Smoke dynamics in compartment fires: large scale experiments and numerical simulations

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ABSTRACT

Today, during compartments fire, the decision-making of the rescue teams is mainly based on human decisions, which are the results of gathered experiences. However, a perfect knowledge of the situation, its evolution over time and the dangers that may appear is impossible.

The transition between a localized fire and a generalized fire can take several forms. One of the most important vectors in the propagation of combustion for compartment fires is smoke due to its high temperature and the large amounts of energy it contains. Despite its extreme danger, smoke remains important to study because it convey valuable information, especially on the appearance of thermal phenomena feared by firemen.
To carry out this study, a large scale experimental cell is used. A burner fueled with propane produces hot fumes in a so-called "real fire" configuration. All the measurements carried out are compared with LES (Large Eddy Simulation) simulations of the experiment using FDS.

The numerical component allows defining scenarios (fire fully developed, fire under ventilated ...), which are verified by the experiments.

The dual competence numerical /experimental data is essential in this type of study since the experimental data suffer from a lack of resolution (spatial, temporal) but nevertheless represent information necessary for validating the codes.

Keywords

Compartments fire, numerical simulations, FDS, smoke dynamics.

INTRODUCTION

Nowadays, during a fire intervention, the decision-making of the emergency services is mainly based on rapid disaster analysis. The analysis is coming from the experience gained over the years but also during the training given in the Firefighter fire simulators.

However, this type of analysis does not allow for a complete knowledge of the disaster since it is mainly based on empirical knowledge. The evolution of fire, the appearance of a secondary focus or certain thermal phenomena, particularly feared by the rescue services are difficult to predict with accuracy. These are all factors which mainly lead to fatal accidents.

Indeed, the rescue teams are regularly victims of thermal phenomena that are difficult to predict. Every year firefighters die on interventions where the fire degenerates into flashover or smoke explosion (backdraft). We remember in particular the explosion of Neuilly sur Seine in 2002 when five firefighters of Paris died during a priori banal room fire.

During a fire, two thermal phenomena representing a major danger for rescue teams may occur:

- Flashover. This phenomenon occurs when the combustible surfaces, heated by the fumes or the radiation, are spontaneously ignited and simultaneously the pyrolysis occurs. To observe this phenomenon, the supply of oxidizer must be sufficient;

- The explosion of smoke is backdraft. This phenomenon appears during under ventilated fires lack of oxidizer. Very high temperatures are also observed. When an opening is created, the sudden intake of fresh air and the exit of hot fumes cause a mixture that ignites spontaneously. The increase in pressure due to this reaction causes a violent explosion outside the premises concerned.

In order to optimize and secure the intervention of rescue services, knowledge of fires, their dynamics and the danger they represent is a major asset. One of the main aspect remains in determining the smoke dynamics at the openings, where fresh air, hot fumes mix together. For this, we are interested in the theory of plumes. Theoretical knowledge on these phenomena will make it possible to improve the understanding of smoke flows, in particular at outlets (Morton et al., 1956).

The direct link between the mass of the flow and the air entrained by the plume justifies our interest in this work. Indeed, a good physical approach of the plumes will allow a better understanding of the smoke in fires (Heskestad, 1998).

The physicochemical processes governing compartment fires and associated thermal phenomena are extremely complex. Fumes play an important role in the spread of fires. As a result of convection and pressure fluctuations, they spread through all kinds of ducts (corridors, stairwells, elevator shafts, technical ducts, sanitary ducts, etc.).

Due to their very high temperature, smoke which enters a fresh volume can ignite spontaneously in contact with air or ignite the fuel present. This situation can lead to the generalized fire of a building from a focal point located in a single volume (Francis and Chen, 2012).

Unlike other intervention techniques, technological means to avoid this type of accident have received little attention. Due to difficult operational environments, research projects have been launched to allow firefighters to improve their spear techniques, particularly in the attack on semi-confined fires. This is the case of the PROMESIS research program, which brought together a consortium of professionals and academics to enable intervention teams to adapt their attack techniques. You et al. (2010) have defined the effective pulse time, size and flow rate in the control of confined fires.

In this context, the ANR program FIREDIAG has the objective of setting up a decision support tool. Indeed, this research project is based on the information conveyed by the fumes. The objective is to provide the fire officer a technological tool to analyze the situation and help decision-making in real time. The difficulty of developing these tools remains on the complexity of the phenomena involved in compartment fires (combustion, explosion, smoke flow, etc.). Numerous parameters have to be taken into account (temperature, gas flows, heat exchanges, etc.) but are difficult to measure (sensors, detectors, etc.). Moreover, the information received by the intelligent and communicating system must be able to be transmitted in order to be construed quickly and efficiently.

To sum up, this type of technology could include:

- Improve the speed of the detection of a disaster;
- Give information on the nature of the fire, its development speed in order to adapt the emergency means to the fire progression;
- Monitor the evolution of the disaster in real time, particularly in terms of propagation or the appearance of thermal phenomena.

In order to carry out this study, an experimental cell is installed on the firefighting site of the Seine Maritime‘s firefighters. This platform which size is 6m long, 2.59m high and 2.45m wide allows to produce hot fumes in a so-called "real fire" configuration using a propane fueled burner. Fumes are analyzed using non-intrusive measurement techniques such as PIV for the velocity fields. Large velocity fields using PIV in confined environments is a complex task (Hou et al., 1996). Subsequently, tests have already been carried out at the level of the fireplace (Tieszen et al., 2002), and then at the level of the doorways in the PIV Fire project carried out by the IUSTI laboratory and the Cadarache IRSN (Koched et al., 2012). These studies showed that PIV allows very reliable and less intrusive measurements of speed than bidirectional probes. However, these tests were conducted with thermal powers lower than our experiment (21,7kW). Measurements by PIV (large fields) will be done and compared to LES simulations of the experiment (with Fire Dynamics Simulator, Fire Dynamics Simulator Technical Reference Guide Volume 1, 2, 3: Mathematical Model, Verification, Validation, McGrattan et al., 2007). However, due to inherent issues with large scale PIV, which are still under process, the present study mainly focuses on temperature measurements in the experimental. The experimental data are compared with simulations using FDS code.

Experimental test

To carry out this project, the different partners have established the specifications of an experimental unit which is close to real fires. Therefore, the analysis of thermal phenomena studied in the experimental test bench is likely to be found by firefighters during their missions. This cell is actually made of two maritime containers set up perpendicularly and called respectively "measure cell" and "test cell", Figure 1.

Figure 1: Picture of the experimental cells, Top view

The standard size of the maritime containers is 6m long, 2.59m high and 2.45m wide. Initially, these structures have emerged as training tools in rescue services in order to train firefighters to detect the signs of thermal phenomena and to fight effectively against them. Moreover, the volume of these containers is close to that of a room of standard flat, approximately 15m ².

To reproduce the conditions of a fire, a propane fireplace is installed. The latter consists of 36 burners spread over an area of 1m² that can reach a power of 1MW and a temperature of 1000 ° C, Figure 2.

Figure 2: Picture of the 36 burner arrangement for the 1MW burner

Although propane produces only a small amount of soot compared to real fires, this type of burner has been chosen because it has the advantage of perfectly controlling the power. Moreover, the reproducibility is ensured. To produce soot that is missing from the fire, ethylene can be injected into a small amount in the burner.

Due to the high temperatures that are reached during the measurement campaigns, insulation has been an important step in the design of the measurement cell, Figure 3. It is composed as follows:

- Blocks of cellular concrete with a thickness of 70mm on the ground;
- Rock wool and mineral wool installed on the ceiling;
- Mineral wool and vermiculite plates (30mm) on the side walls.

Figure 3: Picture of the experimental cells, inside view

To study different scenarios, the volume of the test cell can be modulated thanks to a removable wall. Its optical access of 1m ² in quartz allows the installation of optical laser based measurement techniques directly in the axis of the fireplace. In addition, the hot gases can flow outside the container through two outfalls. The interaction between the ambient air and the hot gases will be studied, in particular by using bidirectional probes and PIV technique at the exit.

The test cell is equipped with 2 shafts of 10 type K thermocouples, an opacimeter and a gas analyzer, making it possible to measure CO and O2 concentrations. The measurement cell is equipped with 2 quartz windows to carry out velocity fields and scalar field measurements by large scale PIV. The flow dynamics and the scalar fields will be studied on the central horizontal and vertical planes as well as at the exit, just below the ceiling.

Numerical simulations

For the numerical simulations, the calculation code Fire Dynamics Simulator (FDS) (Desanghere, 2006), has been retained. Widely used in fire safety engineering, this code allows obtaining a faithful representation of the fire dynamics

In order to optimize the reliability of this software, meshes of 5cm are used for the simulations presented later. A sketch of the numerical design is shown in Figure 4. For the experimental cell, this represents slightly more than 285,000 nodes. To optimize the computation time, the simulations are carried out using a supercomputer attached to the laboratory, CRIAAN meso calculation center.

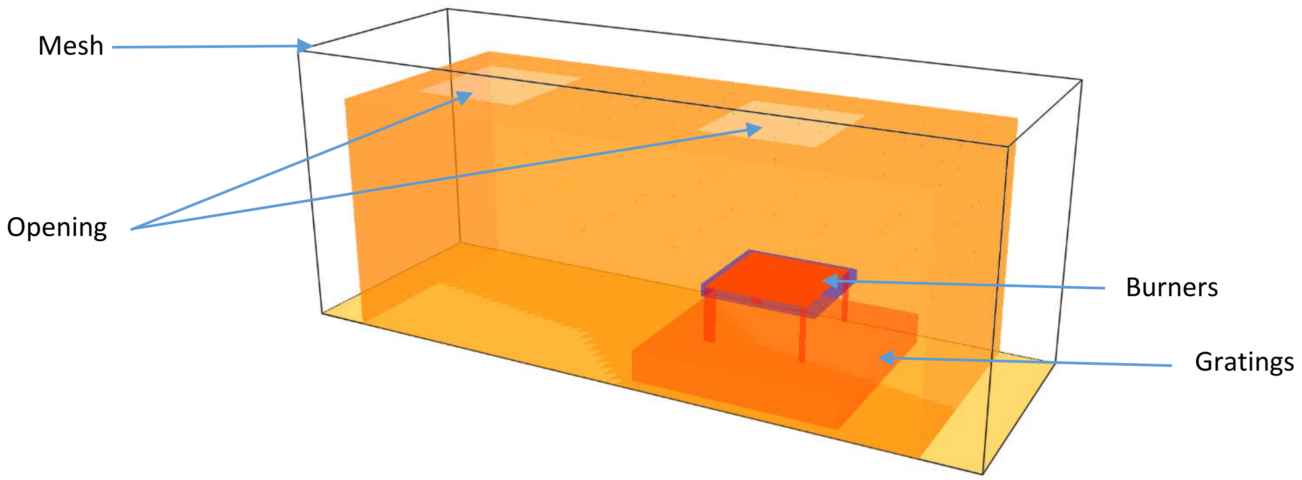

Figure 4: Modeling FDS of the cell

The entire set of FDS results is post processed using the Matlab software.

For this study, four main configurations are chosen:

- Scenario 1: Large volume, an open outlet;
- Scenario 2: Large volume, two open outlets;
- Scenario 3: Small volume, an open outlet, Figure 5;
- Scenario 4: Small confined volume.

For all the current simulations, a power of 500 kW is applied. For the different scenarios, the firepower can be modified. This is the case of Scenario 1 or calculations are carried out up to 1MW.

In order to compare the numerical simulations with the first experimental measurements, sensors are placed in the same places, numerically and experimentally. The position of the sensor for case 3 is given in Figure 5.

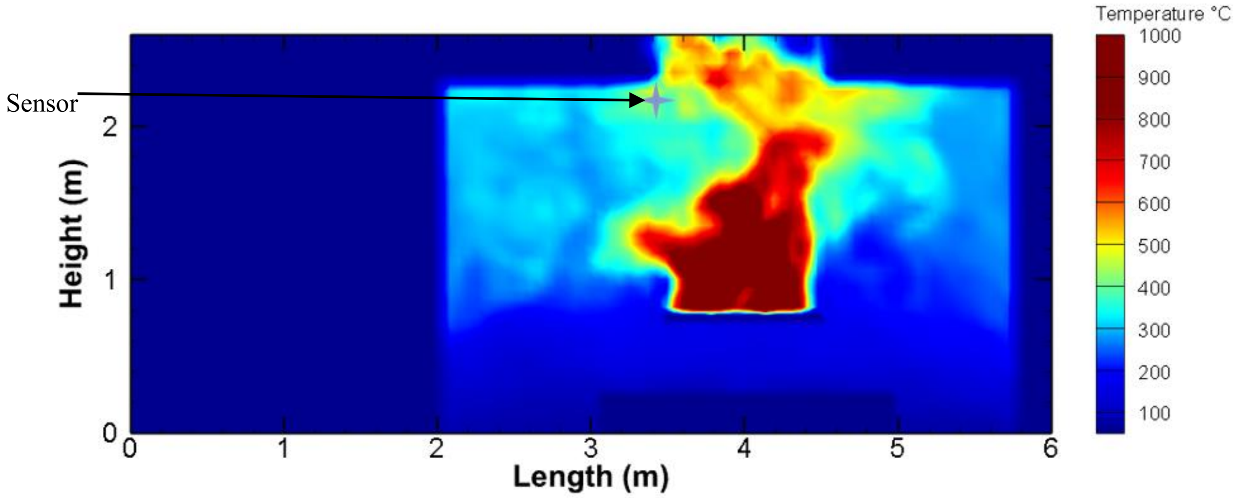

Figure 5: Modeling of the temperature of scenario n ° 3 (° C)

In addition, other numerical simulations are carried out in the large volume configuration with an open outlet. The purpose of these simulations is to observe the behavior of the fire with an opening serving both for the entry of fresh air and for exiting hot fumes. Subsequently, these test cases are reproduced in the experimental chamber in order to verify the numerical results. The simulation software FDS is not verified in this type of configuration (under ventilated), this comparison between numerical and experimental measurements is therefore very interesting for the research community fire.

RESULTS

Numerical scenario

The following section shows the development of the fire at 500 kW considering case 1. The fireplace is located to the right of the cell with the outlet open to the left. The conditions at the walls are considered adiabatic. For this simulation, the mesh is also made with cells of 5cm x 5cm. An instantaneous temperature field at time t=50 after the fire starts is shown in Figure 6.

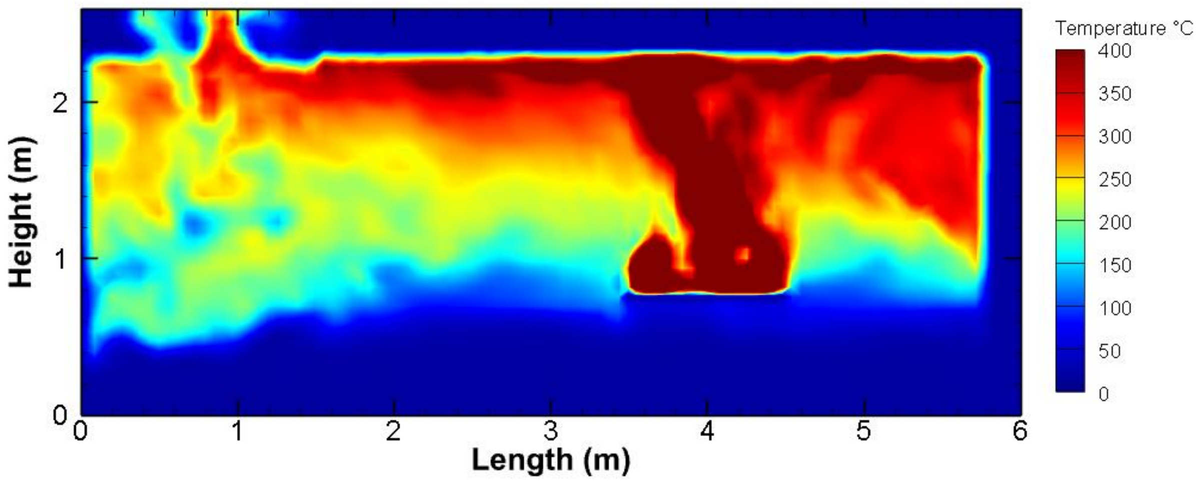

Figure 6: Modelling of the temperature of scenario n ° 1 at 50 seconds

At 50 seconds, the fire develops normally. There is a layer of stratified hot flue gases in the upper part of the volume concerned. At 300 seconds, Figure 7, the fire behavior is completely different. A large part of the oxygen of the volume has been consumed. The initial focus is no longer localized at the burner Indeed, it is observed that the flame moves at the outlet position. On the modeling, the flame position is highly fluctuating. This phenomenon represents the alternation of fresh air intake and evacuation of hot smoke.

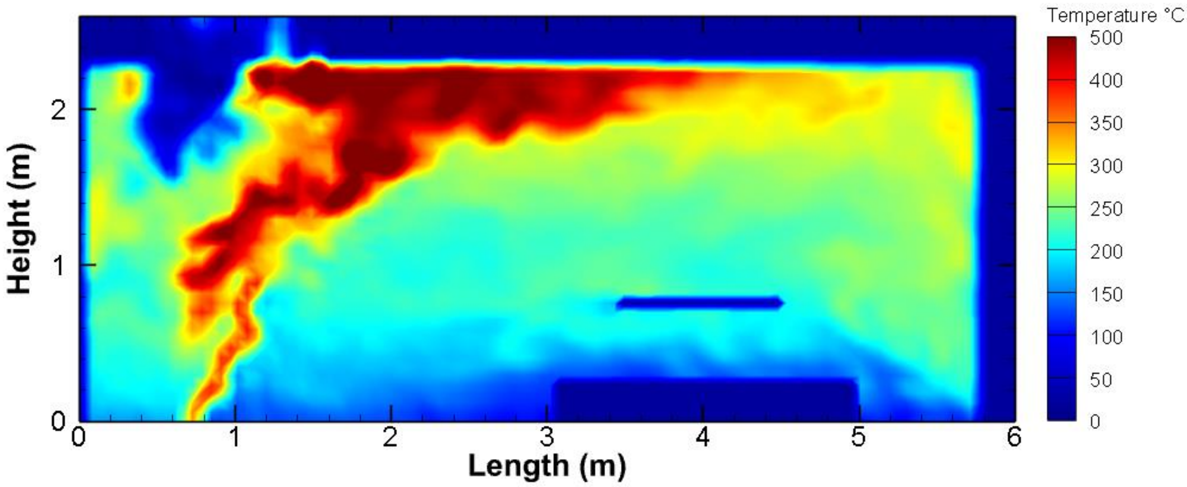

Figure 7: Modelling of the temperature of scenario n ° 1 (° C) at 300 seconds

Averaging the temperature field, Figure 8, we can observe that the flame is mainly positioned at the outlet. Where there exists a. In a under ventilated fire situation, this phenomenon is explained by the lack of oxidant (here the oxygen) necessary for the home to develop properly.

Indeed, when the fireplace lacks oxygen to burn the whole of the fuel present, the pressure in the enclosure decreases and will allow fresh air to enter. This fresh air inlet will restart the combustion and increase the pressure of the volume again (through the increase of smoke) which will lead to a release of hot fumes.

This phenomenon is repeated until the fuel is exhausted. It is illustrated in Figure 8 where a higher temperature is observed at the outlet as well as an absence of flame on the fireplace. However, these numerical observations remain to be verified with the experimental one. Indeed, the FDS code is limited when modeling under ventilated fires. It tends to overestimate the appearance of ghost flames (flame that comes off the burner to use the oxidizer of the room). Although this phenomenon is scientifically possible, the focus could just as well be extinguished and the flame would disappear.

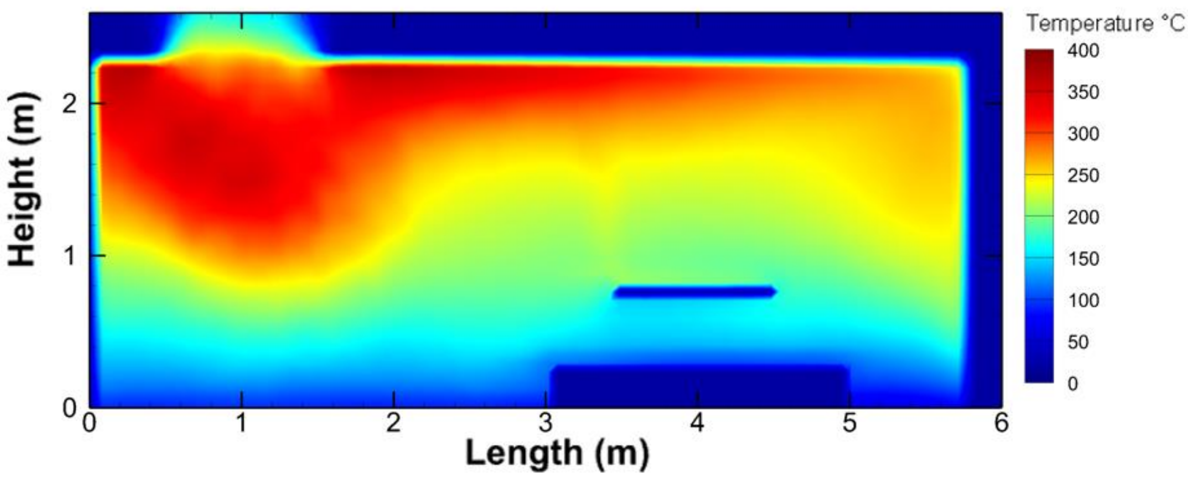

Figure 8: Modelling of the average temperature of scenario n ° 1 (° C)

The following section shows the development of the fire at 500 kW considering case 3. The fireplace is always on the right. The volume considered is the small volume (removable wall in place) with the outlet open. As for the previous simulation, the conditions at the walls are considered adiabatic. The mesh is also made with cells of 5cm x 5cm. An instantaneous temperature field at time t=50 after the fire starts is shown in Figure 9.

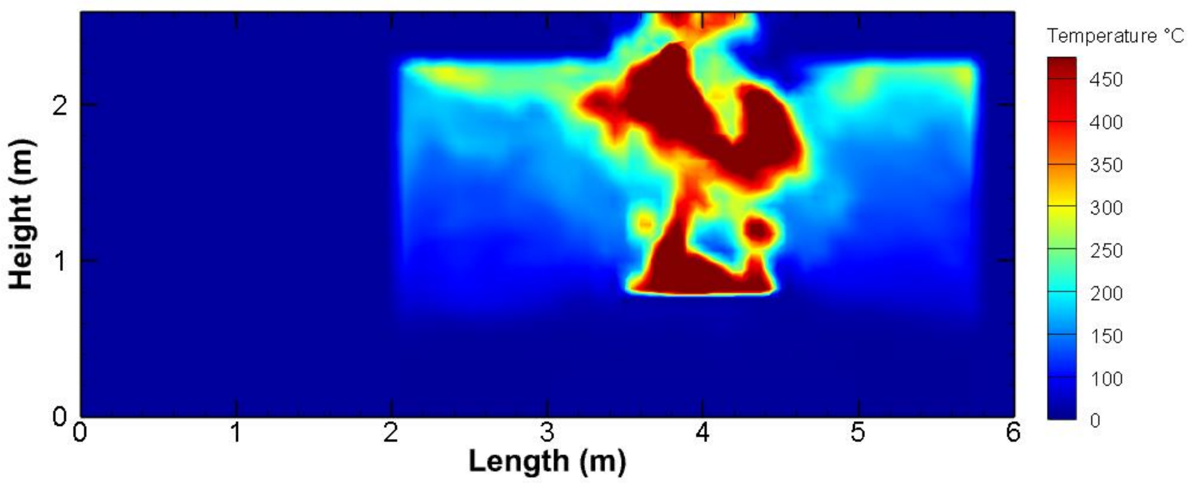

Figure 9: Modelling of the temperature of scenario n ° 3 at 50 seconds

At 50 seconds, the fire develops normally. Unlike scenario 1, the hot gases are evacuated and very little stored in the volume. This can be explained by the direct presence of the outlet above the fireplace, thus avoiding the displacement of the fumes in the experimental cell. At 300 seconds, Figure 10, the fire is quite similar. The layer of hot smoke is more developed. It is lower in the volume and makes it possible to demonstrate a clear stratification of the fumes.

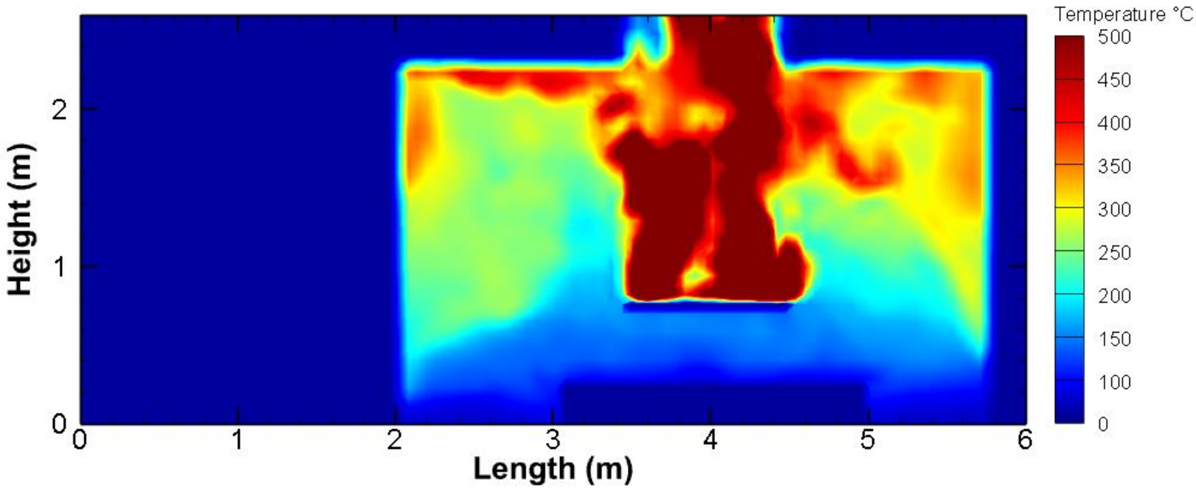

Figure 10: Modelling of the temperature of scenario n ° 3 (° C) at 300 seconds

The intermittent phenomenon alternating between fresh air intake and outlet of hot fumes is also present. However, due to the volume configuration, the fireplace is much less ventilated. There is therefore no ghost flames as observed in case 1.

Averaging the temperature field, Figure .11, we can observe that the temperature field is close enough to what has been shown in Figure 10. The smoke plume and the stratification of the hot gases are easily observed. This type of fire development is common in properly ventilated fires.

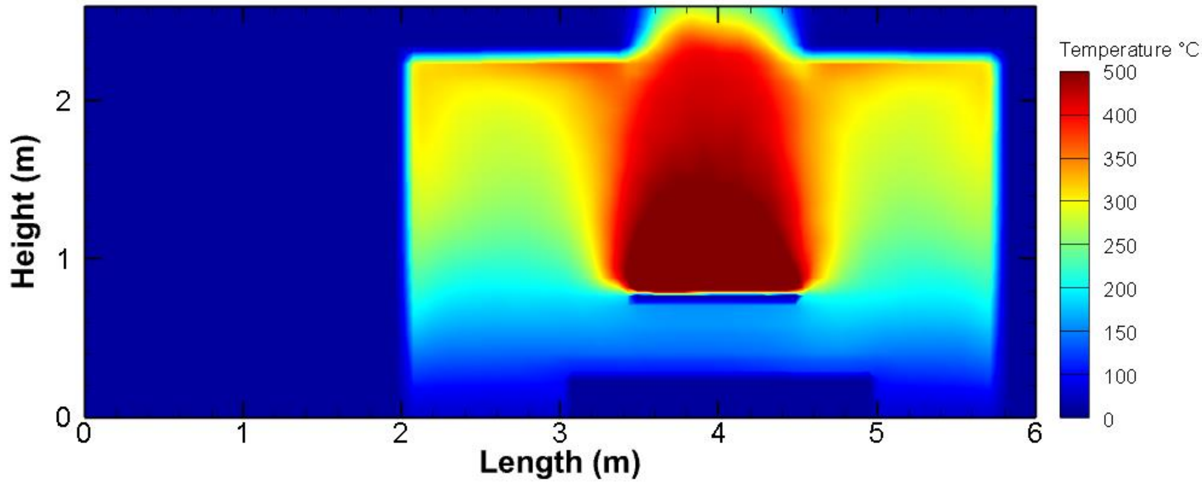

Figure 11: Modelling of the average temperature of scenario n ° 3 (° C)

Experimental test

In order to validate the numerical results presented above, an experimental test was carried out under case 3, namely, small volume, 500 kW, open outlet. The 36 burners were turned on. The thermocouple taken into account for the results below is placed in the same place as the digital sensor, Figure 5. Figure 13 shows the fireplace with the 36 burners burning. However, for better modularity, the number of burners can be changed, thus modifying the power flux-density.

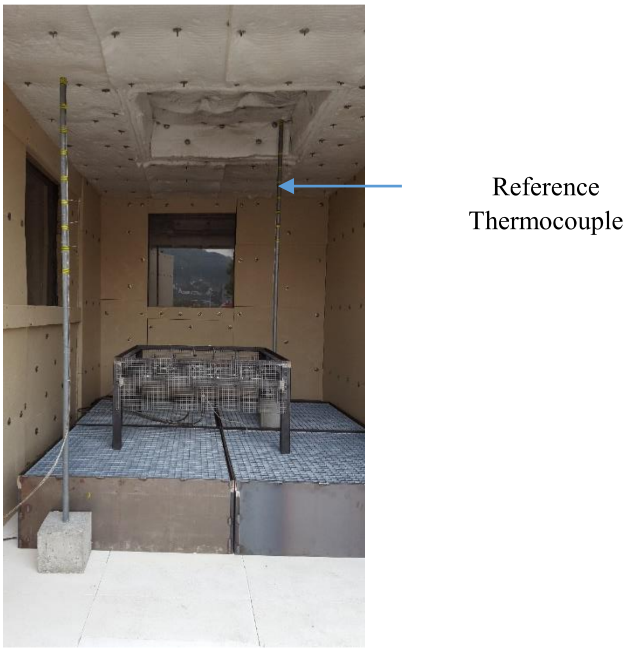

Figure 12: Test cell

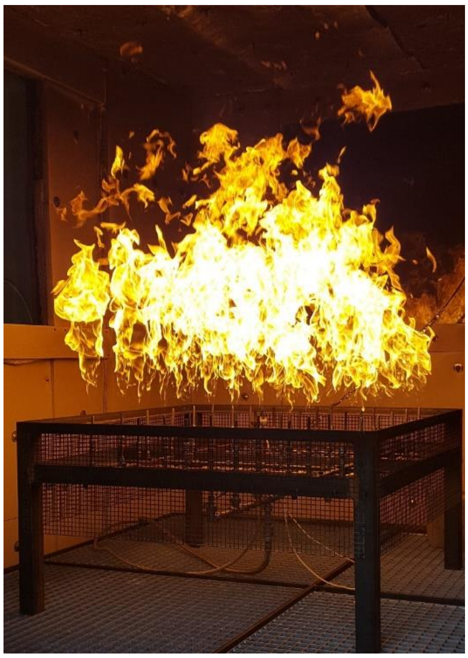

Figure 13: Fireplace 500kW, 36 burners

Following this test, the following temperature against time curve is plotted, Figure 14. The experimental curve is represented in red, the adiabatic in pink and the curve in the normal conditions FDS in orange.

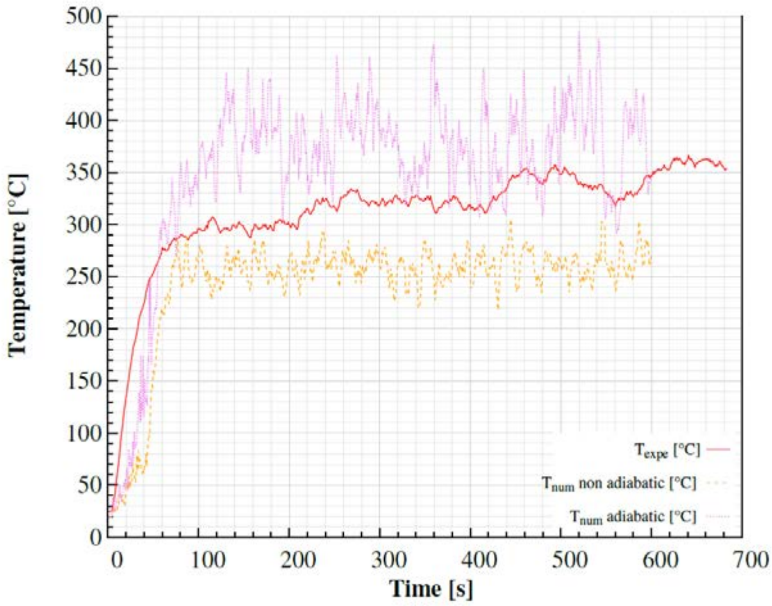

Figure 14: Curves to 500kW

From the simulations, adiabatic and real configurations are tested. Compared to the numerical values, Figure 14, it can be observed that the three curves are very similar. However, the adiabatic numerical values (pink curve) are slightly higher than the experimental values, whereas the non-adiabatic case is under estimating the temperature. However, good agreement is observed. On the experimental curve, we can observe that the steady state is not reached, in contrast to the numerical simulations presented above. On the other hand, the rise in power is underestimated in numerical terms. In order to get closer to the experimental, improvements have to be made on numerical simulations.

Figure 15 shows the evolution of the temperature as a function of time. The red curve always represents the experimental value. The blue curve represents the result of the improved numerical simulation. In order to get closer to the measured temperature, three improvements were made.

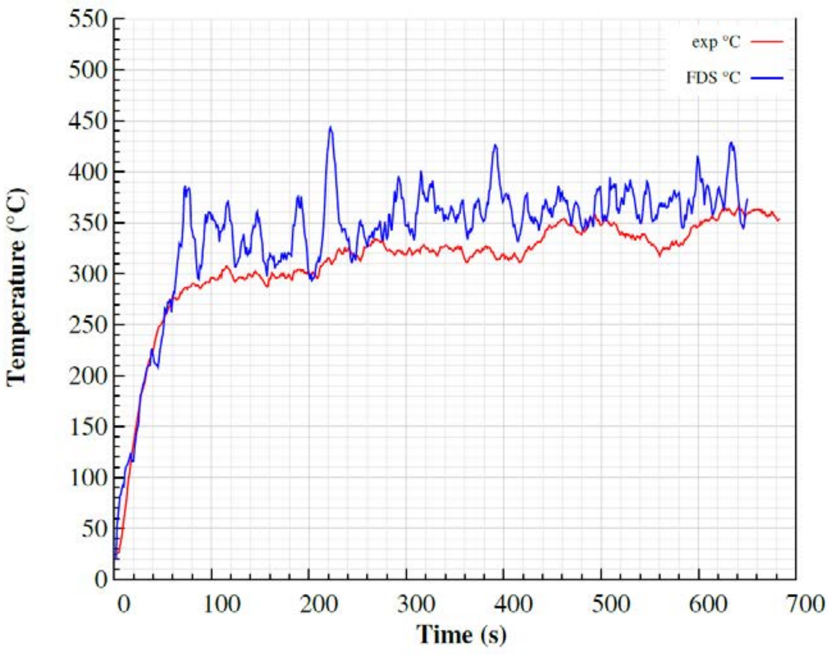

Figure 15: Experimental and modified curves to 500kW

Firstly, the ramp-up has been reduced. The fuel being propane, the combustion is extremely fast. Secondly, an opening in the lower part was created. It aims to simulate the leakage observed on the cell during the tests. Thirdly, the digital firepower has been adapted. Indeed, for reasons related to the experimental installation, the power of the fireplace cannot remain constant at 500kW. Propane bottles are frozen and the power is changed. After checking, the firepower is closer to 460kW. The numerical simulation presented here was carried out with this value.

Following these improvements, there is a very similar increase in power in experimental and with numerical simulation. The gap between the curves and reduces. Moreover, it can be seen that the digital curve does not reach the steady state.

CONCLUSION

To conclude, the first numerical and experimental results are conclusive. Indeed, it is observed that the temperature profiles obtained are quite similar. Technical points from the CFD need to be slightly adapted. Other measures will soon be initiated in order to compare other physical quantities and thus further refine the numerical model including speed measurements by PIV. These measurements will make it possible to compare the numerical and experimental results for the speed, another significant physical magnitude for the compartment fires. The series of experimental tests will allow to verify the numerical results obtained for configurations under ventilated and will thus validate the calculation code FDS. In addition, with the aim of checking the code, scenarios with different firepower (up to 1MW) will be simulated and experimentally tested. In addition, measurements of opacimetry and a gas analyzer will complement the experimental cell. These measures will also be used to compare numerical values and thus enhance the reliability of the code.

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