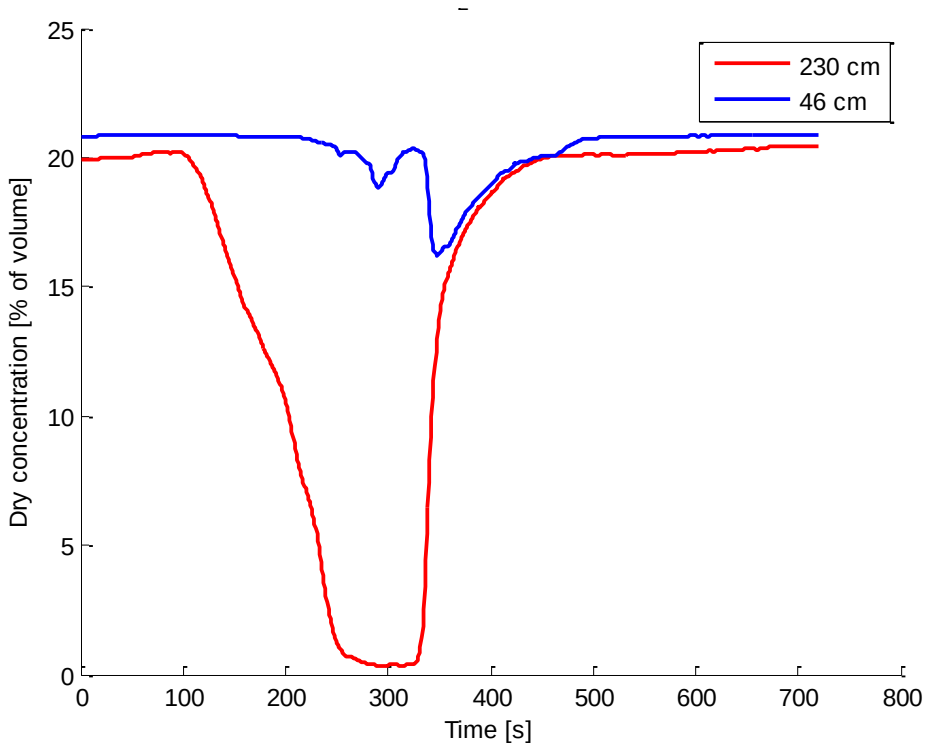

Figure 97: O_2 concentration.

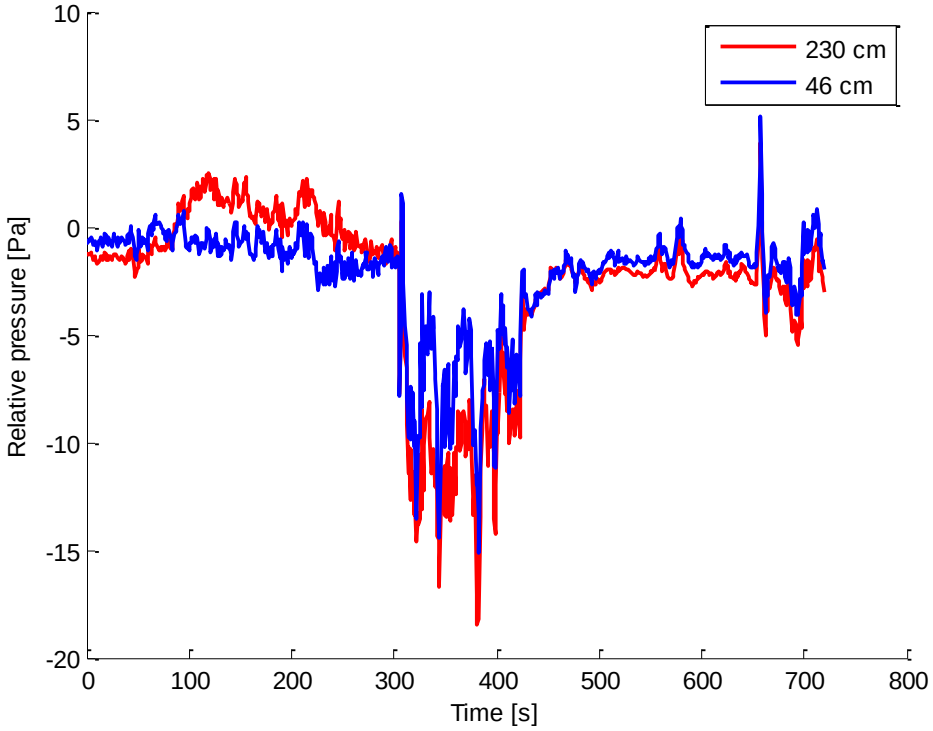

Figure 98: Relative pressure.

B.2.3 **Test 3**

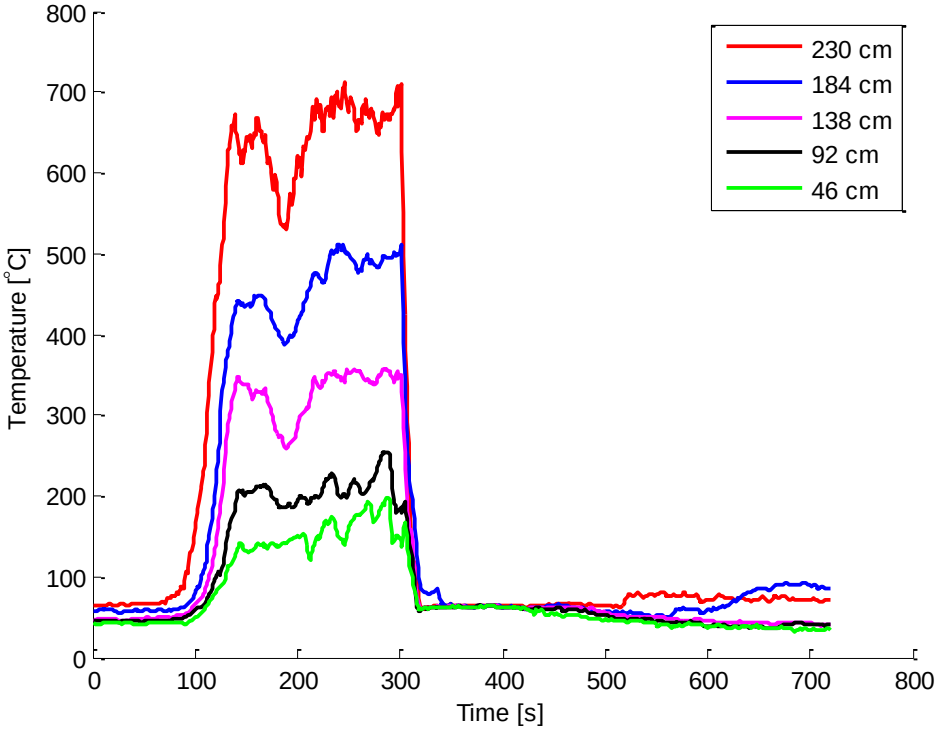

Figure 99: Temperatures, thermocouple tree T1.

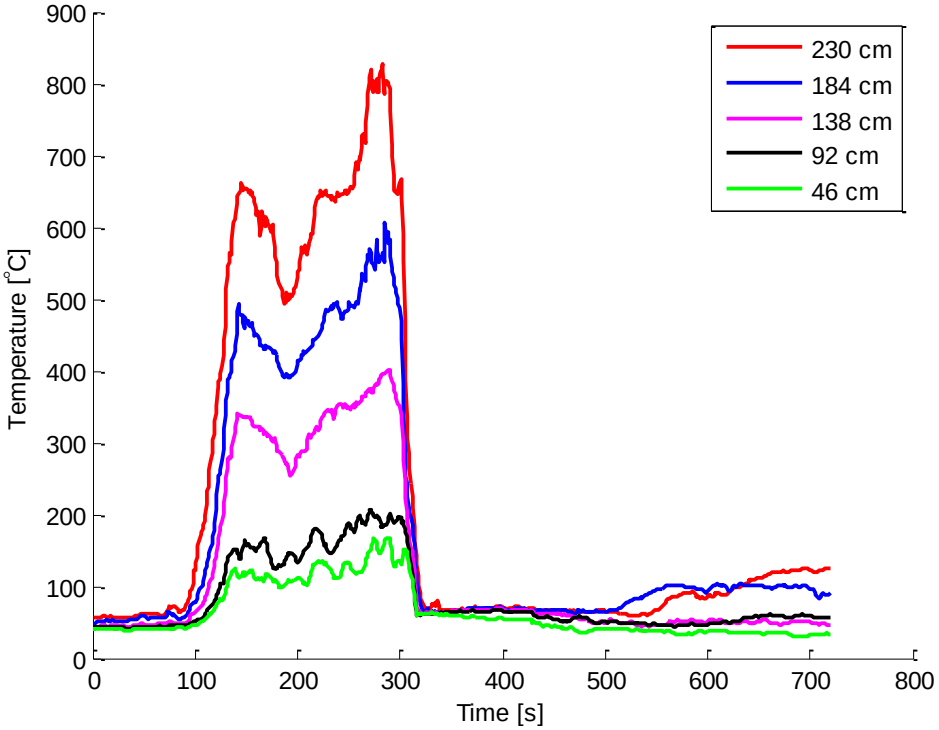

Figure 100: Temperatures, thermocouple tree T2.

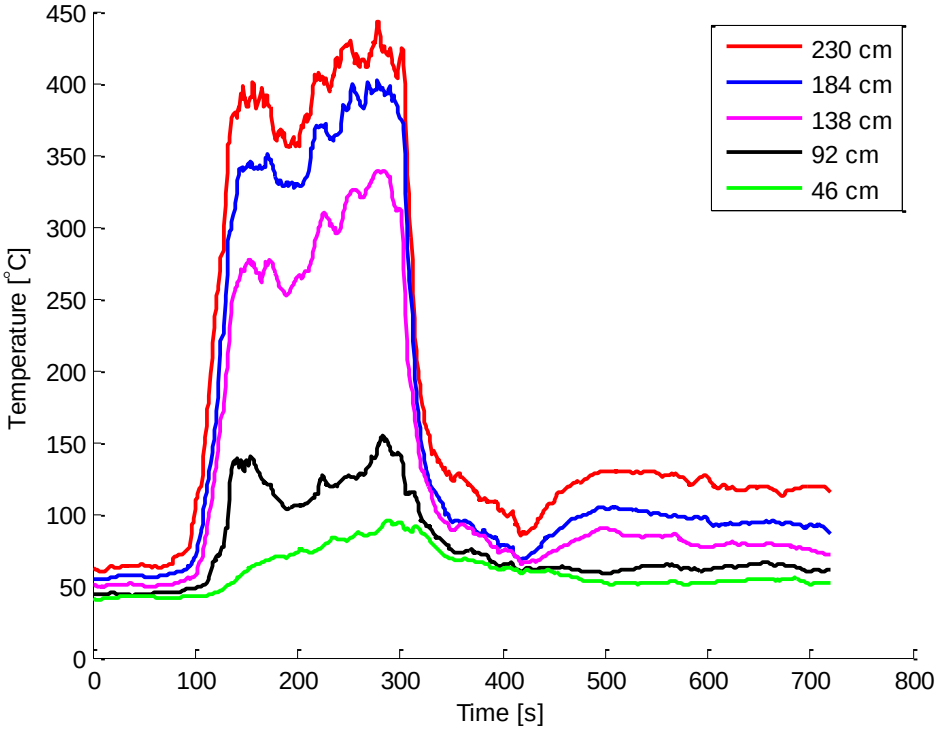

Figure 101: Temperatures, thermocouple tree T3.

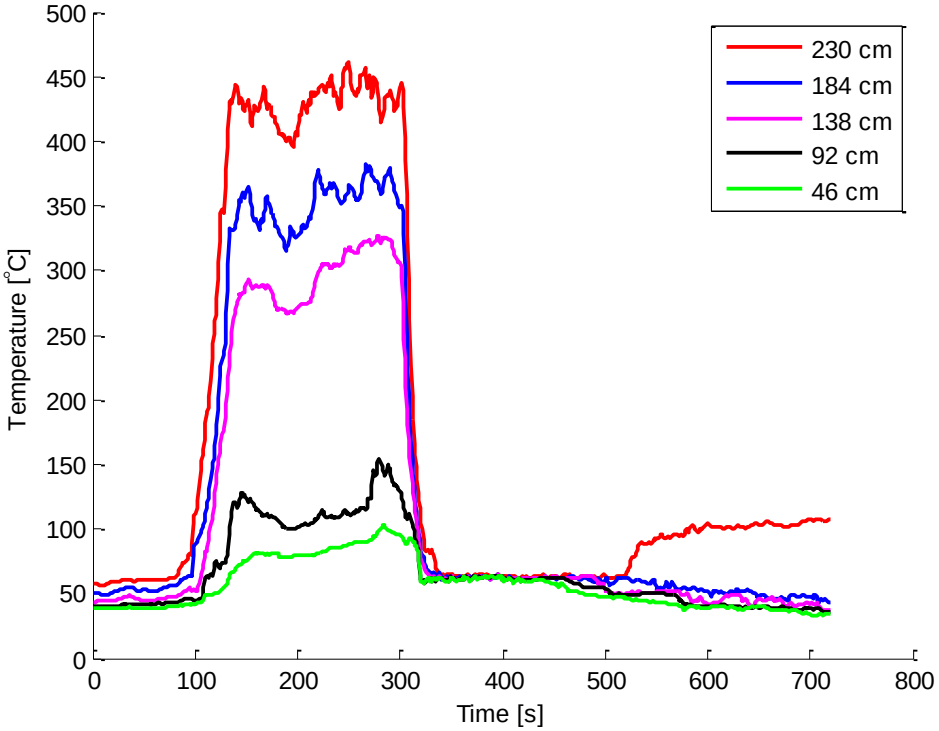

Figure 102: Temperatures, thermocouple tree T4.

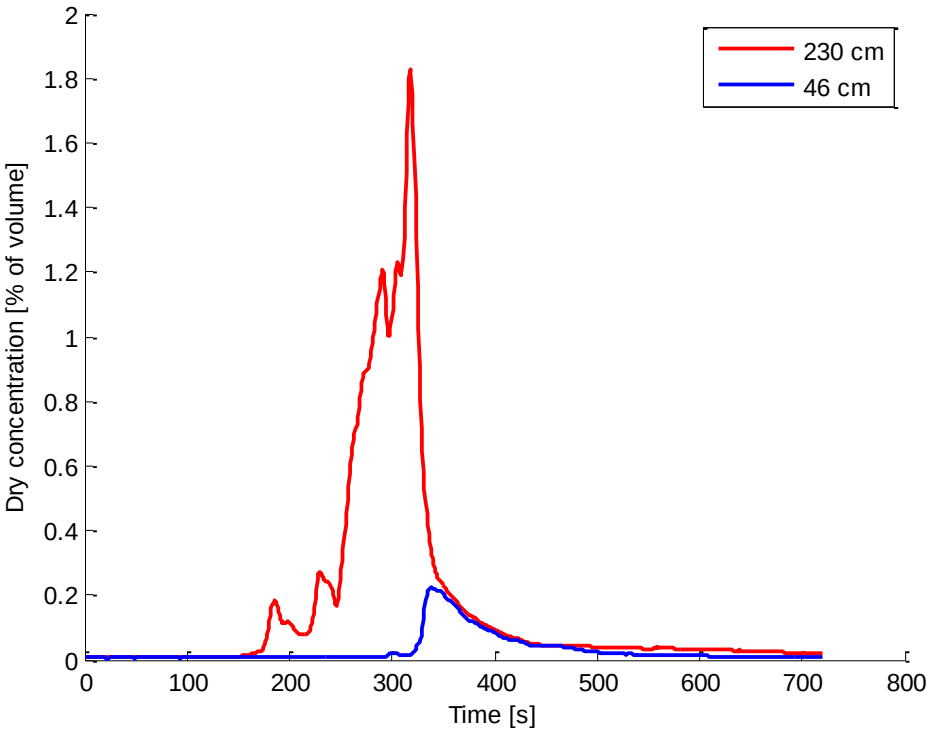

Figure 103: CO concentration.

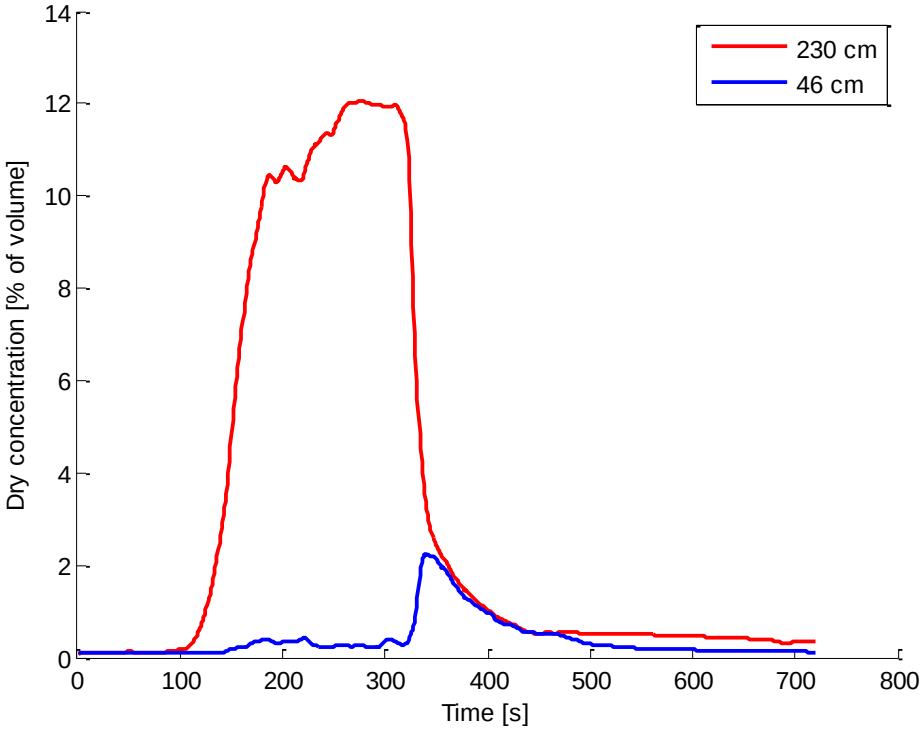

Figure 104: CO_2 concentration.

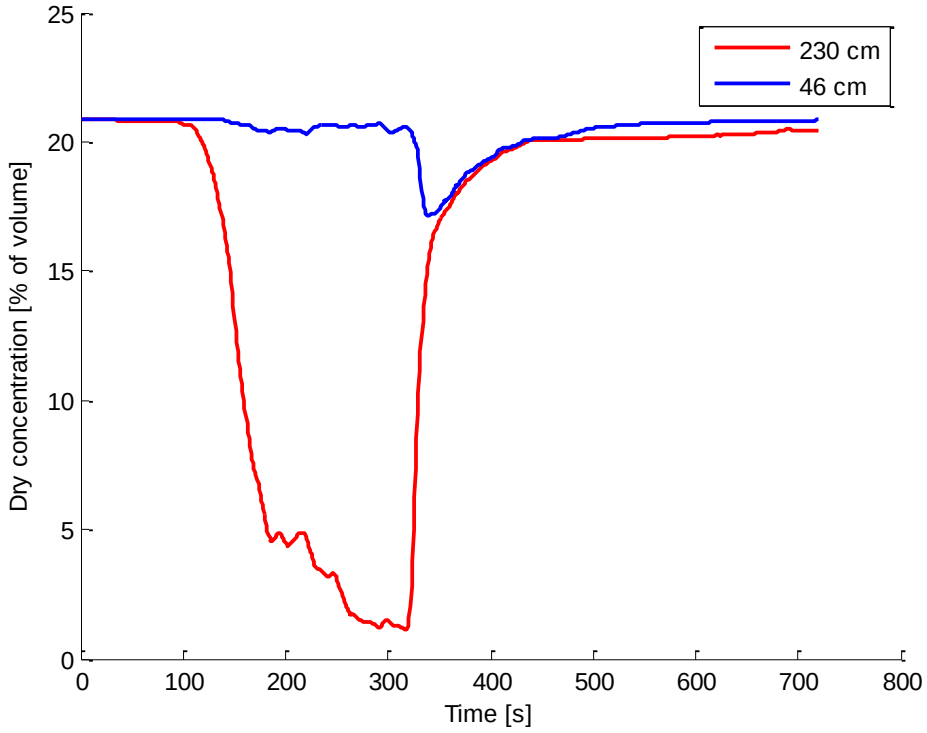

Figure 105: O_2 concentration.

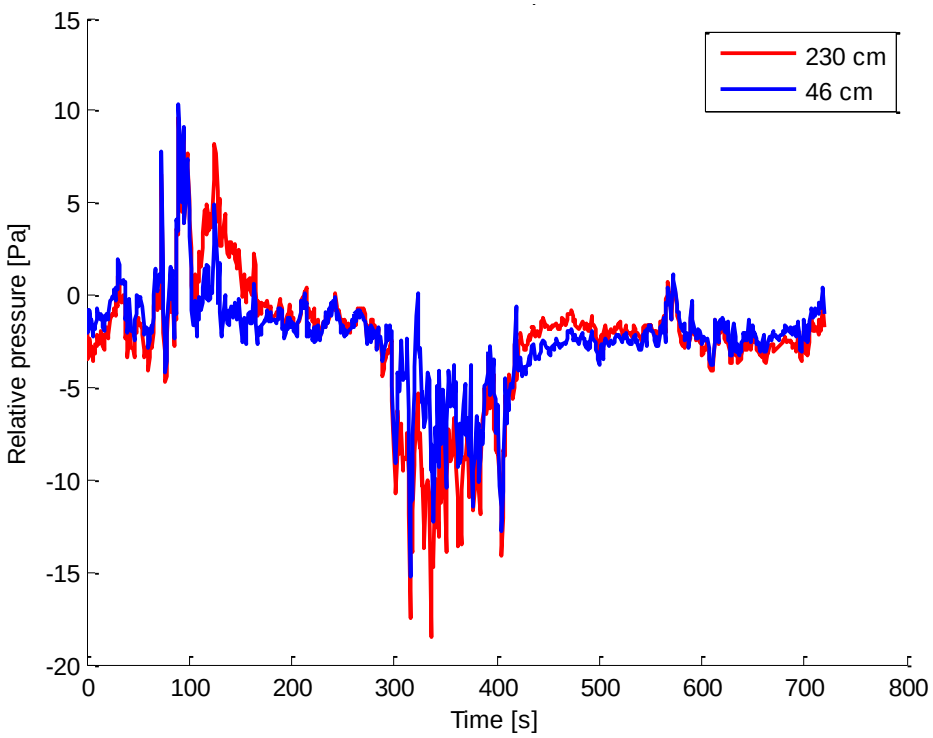

Figure 106: Relative pressure.

B.2.4 **Test 4**

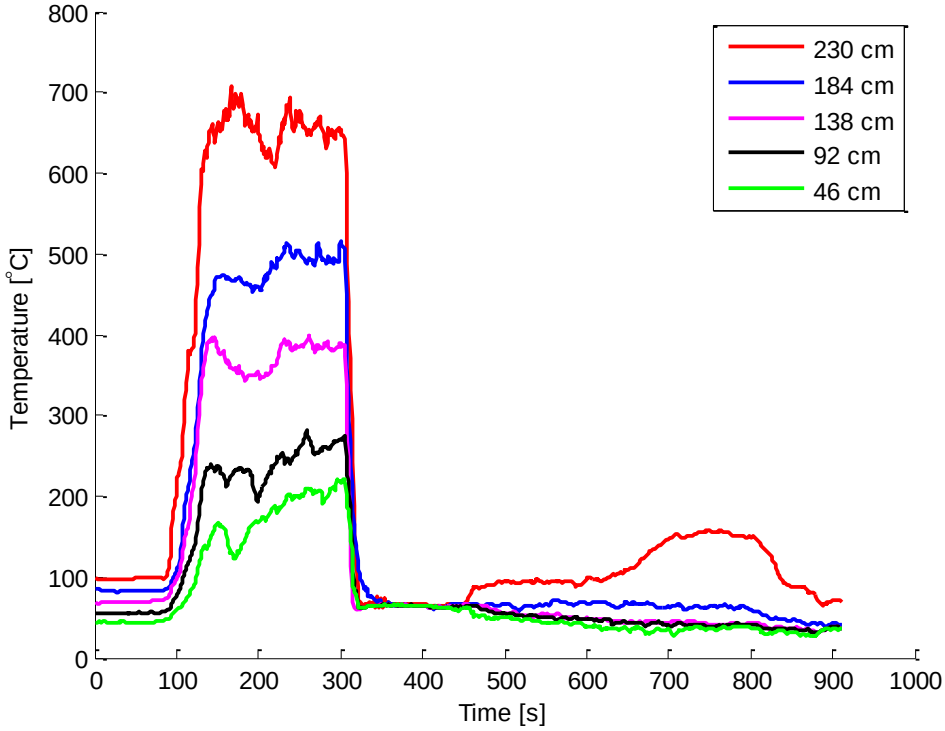

Figure 107: Temperatures, thermocouple tree T1.

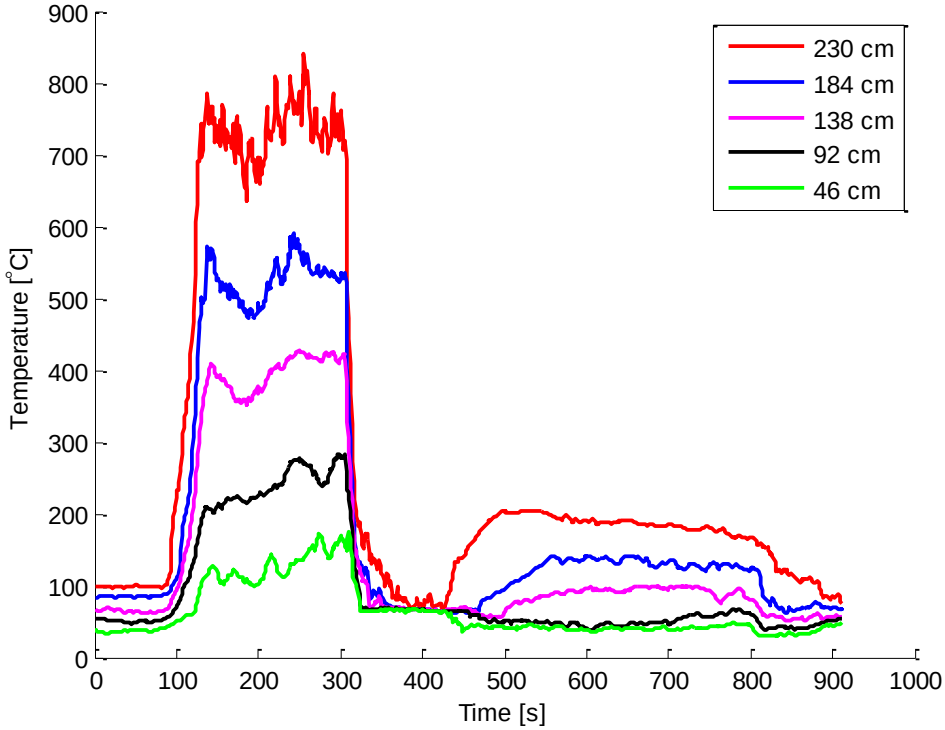

Figure 108: Temperatures, thermocouple tree T2.

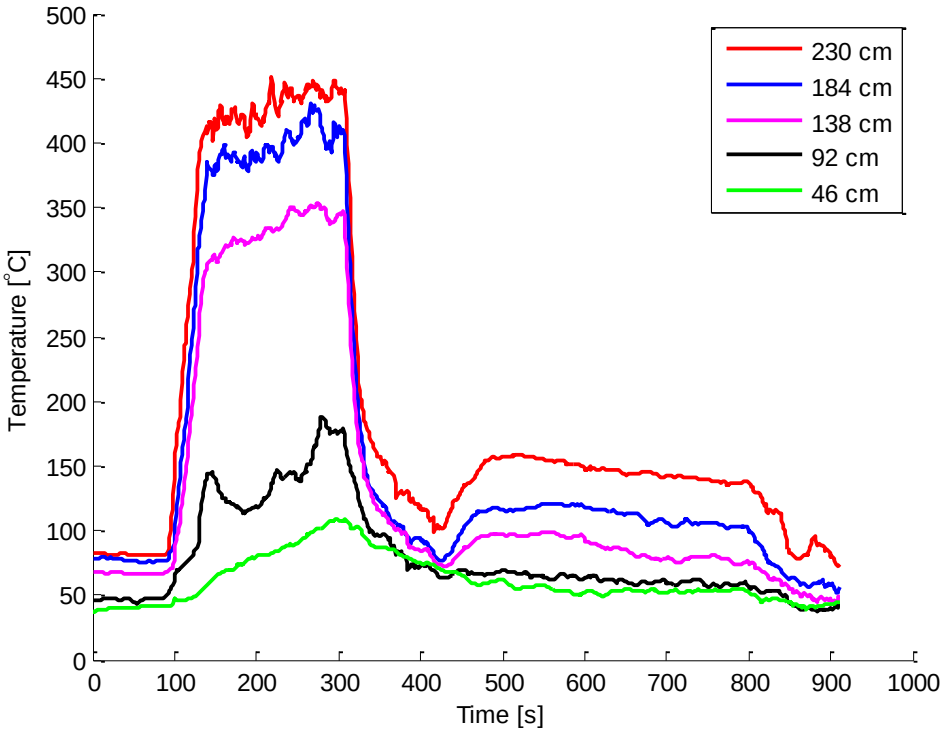

Figure 109: Temperatures, thermocouple tree T3.

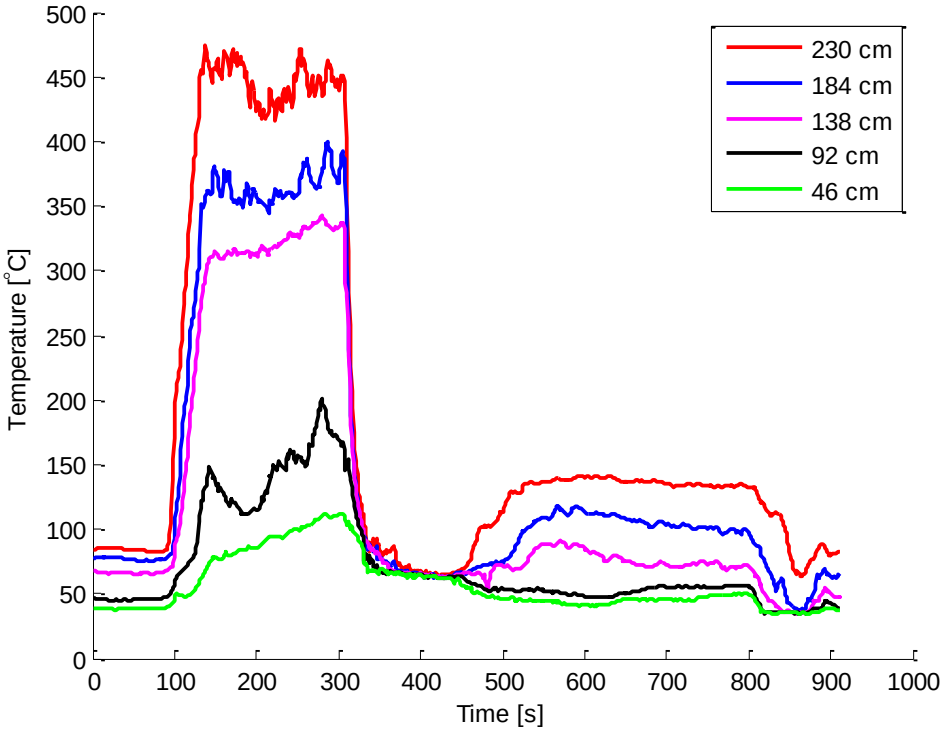

Figure 110: Temperatures, thermocouple tree T4.

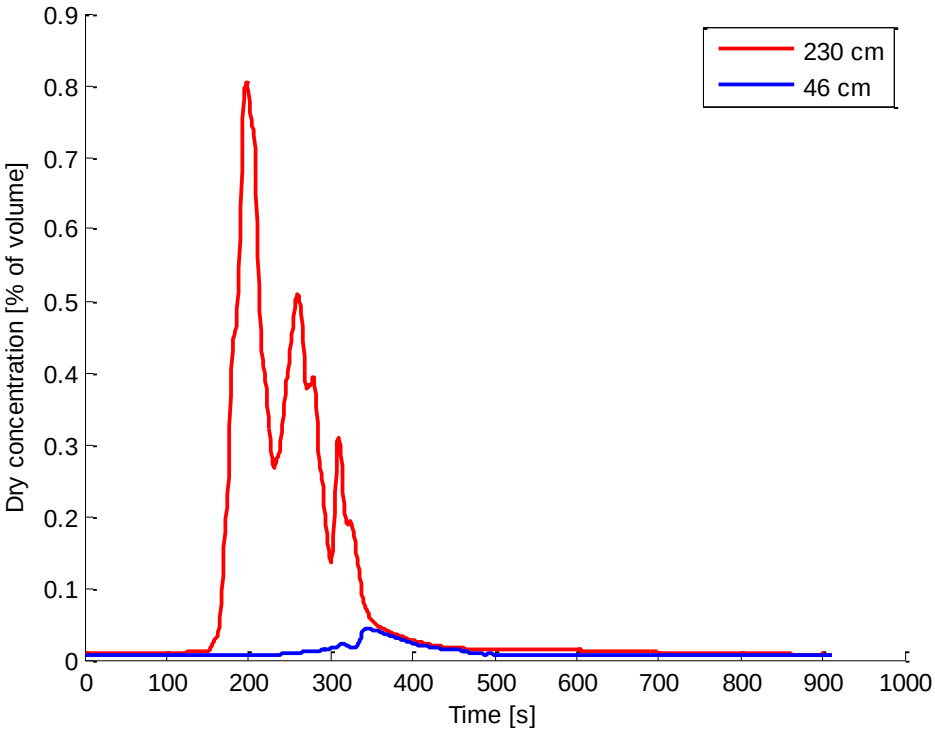

Figure 111: CO concentration.

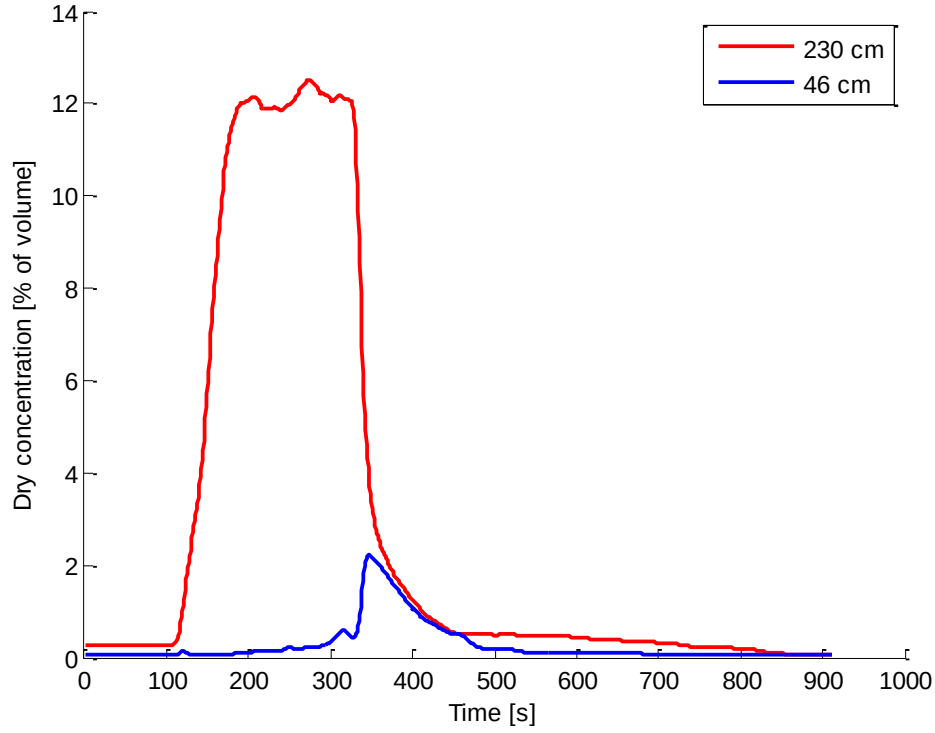

Figure 112: CO_2 concentration.

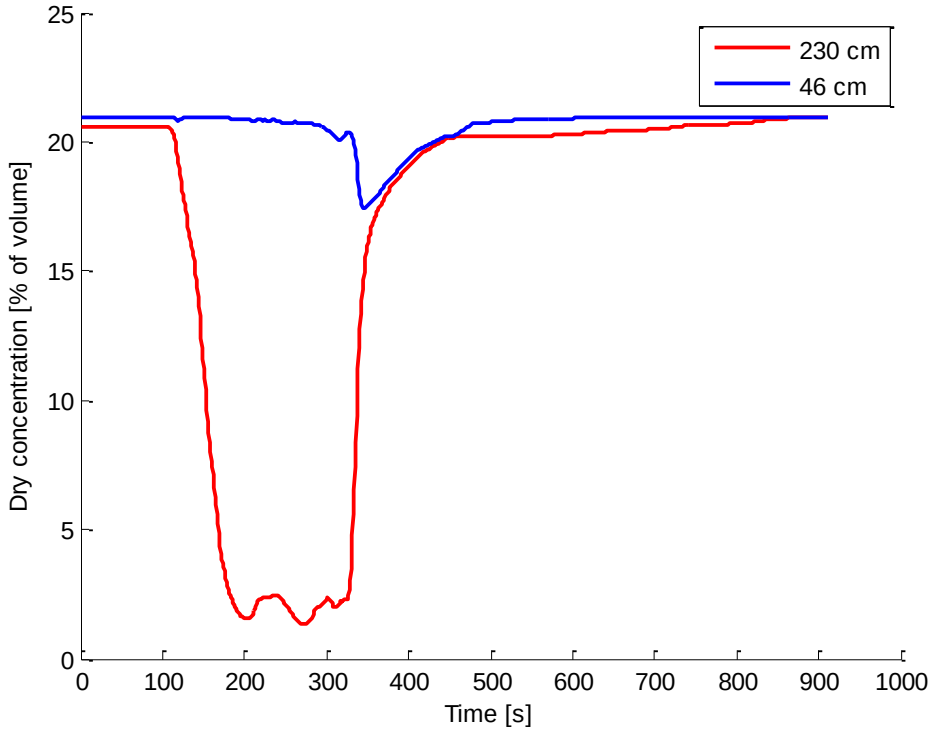

Figure 113: O_2 concentration.

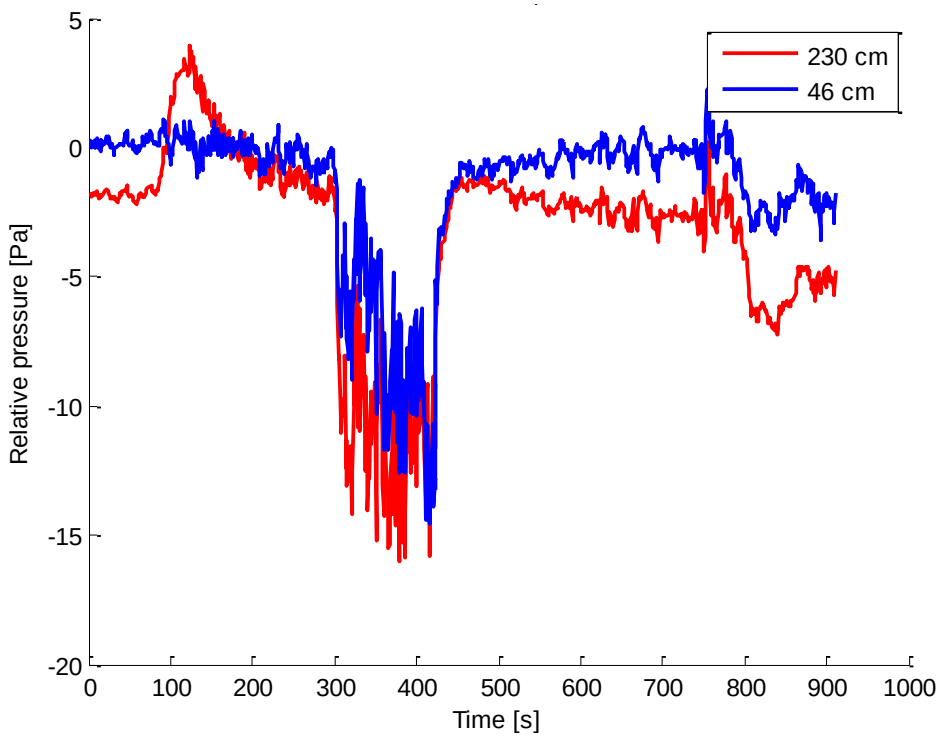

Figure 114: Relative pressure.

B.2.5 **Test 5**

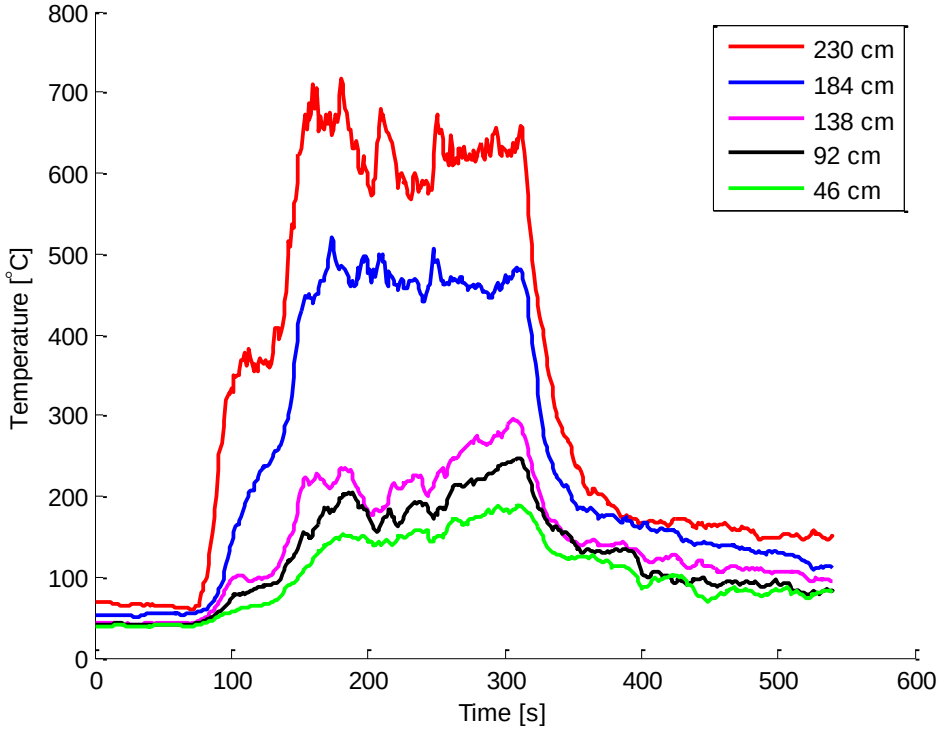

Figure 115: Temperatures, thermocouple tree T1.

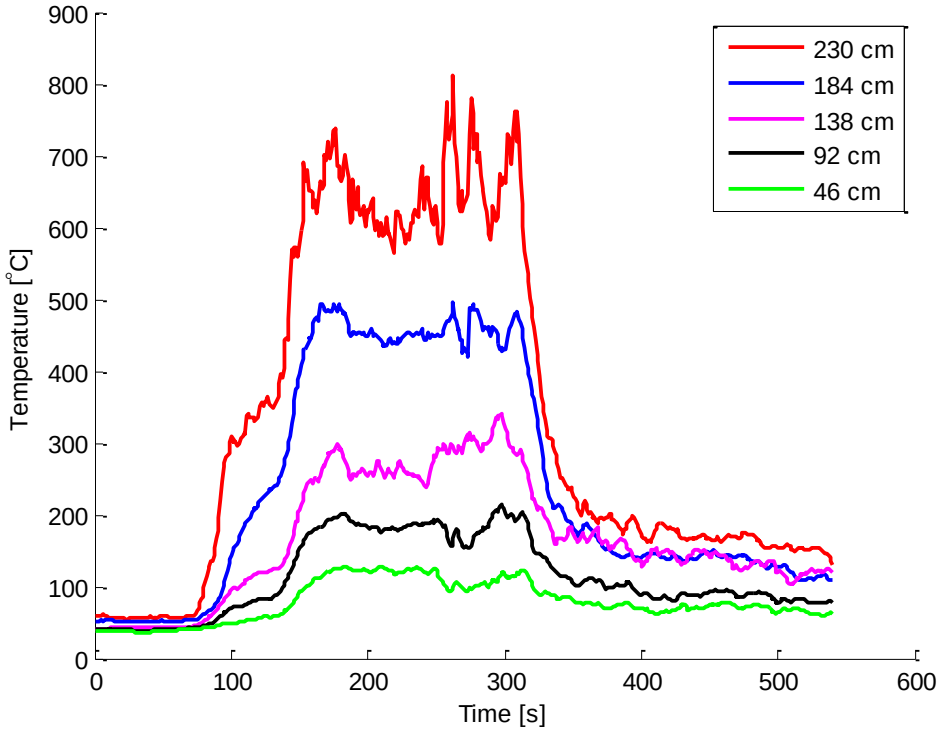

Figure 116: Temperatures, thermocouple tree T2.

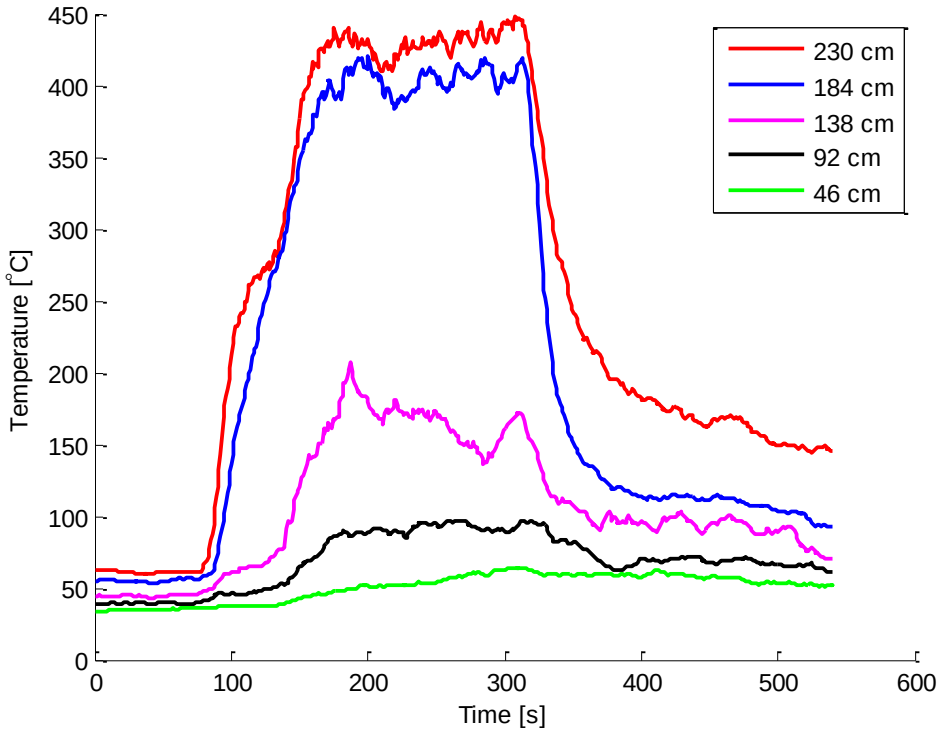

Figure 117: Temperatures, thermocouple tree T3.

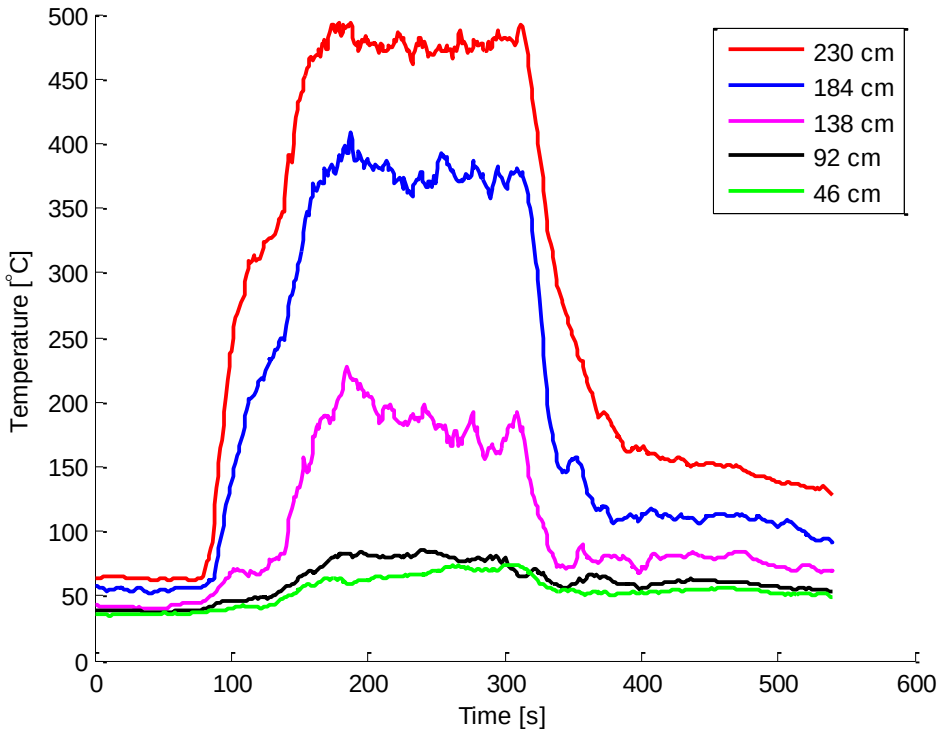

Figure 118: Temperatures, thermocouple tree T4.

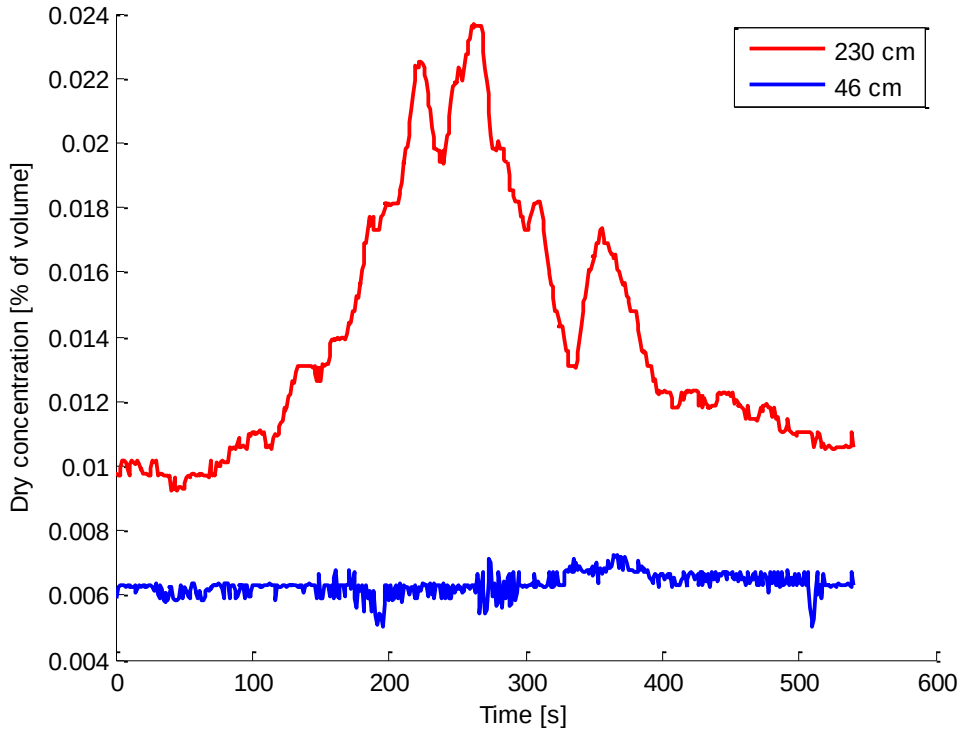

Figure 119: CO concentration.

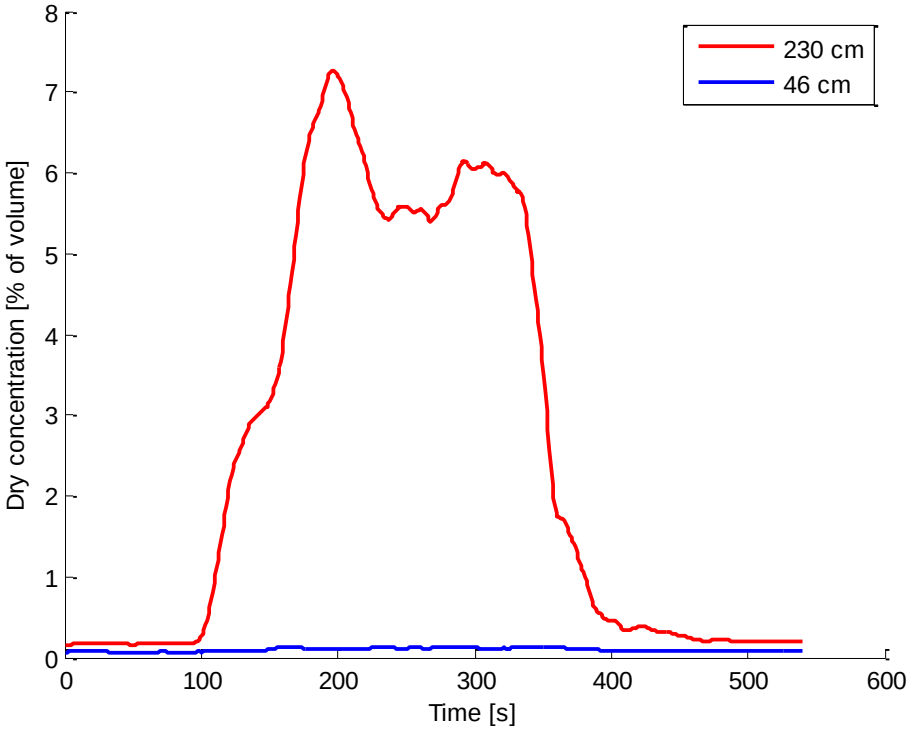

Figure 120: CO_2 concentration.

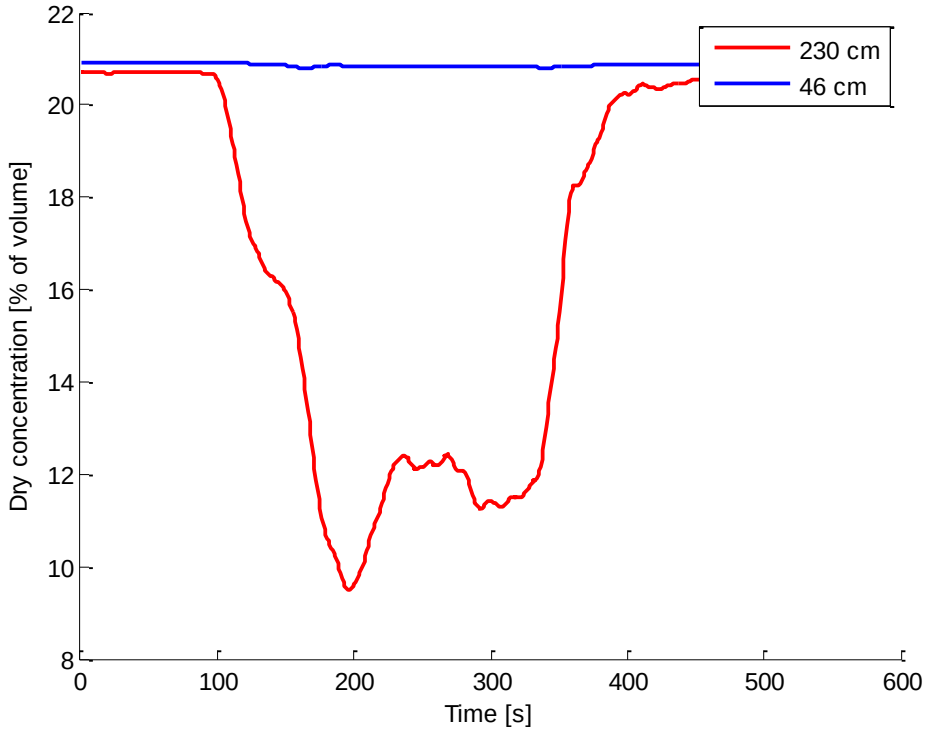

Figure 121: O_2 concentration.

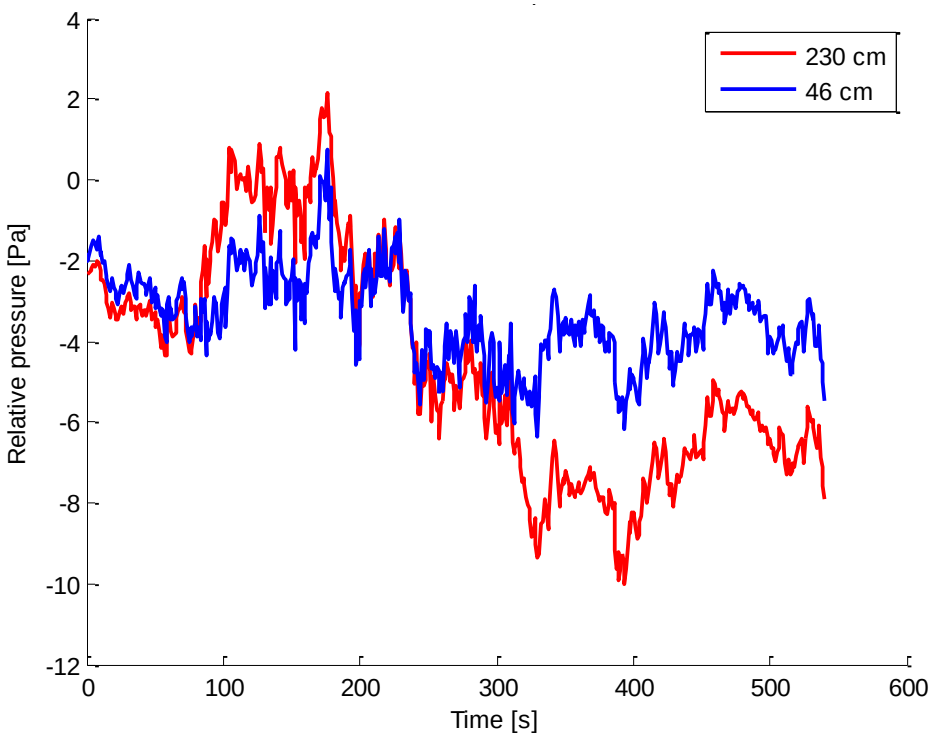

Figure 122: Relative pressure.

B.2.6 **Test 6**

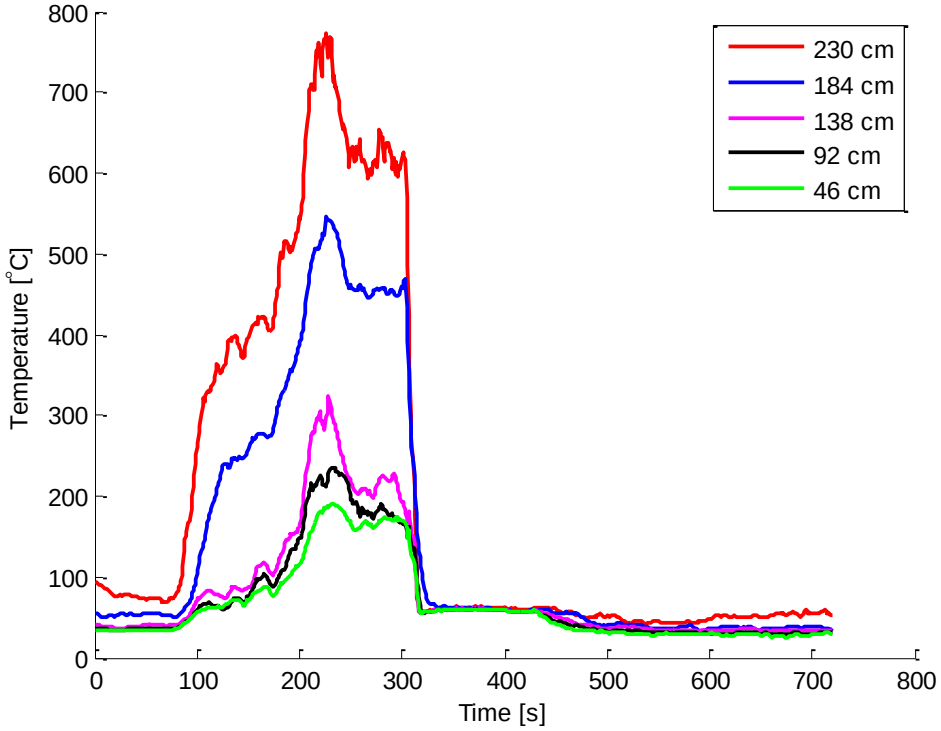

Figure 123: Temperatures, thermocouple tree T1.

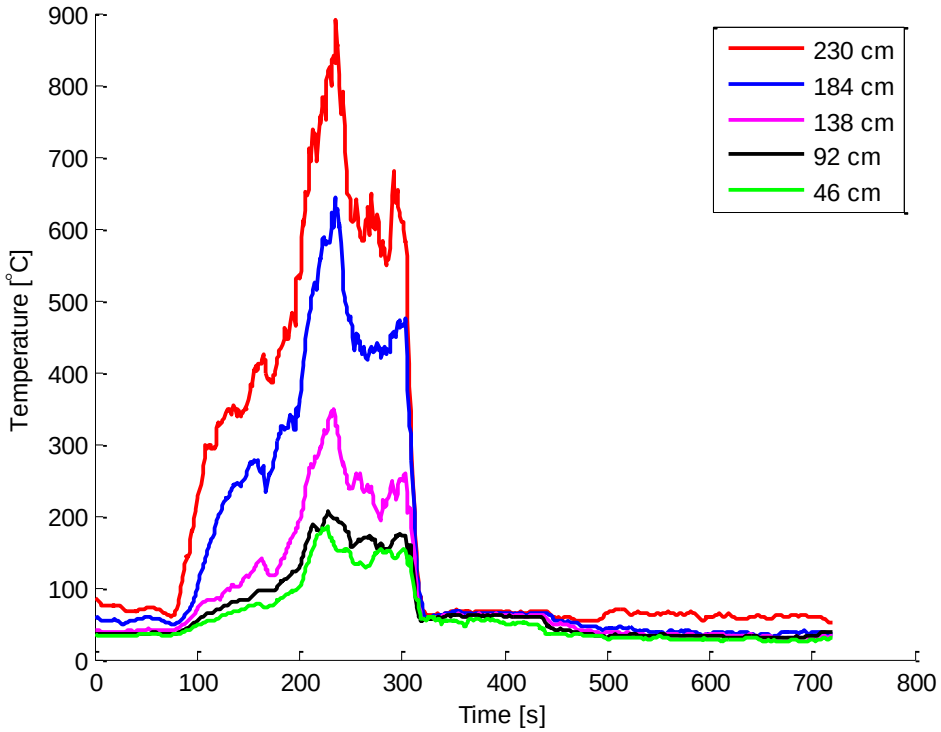

Figure 124: Temperatures, thermocouple tree T2.

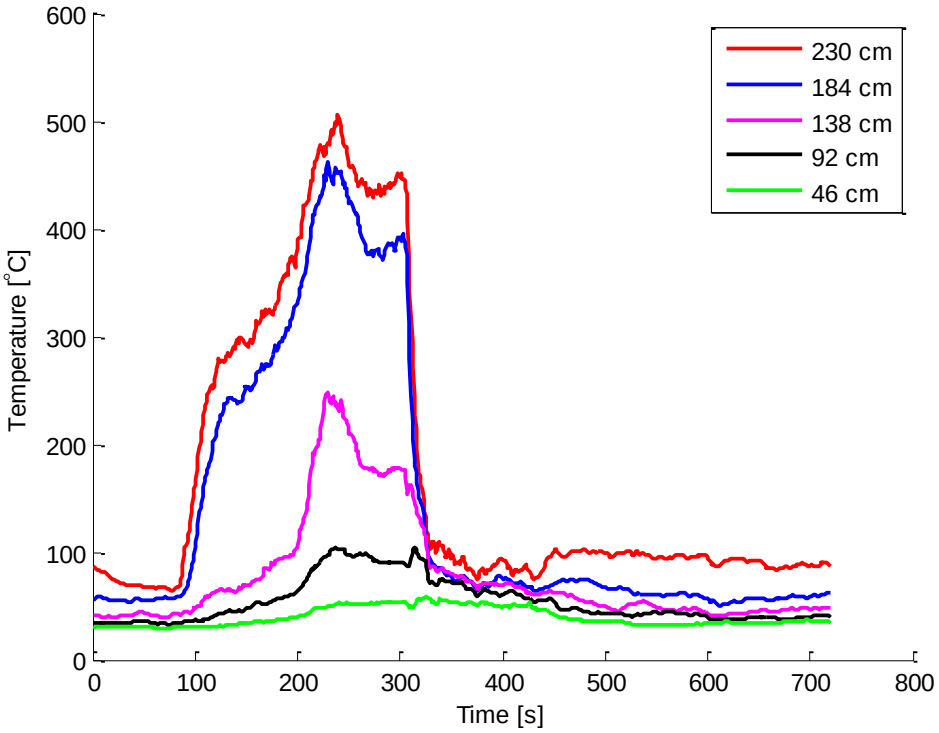

Figure 125: Temperatures, thermocouple tree T3.

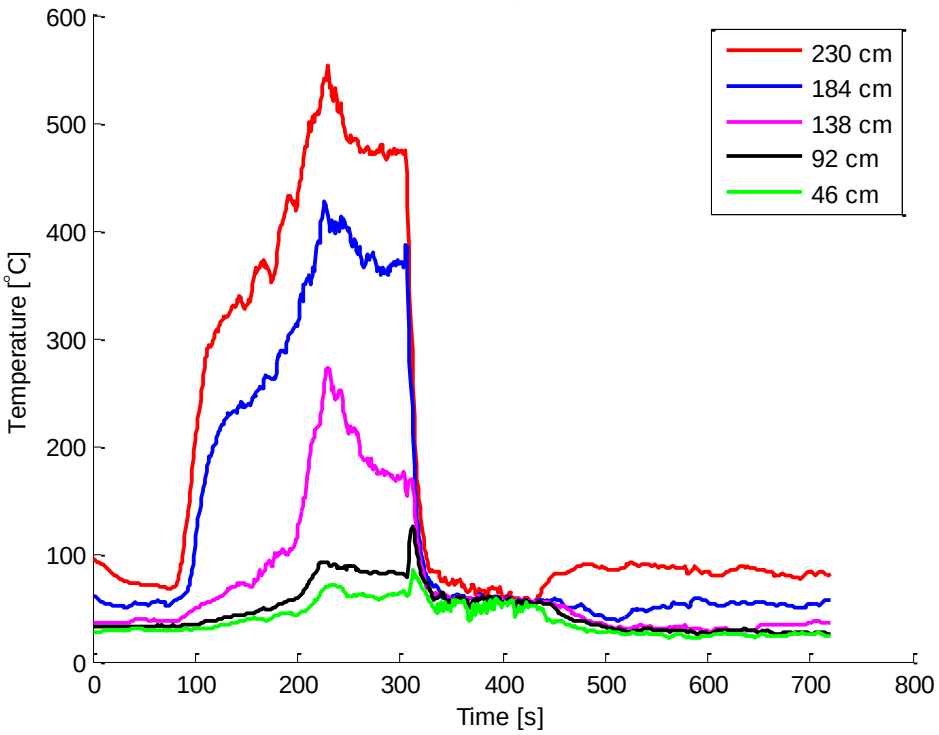

Figure 126: Temperatures, thermocouple tree T4.

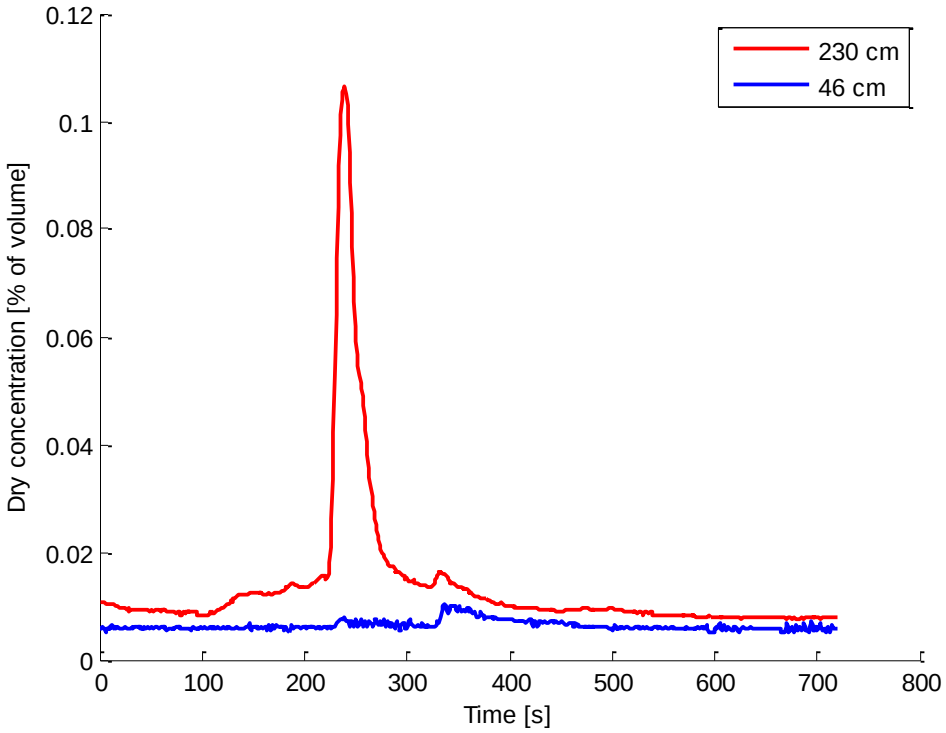

Figure 127: CO concentration.

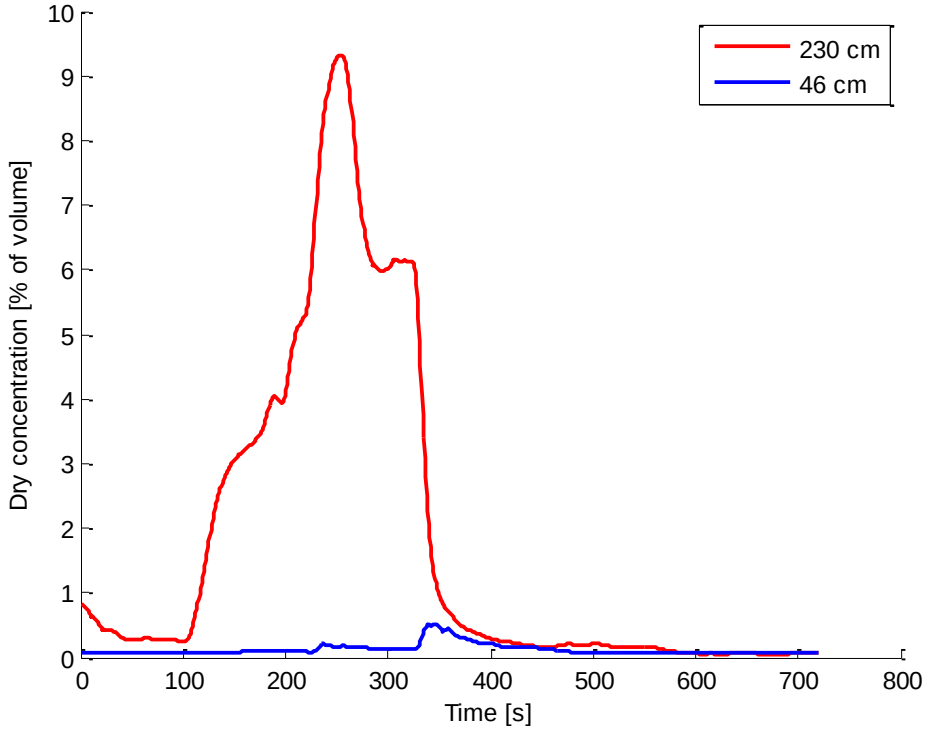

Figure 128: CO_2 concentration.

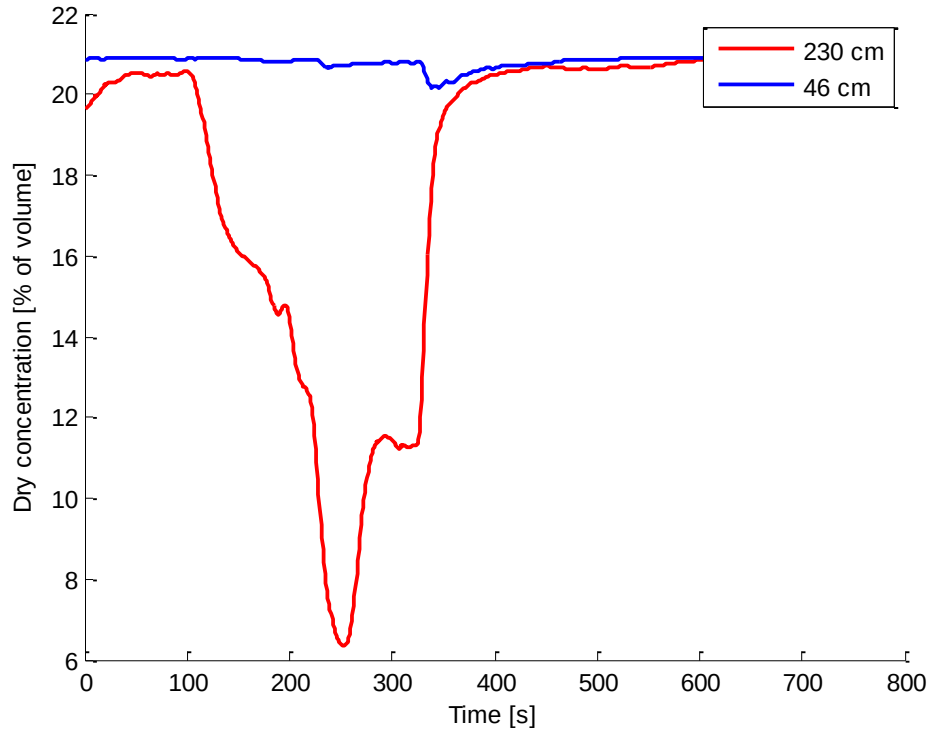

Figure 129: O_2 concentration.

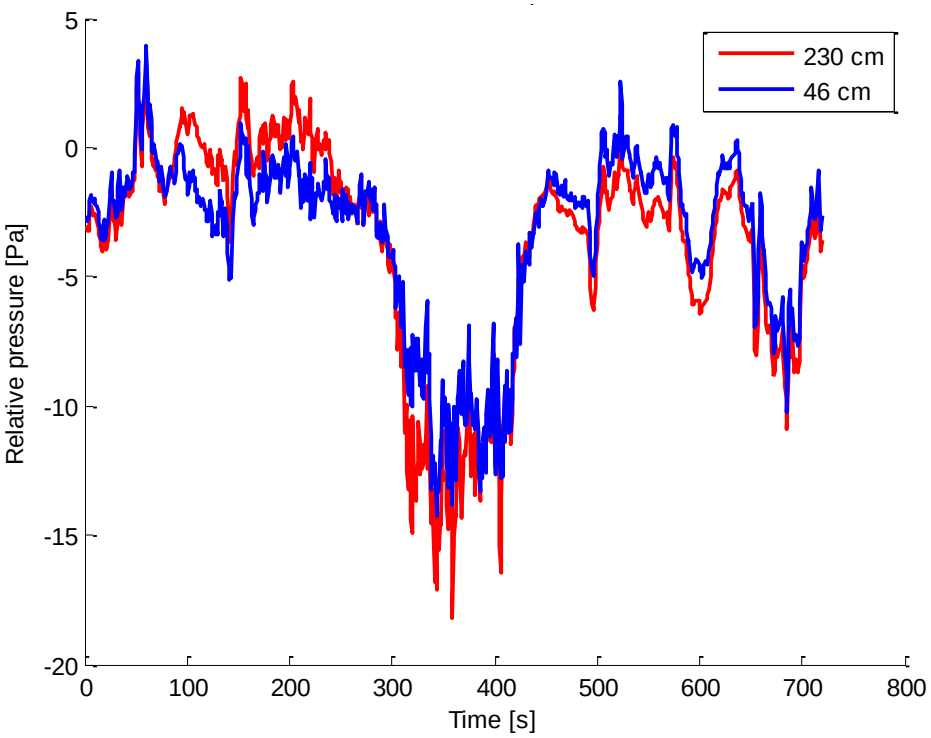

Figure 130: Relative pressure.

B.2.7 **Test 7**

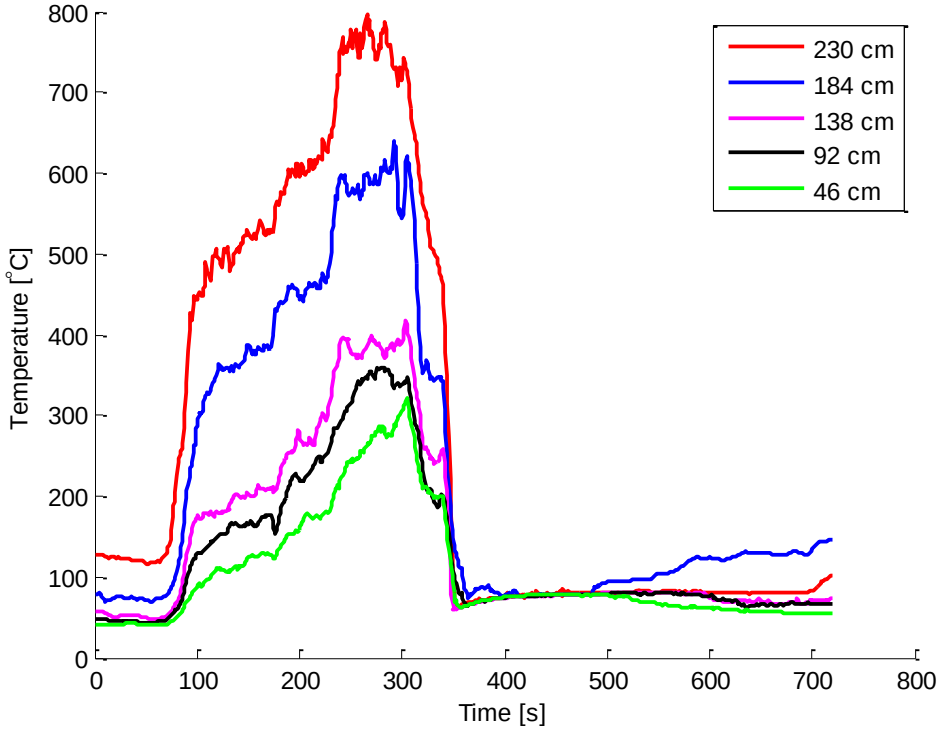

Figure 131: Temperatures, thermocouple tree T1.

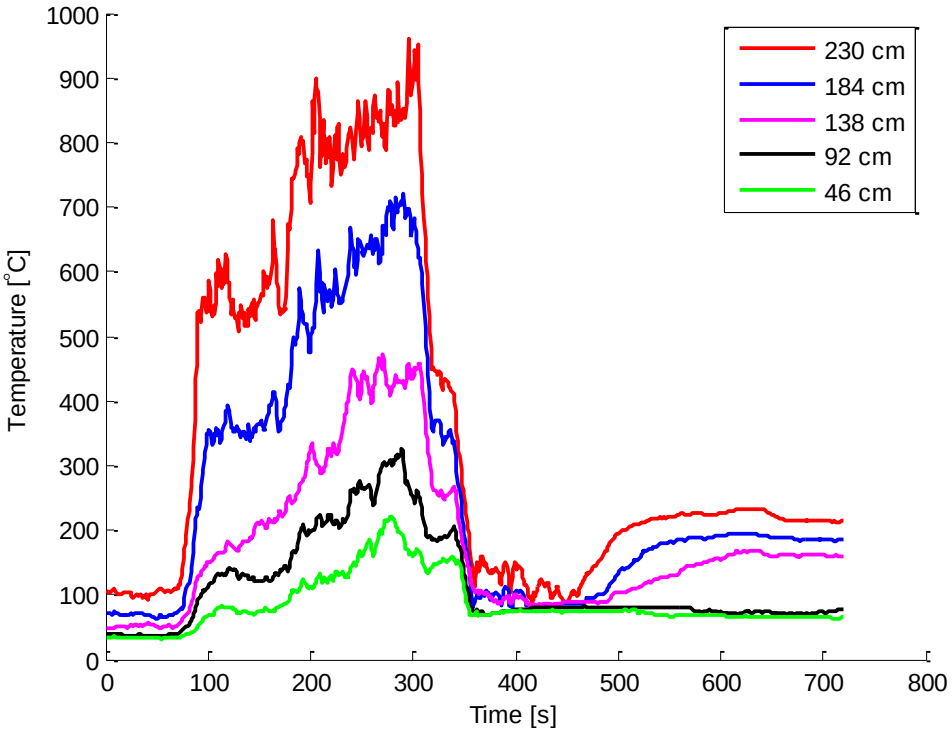

Figure 132: Temperatures, thermocouple tree T2.

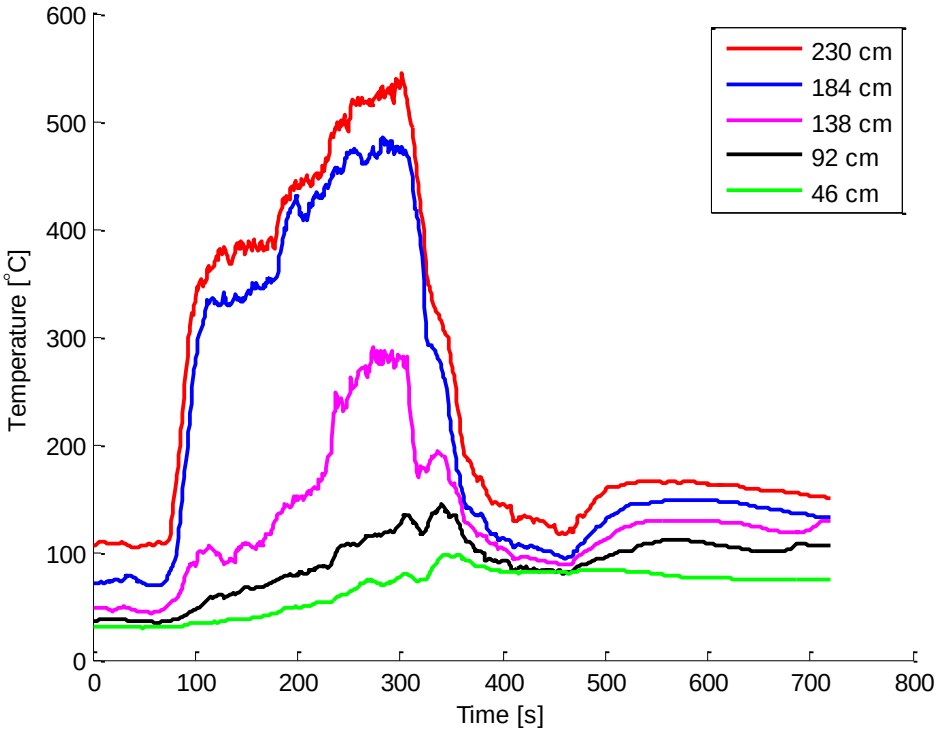

Figure 133: Temperatures, thermocouple tree T3.

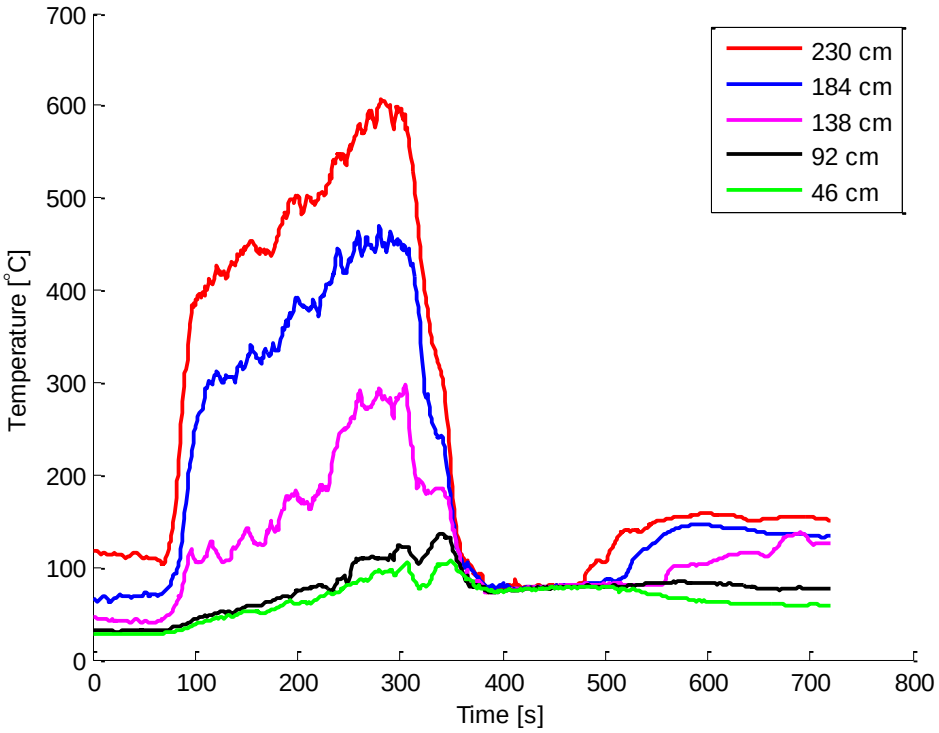

Figure 134: Temperatures, thermocouple tree T4.

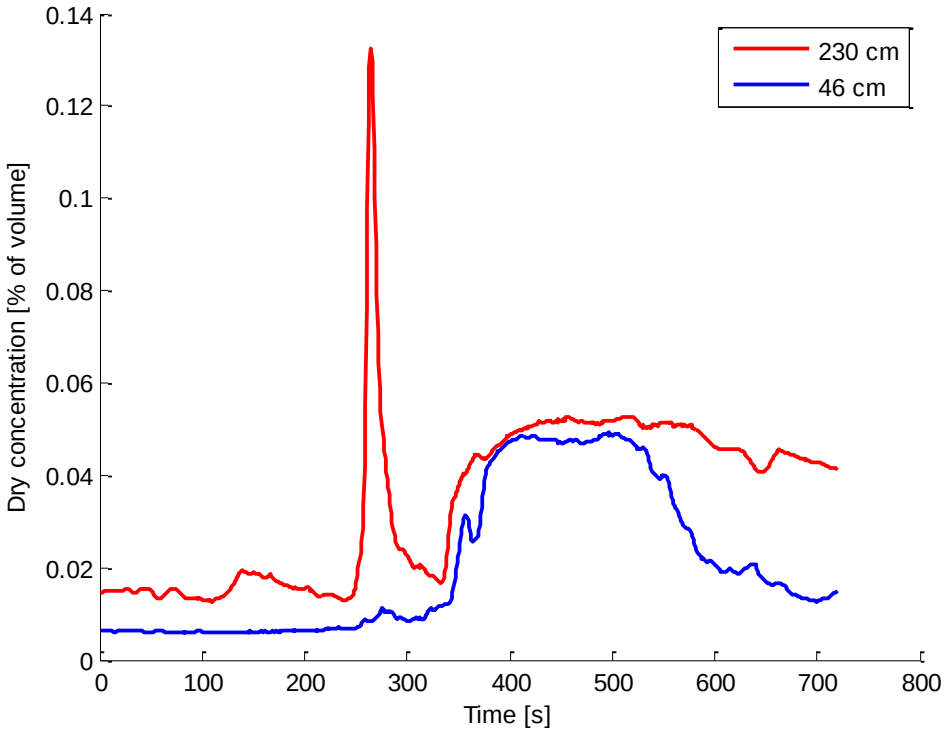

Figure 135: CO concentration.

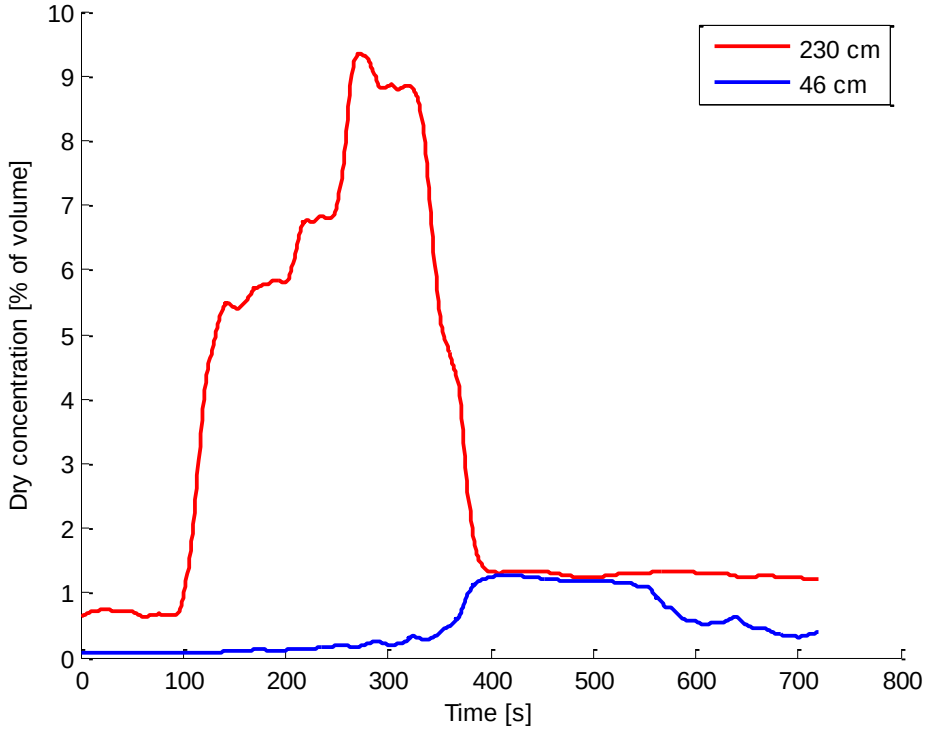

Figure 136: CO_2 concentration.

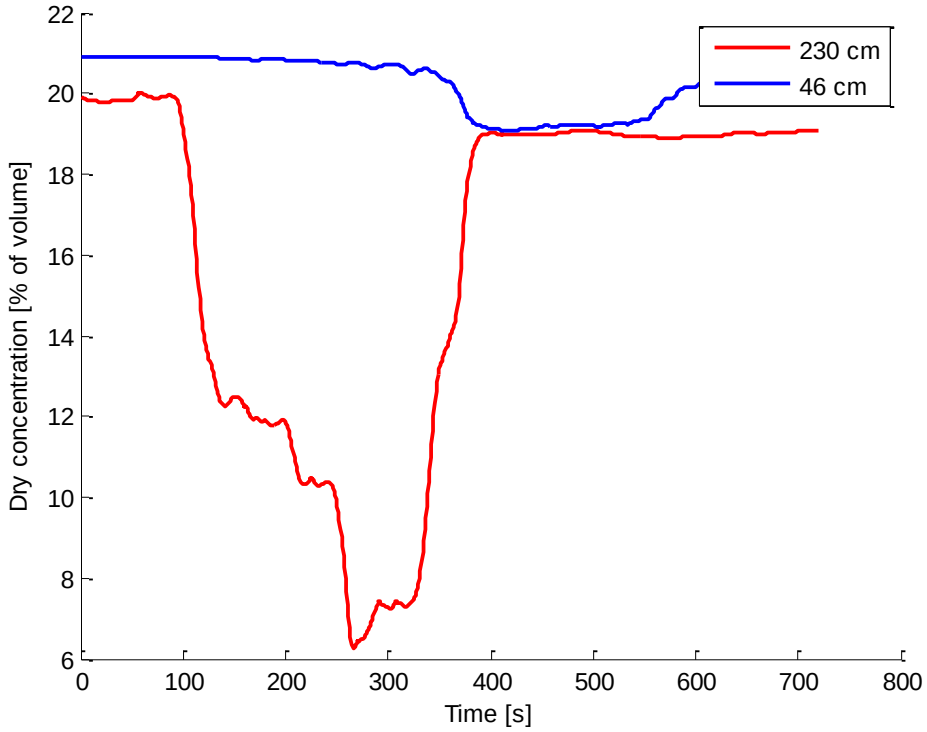

Figure 137: O_2 concentration.

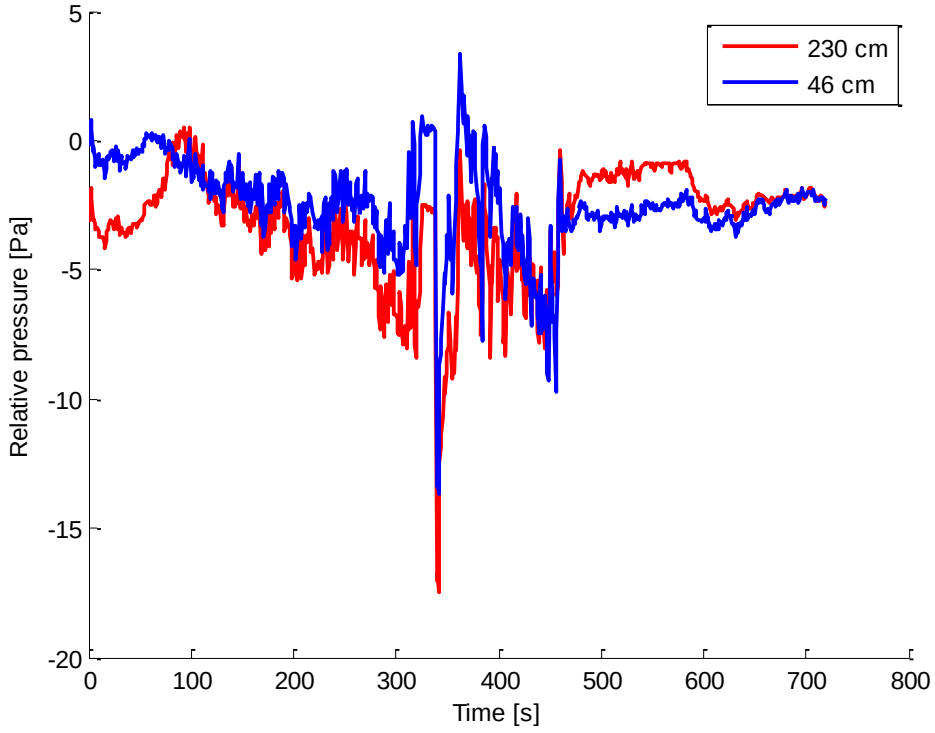

Figure 138: Relative pressure.

B.2.8 **Test 8**

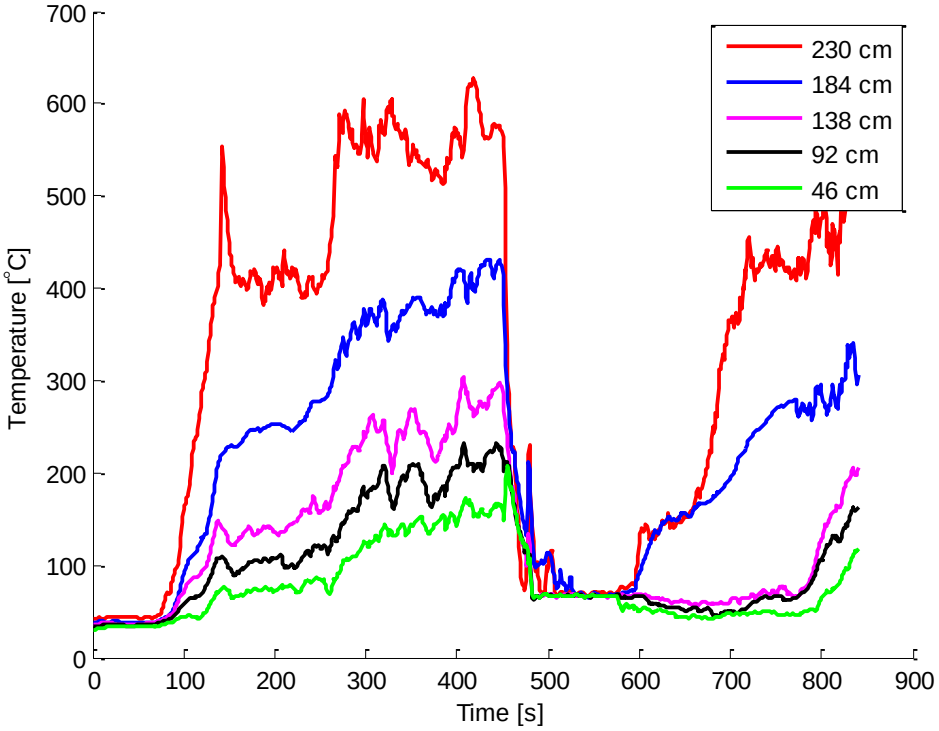

Figure 139: Temperatures, thermocouple tree T1.

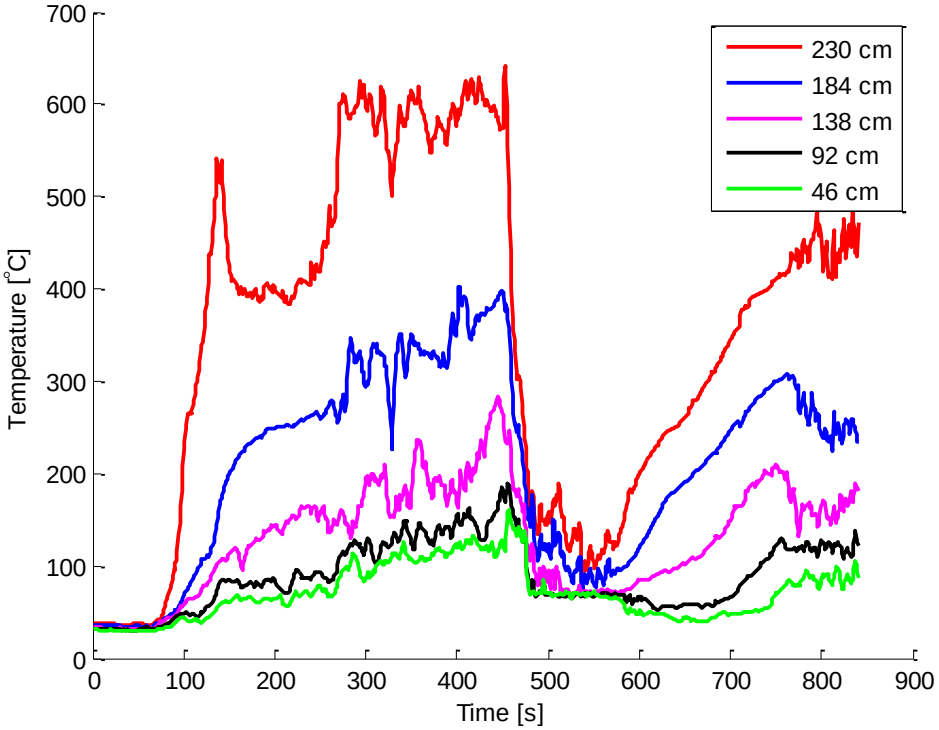

Figure 140: Temperatures, thermocouple tree T2.

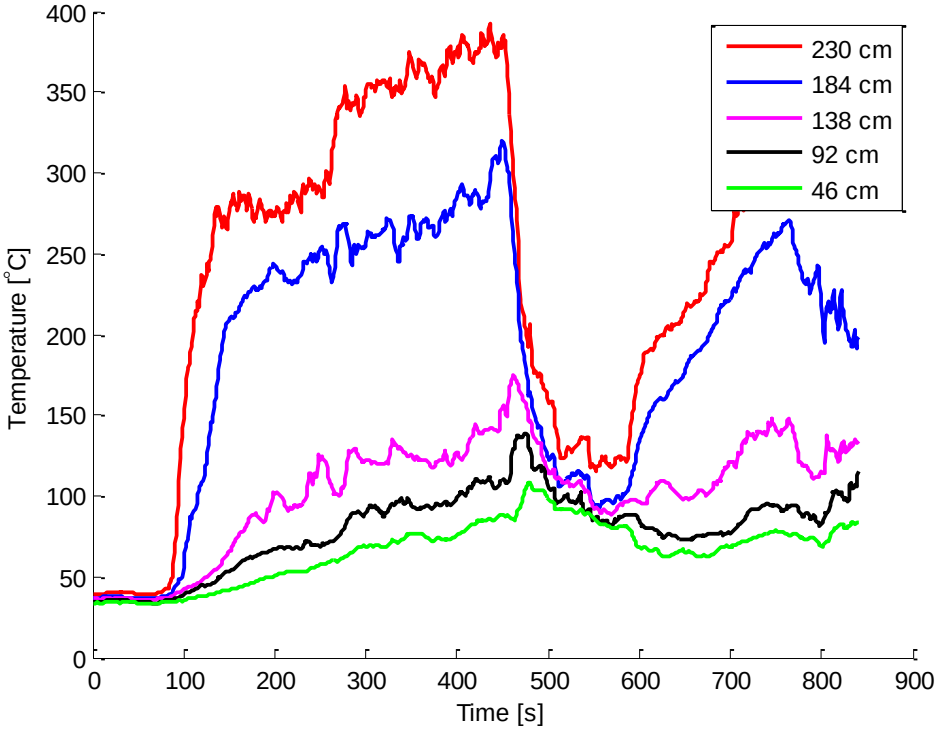

Figure 141: Temperatures, thermocouple tree T3.

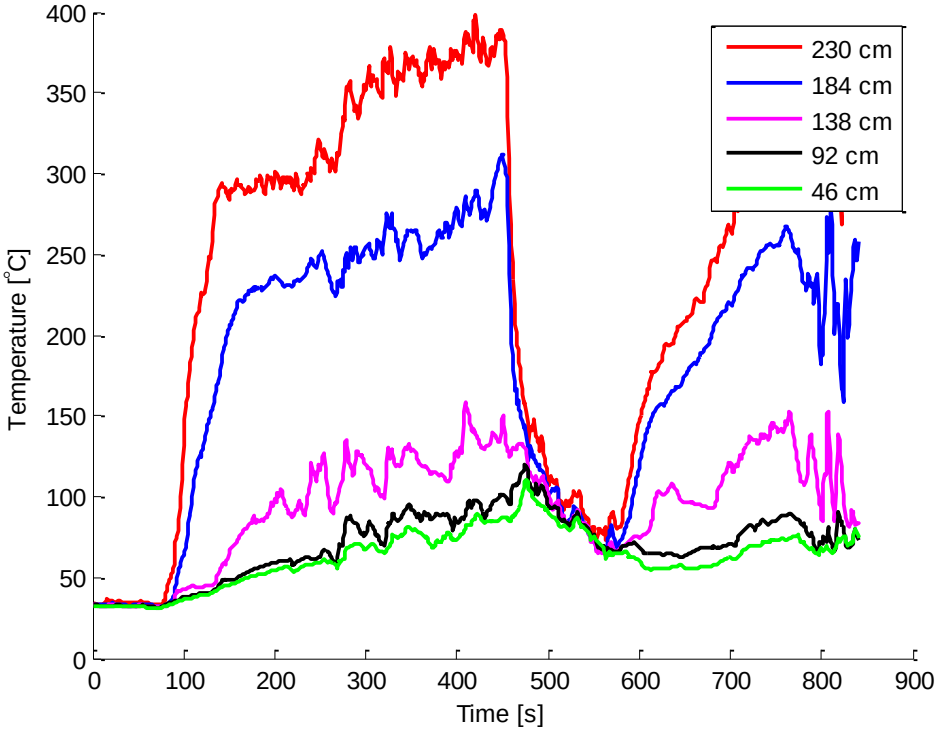

Figure 142: Temperatures, thermocouple tree T4.

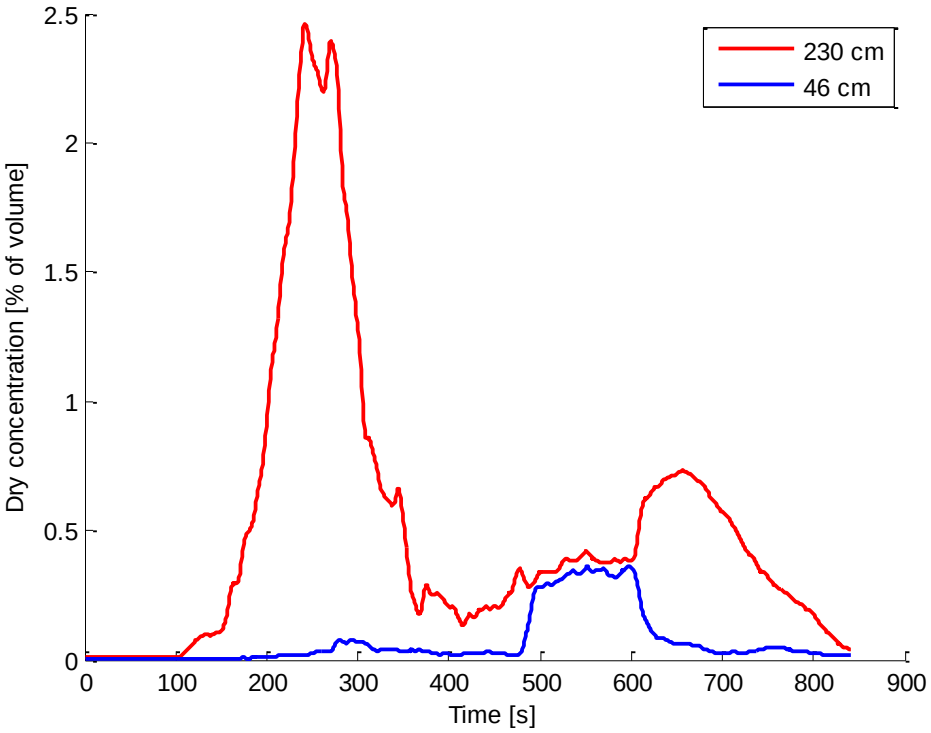

Figure 143: CO concentration.

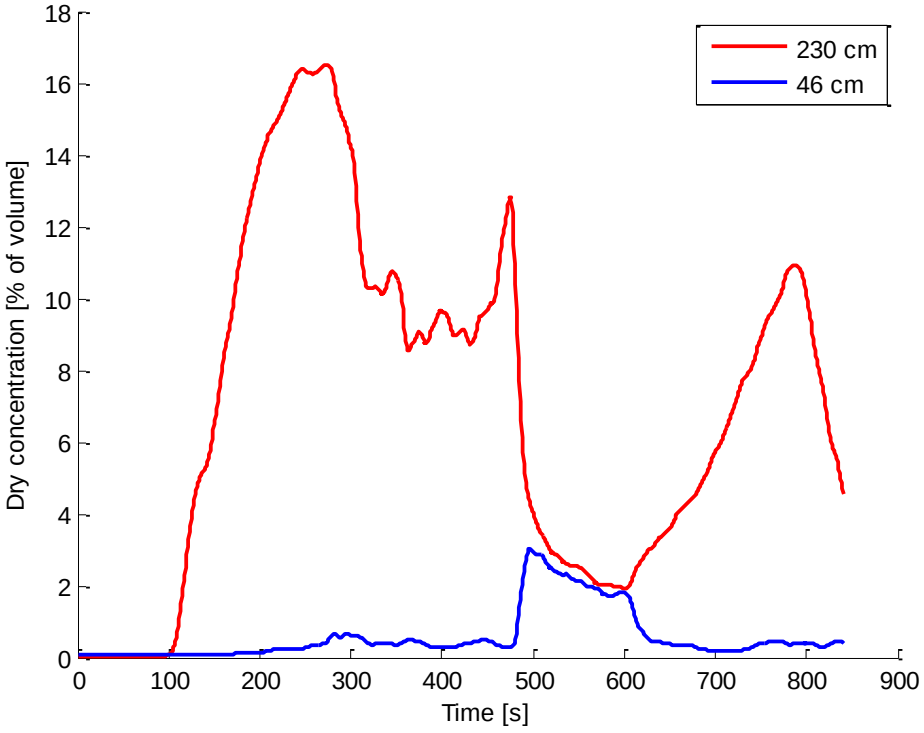

Figure 144: CO_2 concentration.

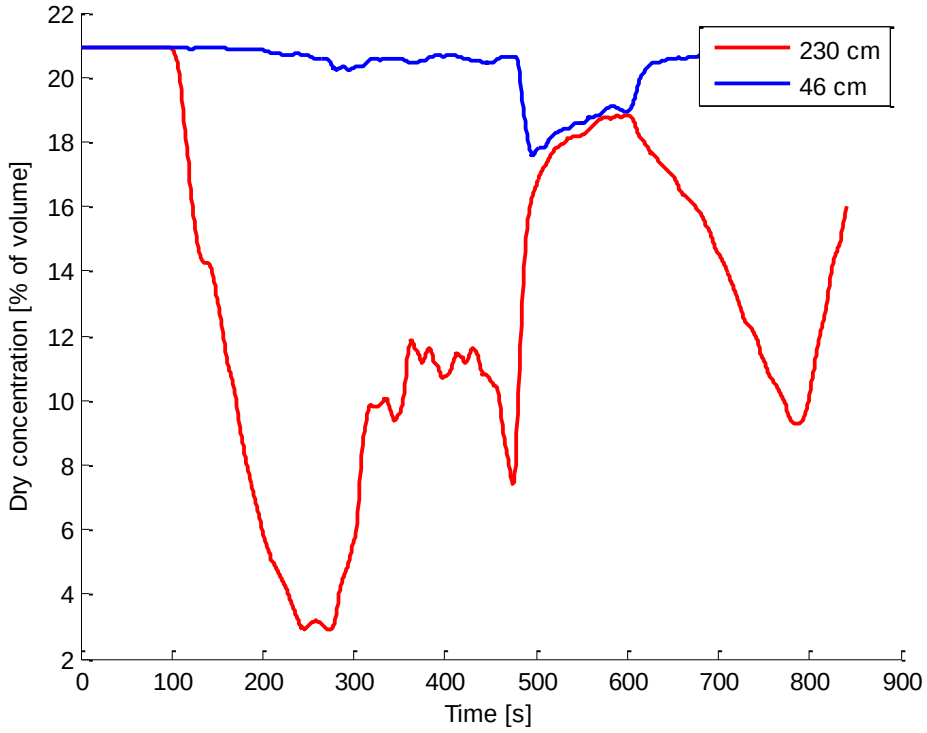

Figure 145: O_2 concentration.

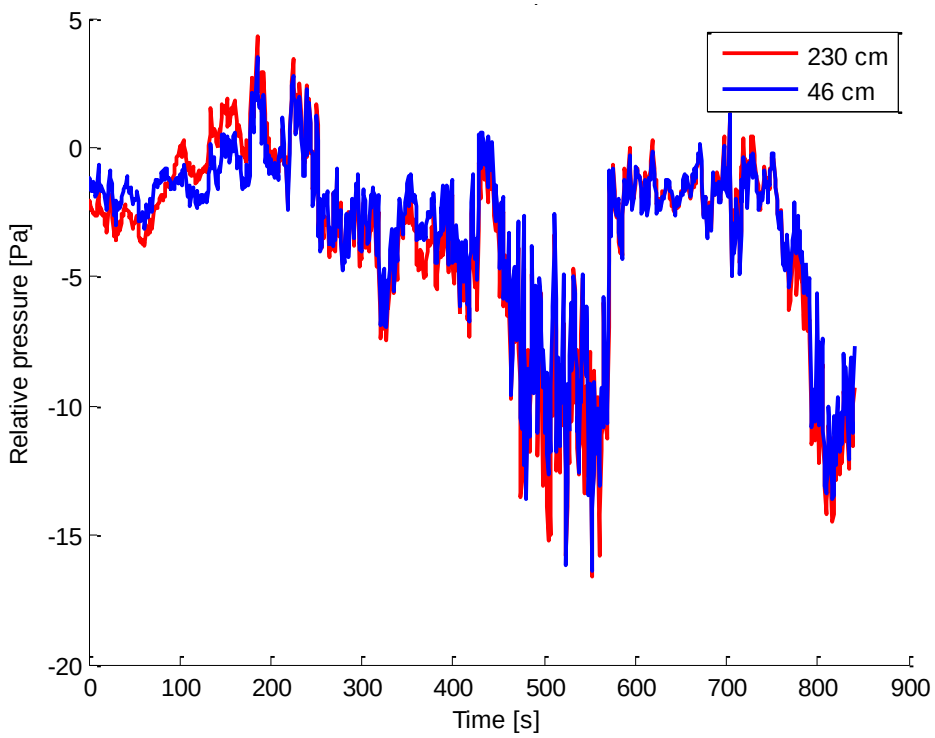

Figure 146: Relative pressure.

B.2.9 **Test 9**

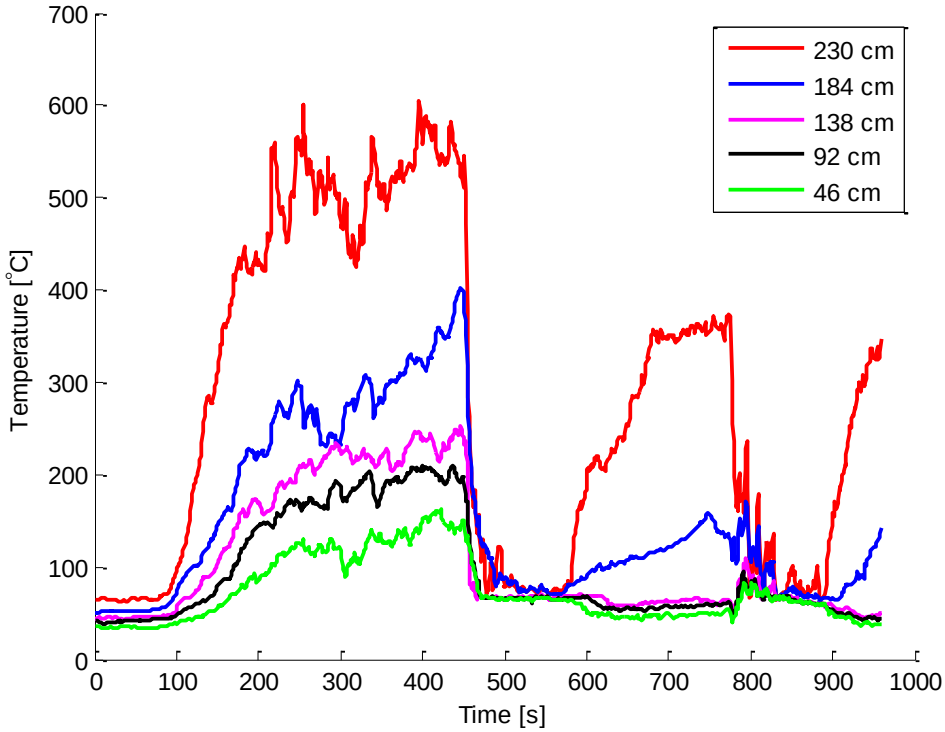

Figure 147: Temperatures, thermocouple tree T1.

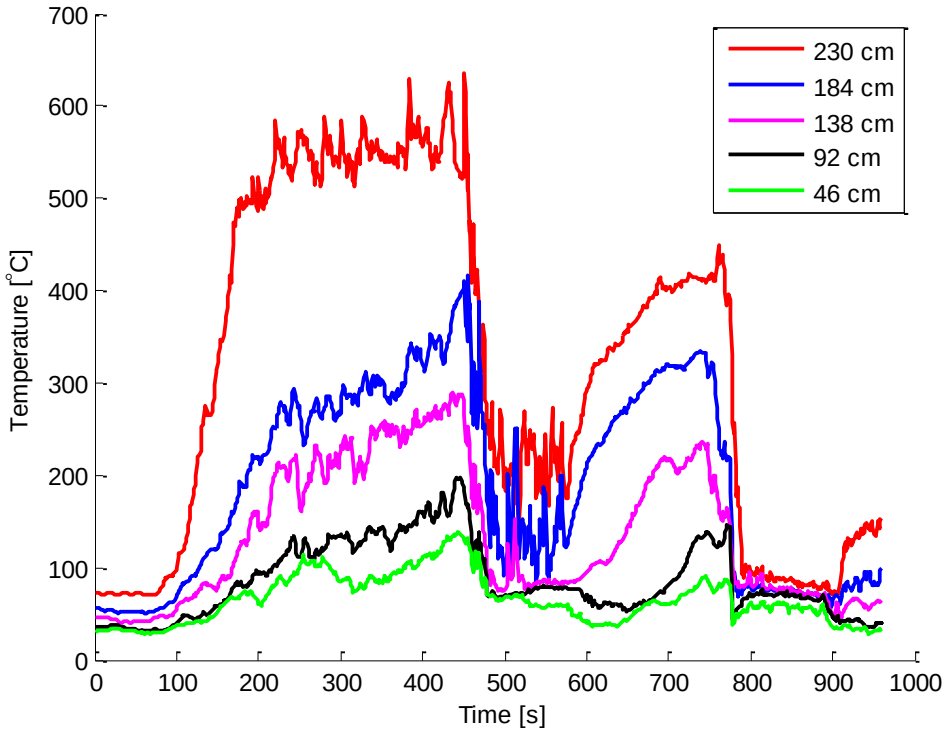

Figure 148: Temperatures, thermocouple tree T2.

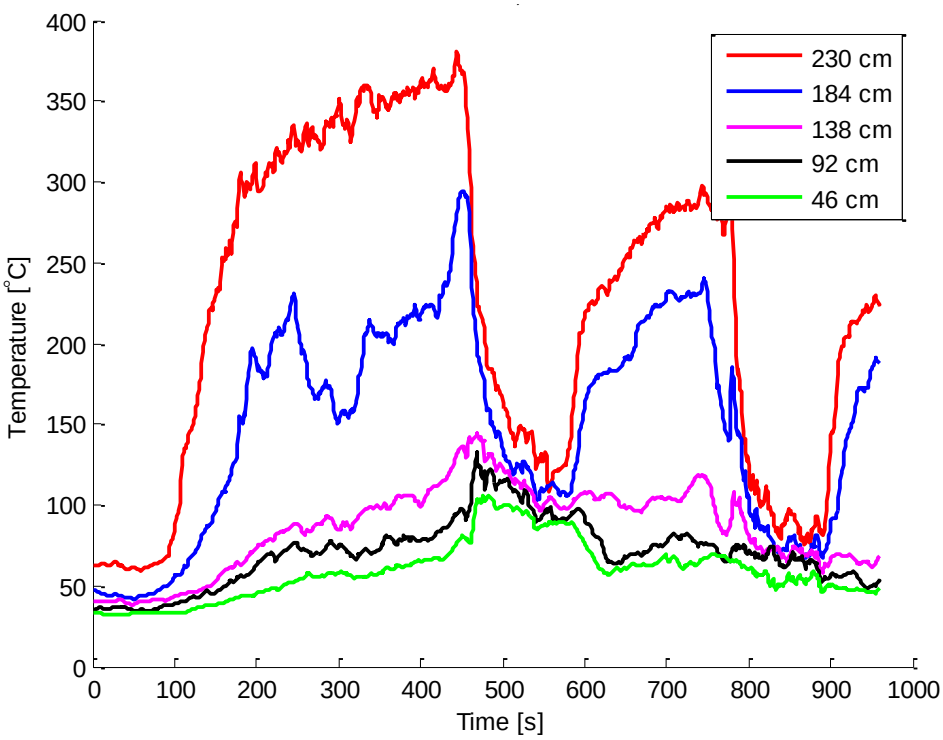

Figure 149: Temperatures, thermocouple tree T3.

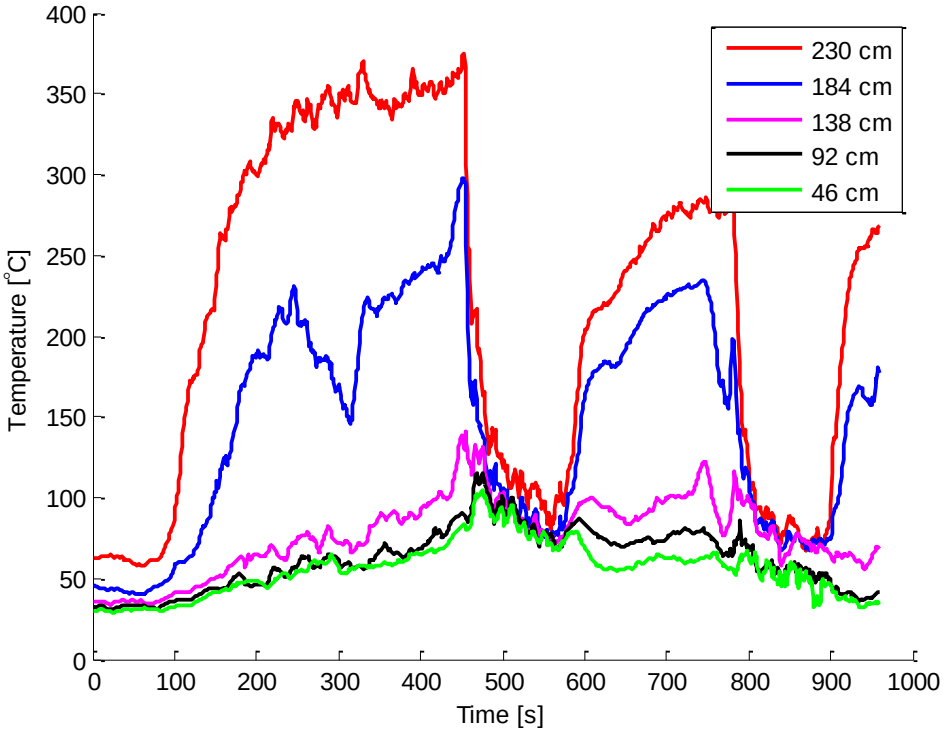

Figure 150: Temperatures, thermocouple tree T4.

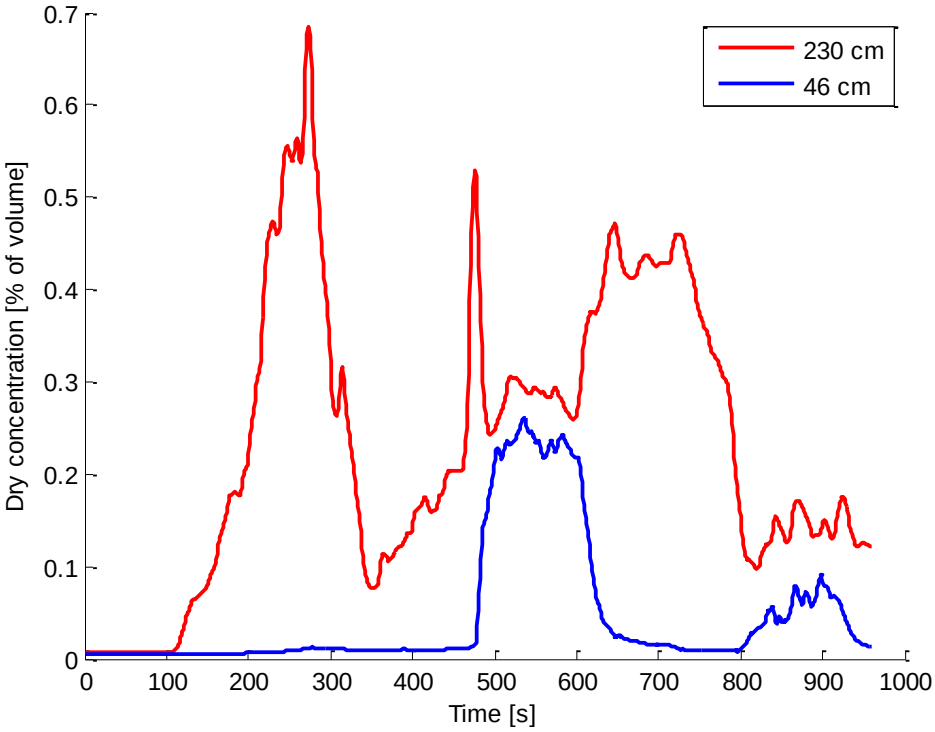

Figure 151: CO concentration.

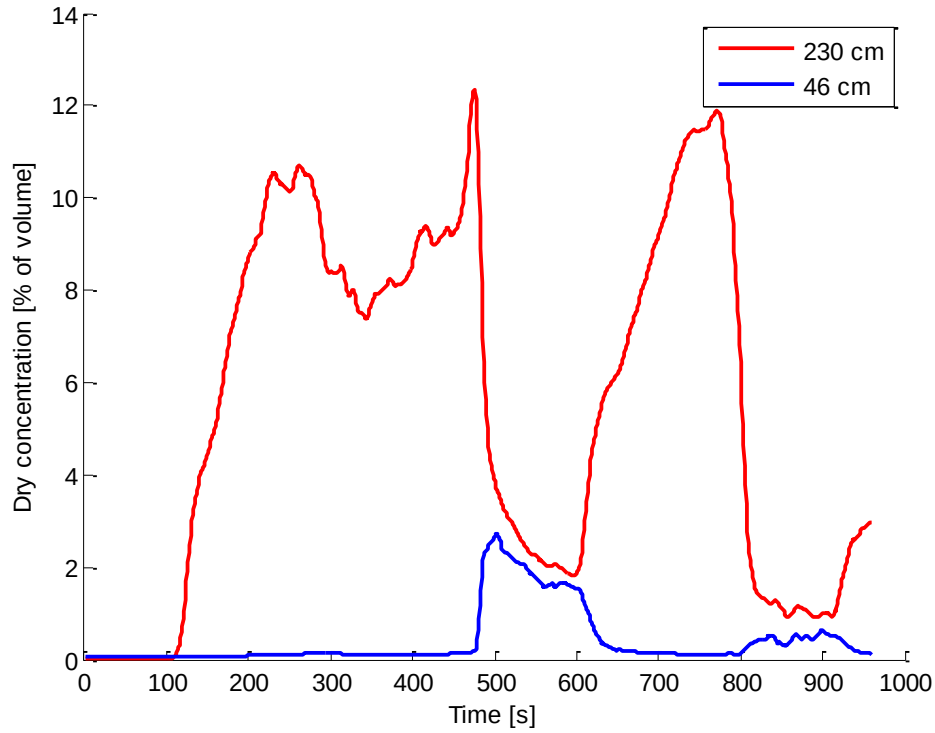

Figure 152: CO_2 concentration.

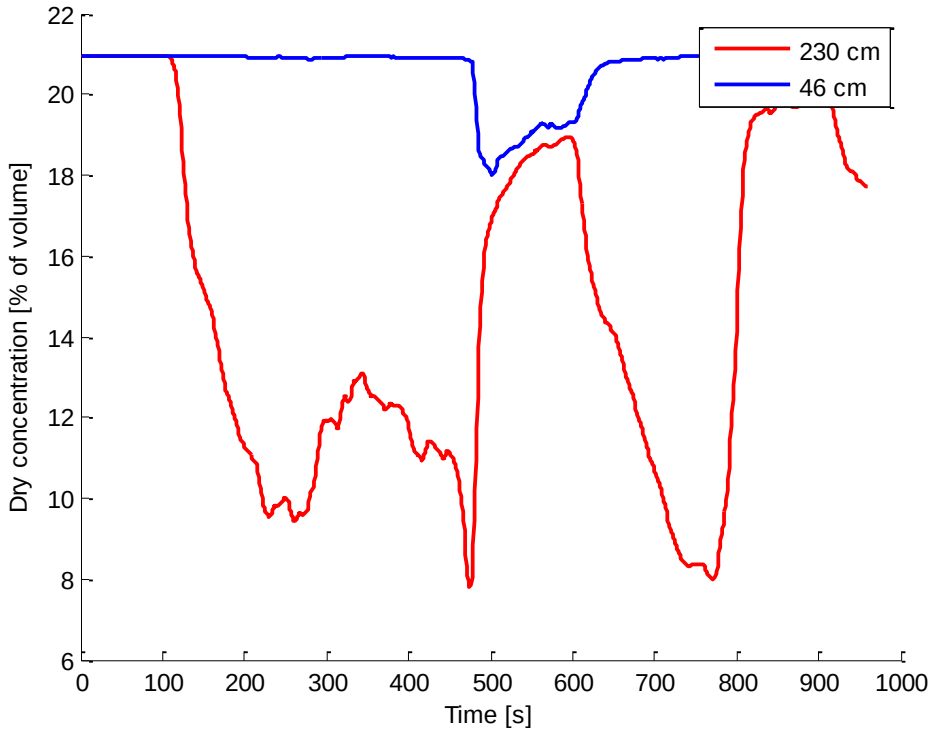

Figure 153: O_2 concentration.

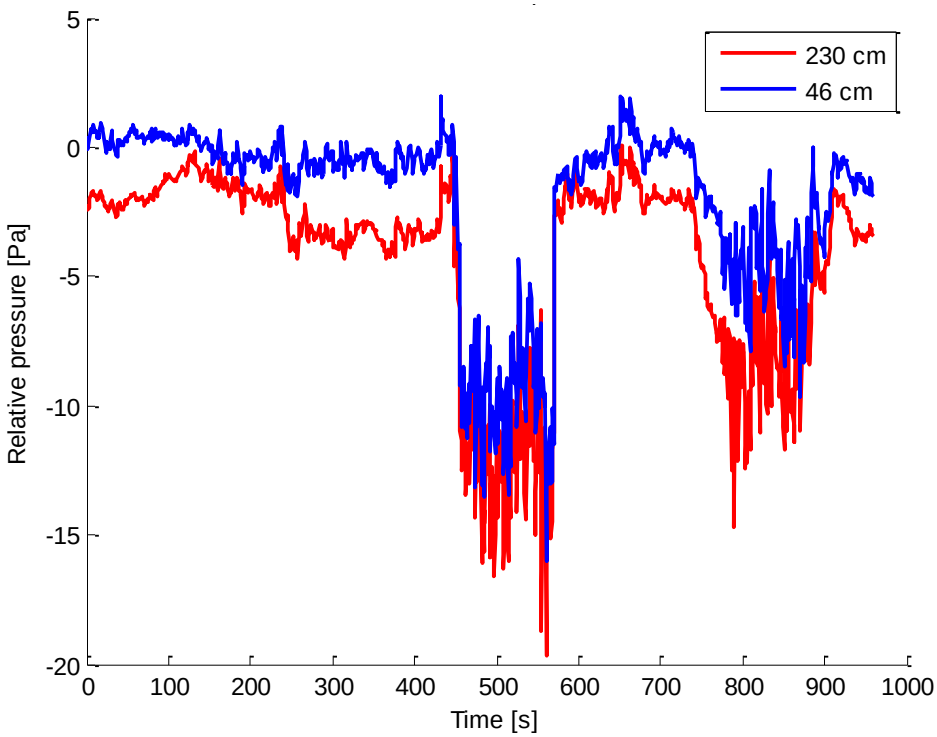

Figure 154: Relative pressure.

C Selection of CFD software

The goal of WP1 in the project was to investigate different CFD software to find a suitable candidate to simulate water mists.

C.1 Information gathering

An enquire with technical and price questions was sent to the software companies Comsol and Ansys which led to video and physical meetings with representatives from both companies. The plan was to post the same technical questions on a forum for FDS and a general forum for CFD. But it seemed hard to get unbiased and well-motivated answers for these kind of questions so the idea was abandoned. Apart from the email, we have talked to people from VTT who have developed parts of the FDS code. We have also spoken to experienced OpenFOAM users to ask of their opinion of using OpenFOAM for water mist simulations. Finally, we have also read parts of some of the software's manuals.

In the email we gave general information about the cutting extinguisher, about the planned configurations, and emphasized the fact that transient simulations are required. We also gave the following specific information:

The information known from previous experiments that can be used in the setup of the simulation:

a) The shape of the water jet (A cone with an angle of first 5° then 10°).
b) Mean velocities of the water droplets at 0, 10 and 15 meter from the nozzle (220, 7 and 5 m/s).
c) Droplet size distribution at 8,10 and 15 meter from the nozzle.
d) Water flow in the jet (60 l/min).

The most important properties to be simulated are:

a) Transport of water spray.
b) Transport of water vapour.
c) Convective heat transfer between air/fire and droplets.
d) Vaporization of droplets.
e) Oxygen reduction around a fire.
f) Air entrainment into spray.
g) Mixing of the air in the room due to spray.
h) Drag forces on spherical droplets (to know the transport).

As second priority are:

a) Spray/wall interaction.
b) Breakup of droplets.
c) Breakup of liquid jet.

If it is possible to simulate a fire it would also be of interest to study:

a) Radiative heat transfer between fire radiation and droplets.
b) Radiative heat transfer between fire radiation and water vapour.

And at lowest priority are the studies of:

a) Effects of compressibility due to high spray velocities. Since the initial velocity of the water jet is 200 m/s.
b) Drag forces on deformed droplets.

C.1.1 Reasonable general simplifications

After the information gathering we learned about some general simplifications that most probably have to be made to solve our problem, no matter which software we choose.

a) All simulations of breakup of the liquid jet and the droplets might be theoretically possible but practically impossible due to mesh limitations and the size of the computational domain.

b) Simulations of a fire seems to only be possible in FDS and maybe OpenFOAM with FireFOAM. To simulate a fire and the spray transport at the same time might not be practical due to the time increase of the simulations and the increased complexity.

c) The mist will most likely have to be initiated a distance from the nozzle, no matter which software is used, due to mesh limitations.

C.2 The considered softwares

A summary of the software is given below and in **Error! Reference source not ound.**. All the softwares have tools available for visualization so that aspect have not been taken into consideration when the softwares were evaluated. A summary of the software is given below.

C.2.1 Comsol

Comsol was contacted by email which lead to phone calls and a video meeting. Prior to the meeting, the Comsol representatives had prepared a simplified simulation of the problem where the gas phase could interact with the droplets but not the opposite. The Comsol representatives had already in an earlier phone call stated that they thought the problem was too complex to solve with Comsol.

C.2.2 ANSYS Fluent and ANSYS CFX

We have had phone and email contact, and a physical meeting, with a salesperson and a PhD in multiphase physics from ANSYS. Both Fluent and CFX are, according to ANSYS, suitable softwares for our problem since they had relevant models for droplets. Since we have some experience with Fluent but not with CFX, Fluent would be the preferred software for us. The main reason for not choosing Fluent would be the price of 25k €/year for a license to use with up to four processor cores.

C.2.3 **FDS**

FDS is a free software primarily developed by NIST and VTT. The software is open source, so any user with enough knowledge could modify the software for personal use. FDS is a CFD software developed to simulate low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. FDS is a frequently used software at SP Fire Research and we have some experience of simulating high speed sprays with small droplets.

C.2.4 **OpenFOAM**

OpenFOAM is a free, open source CFD software. It has an extensive range of features to solve anything from complex fluid flows involving chemical reactions, turbulence and heat transfer, to solid dynamics and electromagnetics. OpenFOAM is used together with different solvers depending on the physics that should be simulated. There are solvers for both particles and fires (FireFOAM). Therefore OpenFOAM is most probably well suited to solve our problems, but the software demands a lot from the user and has a steep learning curve. Since no one of the involved persons from SP has experience with OpenFOAM, we believe that there is not enough time to learn the software within this project.

C.2.5 **STAR-CCM**

STAR-CCM seems to be a CFD software, similar to Fluent, competent of solving our water mist problem. The price should be similar to Fluent's and this software is therefore not further considered.

C.3 Conclusion

The recommendation by SP Fire Research is to use FDS for this project. The main reasons is the price, experience within SP, and the possibility to give the final code to CCS and Emergency services for modifications when the project is over. We also think that FDS is fairly easy to use, even for people with minor CFD experience.

Table 4. An overview of the investigated CFD softwares

		Fluent	**Comsol**	**FDS**	**OpenFOAM**	**CFX**	**STAR-CCM**
Free software		No	No	Yes	Yes	No	No
Available knowledge	**SP**	Some	Yes	Yes	No	No	No
	CCS	No	No	No	No	No	No
	Rescue services	No	No	Partly	No	No	No
Visualisation possibilities		Yes	Yes	Yes	Yes	Yes	Yes

SP Technical Research Institute of Sweden

Our work is concentrated on innovation and the development of value-adding technology. Using Sweden's most extensive and advanced resources for technical evaluation, measurement technology, research and development, we make an important contribution to the competitiveness and sustainable development of industry. Research is carried out in close conjunction with universities and institutes of technology, to the benefit of a customer base of about 10000 organisations, ranging from start-up companies developing new technologies or new ideas to international groups.