New Generation of Smoke Tests

Juan Jose Blond[1*], Mario Venturini[1], Andreas Kanitz[1] & Ricky Carvel[2]
[1]Basler und Hoffmann AG, Zürich, Switzerland
[2]University of Edinburgh, United Kingdom
*Juan.Blond@baslerhofmann.ch

ABSTRACT

This paper focuses on a new generation of hot smoke tests, using premixed propane flames as a fire source. Premixed flames burn in a highly efficient manner. Thanks to this high combustion efficiency, the flame length is reduced and, consequently, the local temperatures at the ceiling directly above the burner are lower. In fire tests, this allows the level of structural protection above the burner to be reduced. Also, the radiation from the flames is dramatically reduced and heat is almost totally released as convective heat.

The equipment design allows the user to control the heat release rate of the apparatus in real time. Pre-defined 'fire' curves can be reproduced to study the reaction of the detection systems or to evaluate smoke filling times.

Real tests and computer simulations using FDS were used to study and describe the system. Due to the lack of literature regarding the plumes created by premixed flames, it was necessary to run real tests, take measurements and create a computer model in order to collect information and assess the burner performance.

The comparison between the real tests and the computer model allowed the validation of the simulations. The test results showed that the developed testing methodology is suitable to replicate realistic smoke conditions.

KEYWORD: realistic smoke tests, computer models, simulations, premixed flames

INTRODUCTION

Nowadays, tunnels play a critical role for both transportation of people and goods. A fire accident in a tunnel may cause fatalities and always entails economic losses. Modern national and international economies rely on a functional transport infrastructure. If a tunnel has to be closed for days, weeks or months, the economic consequences can be huge due to longer travelling times, fuel consumption or loss of the goods' value (e.g. food industry). Some populations may even be cut off until the tunnel reopens.

When a fire safety strategy is designed the primary goal is always to preserve the life of the tunnel users or occupants. The majority of injuries and fatalities due to fires in enclosed spaces are caused by inhalation of smoke. In an enclosed space such as a tunnel, smoke management systems (ventilation systems) are installed to maintain tenable conditions during the egress process and better conditions during fire-fighting operations.

Different legislations are applicable to tunnels. Both international and national legislations demand certain measures in order to guarantee that the smoke management systems will perform satisfactorily when they are needed. Realistic smoke tests are required to demonstrate the capabilities of ventilation systems.

The European Directive 2004/54/EC [1], applicable in all the EU-countries, requires "*regular tests to* *be carried out in the road tunnels covered under this document, which shall be as realistic as possible, yield clear results and prevent any damage to the tunnel... these tests shall be conducted in each tunnel at least each four years".*

Also the World Road Association (PIARC) [2] although its documents are norms instead of legislation, recommends undertaking *"full scale tests prior to opening a tunnel (...) and complete test at regular intervals".*

Smoke tests for tunnels may be classified in three general groups: (1) cold smoke tests, (2) hot smoke tests and (3) full scale fire tests. Each of these methods can provide valuable results but each one also has associated problems. For example, cold smoke tests don't produce buoyant smoke layers and therefore they are not sufficiently realistic for most ventilation performance studies, while hot smoke tests generally only reproduce constant heat release rates (HRR) and require extensive tunnel cleaning operations after the test. In addition, due to environmental reasons, some of these tests are prohibited or require a large number of authorizations and bureuacracy.

The aim of this work was to develop a novel smoke testing system which is able to reproduce the essential features and performance of hot smoke tests, but without the problems associated with ‘dirty’ smoke.

METHODOLOGY

The methodology applied to study the burner combined both computer models and real-scale tests. A number of different simulations were implemented in order to find a model able to simulate the conditions in the real tests.

As will be discussed, the smoke testing system can produce fires up to 1.2 MW. Four different heat release rates (HRR) of 0.1 MW, 0.4 MW, 0.8 MW and 1.2 MW were tested during the experiments and simulated using the computer models. These values were chosen to obtain a complete view of the burner behaviour for the complete range of work.

SYSTEM DESCRIPTION

The smoke testing system presented in this work is composed of a propane burner and the auxiliary equipment necessary to bring the required amount of gas into the burner under the required pressure conditions.

As can be seen in Figure 1 the fuel and air are premixed to enhance combustion by cross streams. The fuel is supplied at the bottom and the air is supplied through the V-plates.

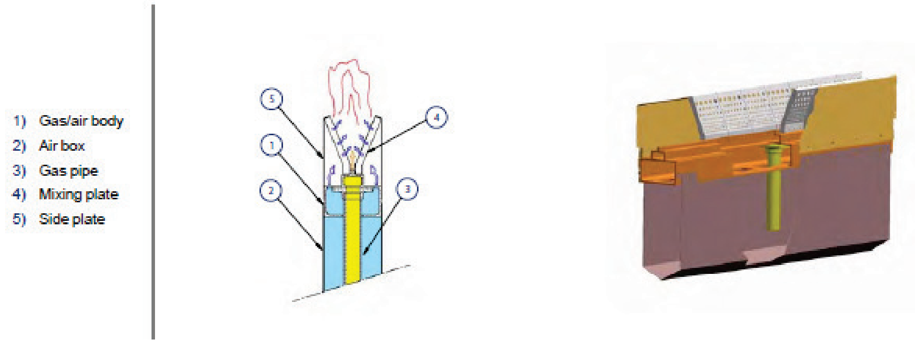

Figure 1 Smoke testing system configuration. The figure shows the V-shape of the mixing plates and offers a schematic overview of the smoke testing system.

One burner unit (burning domain) is 1.22 m long and 0.17 m wide (dimensions of the exit area) and 1 m high. The burner has a maximum capacity of 1.2 MW although, both the ratio air-fuel and the burning capacity are tuneable below this value. Multiple burners could be used to generate fires with HRRs above this limit. The complete system developed to date is comprised of two identical burning units, with a combined peak HRR of 2.4 MW. However, only one unit was used for the work described here.

The plume produced by the system is clean. The soot yield is negligible and the 'smoke' is transparent. In order to track and visualize the plume as smoke, it can be seeded with a clean synthetic agent.

The gas supply system is composed of eight propane bottles and a evaporator needed to bring the proper gas amount in the burner. These propane bottles are standard and can be easily sourced in many countries. A standard propane gas bottle contains around 10 kg. That means that the system can be run without stopping for about 46 minutes (considering an efficiency of 90%) at full power.

The system is equipped with a digital control system which allows the reproduction of fire curves. Linear , t^2 and user-controllable fire growth rates can be modelled, as can the decay phase of a fire, if required.

FDS MODELLING

The system was studied making use of computational fluid dynamics (CFD) software. In this case, the Fire Dynamics Simulator (FDS) v6 was used to model the burner. The new properties implemented in FDS v6 allow the representation of the turbulence around the fire plume in a better way than previous versions of the model, and consequently a better model of the system may be obtained.

However, FDS is not designed to model premixed combustion directly, therefore an alternative solution had to be found. The properties of premixed propane combustion are known and well characterised in the literature, its adiabatic flame temperature under absolute ideal conditions is 2194 °C [3]. Considering this, the burner has been modelled as a hot gas stream ejected from the burner at a temperature above 2000 °C.

The yielded quantities of the main products can be easily calculated for each HRR because the combustion process takes place at stoichiometric ratio:

$$C_3H_8 + 5\,O_2 + 5 \cdot 3.76\,N_2 \rightarrow 3\,CO_2 + 4\,H_2O + 5 \cdot 3.76\,N_2 \qquad (1)$$

The propane heat of combustion can be found in the literature and its value is around 46 MJ/kg [3], and the reaction can be adjusted for each HRR in order to calculate the kg/s of each product yielded.

To model the system, it was critical to define the correct radiation fraction, that is, how much of the heat is released as radiation. The system is intended to work with a stoichiometric air-fuel ratio mixture in order to achieve the highest combustion effiency and reduce the flame height. The available literature regarding premixed flames shows that premixed flames present a very low radiation fraction and therefore the larger part is released as convective heat [3].

It is known that the higher the combustion efficiency, the lower the flame radiation fraction, since less soot is produced and the flame becomes transparent. The fraction of heat released as convective heat, can be calculated using the partial pressures of CO_2 and water vapour in the products [3]. Using the chemical balance, see above Eq. 1, the molar quantities are calculated and these values correspond to the partial pressures (surrounding pressure, ambient pressure, 1 atm).

- CO_2: p_{CO2} → 3 / (3 + 4 + 18.8) → 0.116 atm

- Water Vapour: $p_{H2O} \rightarrow 4 / (3 + 4 + 18.8) \rightarrow 0.155$ atm

Therefore, the heat fraction transferred to the gases as convective heat is:

$$R = 1.7 \cdot 10^{-6} \, (p_{CO2} + 0.18 \, p_{H2O}) \, T^2 = 0.978 \tag{2}$$

The remaining fraction, around 2%, 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.

A very fine cubic mesh of 3.25 cm for the 0.1 MW and 0.4 MW simulations and 6.5 cm for the 0.8 MW and 1.2 MW cases was utilized in the model to minimise the errors. The main advantage of using a computer model is the amount of spatial and temporal information that can be obtained from it. Temperature and velocity can be predicted at any desired location in the domain.

The devices were separated 20 cm (equivalent to one device every three cells) both in X-direction and Y-direction. A total number of 20 devices were placed along the X-direction (10 along the positive direction, 10 along the negative direction) and 30 in the Y-direction (15 along the positive direction, 15 along the negative direction) plus one device at a central position. Taking into account both temperature and velocity devices the number of measurements is 3162.

This grid was reproduced every 19.5 cm in Z-direction, equivalent to 3 cells, up to the height of 6 meters above the burner. The resulting number of levels was 31. This height, 6 meters above the burner, equivalent to 7 meters above the floor, was chosen because this seems a reasonable maximum height for a smoke layer because a typical two lane road tunnel is around 6 meters high.

EXPERIMENTAL TESTS FOR MODEL VALIDATION

A series of experiments for model validation was carried out during August 2013 in an industrial premises. The burner was placed under an opened window installed at the roof in order to avoid the smoke accumulation inside and any possible disturbance of the plume.

Four different HRR quantities, 0.1 MW, 0.4 MW, 0.8 MW and 1.2 MW; were set and both, temperatures and velocities, were measured at different positions in order to compare the real measurements and simulations. However, the uncertainties around the velocity measurements made the use these velocity measurements problematic and no further reference to these is made in this work.

The temperatures were measured at 3 meters, 4 meters and 6 meters high taking the burner as reference. Both the central axis position and two points along the main axis, were measured as the following figure, Figure 2, shows.

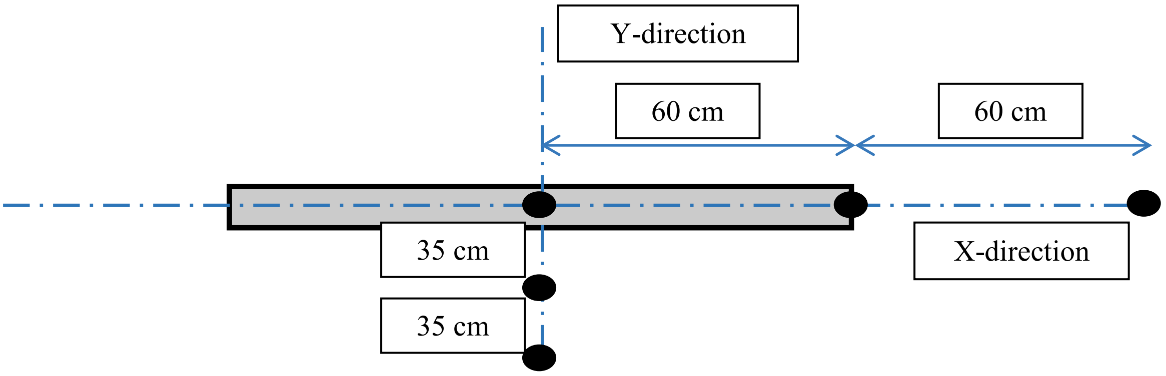

Figure 2 Real test set up

Once the flame was stable, the temperatures were continuously measured every five seconds for two minutes in order to ensure a reliable value. The first minute was discarded because the records showed a certain fluctuation, and the measurements were considered from the second minute on, when the records were more stable. It was not possible to measure along the Y-axis for the higher HRRs of 0.8 MW and 1.2 MW.

The results obtained during the tests were compared to the simulations in order to validate the model. After a sensitivity analisys, it was found that using a flame temperature of 2500°C in the model obtained the best correlation to the test results. This is slightly higher than the calculated flame temperature, but using this temperature in the model consistently gives the most accurate predictions. By increasing the flame temperature, the combustion region is better represented, and consequently the plume properties are better achieved. The results are presented in the following tables:

Table 1 0.1 MW test configuration. Comparison between the temperatures measured during the real test and the results obtained from the simulations.

	Central Position		***X-axis 60 cm***		***X-axis 120 cm***		***Y-axis 35 cm***		***Y-axis 70 cm***	
	Test (°C)	**FDS (°C)**	**Test (°C)**	**FDS (°C)**	**Test (°C)**	**FDS (°C)**	**Test (°C)**	**FDS (°C)**	**Test (°C)**	**FDS (°C)**
3 m	68.85	69	38.7	36.32	23.2	20	45.85	45.3	32	28.44
4 m	61.05	57	34.25	33.5	23.2	20	44.3	45.26	32.5	34.2
6 m	43.05	44	31.8	31.5	23.2	20	42.55	39	36.6	33.05

Table 2 0.4 MW test configuration. Comparison between the temperatures measured during the real test and the results obtained from the simulations.

	Central Position		***X-axis 60 cm***		***X-axis 120 cm***		***Y-axis 35 cm***		***Y-axis 70 cm***	
	Test (°C)	**FDS (°C)**	**Test (°C)**	**FDS (°C)**	**Test (°C)**	**FDS (°C)**	**Test (°C)**	**FDS (°C)**	**Test (°C)**	**FDS (°C)**
3 m	151.3	148.15	74.7	72.76	25.1	20	102.6	84.84	46.95	42.48
4 m	111	108.86	65.1	59.86	25.8	20	89.65	83.91	66.85	59.73
6 m	77.6	74.25	49	51.72	33	22	77.1	65.93	62.45	57.33

Table 3 0.8 MW test configuration. Comparison between the temperatures measured during the real test and the results obtained from the simulations.

	Central Position		***X-axis 60 cm***		***X-axis 120 cm***		***Y-axis 35 cm***		***Y-axis 70 cm***	
	Test (°C)	**FDS (°C)**	**Test (°C)**	**FDS (°C)**	**Test (°C)**	**FDS (°C)**	**Test (°C)**	**FDS (°C)**	**Test (°C)**	**FDS (°C)**
3 m	216.1	217.25	115.6	114.36	24	20.3	-	136.4	-	75
4 m	170.5	168.1	101.6	93.06	33.75	20.2	-	128	-	81
6 m	109	108	77	73.82	41.3	27.44	-	96	-	75

Table 4 1.2 MW test configuration. Comparison between the temperatures measured during the real test and the results obtained from the simulations.

	Central Position		***X-axis 60 cm***		***X-axis 120 cm***		***Y-axis 35 cm***		***Y-axis 70 cm***	
	Test (°C)	**FDS (°C)**	**Test (°C)**	**FDS (°C)**	**Test (°C)**	**FDS (°C)**	**Test (°C)**	**FDS (°C)**	**Test (°C)**	**FDS (°C)**
3 m	264	280.13	174	152.54	22.7	20	-	181.7	-	107.47
4 m	202	206	110.45	117.52	40.25	21	-	158.85	-	111
6 m	132.5	130.65	91	88.12	41.2	33	-	118.3	-	93

This benchmarking exercise has shown an excellent match between the model in FDS and real scale fire tests under a free burning environment. The variations in temperatures are all within 10% of the experimentally recorded values.

The field of temperatures is a consequence of a turbulent mixing process. The FDS model shows satisfactory results for four different HRR outputs within the range of interest. The plume is a buoyant fluid and therefore the field of velocities is mainly imposed by the field of temperatures. The excellent match obtained for the field of temperatures allows to read the velocities obtained from the simulations with a high grade of confidence

The model may therefore be considered 'validated' for this scenario. Further testing, described below, will compare model predictions with test data from a different experiment.

PLUME MODEL AND SMOKE TESTING CAPACITY. COMPARISON BETWEEN NATURAL FIRES AND THE SYSTEM

The previous section has demonstrated that we are able to predict the behaviour of the system generated plume using FDS. It remains to be demonstrated that the system is able to replicate the behaviour of a real fire test.

This smoke testing system uses a rectangular fire source. Therefore, the plume produced is not axisymmetric but elliptical: there is a preferential air entrainment direction, as shown in Figure 3.

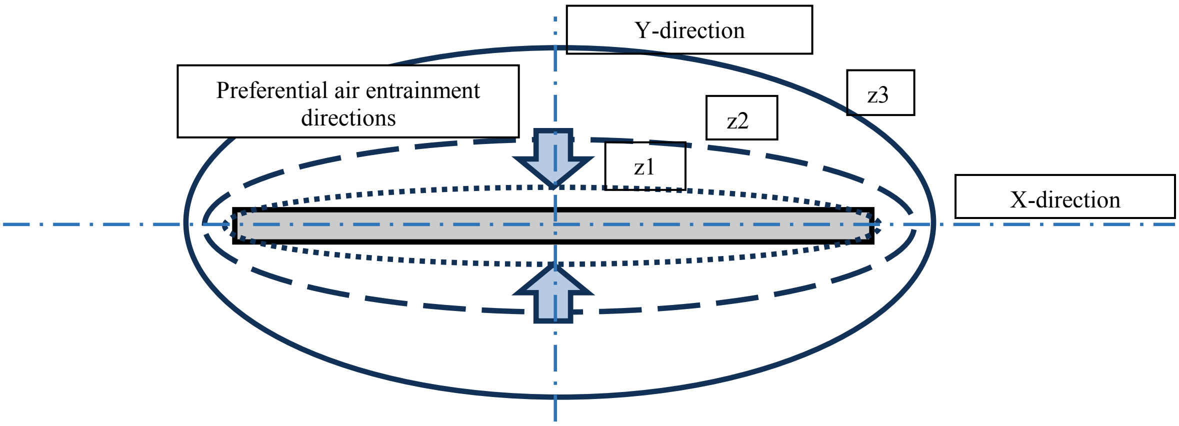

Figure 3 Preferential air entrainment in the plume. The air entrains preferentially along the Y-axis

The plume was studied assuming that it presents a Gaussian profile, therefore, the radius is defined as the distance at which the temperature or the velocity is $e^{-1} \approx 0.368$ times the central value. As the profile is elliptical two radii must be calculated at each level. These radii can be calculated considering either the temperature profile or the velocity; both were calculated and average values were considered for the following calculations. The volume flow was obtained by integrating the velocity profile across the plume area. The following figure, Figure 4, shows the growth of the radii along the X and Y axis, for three different HRR:

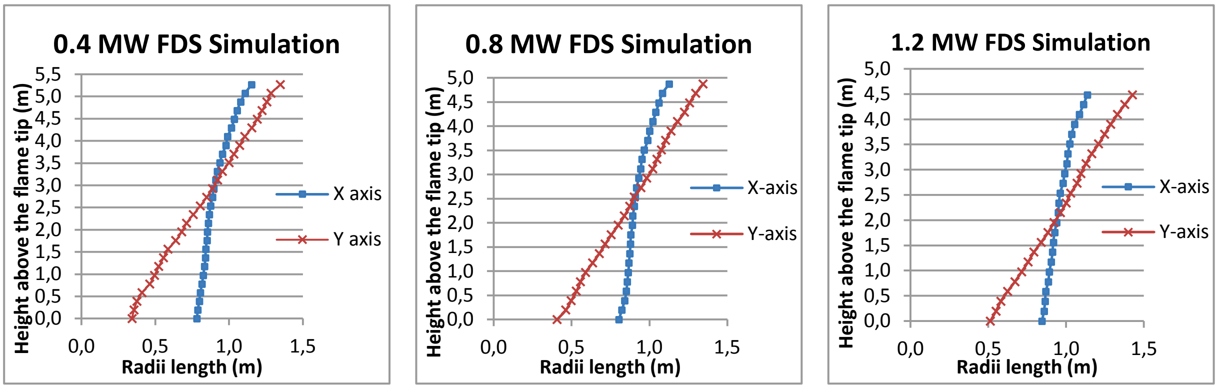

Figure 4 Comparison between the radii growth along the main axis for 0.4 MW, 0.8 MW and 1.2 MW.

These results are in agreement with the hypothesis previously discussed: there is preferential air entrainment direction along the Y-Axis. While the radius along this direction grows by about 300 % as the height is increased, the radius along the X direction grows less than 20 %.

The burner was also compared with equivalent natural fires in order to assess the accuracy of the system in reproducing a natural fire. It is not possible to consider all the possible fires which may take place, therefore, a generic pool fire was chosen to compare the burner with. These fires were represented by the Heskestad equation, Eq (3) and Eq (4), [3]:

$$\Delta T = 9.1 \left(\frac{T_\infty}{g\, C_p^2 \rho_\infty^2} \right) \dot{Q}_c^{\,2/3} (z - z_0)^{-5/3} \tag{3}$$

$$z_0 = 0.083\, \dot{Q}^{3/5} - 1.02\, D \tag{4}$$

In a natural (diffusion flame) fire the radiation fraction is generally held to be between 30% and 40% depending on the fire conditions. Therefore only 60% or 70% of the fire power is transferred to the smoke plume. Taking typical values for a natural fire (65 % for the convective fraction and 35 % for the radiative fraction) and considering the earlier calculation of the radiation from the premixed flame (98% of the heat transferred as convective heat) at its maximum power, the burner will produce the same convective heat as a 1.8 MW natural fire:

Natural fire → 1.8 MW · 0.65 = 1.17 MW (convective heat)
Premixed fire →1.2 MW · 0.98 = 1.176 MW (convective heat)

Figures 5 and 6 show the comparison between the central temperatures of the burner and a natural fire, represented by Heskestad equation, for 0.8 MW and 1.2 MW. Only the region above the flame tip is considered since the combustion mechanisms are different and they are not relevant for the purpose of this work:

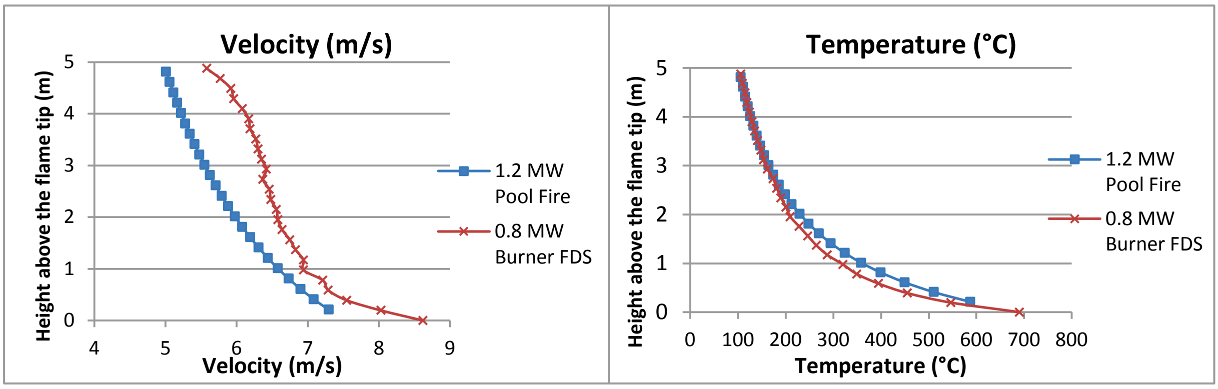

Figure 5 *Comparison between the values for centre-line velocity and temperature for a pool fire of 1.2 MW (represented by Heskestad equation) and data obtained from a simulation of the smoke testing system running at 0.8 MW*

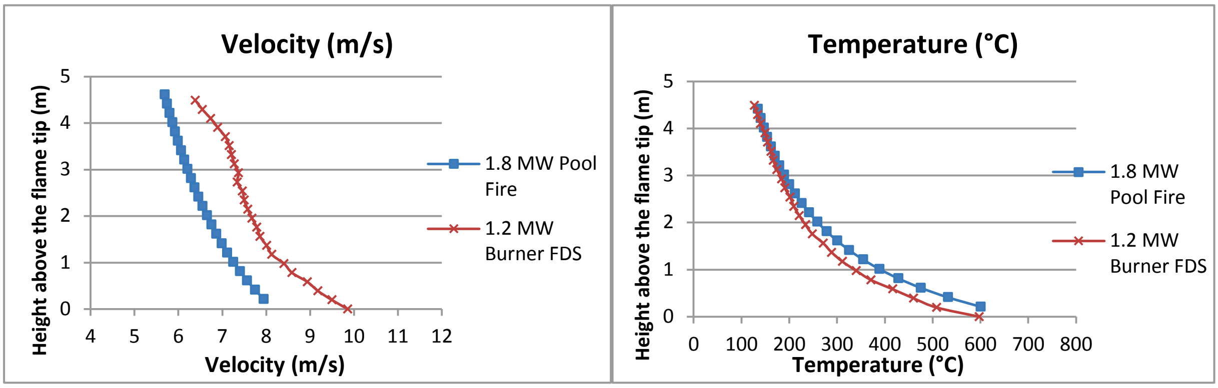

Figure 6 *Comparison between the values for centre-line velocity and temperature for a pool fire of 1.8 MW (represented by Heskestad equation) and data obtained from a simulation of the smoke testing system running at 1.2 MW*

REAL TEST IN AN INDUSTRIAL FACILITY. COMPARISON WITH SIMULATIONS

During the test campaign a complete smoke test was also carried out. Each of the four different HRR were produced for a period of time between 10 to 15 minutes. Twenty temperature sensors were positioned on the ceiling divided into four chains of four sensors and two chains of two sensors. The sensors were placed at 25 cm, 75 cm, 125 cm and 225 cm below the ceiling, in each of the four elements chains, and at 25 cm and 75 cm for the two elements chains. The chains were positioned at 5 meters, 10 meters and 20 meters from the burner.

These tests were later simulated in FDS, in order to test the predictive capabilities of the FDS model. The results presented and discussed below correspond to the burner running at 0.8 MW, equivalent to a natural fire of about 1.2 MW.

The comparison between the temperatures collected during the tests and the temperatures obtained from the simulations show an excellent agreement between the measurements and the model predictions. These results demonstrate the capability of the model to predict the results of the smoke testing system. Data from three different points are presented to support the previous statement:

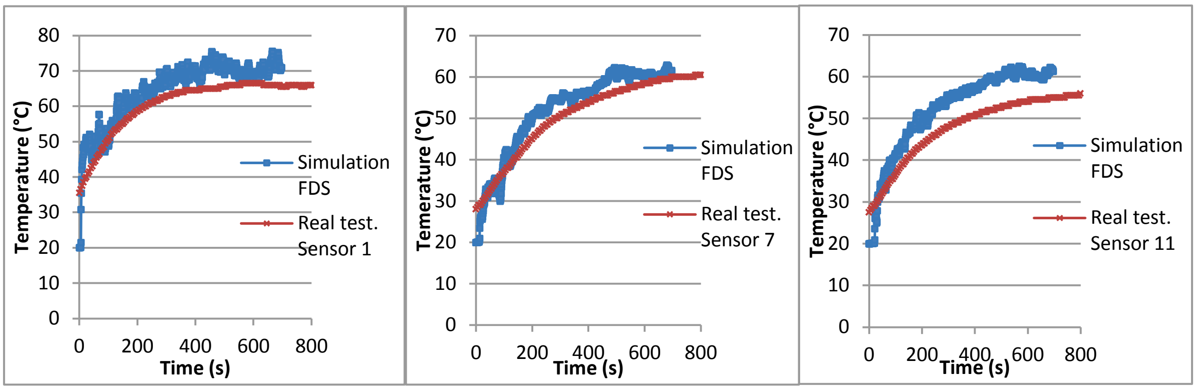

Figure 7 Comparison between the temperatures (°C) measured during the tests and the simulations in FDS for the burner working at 0.8 MW. Sensor 1 was placed at 5 meters from the burner and 25 cm under the ceiling. Sensors 7 and 11 were placed at 10 and 20 meters respectively both at 125 cm under the ceiling.

DESIGN OF SMOKE TESTS

When a smoke test is designed the aims and objectives of the test must be clearly established. Suitable results should be obtained from these tests in order to evaluate the quality of the smoke management system installed in the premises. The concept of a "realistic smoke test" must be always carefully considered because a totally realistic hot smoke test may damage the facility under investigation (e.g. a tunnel, warehouse, etc.) and reduced smoke quantities and temperatures may not be able to adequately assess the performance of the installed ventilation system.

As was previously discussed, the presented smoke testing system can reproduce fully adjustable fires up to 1.8 MW. In situations where the design fire for a particular scenario is l.8 MW or lower, the system can be used to replicate the smoke production and smoke spread properties of such a fire, at full scale, with clean smoke. In situations where a larger design fire is required, a test can be carried out at a reduced power (up to 1.8 MW), this can be modelled in FDS and the model calibrated to the test data, then the ‘validated’ model can be used to simulate the larger fire scenario.

One of the many benefits offered by the system is the reproduction of specified fire growth-curves. A ‘t^2-curve; is widely used to define design fires, such fires can be replicated by this system. Furthermore, the system can replicate any other fire growth curve, for example, the sporadic growth rate observed in a car fire test could be reliably and repeatably reproduced using this system. These capabilities make the system an ideal choice to test and demonstrate the capabilities of fire detections systems as well as ventilation systems. Detection systems aim to discover a fires as soon as possible during the growth phase. Rapidly growing pool fires and constant HRR burners are therefore poor tests for detection systems. The presented smoke testing system can be programmed to provide realistic fire curves, and hence test the capabilities of detection systems.

CONCLUSIONS AND FUTURE WORK

The smoke testing system presented here offers the possibility of carrying out smoke tests equivalent to a 1.8 MW fire using a premixed gas burner. The system has a number of advantages over current hot smoke and pool fire tests, including:

- Full control of the HRR in real time, allowing any fire curve to be replicated.
- Clean smoke, which considerably reduces the post-test cleaning activities.
- Tests can be carried out at up to 1.8MW for up to 46 minutes.
- Ease of use and rapid repeatability.

The smoke testing system has also been accurately simulated using a validated FDS model. This allows further scenarios to be considered, beyond the limitations of the experimental apparatus.

The smoke testing system is being tested in a number of other geometries, including a full scale tunnel, in order to reinforce the results presented in this work. Results from these tests will be published in due course.

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