Influence of Different Make-Up Air Configurations on the Fire-Induced Conditions in an Atrium

Cándido Gutiérrez-Montes [a,*], Enrique Sanmiguel-Rojas [a], Antonio Viedma [b]

[a]Fluid Dynamics Division of the Department of Mining and Mechanical Engineering, University of Jaen, Jaen, Spain
[b]Department of Thermal and Fluid Engineering, Technical University of Cartagena, Murcia, Spain

*Corresponding author: Tel.: +34953212903; fax: +34953212870.
E-mail address: cgmontes@ujaen.es (C. Gutiérrez-Montes)
Postal address: Despacho 022/023, Área de Mecánica de Fluidos, Departamento de Ingeniería Mecánica y Minera, Edificio A3, Campus Las Lagunillas, 23009, Jaén, España.

Abstract:

This paper provides with a set of full-scale experimental data of atrium fires. These data could be used as benchmarks for future numerical validation studies. In particular, the influence of the make-up air velocity as well as the position and area of the vents in an atrium is assessed both experimentally and numerically. Experimentally, the effect of different make-up air supply positions and inlet area on the fire-induced inner conditions and smoke layer descent was studied by means of three full-scale fire tests conducted in a 20 m cubic atrium. Detailed transient measurements of gas and wall temperatures, as well as pressure drop through the exhaust fans and airflow at the inlets were recorded. Later computational fluid dynamics (CFD) simulations of these tests were performed with the code Fire Dynamics Simulator (FDS). Experimentally, the lack of symmetry in make-up air vents and the large inlet area turn the flame and plume into more sensitive to outer effects. However, no significant difference has been observed between the make-up air topologies assessed. Even make-up velocities higher than 1 m/s, with symmetric venting topology, have not induced important flame or plume perturbations. Numerically, the simulations agree well with the experiments for the cases with make-up air velocities lower than 1 m/s. Poor agreement has been found for the case with inlet velocities higher than 1 m/s.

Keywords: make-up air, mechanical exhaust; CFD simulations, atrium, full-scale fire tests.

1. Introduction

The rapid smoke spread through an atrium in case of fire is a major concern. At this point, mechanical exhaust systems are commonly installed in big atria for smoke control. It is believed that these systems have more reliable performance (than others) as it does not depend strongly on ambient conditions. However, the performance of these systems can be influenced by various factors like the temperature of the smoke, the formation of a pre-stratification layer in the atrium, the exhaust rate, the outer wind or the make-up air among others. All these factors have to be studied and taken into account when designing a smoke exhaust system [9_1].

When using a mechanical exhaust system it is necessary to supply make-up air to conserve mass [124_2]. Without it, the atrium smoke exhaust component cannot be expected to perform as desired. In general, some of the goals for the make-up air to be accomplished are to be uncontaminated outdoor air, to be supplied from positions below the smoke layer [123_3] or to be supplied at low velocity not to disturb the flame and plume. An extensive explanation of these goals, as well as the main methods for supplying the make-up air, was presented by Duda [Duda_4]. Failure to achieve these goals could lead to ineffective designs of smoke exhaust systems. At this point, there is a lack of practical guidance for supplying replacement (make-up) air.

In addition, nowadays, there is greater design flexibility [tubs_5], which puts more responsibility on the designer. Fire engineers can give architects and building designers greater scope for achieving their architectural vision in an atrium. This is a fundamental idea and gets fire scientists involved in the creative process. Make-up air vents are one of the most significant concerns for architects since they are at lower levels and are more visible, whereas mechanical venting is often on the roof and rarely as important aesthetically.

In relation to make-up air, some standards and codes [9_1, 3)_6] suggest that make-up air should not exceed 1 m/s in areas, unless a higher velocity is supported by engineering analysis. This limit prevents significant deflection of the plume and disruption of the smoke layer. This type of engineering analysis could be based on comparisons developed with full-scale, scale, or CFD modelling. At this point, CFD modelling can be the basis for exceptions for the requirements to smoke-layer depth, the 1 m/s limitation on make-up air, and plugholing, among others. Nowadays, with the possibility of implementing engineering performance-based fire codes, CFD fire models [58_7] are commonly used in hazard assessment in atria. However, these computational models need of further validation and verification studies of atrium fire modelling [nuclear_8], especially full-scale data verification, in order to limit their range of applicability and their reliability in case of different boundary conditions, including the case of different air supply and smoke exhaust conditions. Whether these models are suitable for use is queried, leading to challenges [chow_complex_9)].

So far, few studies on the effect of make-up air have been conducted. Some authors like Hadjisophocleous and Lougheed [142_10] performed studies on mechanical exhaust with different make-up air positions. Yi et al. [122_11, 144_12] carried out full-scale experiments at the PolyU/USTC Atrium, of 22.4 m × 11.9 m × 27 m, and numerical simulations to study the effects of make-up air inlet vents location. They concluded that, if the minimum smoke layer interface height was above the safe level then air inlets lower than that should be installed whereas, on the contrary, extraction with higher air inlets could be advisable, as it would reduce the smoke temperature.

There are other important factors such as the distribution of air inlets, distance of the air inlet from the fire, and air flow velocity through the air inlet, that should also be considered. Recently, Kerber and Milke [145_14] studied numerically the possible effects of various make-up air supply arrangements (symmetrically located vents placed low in the spaced, an array of vents distributed from the floor to the ceiling, and asymmetrically located vents) and velocities (from 0.5 to 3.0 m/s) in an atrium smoke management system within a 30.5 m high cubical atrium. It was found that the best layout of vents was that in which make-up air was supplied to the fire symmetrically to avoid plume perturbations. In addition, it was found that even velocities lower than 1 m/s could cause the smoke layer to descend below the design criterion. As a consequence, it was stated that the inlet velocities should be diffused so that they were very low when they reached the fire and had no effect on it.

Lately, an ASHRAE research project was conducted to investigate the maximum velocity of makeup air in atrium smoke control applications. Zhou and Hadjisophocleous [2_15] studied numerically the influence of different parameters such as the outer wind or the locations of the make-up air vents on fire plumes. It was noticed that, placing openings at the bottom and the top of the atrium caused the least disruption to the plume. However, locating the opening at the top caused significant mixing of smoke with the air of the lower layer. Besides, Hadjisophocleous and Zhou [3_16] studied numerically the influence of make-up air velocities, considering different fire sizes in various size atria (heights from 10 to 60 m, HRR from 1 to 5 MW and different fire locations, inlet velocities from 0.5 to 1.5 m/s). It was concluded that the increased make-up air velocity lowered the interface height in the atrium, that the make-up air velocity restriction of 1 m/s was not conservative, as it caused plume disturbances that resulted in lower interface heights, and that the impact of the make-up air velocity was more pronounced in atria with height less than 20 m.

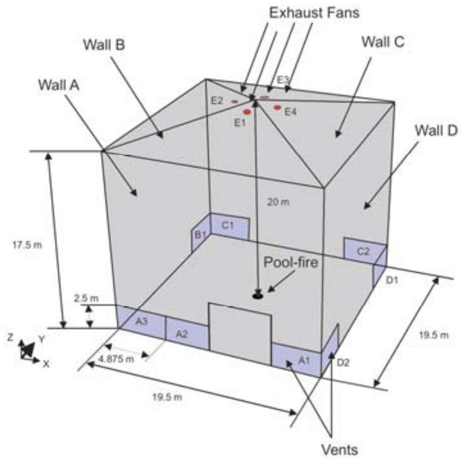
The main aim of the present work is to provide with a set of full-scale experimental data of atrium fires. These data could be used as benchmarks for future numerical validation studies. The tests were carried out as part of the Murcia Atrium Fire Tests, performed in Murcia, Spain (see [B&E 1 y 2] for details). In these tests the make-up air inlet area and vents distribution have been varied. In the first test, all the vents were completely open with asymmetric layout. In the second test, some of the vents were completely open with symmetric layout. Finally, in the third test, the vents open in the previous test were partially open. Detailed transient measurements of gas and wall temperatures at different heights, as well as the pressure drop through the exhaust fans and airflow at the inlets, were taken. Later CFD simulations of the experiments have been performed using FDS in order to check its capability to properly predict the fire-induced conditions for the different make-up air configurations.

2.- Murcia Test Facility and Fire Tests

- **Test facility**

The fire tests reported here have been carried out in the atrium of the Centro Tecnológico del Metal, Spain (Figure 1 a) [18]. This facility, unique in Spain and one of the few full-scale facilities in Europe for these kinds of tests, has global dimensions of 19.5 m x 19.5 m x 19.5 m. The walls and roof are made of 6 mm thick steel and the floor is made of concrete. There are four exhaust fans installed on the roof, each with a diameter of 0.56 m and a nominal flow rate of 3.8 m^3/s. There are eight grilled vents arranged at the lower parts of the walls. Each vent has dimensions of 4.88 m x 2.5 m. A drawing of the rig with dimensions is shown in Figure 1 b.

a)



b)

Figure 1. Photo of the fire tests facility in a), and sketch and main dimensions in b).

The atrium contains up to 61 sensors distributed in 4 different regions: the front wall (wall A), the back wall (wall C), a central section parallel to walls A and C and the roof and fans region. A sketch of the location of the *main* sensors considered for this work as well as their nomenclature is shown in figure 2. The variables reported here are the air temperature next to the walls and the make-up air temperature and velocity, figure 2 a) and b), 30 cm inside the atrium, the temperature at the central section, figure 2 c), and the smoke through the fans temperature, figure 2 d). For the air temperature, class B bare Pt100 thermistor probes have been used at the fans, walls and vents. For the gas temperature at the central section, sheathed type K thermocouples have been used. For the make-up air velocity hot wire anemometers have been used. A Modicom TSX Premium automaton connected to a PC has been used to register the data with a frequency of 10 Hz. A digital camera has been also used to take graphic records of the flame. Finally, the weather conditions have been measured with a meteorological station monitoring the wind velocity, temperature, humidity and pressure outside the facility.

An uncertainty analysis for the measurements conducted in [18] showed a total experimental uncertainty of 1.5% for the thermocouples, of 0.4% for the thermistors, of 4% for the velocity probes and of 1 % for the mass loss rate of fuel.

- **Fire Tests**

Results from three full-scale fire tests with different make-up air venting conditions are reported. The burning fuel was heptane contained in a pool-fire, of 0.92 m diameter and

0.25 m deep, placed at the centre of the atrium floor. For the first test, all the make-up vents were completely open, with a total inlet area of 97.50 m^2, figure 3 a). For the second test, the vents were completely open with symmetric layout. In this case, the two vents of the wall C (back wall) and the two vents at the corners of the wall A (front wall) were completely open, with a total inlet area of 48.75 m^2, figure 3 b). Finally, for the third test, the same vents as in the test #2 were partially open, at 22% percent of their area, with a total inlet area of 10.83 m^2, figure 3 c). In all tests, a layer of 2 cm of water was added to the pan before the heptane was poured to insulate the metal from the burning pool heat, thus providing a more stable steady burning regime. At the end of each test, the volume of water was measured again to confirm that no water had been lost. A summary of the laboratory and ambient conditions during the tests is presented in table 1.

Fire test	**Volume of heptane (l)**	**Burning time (s)**	**Open vents**	**Exhaust fans on**	**Ambient Temp (ºC)**	**Pressure (mbar)**	**HRR (MW)**
test #1	44	837	All	All	16.7º	1018	1.35
test #2	52	883	A1, A3, C1, C2 100%	All	28.9	1008	1.51
test #3	52	1094	A1, A3, C1, C2 22%	All	27.5	1007	1.22

Table 1. Summary of laboratory and ambient conditions during the fire tests.

The heat release rate (HRR), $\dot{Q}$, of each test has been calculated as,

$$\dot{Q}(t) = \dot{m}(t)\chi_{eff}\Delta H_c, \qquad (1)$$

where $\dot{m}(t)$ is the mass loss rate of the fuel, ΔH_c is the heat of combustion and χ_{eff} the combustion efficiency. The heat of reaction of heptane for complete combustion is 44.6 MJ/kg [7]. The combustion efficiency for a well ventilated heptane pool-fire of 0.92 m diameter is 0.85±0.12 [16, 20, 21]. Figure 4 shows the HRR of the test #2. The uncertainty associated with the HRR is estimated to be around ±15 %. A detailed explanation of these measurements is presented in [B&E paper 2].

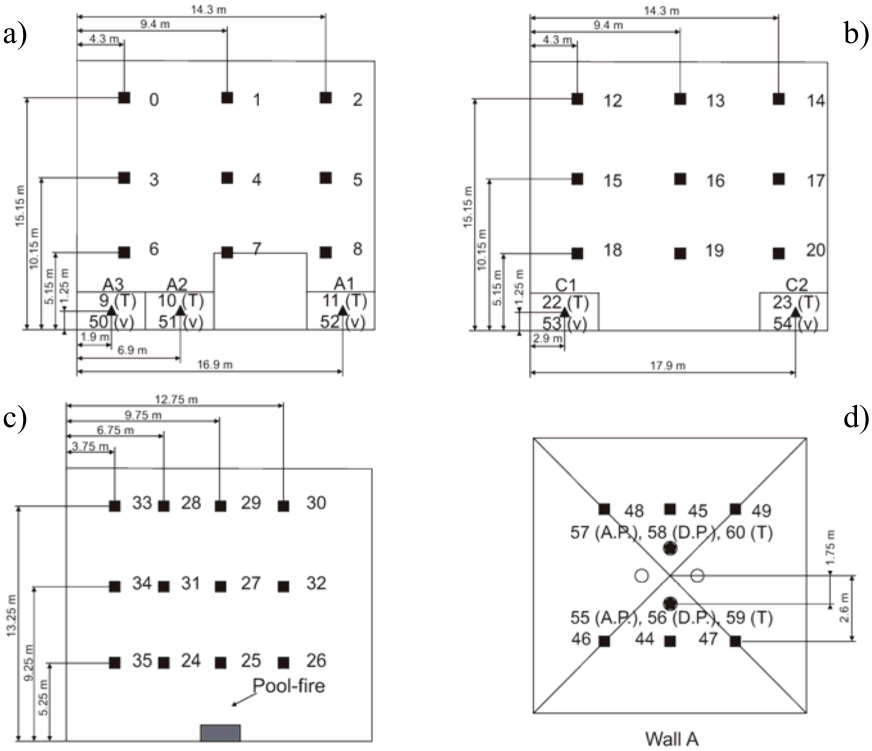


Figure 2. Layout of the main sensors considered. Wall A, from the outside, in a), wall C, from the outside, in b), central section, from the wall A, in c) and roof and fans, from the top, in d). Temperature sensors in squares, velocity and temperature sensors in triangles and pressure and temperature sensors in pentagons.

The complete set of measurements from the experiments is shown and discussed in section 5 of the paper, after the description of the fire simulations.

a)

b)

c)

Figure 3. Venting topology of the tests. Test #1: vents open in walls D (D2) and A (A1 and A2), in a), test #2: vents in wall A (A1 and A3 open, A2 closed) in b), and test #3: vents in wall C (C1 and C2 partially open) in c). Views from inside.

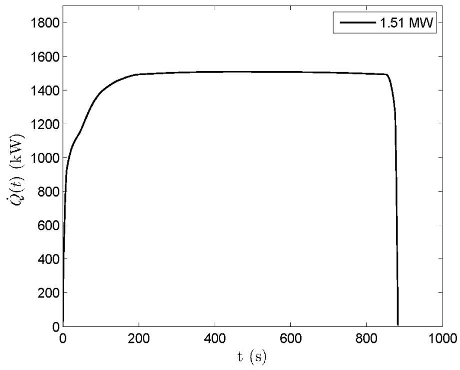


Figure 4. HRR vs time of test #2.

4.- Description of Fire Simulations

- Mathematical Model

The CFD code FDS [22] has been used for the simulation of the three fire tests to check its capability to predict properly the fire induced conditions. The turbulence has been modelled using a large-eddy simulation (LES) approach [23], and the combustion model is based on the mixture fraction approach which assumes a mixing-controlled combustion, appropriate for the simulation of turbulent diffusion flames with fast chemistry such as pool-fires. The radiative heat transfer is computed by solving the radiation transport equation for a non-scattering grey gas. The HRR is prescribed as an input, function of time, at the pool, figure 4. The radiative fraction for a heptane pool-fire is 0.35 [12, 24]. The fans have been set a constant exhaust velocity across their area providing the nominal flow rate of 3.8 m^3/s each. The grilled vents have been simulated as openings to the atmosphere at ambient pressure. Finally, the walls and roof have been modelled as 6 mm thick steel sheets ([25 y paper B&E 2]) and the floor as a thick layer of concrete ([25 y paper B&E 2]).

- Grid Sensitivity Study

The computational domain includes the atrium space, the walls and the roof. The grid has been systematically refined until no significant difference is noticed with a cell size reduction and a compromise solution between numerical accuracy and computational cost is achieved. Six different grids have been assessed, 40, 60, 90, 120, 150 and 180 cells per side of the cubic atrium. For this study, *constant HRR fires of 1.3 MW have been simulated and averaged quasi-steady conditions at different locations have been considered*. The results have been compared between them, and with the finest grid results, to quantify grid independence. In LES is not possible to archive perfect grid independence although little variations can be theoretically expected between grids if they are fine enough [23, 27]. Table 2 shows the temperature predictions in the atrium for each grid. It can be observed that the temperature values and the relative errors for the three coarser grids are quite large. The temperature differences are lower than 10 % at the upper parts, above 13 m high, from 120 cells per side. Thus, it could be concluded that any of the three finer grids (120, 150 and 180 cells per side) could be valid for simulating the fire tests.

Height	Temperature predictions (ºC)						Relative error respect to finest grid (%)				
	40 cells	60 cells	90 cells	120 cells	150 cells	180 cells	40 cells	60 cells	90 cells	120 cells	150 cells
Exhaust fan	49	66	64	53	58	56	13	18	14	5	4
Plume at 13m	64	110	99	78	81	74	14	49	34	5	9
Plume at 9m	80	152	173	129	160	136	41	12	27	5	18
Plume at 5m	116	226	333	293	503	487	76	54	32	40	3

Table 2. Centreline averaged plume temperatures at different heights as a function of the grid size for a 1.3 MW fire. Grids are expressed as number of cells per atrium side (19.5 m)

This grid sensitivity study would be enough for a conventional simulation. However, as a LES technique is used, the grid spatial resolution, R^*, is needed to be between,

$$\frac{1}{10} < R^* < \frac{1}{5} \tag{2}$$

for a proper simulation [21, 22]. The grid spatial resolution, R^*,

$$R^* = \frac{\Delta x}{z^*}. \tag{3}$$

is defined in terms of the characteristic diameter of a plume [21, 7], z^*,

$$z^* = \left(\frac{\dot{Q}}{\rho_\infty c_{p,\infty} T_\infty \sqrt{g}} \right)^{2/5}. \tag{4}$$

In the above expressions Δx is the characteristic length of a cell for a given grid, g is the gravity acceleration modulus and ρ_∞, $c_{p,\infty}$ and T_∞ are the ambient density, specific heat and temperature, respectively. Table 3 shows the necessary grid cells per side regarding the above resolutions. Regarding this criterion, the results from table 2 and in order to assure grid independency, grids of 180 cells per side (≈ 5.8 million cells) have been used, that is, cells smaller than 0.11 m in length.

Fire test (MW)	**Cells number for R^* = 1/5**	**Cells number for R^* = 1/10**
1.34	90	181
1.50	86	173
1.22	94	188

Table 3. Number of cells needed in each direction for different grid resolutions.

Finally, figure 5 shows a comparison with the experimental results from [paper B&E 2] for a 1.3 MW heptane fire test conducted at the Fire Atrium of the Centro Tecnológico del Metal. The agreement between experiments and the grids of 150 cells and 180 cells per side is good, confirming the results from the grid sensitivity and spatial resolution requirements.

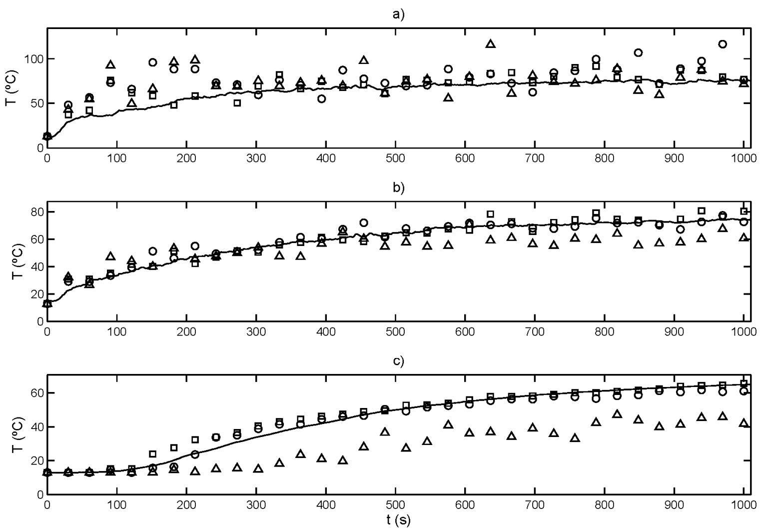


Figure 5. Comparison of temperature measurements and predictions for different grid sizes for a 1.3 MW test [paper B&E 2] at the plume 12.55 m high in a), fans in b), and 10 m high near wall A in c). Experiments in solid line, 120 cells per side in triangle, 150 cells per side in circle, and 180 cells per side in square.

5.- Results & Discussion

Next, the fire-induced transient conditions within the Fire Atrium are studied. In this section, the main results from the fire tests and the simulations as well as from the comparisons between them are reported and discussed. Results in four key regions are considered: the centreline temperature (ideally the plume), the smoke through the fans temperature, the air close to walls temperature and the make-up air inlet velocity at the vents.

The temperature evolution near the walls shows the built up of the smoke layer. The smoke layer height has been calculated experimentally by means of the N-percent method [29paperFDS] and compared with the one predicted by FDS. Experimentally, temperature increases from ambient temperature of 10 - 20 % [29paperFDS] and of 30 % [14Chow] of the highest temperature rise have been assessed to locate the smoke layer interface. In general, good agreement has been achieved between FDS and the value of N = 30 %.

- **Test #1:**

This test was with the four exhaust fans activated and all the vents completely open (total inlet area of 97.5 m^2), therefore, non-symmetric venting conditions were tested, figure 3 a). Figure 1.1 shows the measurements and predictions vs time at different locations.

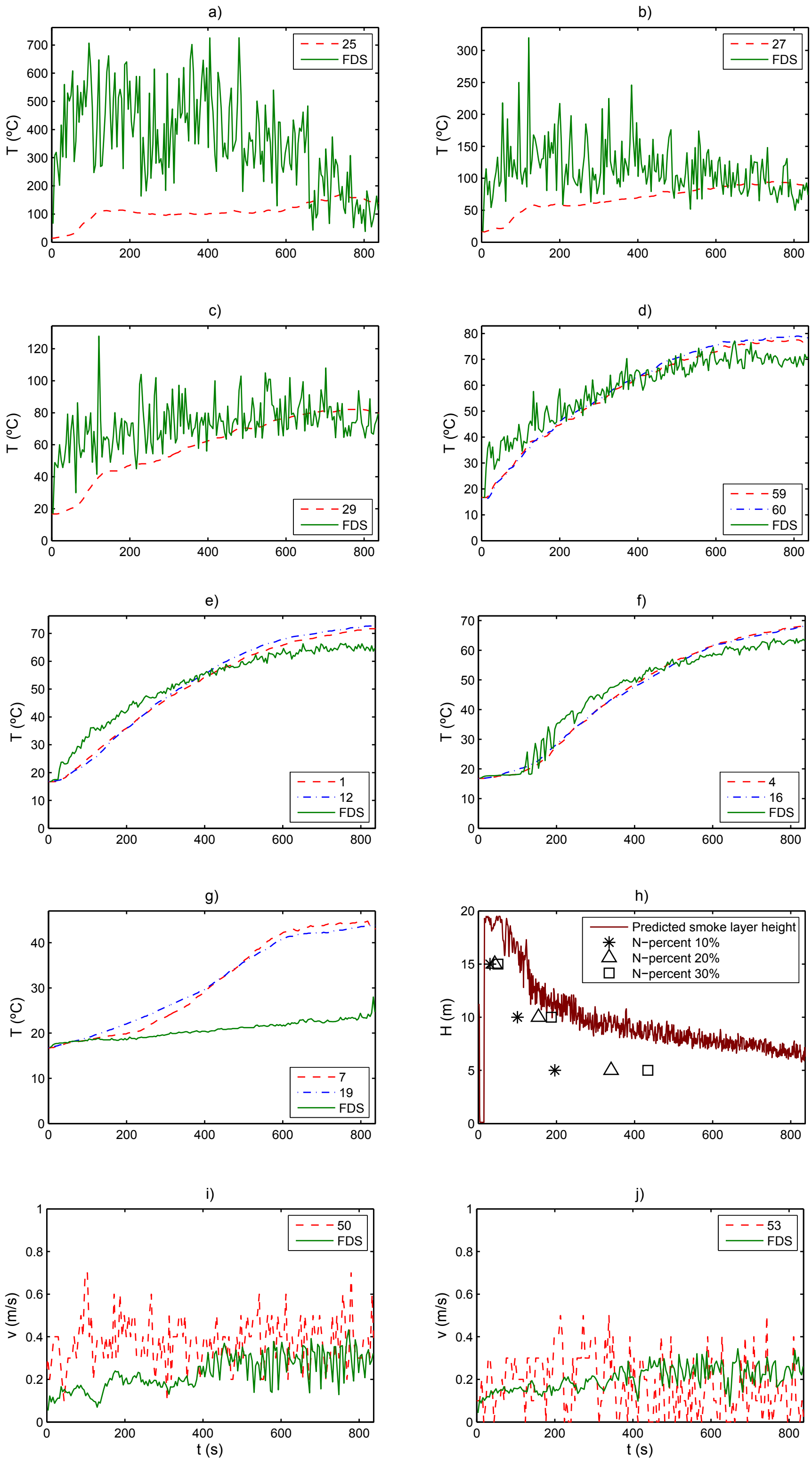


Figure 1.1. Test #1 measurements and predictions. Temperature at the plume at 5.25 m high in a), 9.25 m high in b), 13.25 m high in c), at the exhaust fans in d), near the walls at 15 m high in e), 10 m high in f), and 5 m high in g). Smoke layer height in h). Make-up air velocities at the vent A1 in i), and C2 in j). Measurements identified by sensor number according to figure 2.

During the test, the flame and plume presented small but persistent deviations due to the non-symmetric vents layout, figure 1.4. This can be observed from the temperature registered at the centreline close to the flame, figure 1.1. At h = 5.25 m high, figure 1.1 a), the temperature rises fast at the first instants due to the growing combustion phase, which lasts 200 s. Then, it stabilizes at 100 ºC, below the temperature obtained from the correlation from Heskestad [Heskestad] for axis-symmetric plumes, T = 210 ºC. At the final stages, from t = 590 s, the flame becomes nearly vertical and the temperature rises up to 170 ºC. The same trend has been observed at h = 9.25 m, figure 1.1 b), where the temperature increases up to T = 80 ºC at t = 470 s, near the temperature obtained from [Heskestad], T = 88 ºC, and keeps on increasing slowly to 95 ºC at the end. At higher locations, i.e. h = 13.25 m, these flame and plume deviations hardly affect the temperature evolution as the flame deviations are not very strong and the temperature increases continuously due to the smoke accumulation at the upper parts, figure 1.1 c).

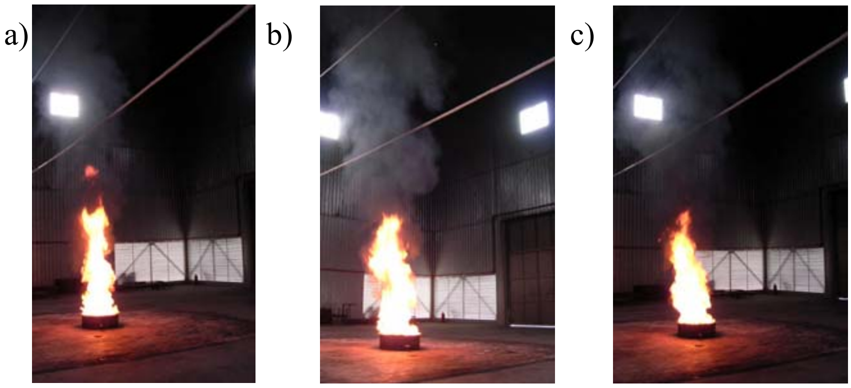


Figure 1.4. Flame slightly leaned because of the non-symmetric venting conditions, t = x s in a), t = y s in b), and t = z s in c).View from wall B.

At the far field, there is no influence of the flame inclinations and plume deviations. At the exhaust fans, figure 1.1 d), the temperature increases reaching steady-conditions at t = 590 s, when T = 75 ºC, remaining constant until the end. At the higher locations near the walls, h = 15 and 10 m, the temperature rises continuously reaching quasi-steady conditions at the end, with T = 72 and 68 ºC, respectively, figures 1.1 e) and f). At h = 5 m, figure 1.2 c), the temperature rises fast to 42 ºC at t = 600 s, then it remains almost constant. These trends observed at the near the walls region indicate that the inner fire-induced conditions were near to reach steady values within the whole facility. At the vents, figures 1.1 i) and j), averaged make-up air inlet velocities ranging from 0.2 to 0.4 m/s were measured, below the recommended value of 1 m/s.

Numerically, no perturbation affecting the flame or the plume was observed in the beginning. However, from t = 630 s, the flame started to lean provoking subsequent plume deviations, figure 1.2. These are small perturbations that affect mainly the region close to the flame. This can be appreciated at h = 5.25 m, figure 1.1 a), where sudden temperature drops are observed at the end of the simulation. These effects have little influence at higher locations, above h = 13 m, and the far field, where no significant disturbance is observed in the temperature evolutions.

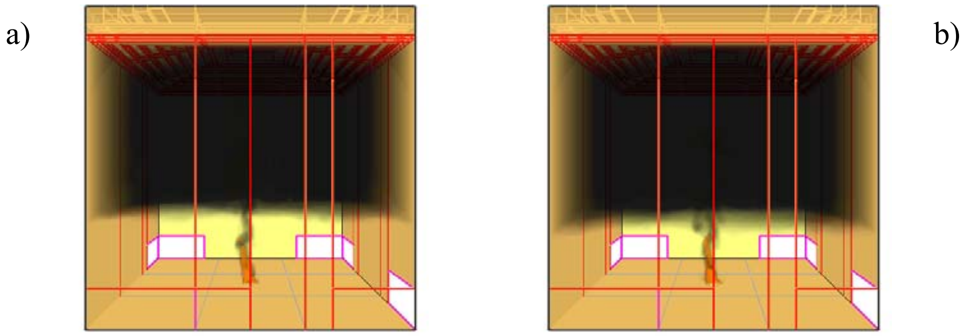
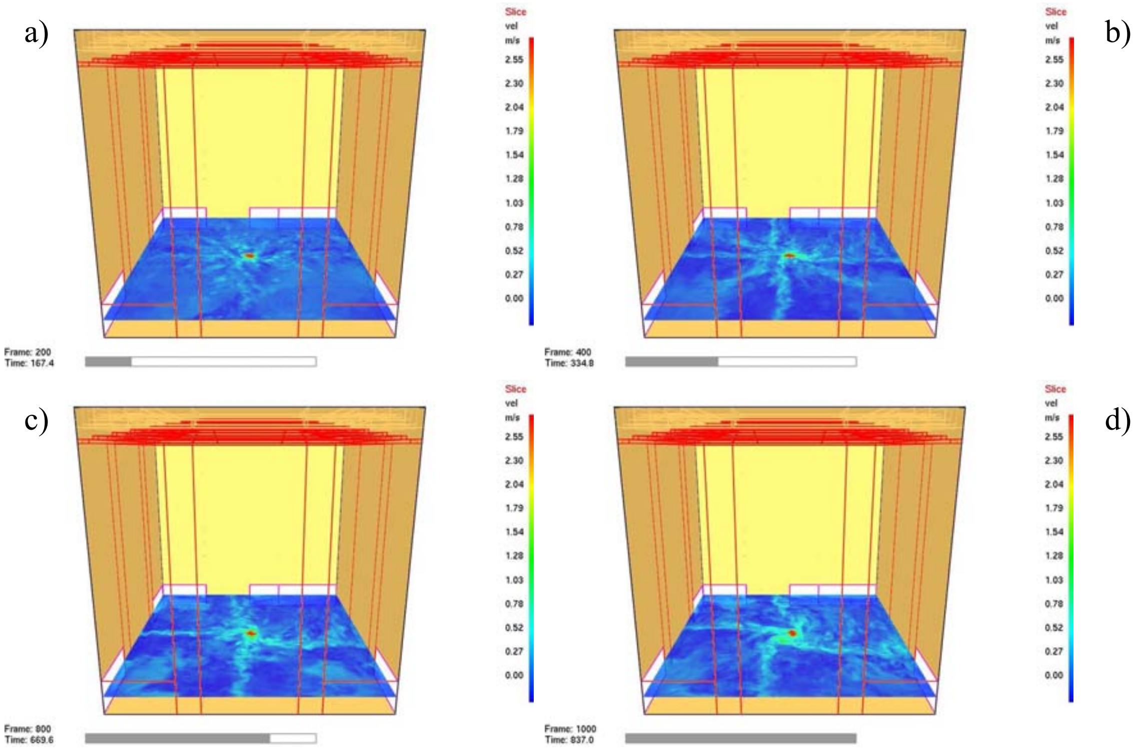


Figure 1.2. Predicted flame inclinations due to the ventilation asymmetry, t = 678 s in a); t = 773 s in b). View from wall A.

These little flame inclinations are provoked by the non-symmetric make-up air vents layout. Figure 1.3 shows the formation of a circular air stream around the fire, which increases its intensity with time. At the final moments, figure 1.4, azimutal velocity values higher than 1.5 m/s are observed around the fire, which disturbs it and makes it to rotate and lean, figure 1.4.



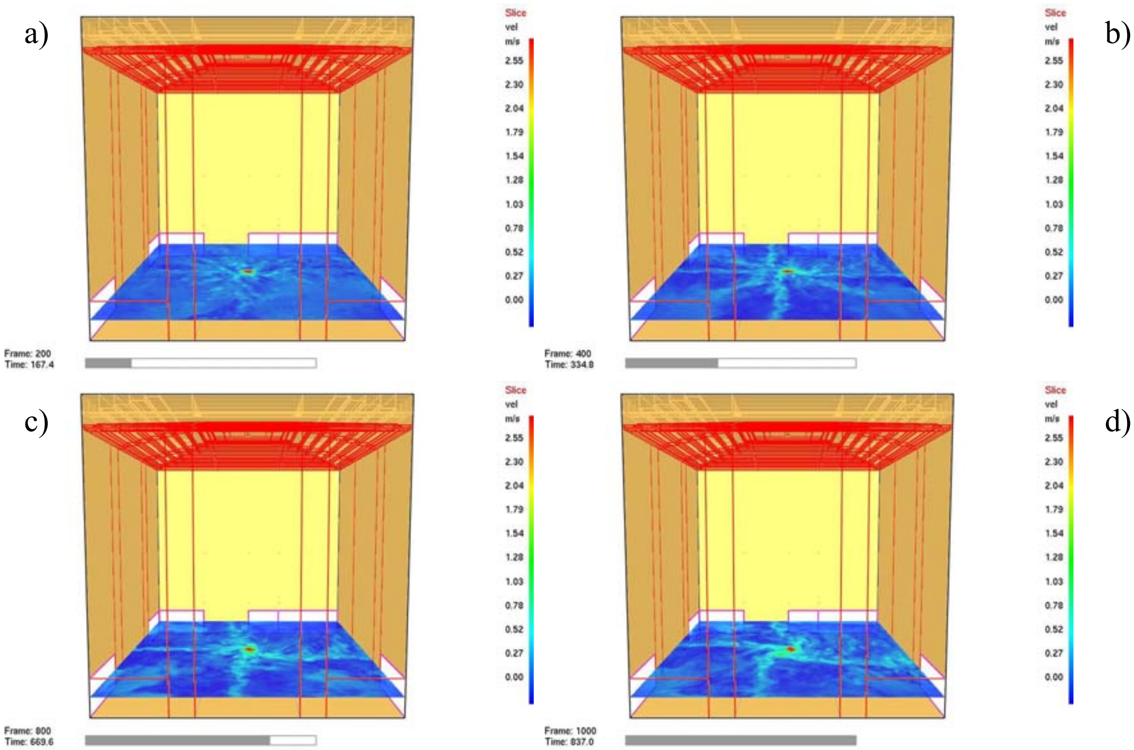


Figure 1.3. Predicted velocity contours at h = 1.25 m, t = 167 s in a), t = 335 s in b), t = 670 s in c), and t = 837 s in d).View from wall C.

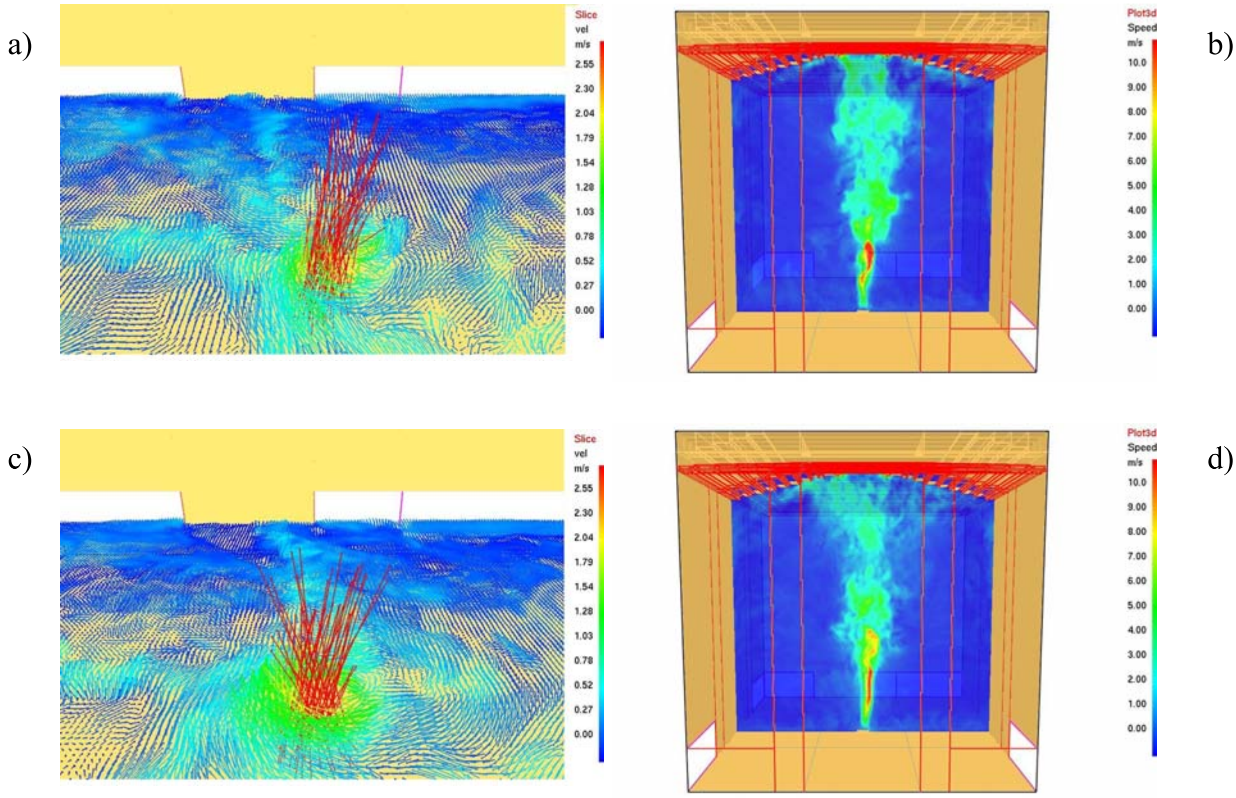


Figure 1.4. Detail of predicted velocity vectors near the flame, h = 1.25 m, t = 662.9 s in a) and t = 823.6 s in c). Predicted speed/temperature contours at the central section, t = 669 s in b) and t = 837.0 s in d). View from wall C.

All these phenomena affecting both the experiment and the simulation generate differences between the measurements and the predictions. Comparison between them shows that FDS over-predicts the temperature near the flame at the centreline, figure 1.1. The bigger discrepancies are found in the beginning, when FDS predicts faster temperature rises. These are enhanced by the perturbations affecting both the experiment and the simulation, which generate relative errors of 300 %, at h = 5.25 m, of 100 %, at h = 9.25 m, and lower than 50 %, at h = 13.25 m. At the quasi-steady combustion regime, the differences reduce and remain fairly constant. These differences reduce with height, being the agreement good at h = 13.25 m from t = 400 s. At the final stages, there is good agreement at the centreline caused by the predicted flame inclinations due to the make-up air effect.

The far field conditions are not influenced by the flame inclinations. At the exhaust fans, figure 1.1 d), the predicted temperatures agree well with the measurements during the tests. From t = 700 s, FDS slightly under-predicts the temperature with differences lower than 9 %. At the upper parts of the near the walls region, h = 15 and 10 m, the agreement is also good, with relative errors of 8 and 6 % at the end, figures 1.1 e) and f). At h = 5 m near the walls, figure 1.1 g), experimentally the temperature rises continuously to 42 ºC at t = 600 s, remaining constant until the end. However, numerically no temperature rise was predicted. The differences at this location are of 50 % at the end. As a consequence, the predicted final smoke layer height is higher than the experimental one, figure 1.1 h). At the vents, figures 1.1 i) and j), FDS predicts well the make-up inlet velocities. Therefore, it could happen that, for the grid used, the simulation predicts stronger disturbances on the flame, caused by the non-symmetric make-up air topology, than those observed experimentally. This will be better appreciated in test #3.

- **Test #2:**

This test was with all the fans activated and the vents completely open with symmetric layout (total inlet area of 48.75 m^2), that is, the two vents of the wall C (vents C1 and C2) and the vents closest to the corners of wall A (vents A1 and A3), figure 3 b). Figure 2.1 shows the measurements and predictions vs time at different locations.

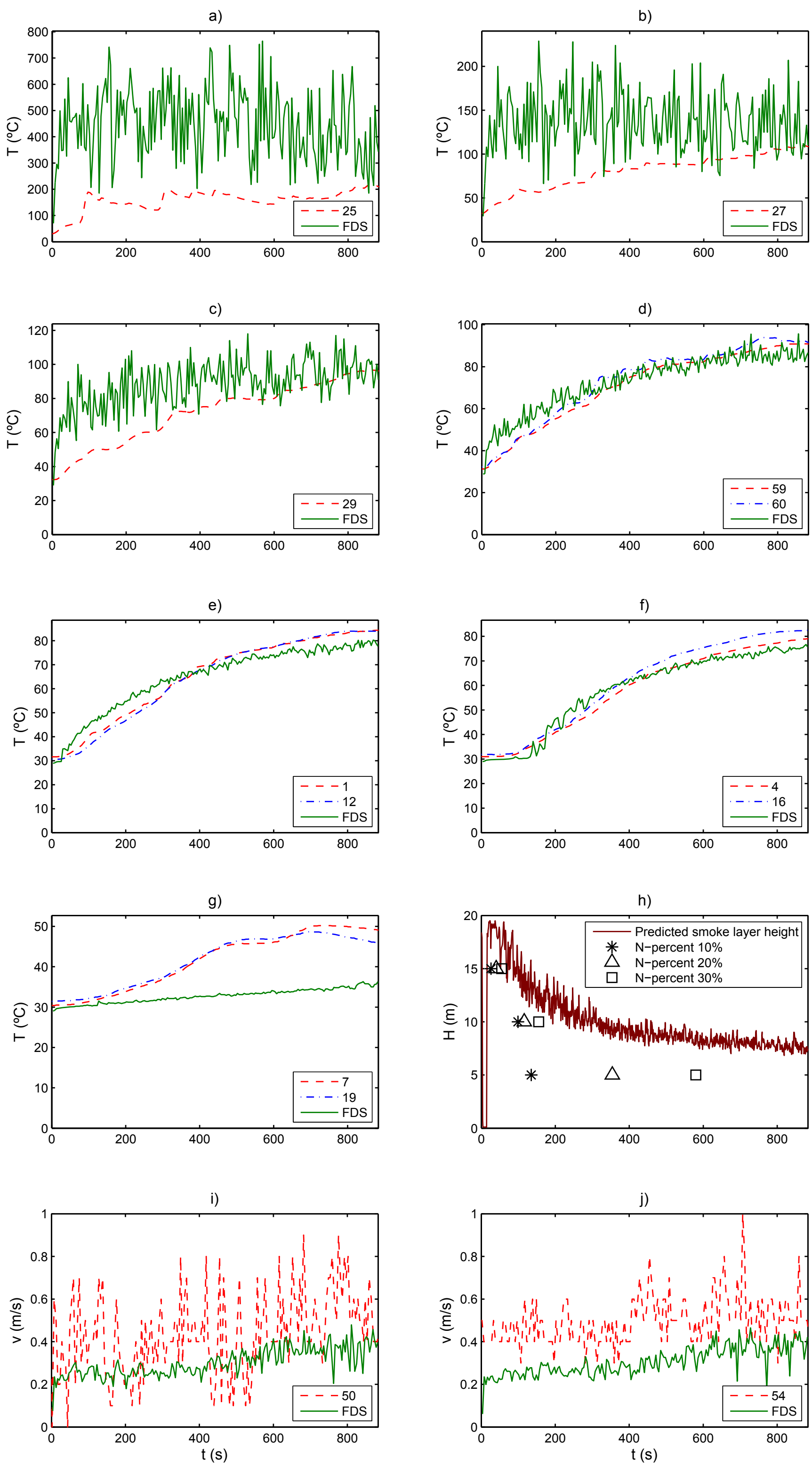


Figure 2.1. Test #2 measurements and predictions. Temperature at the plume at 5.25 m high in a), 9.25 m high in b), 13.25 m high in c), at the exhaust fans in d), near the walls at 15 m high in e), 10 m high in f), and 5 m high in g). Smoke layer height in h). Make-up air velocities at the vent A1 in i), and C2 in j). Measurements identified by sensor number according to figure 2.

During the experiment, small flame inclinations were observed, figure 2.2. These effects can be noticed at the locations closest to the flame, e.g. h = 5.25 m, where sudden temperature drops and rises are registered, figure 2.1 a). These perturbations weaken with height, being negligible at the far field.

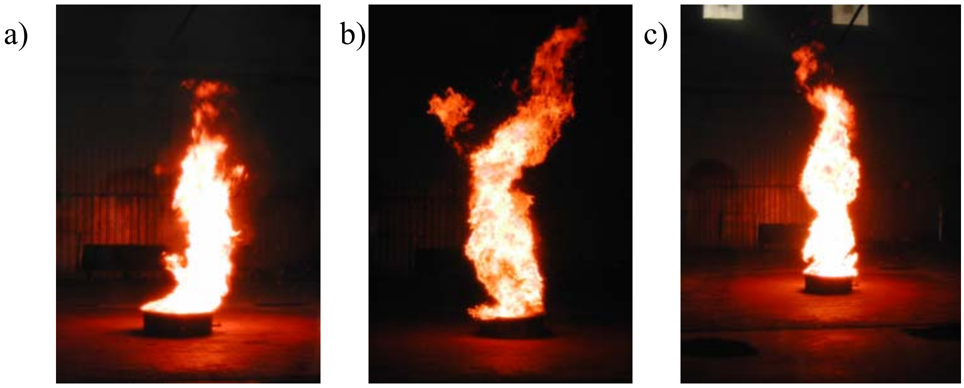


Figure 2.2. Flame inclined/leaned because of the outer wind effect. t =55 s in a), t = 280 s in b) and t = 330 s in c). View from wall B.

Numerically, the simulation evolved normally without any noticeable perturbation affecting the flame or the plume. At this simulation, no air stream formed around the flame, figure 2.3, therefore, the flame and plume remained vertical most of the time.

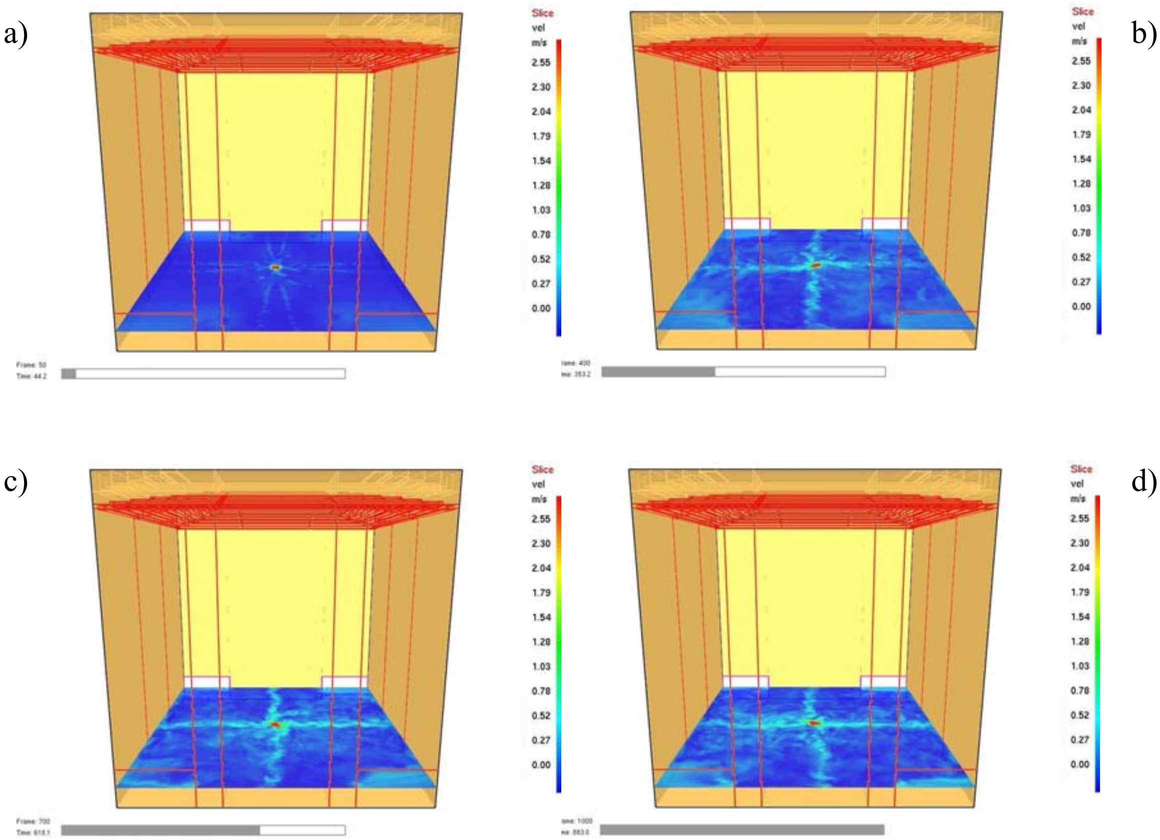


Figure 2.3. Predicted velocity contours at h = 1.25 m. t = 40 s in a), t = 353 s in b), t = 618 s in c) and t = 883 s in d). View from wall A.

Comparison with the experimental data shows that FDS over-predicts the temperature near the flame, figures 2.1 a) to c). For the quasi-steady combustion regime, the relative errors are between 50 % and 100 %, at h = 5.25 m, and lower than 50 %, at h = 9.25 m, where good agreement is found at the end. The differences reduce with height being the agreement really good at h = 13.25 m, where no difference is found at the end.

At the exhaust fans, figure 2.1 d), the agreement is good too, with differences lower than 5 % during the whole fire. At h = 15 and h = 10 m near the walls, figures 2.1 e) and f), FDS predicts faster temperature rises at the fire growing period. Then, the differences reduce being the agreement good until the end, when the differences are lower than 7 and 8 %, respectively. These discrepancies are larger at the lower regions of the far field. At h = 5 m high, figure 2.1 g), experimentally the temperature increases to 50 ºC, at t = 700 s, remaining constant until the end whereas, numerically no temperature increase is predicted. This provokes that the smoke layer arrival to the upper locations near the wall is well predicted but the final smoke layer height is over-estimated, as in the previous test, figure 2.1 h). At the vents, FDS predicts well the make-up air velocity, which is ranged between 0.3 and 0.5 m/s, approximately. Experimentally, the influence of outer effects such as the outer wind cause larger velocity variations than the predicted ones. However, the average velocity values agree well, above all from the middle stages of the fire.

- **Test #3:**

This test was with all the fans on and the vents partially open (total inlet area of 10.83 m^2) with symmetric layout, as in the test #2 but at 22 % of their inlet area , figure 3 c). In this case, large discrepancies between the experiment and the simulation have been observed. Figure 3.1 shows the measurements and predictions vs time at different locations.

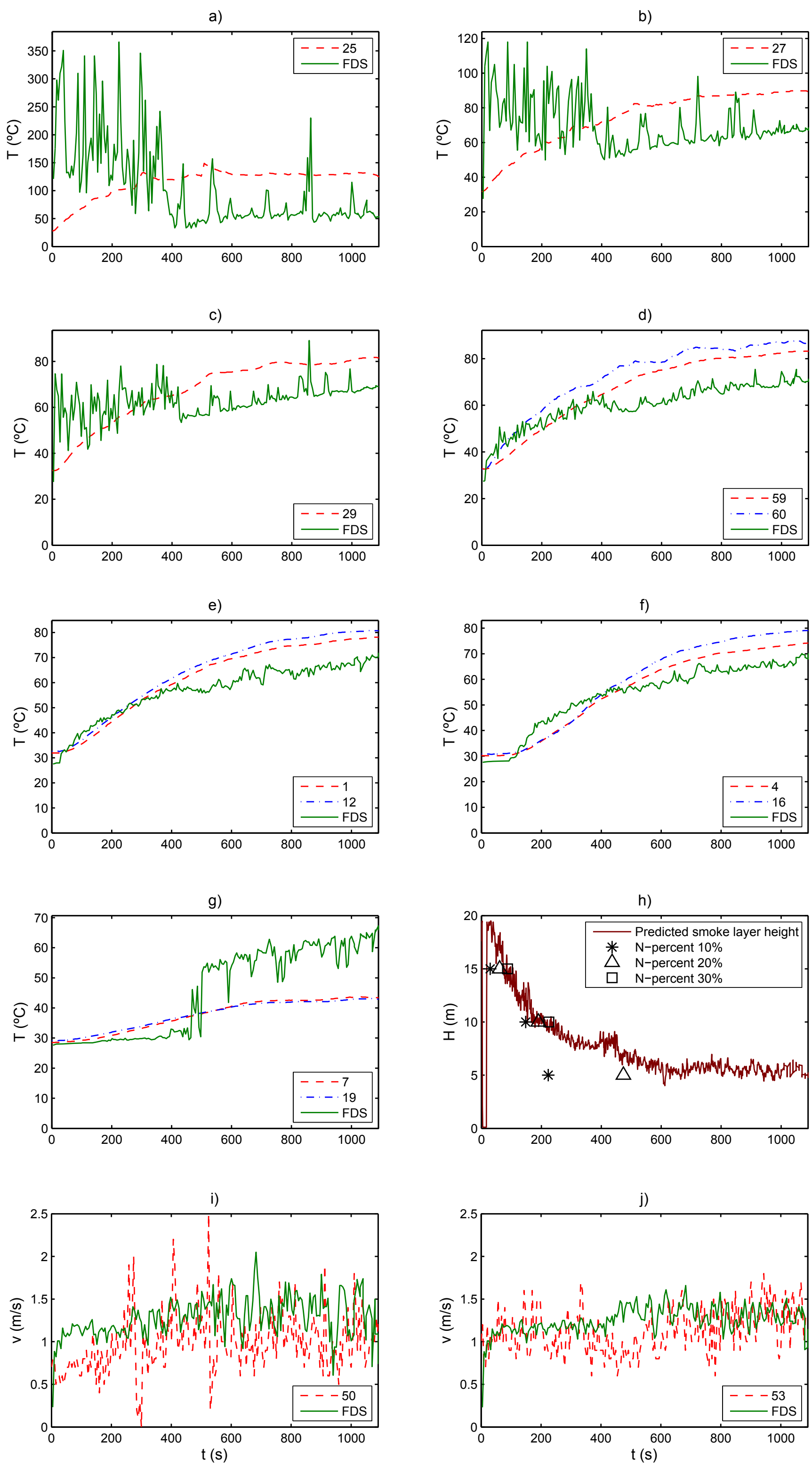


Figure 3.1. Test #3 measurements and predictions. Temperature at the plume at 5.25 m high in a), 9.25 m high in b), 13.25 m high in c), at the exhaust fans in d), near the walls at 15 m high in e), 10 m high in f), and 5 m high in g). Smoke layer height in h). Make-up air velocities at the vent A1 in i), and C2 in j). Measurements identified by sensor number according to figure 2.

Experimentally, small but fairly persistent flame inclinations and plume deviations towards wall C were observed during the fire, figure 3.2. These flame inclinations can be also appreciated from the temperature measurements at the centreline at h = 5.25 m, where they are lower than those obtained from [Heskestad], T = 200 ºC. However, these flame inclinations were not very strong as, at h = 9.25 m, the temperature measurements agree well with [Heskestad], T = 89 ºC, from t = 400 s. At higher locations and the far field no influence of these perturbations has been observed. At the exhaust fans, figure 3.1 d), the temperature rises continuously reaching quasi-steady conditions at t = 700 s and, at the near the walls region, similar temperature evolution trends are observed in both walls, showing the high symmetry of the smoke layer growth.

a)

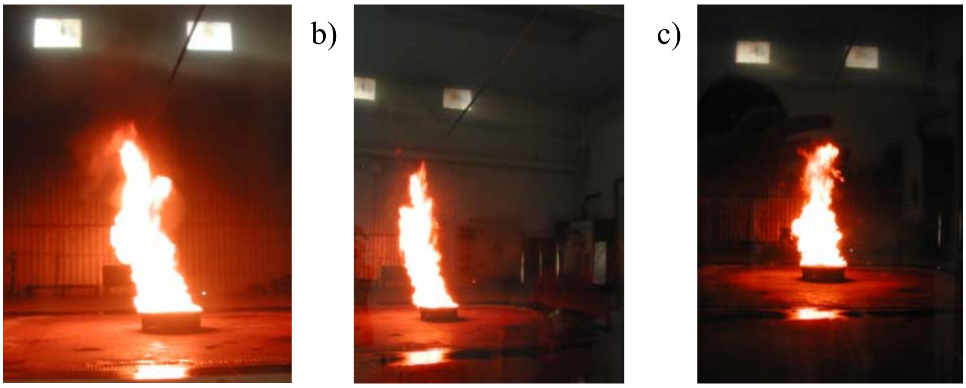


Figure 3.2. Flame slightly leaned towards wall C, t =375 s in a), t = 720 s in b), and vertical flame at t = 1005 s in c). View from wall B.

Numerically, different fire-induced conditions have been predicted. For this case study and grid resolution a no physical solution is obtained. The fire evolved normally during the first 200 s. From then on, strong flame inclinations and plume deviations caused by the make-up air influence are observed, figure 3.3. As happened in test #1, a circular air stream surrounding the flame forms at lower locations and grows in intensity with time, figure 3.4. In addition, the HRR of these fire tests are relatively low and the influence of the make-up air becomes even more important. This effect can be clearly appreciated from the speed iso-contours at the central section which are completely chaotic from t = 300 s, figure 3.5. From that moment, azimutal velocity values higher than 1.3 m/s appear around the flame, increasing to values of 2.5 m/s at t = 500 s and higher than 3.5 m/s near the end, figure 3.4. As a consequence, the plume becomes unsteady and looses its verticality, leaning towards the walls randomly, figure 3.3.

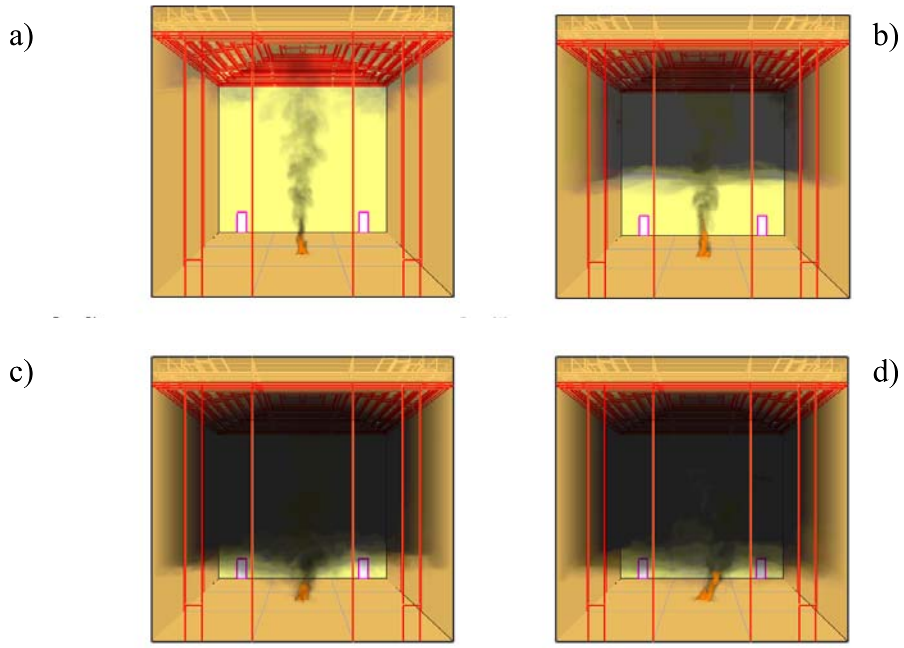


Figure 3.3. Predicted flame inclinations due to the make-up air influence, t = 59 s in a), t = 266 s in b), t = 719 s in c), and t = 696 s in d). View from wall A.

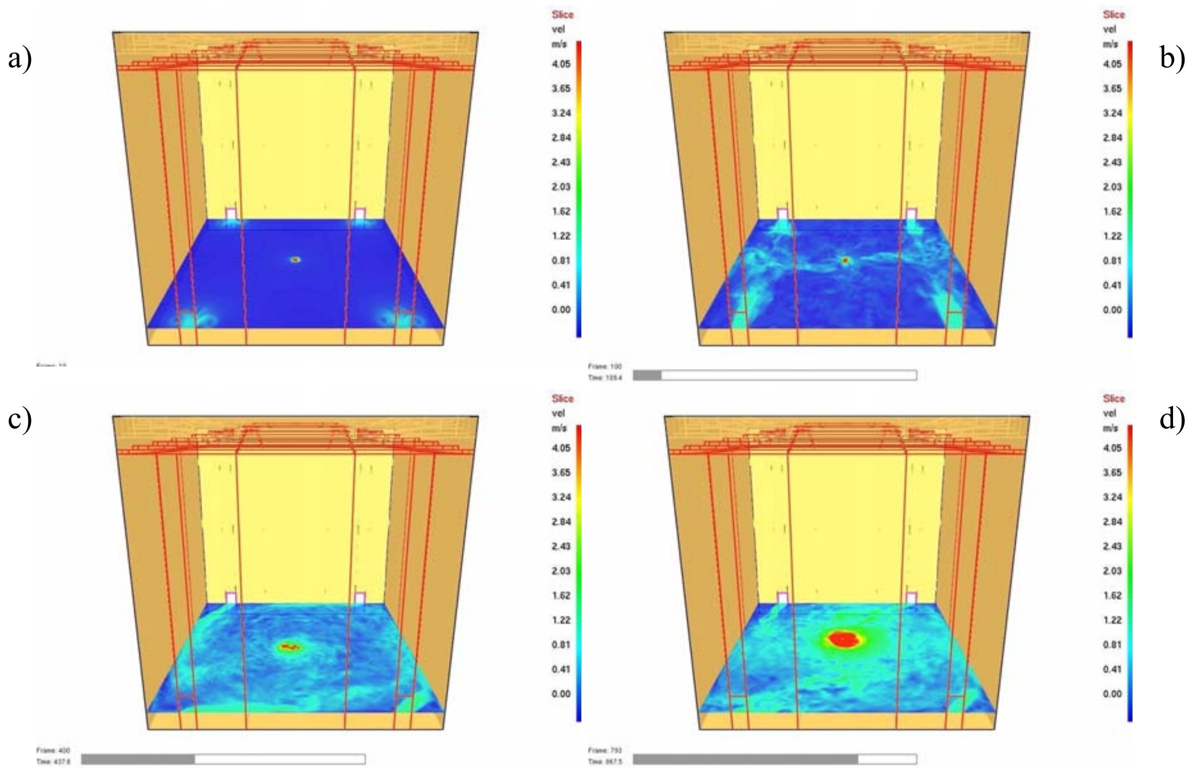


Figure 3.4. Predicted velocity contours at h = 1.25 m high. t = 11 s in a), t = 109 s in b), t = 437 s in c), and t = 867 s in d). View from wall A.

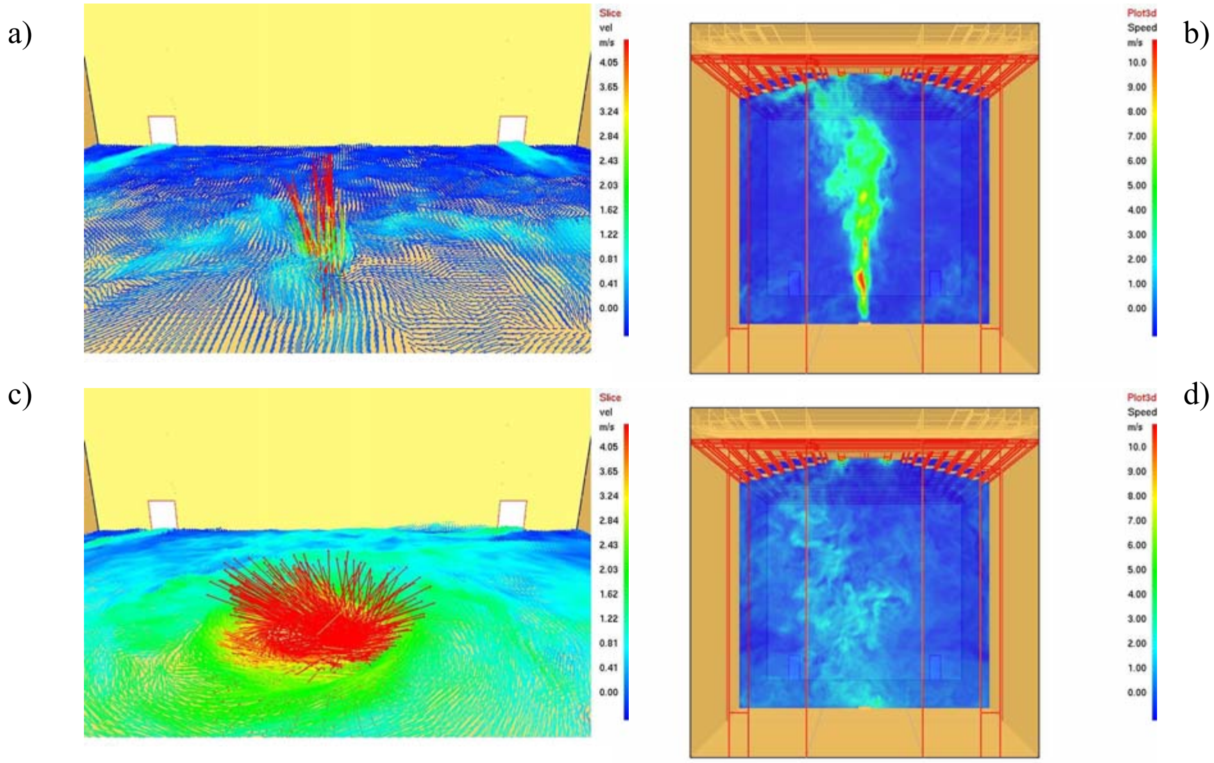


Figure 3.5. Detail of predicted velocity vectors near the flame, h = 1.25 m, t = 219 s in a), and t = 853 s in c). Predicted speed/temperature contours at the central section, t= 219 s in b), and t = 853 s in d). View from wall A.

These perturbations cause big discrepancies between the experimental data and the numerical predictions. At the near field region, numerically the temperature drops suddenly from t = 300 s, figures 3.1 a) to c), and values much lower than the measurements are predicted. For this case study and grid resolution, the disturbances caused by the make-up air affect the whole facility. In this way, at the exhaust fans, figure 3.1 d), and h = 15 and h = 10 m near the walls, figures 3.1 e) and f), there is good agreement until t = 350 s. Then, the predicted temperature drops to values lower than the experimental ones. At the end, temperature differences between 22 and 30 % at the exhaust fans, and equal to 18 % at h = 15 and h = 10 m near the walls are found. This effect is more important at h = 5 m near the walls, figure 3.1 g). At this location, no temperature rise is predicted at the beginning. Then, when the perturbations become important, the temperature rises suddenly. This indicates that the mixing rate at the smoke layer interface increases considerably. As a consequence, the smoke dilutes and cools and the smoke layer thickens. The mixing enhancement between the smoke layer and the fresh air provokes that the simulation over-predicts the temperature at this location by more than 55 % at the end. The predicted smoke layer height is also lower than the measured one, figure 3.1 h), eventually reaching the height of h = 5 m high. At the vents, there is good agreement, figures 3.1 i) and j), where the inlet velocities are ranged from 1 to 1.5 m/s in average.

These numerical perturbations have been observed not only in one simulation and neither with only one grid cell size. Up to three different simulations with a grid of 180 cells per side and an additional one with a grid of 150 cells per side have been performed with the same result, figure 3.6. It has been also observed that these numerically predicted perturbations grow with the grid resolution, which, on the other side, is essential for obtaining reliable predictions.

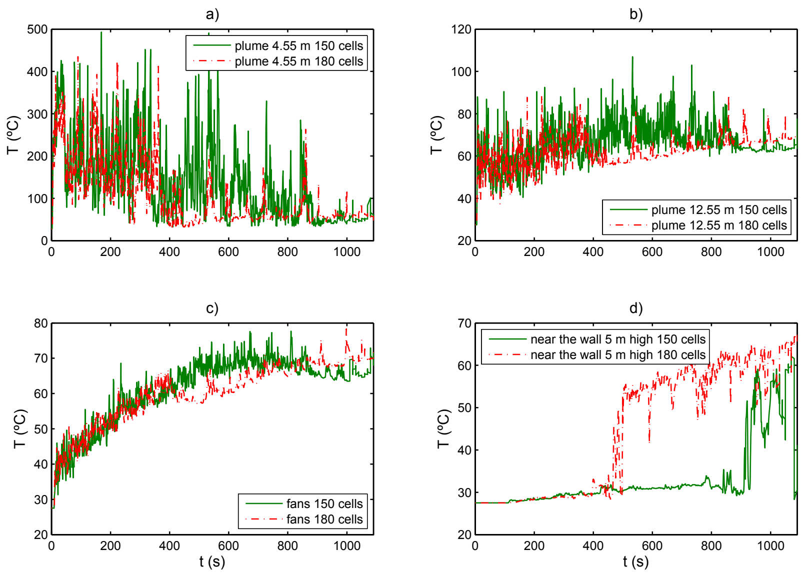


Figure 3.6. Comparison of temperature predictions from a 150 cells grid and a 180 cells grid. Plume at h = 4.55 m high in a), plume at h = 12.55 m in b), exhaust fans in c), and near the walls at h = 5 m high in d).

The predicted smoke layer height has been compared with the experimental results obtained by means of the N-percent method [29, 14 FDS B&E]. In general, there is good agreement between FDS predictions and the 30% temperature increase. It is observed that the simulations over-estimate the final smoke layer height for the two first tests, in agreement with other works [14]. For the particular case of the third test, figure 3.1 h), good agreement is found for the higher locations, before the numerical perturbations become important. From that moment, the predicted smoke layer growth varies significantly, e.g. at t = 400 s. At t = 600 s the smoke layer reaches a quasi-steady value equal to 5.5 m, lower than the final values for tests #1 and #2 of higher HRR.

Finally, the time needed to reach a certain temperature increase at the exhaust fans and at h = 15 and h = 10 m near the walls has been calculated from the experimental results in order to roughly evaluate the influence of the make-up air inlet area, figure 4.1. From this comparison, no significant difference has been noticed at the smoke layer growth. The times needed to reach a certain temperature increase are the same for tests #1 and #2, which indicate that there is no influence of the make-up air inlet reduction on the smoke layer growth, in agreement with [NFPA92b], as the make-up air velocities are lower than 1 m/s. For the test #3, make-up air inlet velocities higher than 1 m/s have been measured. In this case, the times needed for a certain temperature increase are similar or even larger than in previous tests, due to the HRR difference between them. From these results, make-up air velocities higher than 1 m/s do not necessarily have to influence the smoke layer descent velocity for this case study.

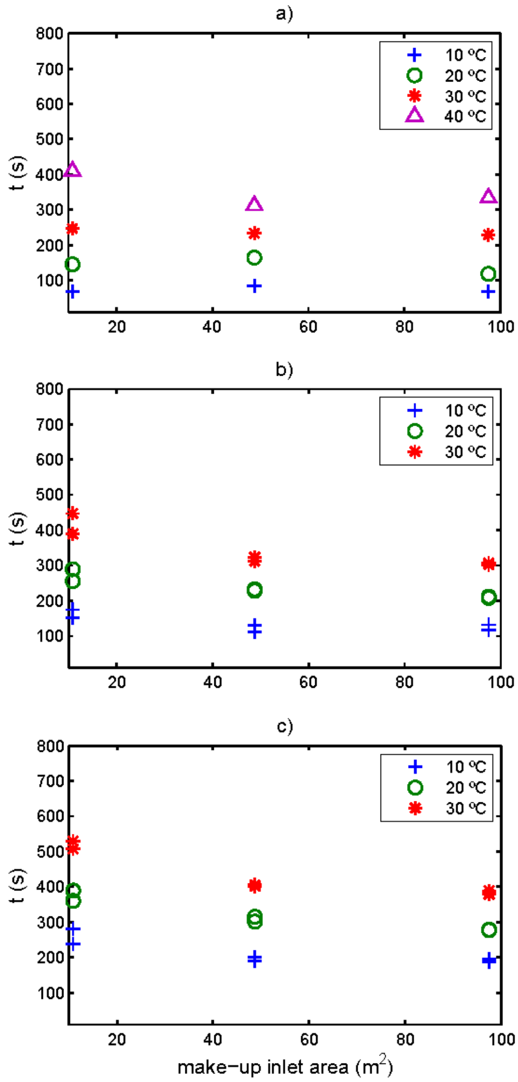


Figure 4.1. Time needed for a certain temperature increase vs make-up air inlet area. Exhaust fans in a), h = 15 m near the walls in b) and h = 10 m near the walls in c). Walls A and C have been considered for these calculations.

6.- Conclusions

This paper reports results from three full-scale atrium fire tests carried out as part of the Murcia Fire Tests. At these tests, the effect of different make-up inlet positions and area on the fire-induced conditions has been studied. These tests have been conducted placing a heptane pool-fire of 0.92 m diameter at the centre of the floor and with four exhaust fans activated on the roof. The test #1 has been carried out with all the vents open (97.5 m^2 of inlet area) and non-symmetric layout. The test #2 was with half of the inlet area of the previous one (48.75 m^2 of inlet area) and symmetric layout. In the test #3, the same vents than in test #2 were partially open, to 22 % of their area (10.83 m^2 of inlet area). ~~The experimental data presented here could be used as benchmark for the ongoing validation and verification studies of the existing fire codes.~~ Later CFD simulations of the tests have been performed using FDS, in order to check the capability of this code to predict the fire-induced inner conditions.

Experimentally, the tests with the larger make-up inlet areas (test #1 and #2), induce make-up air velocities much lower than 1 m/s (average values ranged from 0.2 to 0.5 m/s), within the recommended values [Nfpa92b]. However, large areas of make-up air supply turn the flame and plume into more sensitive to outer effects. In addition, the lack of symmetry can also induce larger instabilities on the flame than when symmetric make-up air supply conditions are considered, in agreement with [paper FDS make-up air Fire Technology]. In the tests reported here, these perturbations have caused small flame inclinations and plume deviations, although no significant disturbance influencing the far field conditions has been noticed. In the test #3, with the smallest vents area, inlet velocities higher than 1 m/s have been measured. However, these have not influenced the flame or plume and, thus, the fire-induced conditions at the far field. Therefore, make-up air velocities higher than 1 m/s do not have to necessarily provoke a significant enhancement of smoke production.

Numerically, for the grid resolution used, FDS predicts well the air inlet velocities at the vents. For the tests #1 and #2, with make-up air velocities lower than 1 m/s, FDS behaves well at the upper parts of the far field, the most important ones for the design of smoke evacuation systems. For these tests, FDS significantly over-predicts the plume temperature near the flame with differences larger than 40 %, below h = 10 m. However, the discrepancies reduce with height being the agreement good above h = 13 m, in agreement with other works [22 paper B&E y paper B&E]. At the exhausts fans and the upper parts near the walls (h ≥ 10 m), the agreement is also good, with relative errors lower than 10 %, whereas, at lower locations, FDS under-predicts the temperatures, slightly over-predicting the final smoke layer height. For the test #3, with make-up air velocities higher than 1 m/s, poor agreement has been found. FDS predicts too strong flame and plume disturbances caused by the make-up air. These numerical perturbations enhance the smoke layer mixing with the fresh lower air homogenizing the smoke layer conditions and thickening it, which generate relative errors larger than 20 % respect to the experimental data.

According to the results, FDS could be used for the performance-based design of smoke evacuation systems in atria, similar to the one used here, when make-up air velocity is lower than 1 m/s. However, for atrium fires of relative low HRR and make-up air velocities higher than 1 m/s, the use of FDS could lead to misleading designs. Larger

HRR fire tests and simulations should be conducted varying the make-up air conditions in order to set bounds to this observation.

References:

[9_1] NFPA 92B. Standard for Smoke Management Systems in Malls, Atria and Large Spaces. National Fire Protection Association: Quincy, MA, 2005.

[124_2] Butcher, E.G.; Pamell, A.C. Smoke control systems – the provision of replacement air. Fire Safety Engineering, 1997, vol. 4(3), 12-13.

[123_3] Klote, J.H.; Milke, J.A. Design of smoke management system; ASHRAE Inc.: Atlanta, GA, USA, 2002.

[Duda_4] Duda, S. Atria smoke exhaust: 3 approaches to replacement air delivery. ASHRAE Journal, 46(6): 21-27, 2004 (Atlanta, GA).

[tubs_5] Tubbs, J.S, Smoke management in the 2006 IBC. Ashrae Journal, 48(10) 2006, pp. 50-55.

[3)_6] International Code Council. (2006). 2006 International Building Code. Country Club Hills, IL: International Code Council.

[58_7] Olenick, S.M.; Carpenter, D.J. An Updated International Survey of Computer Models for Fire and Smoke. Journal of Fire Protection Engineering, 2003; vol. 13, 87-110.

[140_8] Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications, NUREG-1824, vols. 1-7, Final Report; U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research: Palo Alto, CA, 2007.

[Chow_complex_9] Chow, W.K., Li, S.S., Gao, Y., Chow, C.L. Numerical studies on atrium smoke movement and control with validation by field tests. Building and Environment 44 (2009) 1150–1155

[142_10] Hadjisophocleous, G.V.; Lougheed, G. Experimental and numerical study of smoke conditions in an atrium with mechanical exhaust. International Journal on Engineering Performance-Based Fire Codes, 1999, vol. 1(3), 183–7.

[122_11] Yi, L.; Huo, R.; Li, Y.Z.; Peng, L. Study on the effect of unsymmetric air supply to mechanical exhaust in large space fire. Journal of University of Science and Technology of China, 2003, vol. 33, 579–585.

[144_12] Yi, L.; Chow, W.K.; Li, Y.Z.; Huo, R. A simple two-layer zone model on mechanical exhaust in an atrium. Building and Environment, 2005, vol. 40, 869–880.

They modelled three scenarios with different relative positions of the air inlet, above, within and below the smoke layer interface. The parameters varied were the fire size, from 1 to 10 MW, the extraction rates, from 0 to 18 air changes per hour, and the make-up air inlets location, at the floor, 9 and 18 m high. Three tests with a 3 MW fire were conducted. Two of them considered mechanical ventilation, one with an inlet soffit at 11.6 m and an inlet sill at 10.5 m high and one with the inlet soffit at 2.5 m and inlet sill at 0 m high. At the third, no mechanical ventilation was considered.

[65_13] McGrattan, K.; Hostikka, S.; Floyd, J.; Baum, H.; Rehm, R.; Mell, W.; McDermott, R. Fire Dynamics Simulator (Version 5) Technical Reference Guide NIST Special Publication 1018-5; National Institute of Standards and Technology, 2008.

[145_14] Kerber, S.; Milke, J.A. Using FDS to Simulate Smoke Layer Interface Height in a Simple Atrium Fire Technology, 2007, vol. 43, 45–75.

Up to 10 different numerical tests were performed. The fire source used was a stack of pallets with a peak heat release rate of 5 MW. The make-up air velocities were varied from 0.5 to 3.0 m/s. The arrangement of the inlet air vents consisted of symmetrically located vents placed at floor level, an array of vents distributed from the floor to the ceiling and asymmetrically located vents. The size of the vents was also varied.

[2_15] Zhou J., Hadjisophocleous, G.V., Parameters Affecting Fire Plumes, ASHRAE Transactions, Volume 114, Part 1, pp. 140-146, 2008.

[3_16] Hadjisophocleous, G.V., Zhou J., Evaluation of Atrium Smoke Exhaust Make-up Air Velocity, ASHRAE Transactions, Volume 114, Part 1, pp 147-155, 2008.