Simulation of premixed flames with FDS. Application to the hot smoke testing system Izar

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Abstract. The use of premixed flames in hot smoke tests present valuable advantages in comparison with traditional methods. The definition and control of the necessary power, HRR, is a great challenge due to the lack of information about the plumes originated by premixed flames. This work presents a method to simulate the hot smoke testing system Izar in FDS an calculate the temperature field within the created plume.

1. Introduction

In 2013 regarding the new needs of the fire safety mark in Switzerland, the swiss company Basler & Hofmann decided to develop an innovative hot smoke testing system. The result is currently known under the commercial name of Izar.

Izar is the a smoke testing system composed of a gas burner, a gas supply system, and additional fog generators to visualize the smoke layer.

The main characteristic of the system is the use of premixed flames as heat source. The main advantage is the reduction, almost elimination, of the heat loses due to radiation and the elimination of the residues, soot yield, originated by the common diffusions flames. The use of premixed flames made of Izar a pure convective heat source capable of reproducing the equivalent convective part released by the common natural fires with diffusion flames.

The system can release a total power of 1,20 MW, which considered as a pure convective heat source, is equivalent to a natural fire of 1,80 MW. This equivalence considers the standard ratio 2/3 of the total heat released as convective heat and 1/3 as radiation heat. This ratio could be adjusted for each fuel if needed.

This paper summarizes the main results obtained during the development of the hot smoke testing system regarding its modeling in FDS. The entire work was submitted as master thesis [1] within the International Master of Science in Fire Safety Engineering program.

1.1. A brief description of the work context

The presented method belongs to the development process of the hot smoke testing Izar, and must be understood in this context.

The testing system Izar works in buildings or tunnels already in use or just before the commissioning. During a smoke test the “most realistic” conditions must be created in order to proof the smoke management system under the closer conditions to an accidental fire. Therefore, the system must generate the highest temperatures and at the same time guarantee that no damage will occur during the test.

This was one of the challenges faced on this work: to study the temperature field created by the system and to draw valuable conclusions and guaranteeing its safety development. Additionally this work had to be done before the system was ready to use an no laboratory test was already possible at this point.

Different equations and models are available in literature to calculate the plume temperatures for diffusion flames according to its geometry and flame configuration (jet flame, etc.). For the common hot smoke test based on pool fires exits a vast literature and experience which make it possible to adjust the size of the pools according to the room geometry [2], [3]. But no model was found to calculate these parameters for plumes generated during the combustion process occurred in premixed flames.

The processes with premixed flames are normally used normally in closed environments such as industrial ovens, in which the main interest is the combustion efficiency rather than the plumes development and thus, the phenomena is not documented enough.

The rectangular geometry of the burning chamber, made also impossible to consider these traditional models mainly based on experiments with circular fire sources such as the Heskestad plume model [4] and extrapolate their results.

A new framework had to be developed to study the temperature field in the plume created by Izar. The decision was to study the temperature field in the plume modeling the system with FDS [5], [6].

2. Modeling the hot smoke testing system Izar with FDS

The approach of modeling the system with FDS was not straightforward because the program is not mainly thought to simulate premixed combustions.

The solution to simulate premixed flames consists of modeling the combustion like a source of combustion products released at the flame temperature.

Izar uses propane gas as source of energy. The physical properties of the combustible are well documented in the literature. The flame temperature is one of these and it is the main model parameter. The combustion in Izar occurs under stoichiometric conditions achieving very high combustion efficiencies, an very high temperatures. The chosen flame temperature is the adiabatic temperature with dissociation. For the propane this temperature is 1995 °C [7]. Above the combustion region, the plume can be represented using the fluid dynamic equations available in FDS.

The plume contains the combustion products generated during the combustion. In the diffusion flames the efficiency of the combustion process defines the amount of products and particles which are commonly called smoke. However in a premixed combustion these combustion products are well known and do not

Specie	**Molecular weight (g)**	**Amount of products (g)**	**Mass ratio**
C_3H_4	40	-	-
CO_2	44	132	3.3
H_2O	18	72	1.8
N_2	28	526.40	13.16

Table 1. Molecular weight, and mass ratio between propane and combustion products

Specie	**Amount of fuel (g/s)**	**Mass ratio**	**Amount of products (g/s)**
C_3H_4	10.85	-	-
CO_2	-	3.3	35.80
H_2O	-	1.8	19.53
N_2	-	13.16	142.78

Table 2. Calculation example to determine the amount of product released from a 500 kW fire

change under different environment conditions. By a simple chemical balance its is possible to calculate these combustion products and the amount of them:

$$C_3H_8 + 5O_2 + 5 \cdot 3.76N_2 = 3CO_2 + 4H_2O + 5 \cdot 3.76N_2 \tag{1}$$

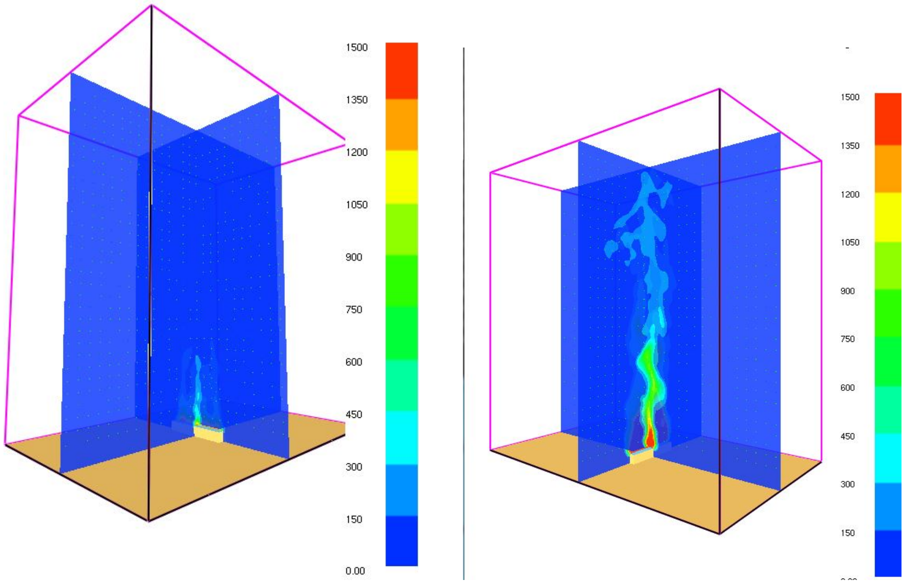
Once the chemical balance is available, the fuel/product ratio can be defined for each specie. This ratio allows calculating the amount of product (kg) produced for each mass unit of fuel.

The propane heat of combustion is well known and can be set to 46 kJ/g [8], it is straightforward to calculate the necessary kilograms of propane required to achieve a certain power.The chemical equation can be afterwards adjusted to determinate the kg of products produced. Using the mass ratio available in the Table 1, the amount of products generated can be calculated.

For example, in order to generate a power of 500 kW, a mass flow rate of 10.78 g/s of propane are needed. Using the mass ratio available in the Table 1, the generated amount of products is calculated. The values for this example are in the Table 2

These calculation guarantees that the proper mass is being introduced in the system, and the subsequent mass balance in the system will be based on correct initial mass values.

These values must be introduced in the FDS code with the unit (kg/m·s). therefore the combustion area must be also considered. In the studied case the burning chamber is open and has a V-Shape; it is 122 cm long and 17 cm wide. The geometry plays also an important roll to define the size of mesh. The mesh must represent the combustion area as accurate as possible. The initial geometry is related to the moment balance in the system, because it defines the initial



(a) 100 kW (b) 1.200 kW

Figure 1. Comparison between two models with different powers. The different heigths of the hot region can be observed. These represent the flames, according to the power of the simulation

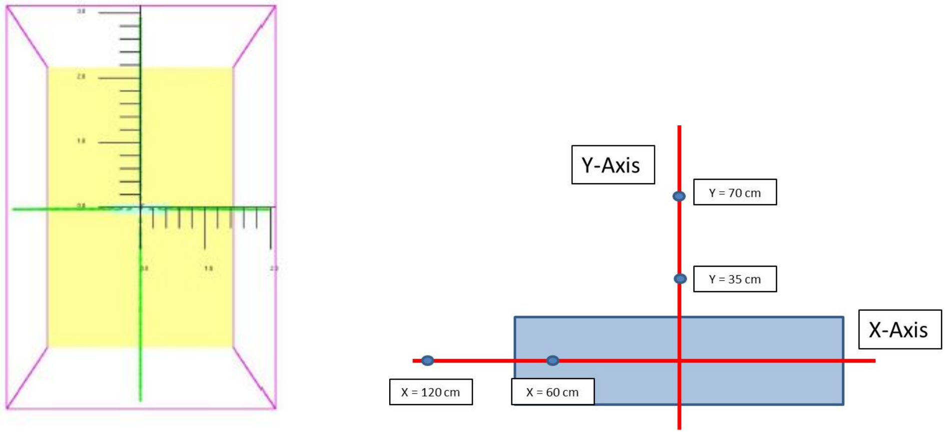
velocities in the system. After a mesh grid sensitivity analysis a 6.5 cm mesh was chosen for this case.

Another significant factor in the model is the initial temperature of the combustion products. The adiabatic combustion temperature of the propane was chosen. Per definition the mixture fuel-air is predefined and known in a premixed combustion.

The definition of the initial temperature by means of the adiabatic temperatures guarantees that the initial energy represents the correct energy system and the subsequent energy balance in the model are based on proper initial values.

Regarding radiation the higher the combustion efficiency, the lower the flame radiation fraction, since less soot is produced and the flame becomes transparent. However a small heat fraction is still released as radiation. The fraction of heat released as convective heat, can be calculated using the partial pressures of CO_2 and water vapour in the products [9]. Using the chemical balance, see above Equation (1), the molar quantities are calculated and these values correspond to the partial pressures (surrounding pressure, ambient pressure, 1 atm). The flame temperature T= 1995 °C is considered:

- CO_2: p_{C02} –> 3 / (3 + 4 + 18.8) –> 0.116 atm
- Water vapour: p_{H20} –> 4 / (3 + 4 + 18.8) –> 0.155 atm



(a) FDS Model (b) Full scale test grid

Figure 2. The figure shows the measure grids use in FDS model and during the full scale tests

$$R = 1.7 \cdot 10^{-6}(p_{CO_2} + 0.18 \cdot p_{H_20}) \cdot T^2 = 0.973 \tag{2}$$

The remaining fraction, around 3%, is the radiative fraction. This result is important both for the computer models implemented to study the system and to estimate the equivalent natural fire that the burner represents.

3. Model validation

Two validation process were carried out: the validation of the plume model and the validation of the geometry for full scale test.

3.1. Validation of the plume model

The temperatures of the plume with the system working at four different powers were recorded during a measuring campaign. The chosen values are representative of the system and cover the low power, 100 kW, the highest power, 1.200 kW; and two intermediate values 400 kW and 800 kW. The temperatures were recorded following a similar grid like the one programmed in the simulations.

In the simulations a measurement grid was implemented along the X and Y axis, with a measurement device positioned each 20 cm and reproduced in the Z- direction each 19.5 cm equivalent to three cells. The validated FDS model for Izar eliminates also the uncertainties related to the fuel and its combustions. The measure grid can be seen in the figure 2.

During the test not all positions could be controlled. Only the central position and two position along the X and Y axis were recorded. These positions were

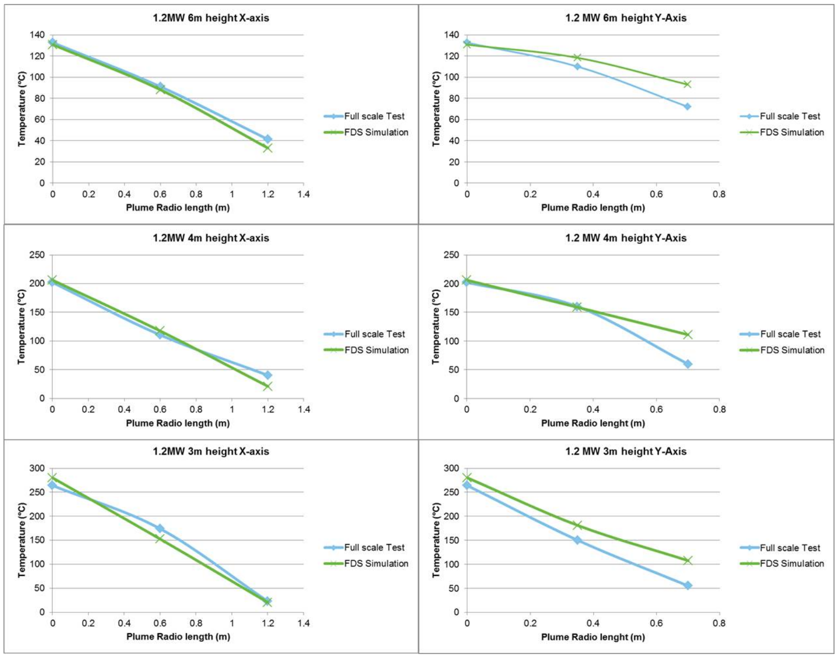


Figure 3. Temperature comparison between the measured temperatures during the real scale test (blue) and the measured temepratures in FDS (green). The indicated heigths are referred to the burning surface. Temperatures obtained with the system working at full power, 1.200 kW

controlled at three different heights above the burner surface: 3 m, 4 m and 6 m. The measurement grid can be seen in the figure 2.

These measurements can be defined as local. The graphs in figure 3 show the comparison between the recorded temperatures in the simulations and the ones recorded during the full scale test.

3.2. Validation of the model during full scale tests

Following the plume validation process the model was compared with the real data obtained from fuel scales tests with Izar in a big industrial hall. The aim of this validation was to confirm that the FDS model of Izar is capable of reproducing the behavior of the system during a real smoke test, and consequently capable of reproducing the generated smoke layer.

The tests took place in a big industrial hall with an approximate area of 3.000 m^2 and 9.5 m high. Different tests with different powers were carried out and the temperatures within the smoke layer were recorded at 5 m, 10 m, and 20 m, from the burner position. A depth of 2.25 m under the ceiling was controlled. The distance between the temperature sensor can be found in the figure 4

The geometry was reproduced in FDS and Izar was modeled using the previous description. The temperature was recorded in the FDS model at the same

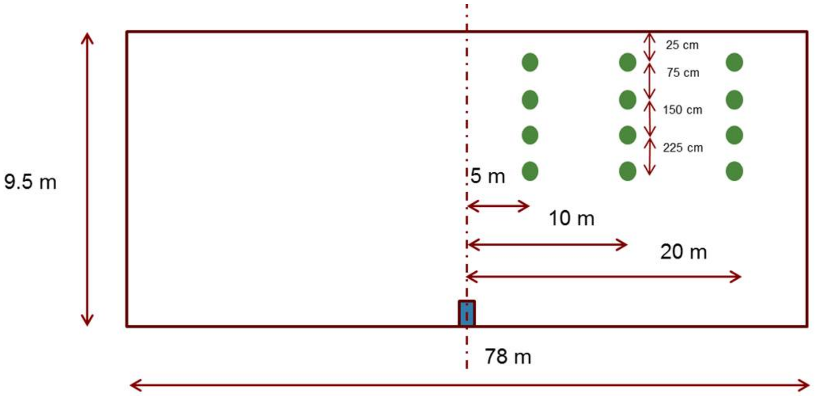
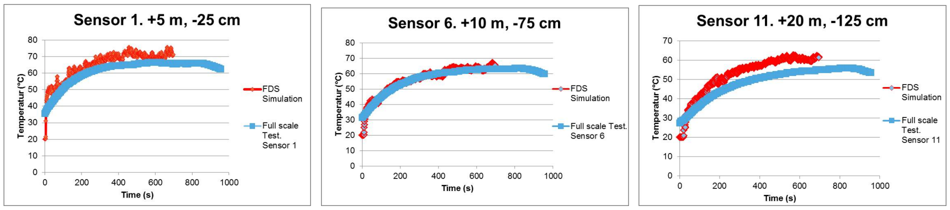


Figure 4. Distribution of the temperature sensor during the full scale test with Izar



(a) 5 m distance, 25 cm under the ceiling

(b) 10 m distance, 75 cm under the ceiling

(c) 20 m distance, 125 cm under the ceiling

Figure 5. Temperature comparison between the measured temperatures and the FDS Model. The positions are individually indicated

positions as in the real test. Figure 5 shows three position comparison between both temperatures at different positions.

4. Conclusion

The methodology presented in this paper is an efficient tool that allows modeling the plumes originated by the premixed combustion generated by the hot smoke testing system Izar in FDS. The model has been validated during a set of full scale test in an industrial hall.

The main model input parameters are the combustion species, the flame temperature and the geometry of the combustion region. The method takes advantage of the properties of the premixed combustion process, which allows defining the combustions products that are released during combustion and characterize its initial temperatures.

The recorded temperatures during full scale test confirm the experimental results and allow the model validation. The agreement between the observed and modeled central plume temperatures is remarkable. These temperatures are the result of turbulence and entrainment process around the entire plume perimeter.

The agreement between the real temperatures and the recorded temperatures in the FDS model, confirms that the turbulence produced by system Izar up to 1.200 kW is well resolved in FDS.

The agreement between the temperatures recorded during the full scale tests and the ones obtained from FDS, confirm that presented FDS model is capable of representing the performance of the smoke testing system Izar.

Thanks to these model it is possible to simulate the hot smoke testing system Izar with FDS and define the plume temperatures for different powers and different heights.

5. Future work

It will be desirable to test the method with different geometries and fuels. The presented results are only based on the experiences with Izar. Different configurations must be investigated to confirm the presented ideas.

If the necessary information is available, a equivalent equation to those available to calculate the plume temperatures from diffusions flames could be developed. These information will be very valuable in order to extend the use of systems with premixed flames, for example a new generation of hot smoke testing systems.

The available validated FDS model for Izar opens a wide range of possibilities regarding FDS as design tool. The design fires exceed the limits during the smoke tests and cannot be reproduced. Untenable temperatures will be reached in the room causing damages. However full scale test can be carried out with Izar under controlled conditions and the necessary measures can be recorded.

The data obtained from the FDS models have a direct application in the design of hot smoke tests systems with Izar. The work experience gained from the commercial hot smoke test carried out with Izar confirms that, considering the room limiting test temperature (defined by factor such as the presence of sprinklers), it is possible to define the maximum test power making use of the correlation between power and plume temperatures, obtained from the FDS plume models. That means that the most realistic hot smoke test for the studied room can be carried out.

These temperature measurements can be used to calibrate and validate the FDS geometry.The last step is to program the design fires in this previously validated geometry which eliminates many model uncertainties.

These kind of “a priori” validated simulations offer a greater grade of confidence and may reduce the safety factors taken in the design of the smoke management systems and thus, optimizing the solutions.

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