Experiments and FDS simulations on the make-up air influence on low-power fires within an atrium

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ABSTRACT

This paper aims to study the influence of different make-up air configurations on the inner conditions induced by low-power fires within an atrium. For this objective, three full scale fire tests in a 19.5 m x 19.5 m x 19.5 m facility have been conducted. In these tests, symmetric and non-symmetric make-up air configurations, as well as different air inlet areas have been assessed. Later FDSv4 simulations of the tests have been performed and comparisons between measurement and predictions are reported. Experimentally, 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 positions, 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. However, the performance of these systems can be influenced by various factors such as the smoke temperature, the exhaust rate, the outer wind or the make-up air, among others. All these factors have to be taken into account when designing a smoke exhaust system [1].

With all mechanical smoke venting schemes, the provision of make-up air is particularly important [2] as, without it, the smoke exhaust component cannot be expected to perform properly. There are several goals for the make-up air to be accomplished [3], which have been presented mostly by Duda [4].

In relation to make-up air velocities, some standards and codes [1, 5] suggest that make-up air should not exceed 1 m/s, unless a higher velocity is supported scientifically. At this point, CFD models [6] are commonly used in hazard assessment in atria. However, these computational models need of further validation and verification studies of atrium fire modelling [7], especially full-scale data verification, including the case of different air supply and smoke exhaust conditions. Whether these models are suitable for use is queried, leading to challenges [8].

So far, few studies on the effect of make-up air have been conducted. Yi et al. [9, 10] carried out full-scale experiments at the PolyU/USTC Atrium, of 22.4 m x 11.9 m x 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. Recently, Kerber and Milke [11] studied numerically the possible effects of various make-up air supply arrangements and velocities in an atrium smoke management system within a 30.5 m high cubical atrium. They found the best layout of vents to be that in which make-up air was supplied to the fire symmetrically. In addition, they found that even velocities lower than 1 m/s could cause the smoke layer to descend below the design criterion. Lately, Zhou and Hadjisophocleous [12] 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 [13] studied numerically the influence of make-up air velocities, considering different fire sizes in various size atria. They 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, and that the impact of the make-up air velocity was more pronounced in atria with height less than 20 m.

The aim of the present work is to study the influence of different make-up air configuration on the fire-induced inner conditions within an atrium. For this objective, three full scale fire tests in a 19.5 m x 19.5 m x 19.5 m facility have been conducted [14, 15]. 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 FDSv4 [16] in order to check its capability to properly predict the fire-induced conditions for the different make-up air configurations.

2.- MURCIA TEST FACILITY

The facility used to carry out the experiments is the Fire Atrium of the Centro Tecnológico del Metal, Spain [14, 15], of 19.5 m x 19.5 m x 19.5 m, figure 1 a). 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. There are eight grilled vents arranged at the lower parts of the walls. Each vent has dimensions of 4.875 m x 2.5 m.

In order to register the fire-induced inner conditions, different sensors have been set up in 4 regions (wall A, wall C, a central section parallel to walls A and C and the roof and fans region), measuring gas phase, walls and roof temperatures, as well as pressure drop at exhaust fans and flow velocities at the vents, figure 1 b). 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. Weather conditions were measured by means of a meteorological station monitoring outside temperature, humidity and pressure.

An uncertainty analysis for the measurements was conducted (see [14, 15] for details). The analysis shows that the total experimental uncertainty for the thermocouples is 1.5 %, that for the thermistors is 0.4 %, for the velocity probes is 4 %, for the mass flow across the fans is 10 % and for the mass loss is 1 %.

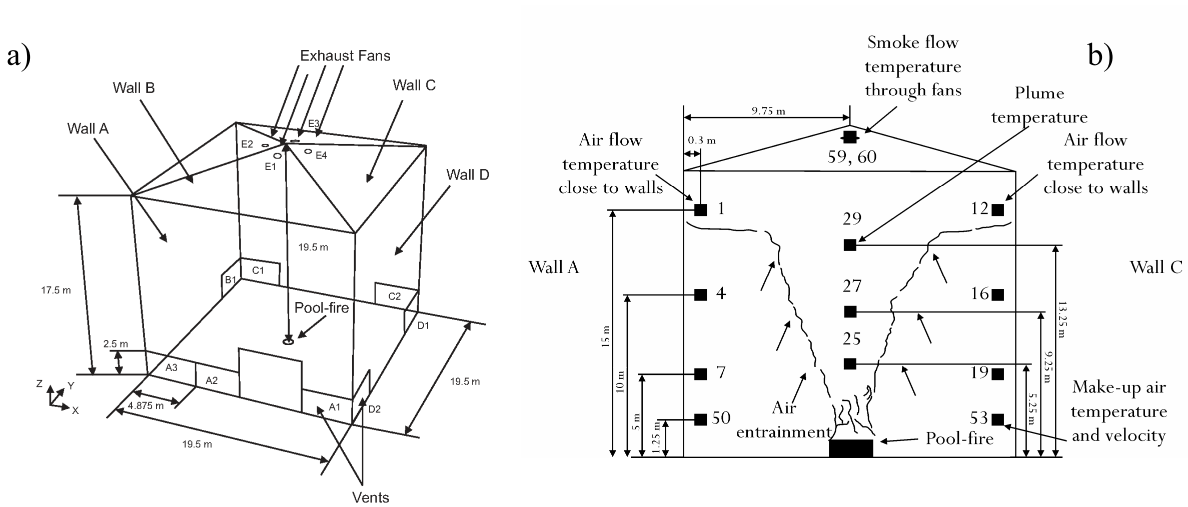


Fig. 1. Sketch and main dimensions of the Fire Atrium in a), and scheme of the layout of the main numbered sensors considered in b) (view of central section from Wall D). Sensors 1, 4, 7, 12, 16, 19, 59 and 60 are Pt100 thermistors, sensors 25, 27 and 29 are type K thermocouples and sensors 50 and 53 are hot-wire anemometers.

3.- FIRE EXPERIMENTS

Three full-scale fire tests with different make-up air venting conditions are presented in this work. The burning fuel was heptane contained in a pool-fire, of 0.92 m diameter, placed at the centre of the floor. For the first test, all the make-up vents were completely open, with a total inlet area of 97.50 m^2. For the second test, the vents were completely open with symmetric layout, that is, the two vents of the wall C and the two vents at the corners of the wall A, with a total inlet area of 48.75 m^2. 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. A summary of the laboratory and ambient conditions during the tests is presented in table 1.

Test	Volume heptane (l)	Burning time (s)	Open vents	Exhaust fans on	Temp (ºC)	Pressure (mbar)	HRR (MW)
test #1	44	837	All	All	16.7	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,

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

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 [17]. The combustion efficiency for a well ventilated heptane pool-fire of 0.92 m diameter is 0.85±0.12 [7, 18, 19]. Figure 2 shows the HRR of the test #2. The uncertainty associated with the HRR is estimated to be around ±15 %, see [15] for more details.

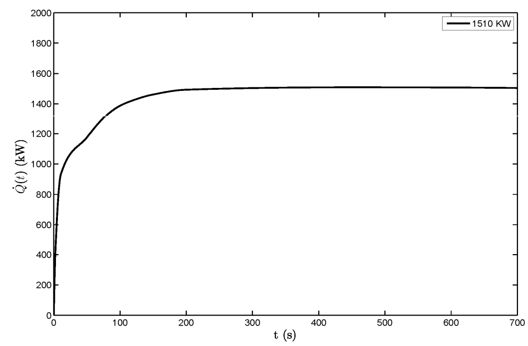


Fig. 2. HRR vs time of test #2.

4.- NUMERICAL SIMULATIONS

CFD simulations have been conducted by means of FDSv4 [16]. The turbulence has been modelled using a large-eddy simulation (LES) approach [20] and, for the heptane combustion, a mixture fraction approach has been used, appropriate for the simulation of turbulent diffusion flames with fast chemistry such as pool-fires. The HRR is prescribed as an input, function of time, at the pool, figure 2. The radiative heat transfer is computed by solving the radiation transport equation for a non-scattering grey gas. The radiative fraction for a heptane pool-fire is 0.35 [21]. 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 [22] and the floor as a thick layer of concrete [22].

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. In addition, it has been also taken into account that, 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 [7, 16], where, R^*,

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

is defined in terms of the characteristic diameter of a plume [7, 17], 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 2 shows the necessary grid cells per side regarding the above resolutions. Regarding this criterion 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. See [15] for more details.

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

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, 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 [23] and compared with the one predicted by FDS. Experimentally, temperature increases from ambient temperature of 10 - 20 % [23] and of 30 % [10] 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 shows the measurements and predictions vs time at different locations.

During the test, the flame and plume presented small but persistent deviations due to the non-symmetric vents layout. This can be observed from the temperature registered at the centreline close to the flame, figure 3. At h = 5.25 m high, figure 3 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 [24] 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 3 b), where the temperature increases up to T = 80 ºC at t = 470 s, near the temperature obtained from [24], 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 3 c).

At the far field, there is no influence of the flame inclinations and plume deviations. At the exhaust fans, figure 3 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 3 e) and f). At h = 5 m, figure 3 g), 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 3 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.

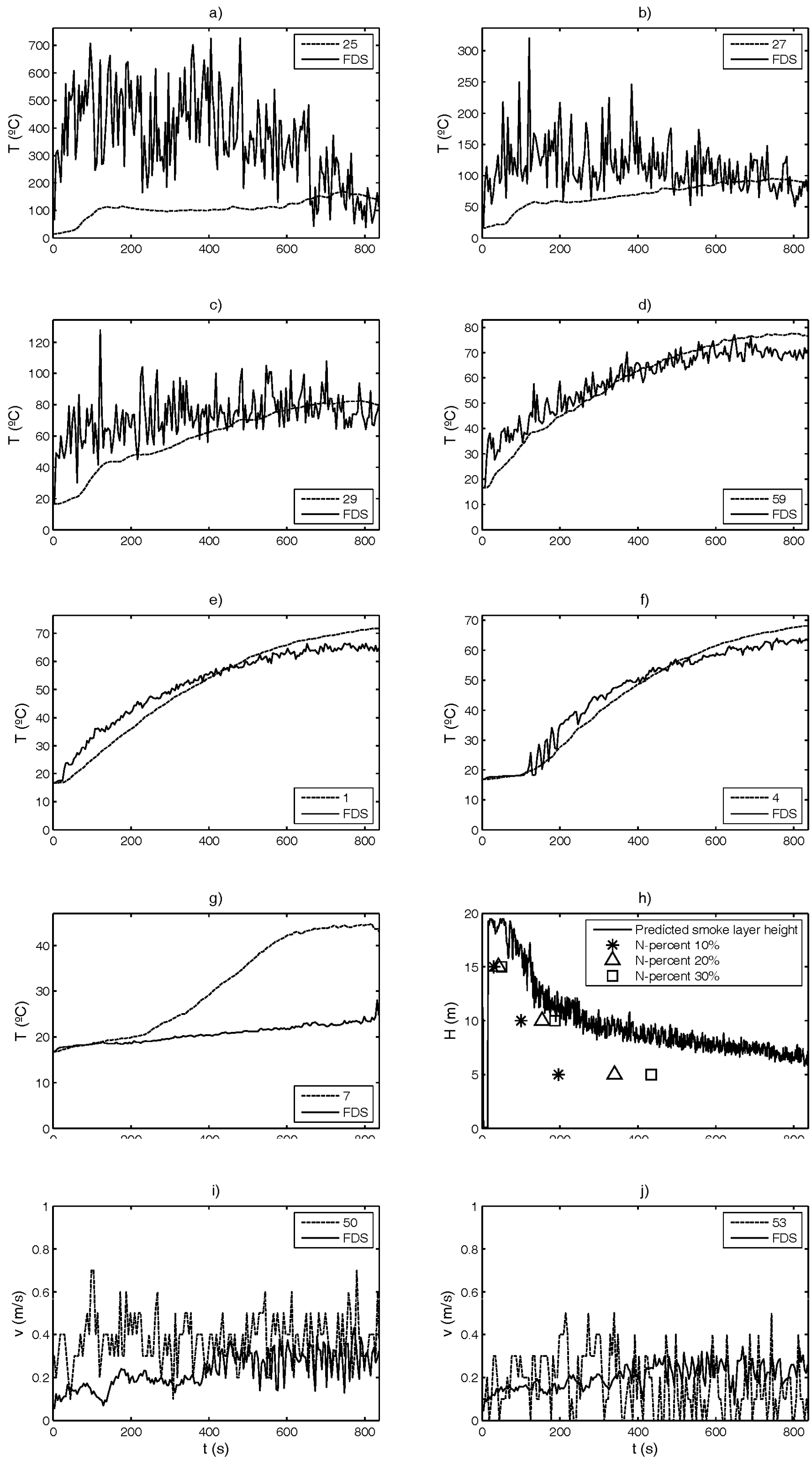


Fig. 3. Test #1 measurements and predictions. Temperature at the plume at 5.25 m high in a), 9.25 m high in b), 13.25 m high in c), at the exhaust fans in d), near the walls at 15 m high in e), 10 m high in f), and 5 m high in g). Smoke layer height in h). Make-up air velocities at the vent A1 in i), and C2 in j). Measurements identified by sensor number according to figure 1 b).

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 4. These are small perturbations that affect mainly the region close to the flame. This can be appreciated at h = 5.25 m, figure 3 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.

a) b)

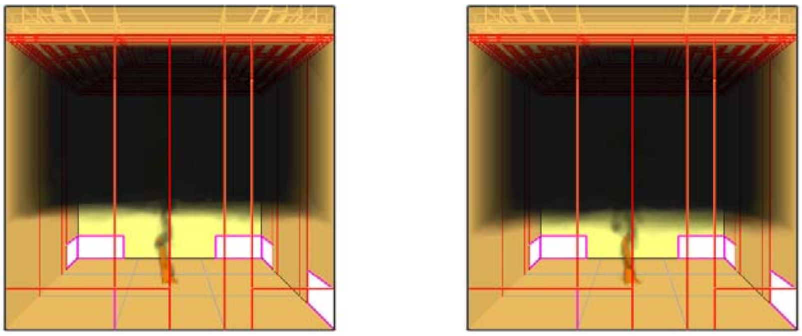


Fig. 4. Predicted flame inclinations due to the ventilation asymmetry, t = 678 s in a) and t = 773 s in b). View from wall A.

These little flame inclinations are provoked by the non-symmetric make-up air vents layout. Figure 5 shows the formation of a circular air stream around the fire, which increases its intensity with time. At the final moments, azimutal velocity values higher than 1.5 m/s are observed around the fire, which disturbs it and makes it to rotate and lean.

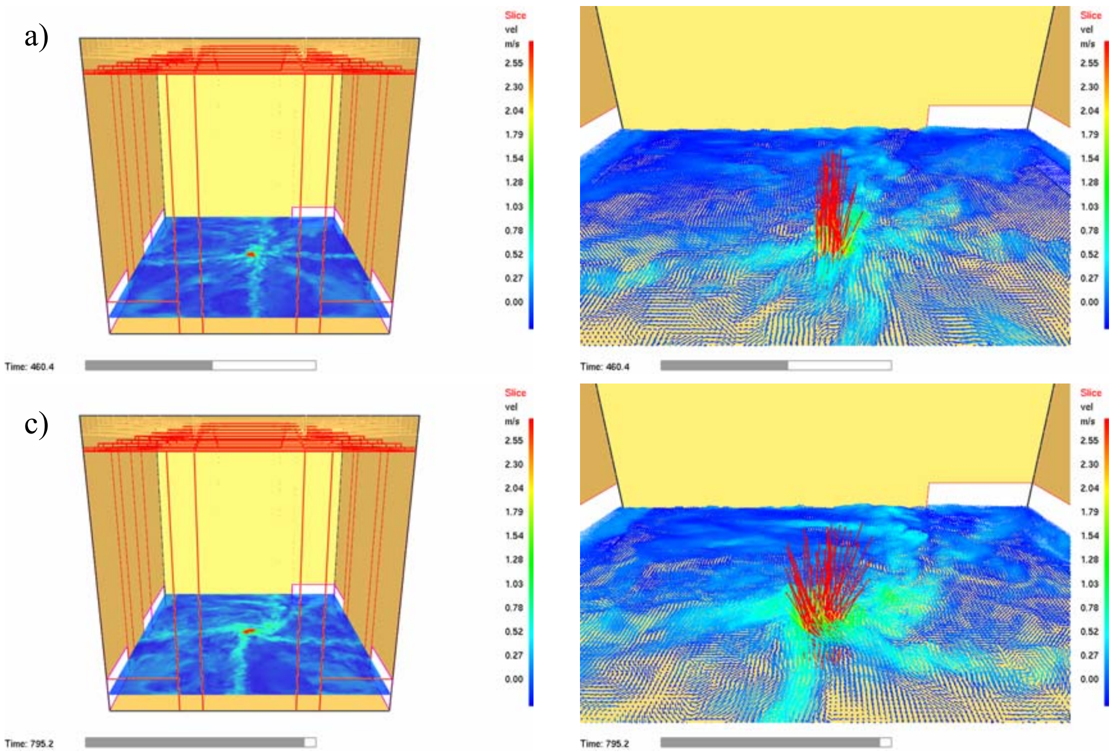


Fig. 5. Predicted velocity contours at h = 1.25 m, t = 460.4 s in a) and t = 795.2 s in c). Detail of predicted velocity vectors near the flame, h = 1.25 m, t = 460.4 s in b) and t = 795.2 s in d). View from wall D.

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 3. The bigger discrepancies are found in the beginning, when FDS predicts faster temperature rises. 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 3 d), the predicted temperatures agree well with the measurements during the tests. From t = 700 s, FDS 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 3 e) and f). At h = 5 m near the walls, figure 3 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 3 h). At the vents, figures 3 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 6 shows the measurements and predictions vs time at different locations.

During the experiment, small flame inclinations were observed, figure 7. 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 6 a). These perturbations weaken with height, being negligible at the far field.

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 8, therefore, the flame and plume remained vertical most of the time.

Comparison with the experimental data shows that FDS over-predicts the temperature near the flame, figures 6 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.

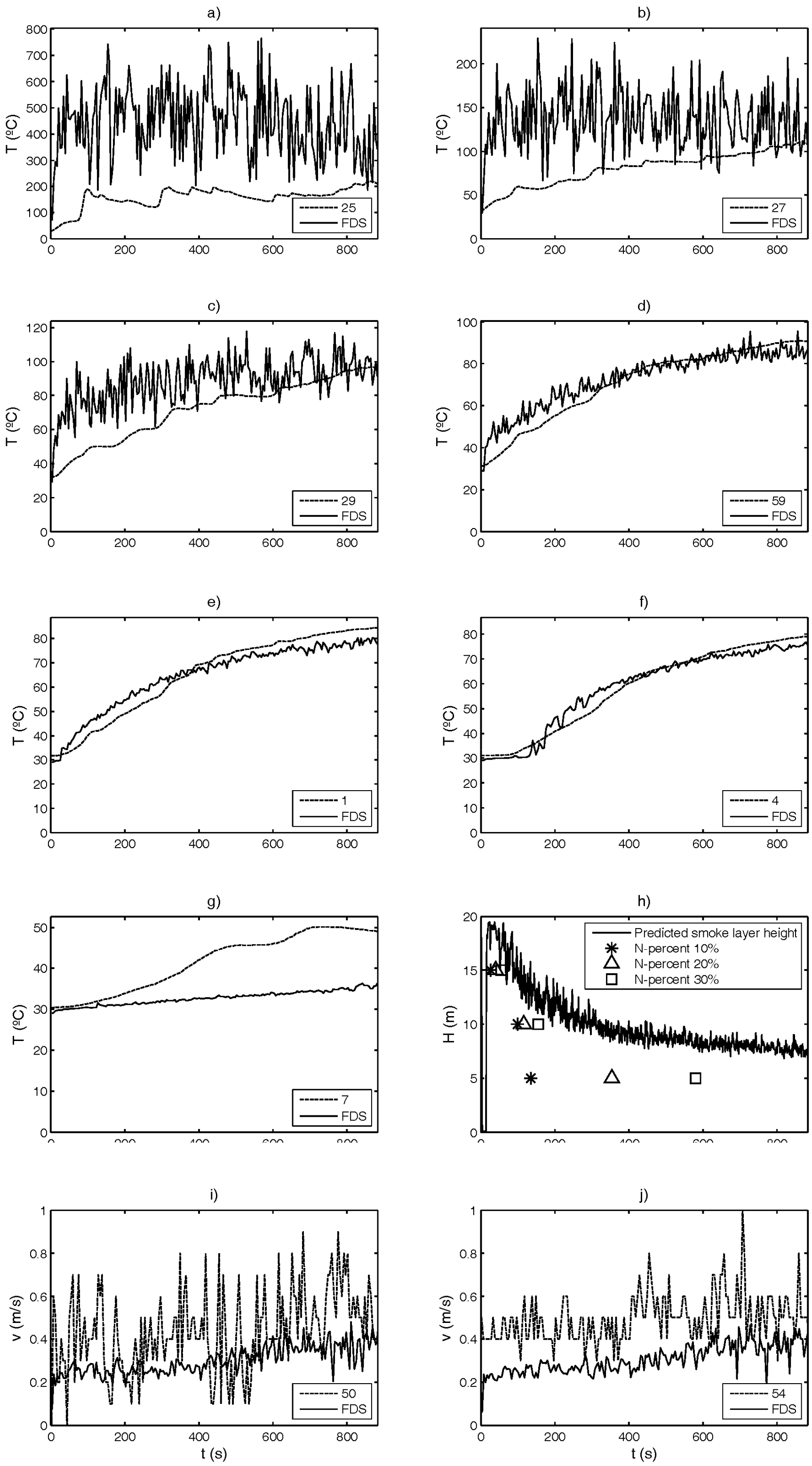


Fig. 6. Test #2 measurements and predictions. Temperature at the plume at 5.25 m high in a), 9.25 m high in b), 13.25 m high in c), at the exhaust fans in d), near the walls at 15 m high in e), 10 m high in f), and 5 m high in g). Smoke layer height in h). Make-up air velocities at the vent A1 in i), and C2 in j). Measurements identified by sensor number according to figure 1 b).

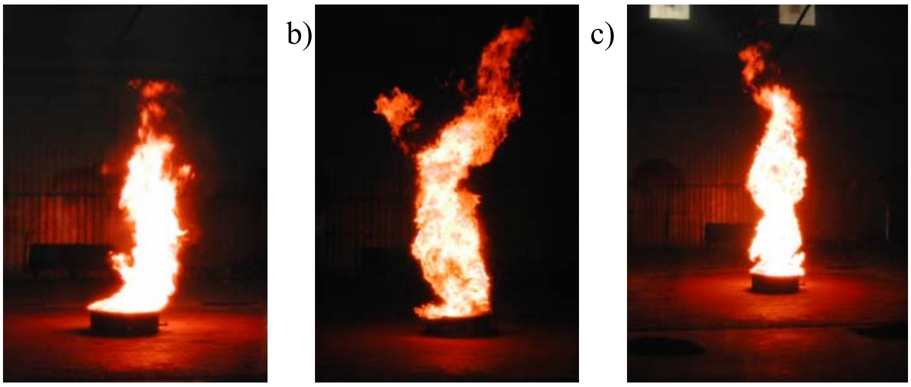
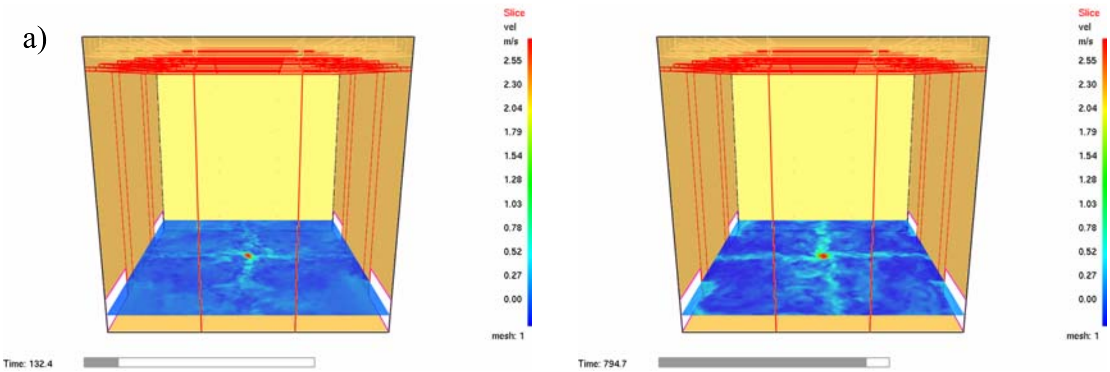


Fig. 7. Flame leaned because of the outer wind effect. t =55 s in a), t = 280 s in b) and t = 330 s in c). View from wall B.

At the exhaust fans, figure 6 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 6 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 6 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 6 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.

a)



b)

Fig. 8. Predicted velocity contours at h = 1.25 m. t = 132.4 in a) and t = 794.7 s in b). View from wall D.

- **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. In this case, large discrepancies between the experiment and the simulation have been observed. Figure 9 shows the measurements and predictions vs time at different locations.

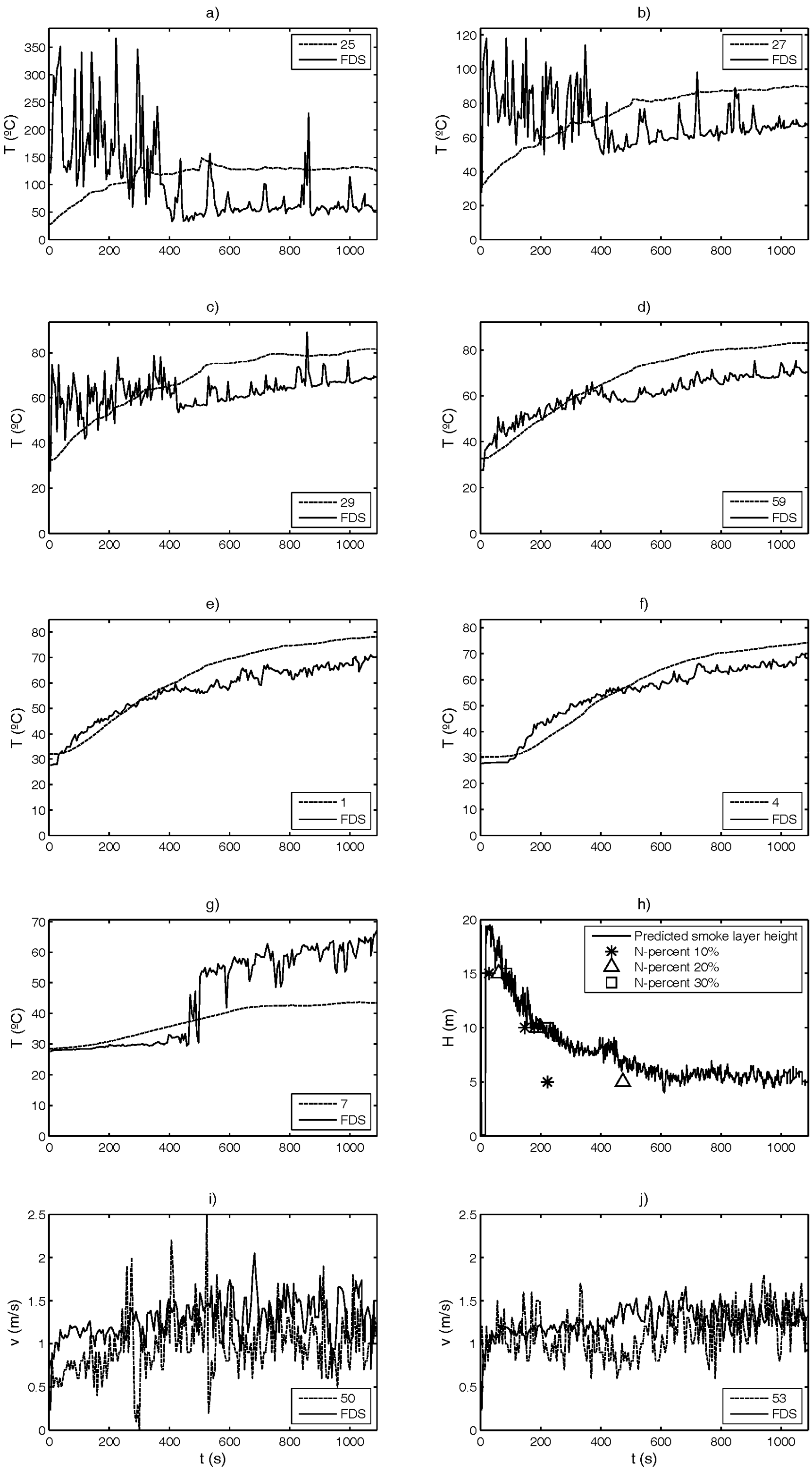


Fig. 9. Test #3 measurements and predictions. Temperature at the plume at 5.25 m high in a), 9.25 m high in b), 13.25 m high in c), at the exhaust fans in d), near the walls at 15 m high in e), 10 m high in f), and 5 m high in g). Smoke layer height in h). Make-up air velocities at the vent A1 in i), and C2 in j). Measurements identified by sensor number according to figure 1 b).

Experimentally, small but fairly persistent flame inclinations and plume deviations towards wall C were observed during the fire, figure 10. These flame inclinations can be also appreciated from the temperature measurements at the centreline at h = 5.25 m, figure 9 a), where they are lower than those obtained from [24], T = 200 ºC. However, these flame inclinations were not very strong as, at h = 9.25 m, the temperature measurements agree well with [24], 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 9 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) b) c)

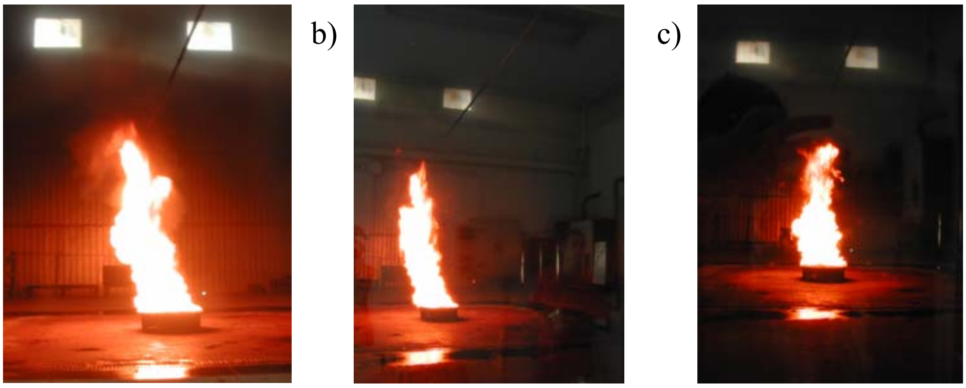


Fig. 10. Flame slightly leaned towards wall C, t =375 s in a), t = 720 s in b), and vertical flame at t = 1005 s in c). View from wall B.

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 11. As happened in test #1, a circular air stream surrounding the flame forms at lower locations and grows in intensity with time, figure 12. 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 vertical velocity iso-contours at the central section which are completely chaotic from t = 300 s, figure 13. 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 12. As a consequence, the plume becomes unsteady and looses its verticality, leaning towards the walls randomly, figure 11.

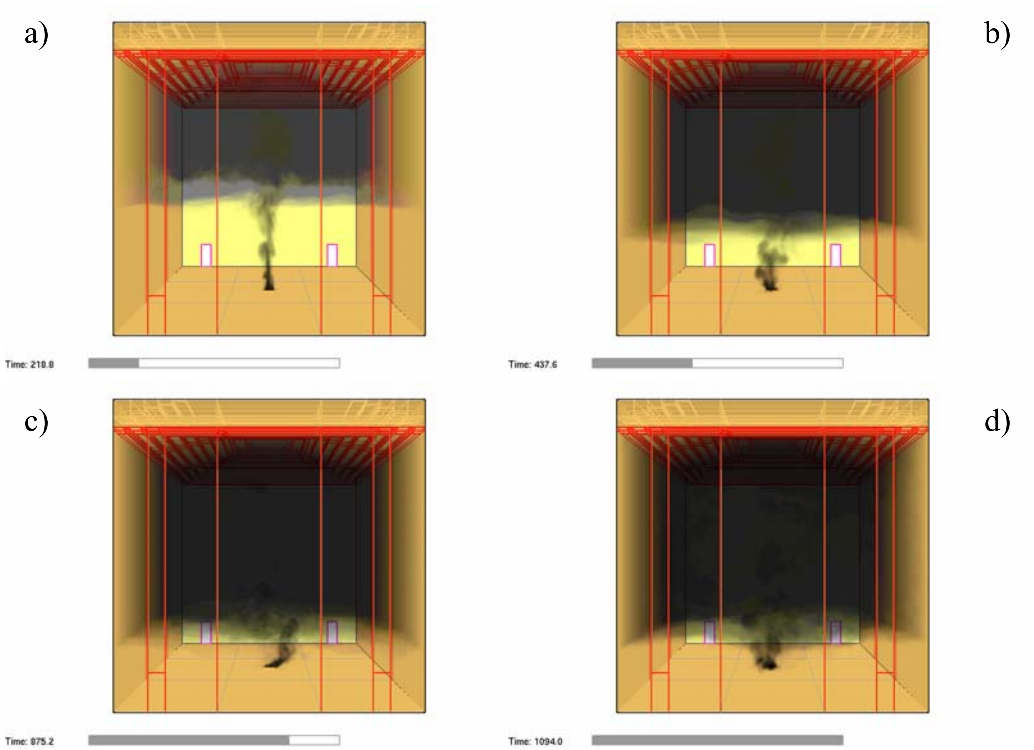


Fig. 11. Predicted flame inclinations due to the make-up air influence, t = 218.8 s in a), t = 437.6 s in b), t = 875.2 s in c), and t = 1094.0 s in d). View from wall A.

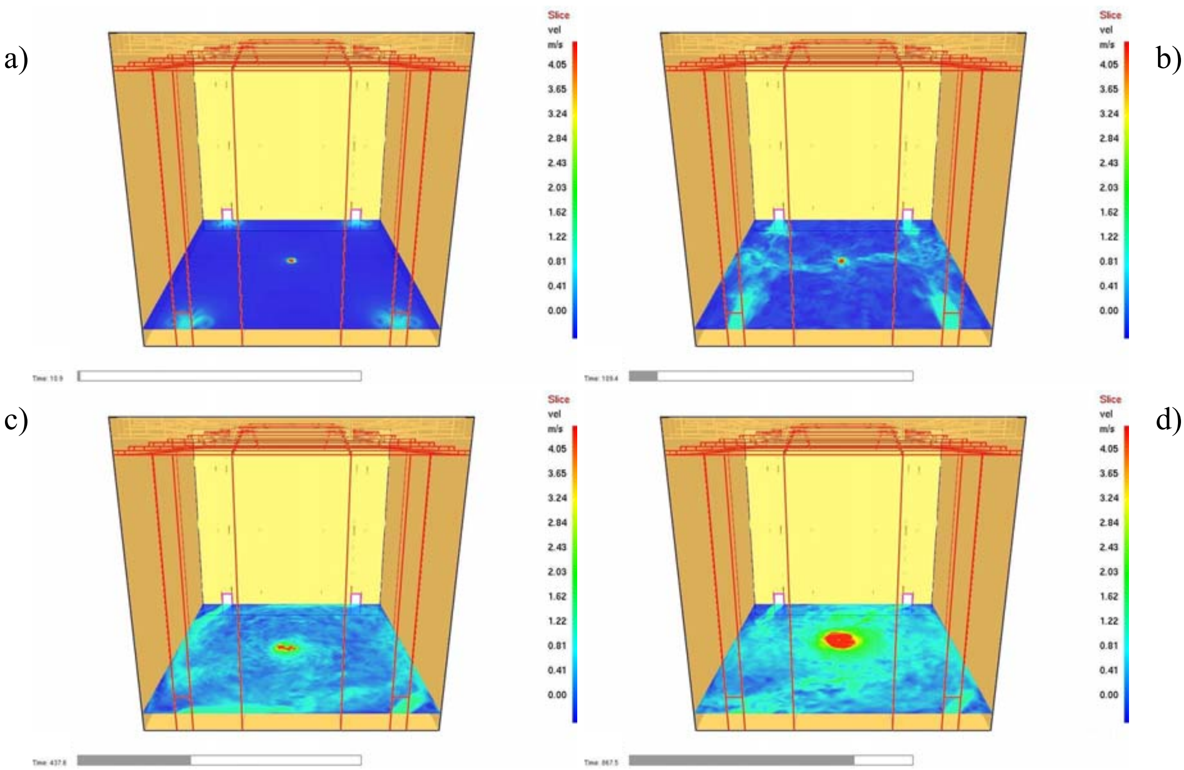


Fig. 12. Predicted velocity contours at h = 1.25 m high. t = 10.9 s in a), t = 109.4 s in b), t = 437.8 s in c), and t = 867.5 s in d). View from wall A.

a) b)

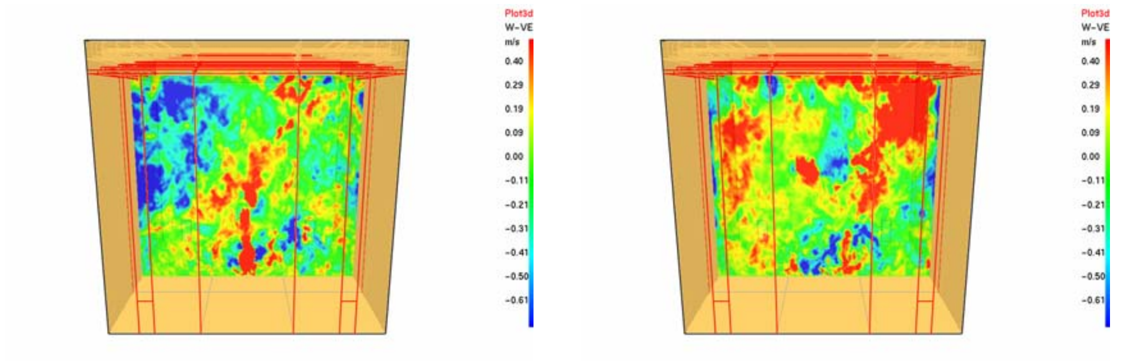


Fig. 13. Predicted vertical velocity contours at the central section, t= 656.4 s in a), and t = 1094.0 s in b). View from wall A.

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 9 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 9 d), and h = 15 and h = 10 m near the walls, figures 9 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 9 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 9 h), eventually reaching the height of h = 5 m high. At the vents, there is good agreement, figures 9 i) and j), where the inlet velocities are ranged from 1 to 1.5 m/s in average.

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 FDSv4, in order to check the capability of this code to predict the fire-induced inner conditions, and to show the validity of the experimental data to be used as benchmark for numerical validations.

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 [1]. 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 [11]. 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 [6, 15]. At the exhausts fans and the upper parts near the walls ($h \geq 10$ 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. A deeper study would be required to make more definitive conclusions on the behaviour of FDS for this case study.

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