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ASSESSMENT OF MATHEMATICAL METHODS TO ESTIMATE THE SMOKE LAYER THICKNESS IN DIFFERENT FIRE SCENARIOS

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Abstract. *Smoke is one of the leading causes of fire deaths. The knowledge of the thickness of the smoke layer is of great importance, since it is possible to know the thermal and flow profile of the same, as well as design smoke control devices and minimize the problems caused by it. In the present work the thickness of the smoke layer is determined by 4 methods: N-percentage rule, Buoyancy Frequency, Integral Ratio and the standard method of FDS (Fire Dynamics Simulation) software. The fire scenarios employed to test those methods were taken from experiments available in the literature, which vary in shape, ventilation and heat release rate: a tunnel, a building and an atrium. The general behavior obtained with the different methods was quite similar for all fire scenarios, showing that there is not a most accurate method that can be applied for any fire scenario, while all methods agreed at least qualitatively with the experimental transient smoke layer heights. Despite that, the standard method of FDS and the N-percentage rule (depending on the choice of N) provided relative errors slightly smaller than the other methods.*

Keywords: *Smoke layer, FDS, N-percentage Method, Integral Ratio Method, Buoyancy Frequency Method*

1. INTRODUCTION

Statistics show that 85% of fire deaths are caused by heat and smoke toxicity, incluing particulate components and products generated by combustion (Brooke, 2009). During a compartment fire, a separation between two distinct layers of gases is formed, one rich in oxygen and with low temperature, positioned in the lower portion of the compartment, and one rich in toxic gases and with high temperature, positioned in the upper portion of the compartment and with a high temperature. It is vital for the survival of people that the layer of toxic gases is above the height of their heads, so that one does not breathe these gases. In 1990, 76% of fire deaths in the United States of America were caused by smoke inhalation (Hall and Harwood, 1995). For these reasons the knowledge of the height of smoke layer is a subject of great importance in the field of fire research. (Cooper et al., 1982) proposed a method for calculating the smoke layer height, known as N-percentage rule method, where the smoke layer thickness is computed based on the ambient temperature and a constant parameter (*N*). Later, (He et al., 1998) proposed the Integral Ratio method, where divides the temperature profile into two layers, one with a higher concentration of smoke and one of air. Recently, Gao et al. (2016), proposed the Buoyancy Frequency method considering the gases as ideal.

Using the software FDS (Fire Dynamics Simulator), the present work reproduces numerically the experiments of Gao et al. (2016) (a tunnel fire), Lai et al. (2013) (a building fire) and Li et al. (1999) (an atrium fire), comparing the experimental data with the above cited methods and the standard method available in, determining the best method to calculate the smoke layer height for each fire scenario.

2. NUMERICAL METHOD

This work computationally simulates the different fire scenarios using the software FDS. FDS solves conservation equations for energy, species concentration, mass, and momentum (Low-Mach number approximation) using Large-Eddy Simulation (LES) methodology. Several models and sub-models are available in FDS, as Simple Immersed Boundary Method for treatment of flow obstructions, different options of chemical reactions, gas radiation modelling, combustion models, boundary conditions, fuels, etc., making FDS an adequate tool to accomplish research studies and engineering applications regarding fire dynamics.

The present work simulates different fire scenarios: (*i*) reduced-scale tunnel studied by Gao et al. (2016), considering its four practical cases, varying the pool size (so fire heat release rate) and exhaustion (with or without upper exhaustion), (*ii*) the room-like construction of case No-01-C (Lai et al., 2013), without exhaustion, analyzing the

6 sets of thermocouples positioned in different positions in the room, and (*iii*) the large atrium studied by Li et al. (1999) considering the simulation by Qin et al. (2008). For all fire scenarios, it is made a comparison between experimental data with numerical results from FDS post-processed with 4 different methods to obtain the smoke layer thickness (N-percentage rule, Integral Ratio, Buoyancy Frequency, and the standard method of FDS).

The N-percentage rule method, Cooper et al. (1982) considers that the interface of the smoke layer is located at the height where the temperature difference at one point and the ambient temperature is equal to a percentage of the difference between the maximum and the ambient temperature. In this method, the smoke layer height is obtained with Eq. (1), where T_i is the temperature at the interfacing height in ºC, T_{amb} is the ambient temperature, T_{max} is the maximum temperature, and *N* is an empirical constant ranging from 10,20,30,40 and 50.

$$T_i - T_{amb} = (T_{max} - T_{amb})N/100 \quad (1)$$

At the Integral Ratio method, He et al. (1998) divides the temperature profile (from the floor to the ceiling) into two distinct regions, one rich in smoke and another rich in air, where H is the height in the celling in meters, H_i' is a possible interface height in meters, *T(z)* is the temperature profile as function of *z* (the vertical coordinate) and r is the Integral Ratio. In this method, Eq. (2) is use to find the height of the smoke layer, being Eq. (2) computed for different values of H_i varying it from 0 to H, the height of the interface H_i' will be the value that results in the least value of r.

$$r(H_i') = \frac{1}{(H-H_i')^2} \int_{H_i'}^{H} T(z)dz \int_{H_i'}^{H} \frac{1}{T(z)} dz + \frac{1}{H_I'^2} \int_0^{H_i'} T(z)dz \int_0^{H_i'} \frac{1}{T(z)} dz \quad (2)$$

Buoyancy frequency method (Gao et al., 2016) uses Eq. (3) to obtain the smoke layer height, where N_L is the frequency of fluctuation in the vertical direction, and g is the acceleration of gravity in m²/s. The N_L parameter is larger when the density difference is greater, so the interface height will be the value N_L between 0 and H that generate the highest value.

$$N_L = \left(-gT_{amb} \frac{\delta(1/T(z))}{\delta z}\bigg|_{z_i}\right)^{1/2} \quad (3)$$

In the FDS user guide (McGrattan et al., 2001), the FDS standard method for calculating the smoke layer height considers two integrals of the temperature function, as shown in Eq. (4) and (5). After computing I_1 and I_2 the smoke layer height is obtained through Eq. (6), where T_l is the lower layer temperature.

$$I_1 = \int_0^H T(z)dz \quad (4)$$

$$I_2 = \int_0^H \frac{1}{T(z)} dz \quad (5)$$

$$H_i = \frac{T_l(I_1 I_2 - H^2)}{I_1 + I_2 T_l^2 - 2T_l H} \quad (6)$$

After performing transient simulations of each fire scenario (tunnel, room and atrium fire), the temperature outputs obtained from virtual thermocouples trees in FDS are post-processed with the different method for obtaining the smoke layer height. Those virtual thermocouple trees are set in FDS at the same positions of experimental thermocouple trees, for comparison purposes. First, the temperature profile at a given time is fitted in a function as that in Eq. (7), where *a*, *b*, *c* and *d* are constants calculated at each time, and *z* is the vertical position of each virtual thermocouple. After that, the three methods (N-percentage rule, Integral Ratio, and Buoyancy Frequency) can be applied to obtain the smoke layer height. The fourth method is standard in FDS and the smoke layer height for this method is promptly available from FDS, without further post-processing. The smoke layer thicknesses obtained with the different methods are then compared to the experimental ones.

$$T_{(z)} = \left(\frac{ab + cz^d}{b + z^d}\right) \quad (7)$$

3. EXPERIMENTS AND SIMULATIONS

The experimental cases discussed in this article present different dimensions and characteristics of each other. The tunnel studied by Gao et al. (2016) is 6 meters (m) long, 2 meters wide and 0.9 meters high, it is open in both ends (left and right boundaries),has a chimney of 0.3 m in length and width with a height of 0.8 m, and it is located 3.2 m from the left side of the tunnel. The tunnel is made of fireproof boards 8 mm (millimeters) thick on its lower, upper and backward faces, the chimney and the front face of the main body is made from 6 mm fireproof glass. The thermocouples are positioned 5 m from the left side of the tunnel, in the center line between the heights of 0.56 m and 0.88 m, the fuel used was a pool of N-heptane with 10 mm depth and two dimensions differing according to the case addressed (see Table 1). As the routine in FDS configures for each case, the mass of fuel burned between two instants of time in the simulation is the same as the variation of the residual mass supplied by Gao et al. (2016). Table 1 shows the 4 cases of the tunnel analyzed. Cases 1 and 2 considers the chimney closed, and Cases 3 and 4 considers it open.

Table 1. Experimental cases studied by Gao et al. (2016) and in this paper.

Cases	Ambient Temperature (ºC)	Pool Size (mm)	Exhaustion Condition	Time Interval(s)
Tunnel 1	16	100 × 150	Without upper smoke exhaust.	40-180
Tunnel 2	15	150 × 200	Without upper smoke exhaust.	40-160
Tunnel 3	15	100 × 150	Natural upper smoke exhaust.	40-180
Tunnel 4	17	150 × 200	Natural upper smoke exhaust.	40-160

Figure 1 shows an example of a temperature slice obtained as output from the FDS simulation performed to reproduce the tunnel fire studied by Gao et al. (2016).

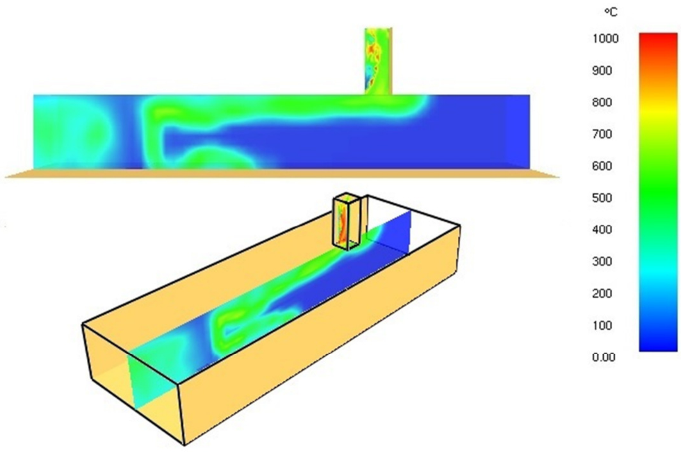


Figure 1. Example of the simulated tunnel fire scenario results: temperature slice at the midplane of the tunnel.

The building fire studied by Lai et al. (2013) has two floors and three rooms, being room 1 (fire room) and 2 (adjacent room) object of study in this article. Room 1 is 5.4 m long and wide, with a height of 3 m, with an opening for the external environment of 2.0 m height by 0.8 m wide, and another opening for room 2 of the same dimensions. Room 2 is 3.4 m wide, 5.4 m long. The building is made of bricks, the fuel is n-octane, the pool is in the middle of room 1 and measure 0.2 m × 0.2 m, the heat release rate is 50 kW and the heat of combustion is 44,400 kJ /kg. The thermocouples trees are positioned according to Fig. 2, where there are 11 sensors per tree. The trees studied in this investigation are called TC1, TC3, TC5 and TC6 (Fig. 3, blueprint on the right slide).

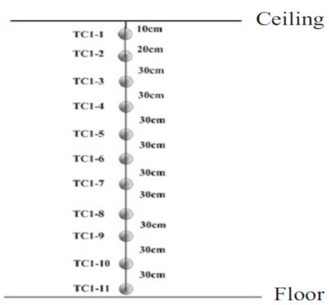
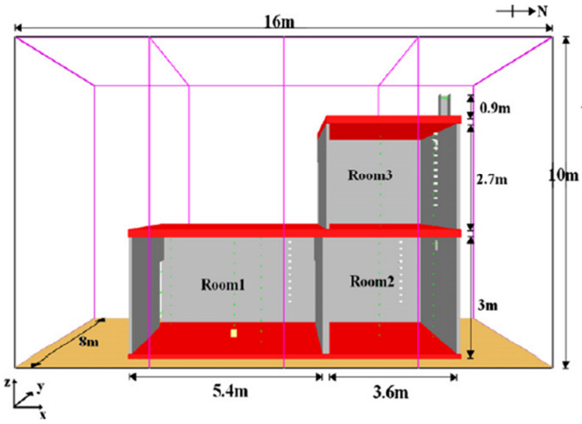


Figure 2. Position of thermocouple trees for the building fire scenario (Lai et al., 2013).



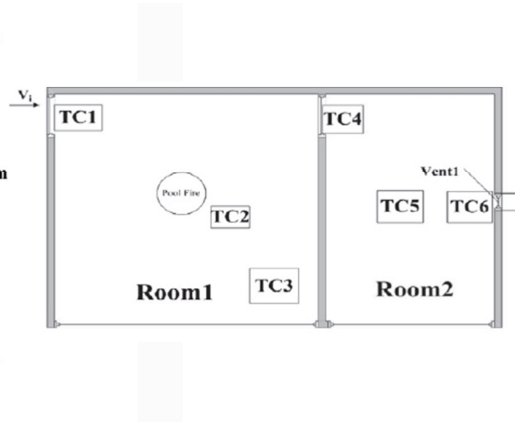


Figure 3. Experimental building fire case studied by Lai et al. (2013).

Table 2 shows the thermocouple trees studied, as well as the time considered according to the article by Lai et al. (2013).

Table 2. Experimental building fire cases studied by Lai et al. (2013).

Cases	Ambient Temperature(ºC)	Time Interval (s)
Building TC 1	27 ºC	0-600
Building TC 3	27 ºC	0-600
Building TC 5	27 ºC	0-400
Building TC 6	27 ºC	0-400

The third fire scenario was studied by Li et al. (1999) and Qin et al. (2008). It is an atrium in a building, a large open space, created by an opening or a series of small openings that connect to upper floors in a building; this kind of construction is found in commercial buildings, malls and shopping malls. Since the atrium is open, the fire that begins in its floor can take smoke to other floors or dependencies of the building, hence its importance to study the thickness of the smoke layer. The studied atrium has external dimensions of 27.6 meters in length, 18.1 meters in width and 30.6 meters in width. Its internal dimensions are 22.4 meters wide by 11.9 meters in length and 27 meters in height. It has two doors 4 meters long by 2 m wide in the center of the front and back walls. The atrium contains 20 different exhaust systems of 1.2 m × 1.2 m, being with 12 windows on the walls and 8 vents on the ceiling. For the present simulation, a 2 m × 2 m diesel pool was considered in the center of the floor with a heat release rate per unit area of 1 MW /m². The thermocouple tree was positioned 4.6 m and 12.5 m far from the front and left walls, respectively, in a tree of 15 sensors positioned between 1.8 and 28.8 m in the z-direction. Figure 2 shows a sketch of the atrium fire.

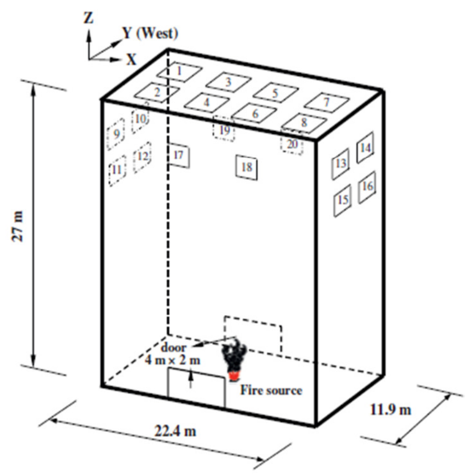


Figure 4. Atrium fire studied by Li et al. (1999) and Qin et al. (2008).

For the simulations, a mesh of 112 mm × 60 mm × 135 mm was used as proposed by the paper by Qin et al. (2008). The case studied was the atrium with all doors and windows closed, except one vent of 0.2 m horizontal for fresh air inlet.

The mesh test was performed through the User Guide of the FDS software proposed by McGrattan et al. (2001) using Eq. (8), where Q is the rate of heat release rate in kW, p_{00} is the density of the ambient fluid in kg/m³, c_p is the specific heat of the fluid in kJ/kg.K.

$$D^* = \left(\frac{Q}{p_\infty T_\infty c_p \sqrt{g}}\right)^{2/5} \tag{8}$$

According to Salley et al. (2007) in the report of the NUREG-1824 (Nuclear Regulatory Commission Regulation), the greater the proportion D^*/δ, where δ is the size of the control, the better the fire dynamics is solved directly and the more accurate the simulation is. Experience shows that a ratio between 5 and 10 produces favorable results for the mesh study with a moderate computational cost, however the higher the result, the more refined the mesh.

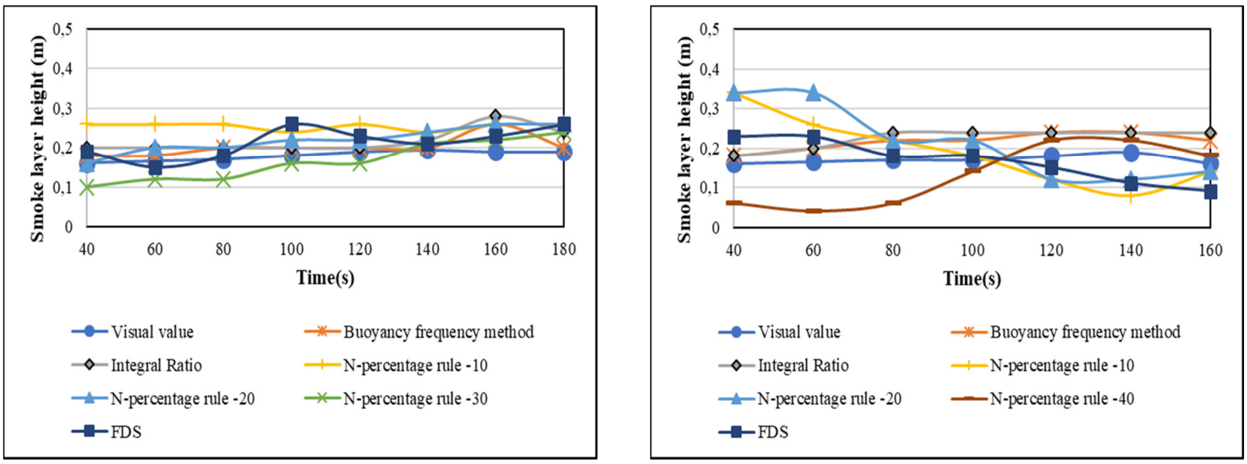
The mesh study performed for fires scenario is presented in Tab. 3, following the recommendations of the NUREG-1824 report (Salley et al., 2007), where it is presented the mesh size and the relation D^*/δ for each case simulated in FDS.

Table 3. Mesh study for the fire cases.

Simulation	Mesh Size	D^*/δ
Tunnel	80	5.8
Tunnel	50	9.2
Tunnel	20	23.1
Building	200	3.78
Building	100	7.70
Building	80	9.46

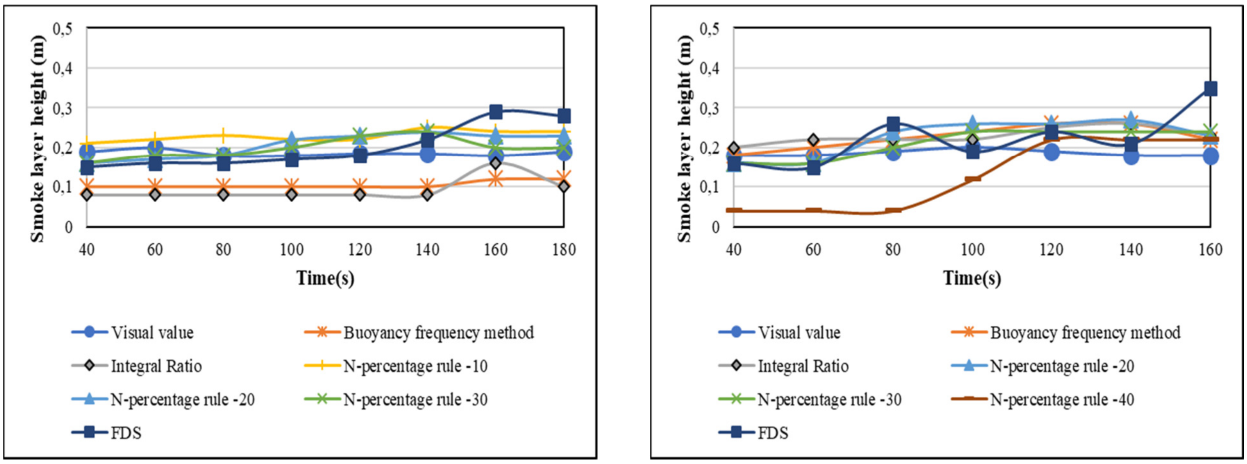
4. RESULTS

Figure 5 and 6 present the transient smoke layer height obtained in the present work by applying the different methods (N-percentage rule, Integral Ratio, Buoyancy Frequency, FDS-standard) in comparison to the experimental data (visual value) of Gao et al. (2016) for the cases Tunnel 1, Tunnel 2, Tunnel 3 and Tunnel 4. It is observed scattered behavior of the numerical methods, while some of them agree qualitatively with the visual values, others are completely sparse and others agree even qualitatively. After showing the graphs for all fire scenarios (building and atrium fires), Tab. 5 is presenting the average deviation between the experimental and numerical results, where it is clearer the good/bad agreement between each method and the experimental data. Those average deviations are discussed later in this paper.



(A) (B)

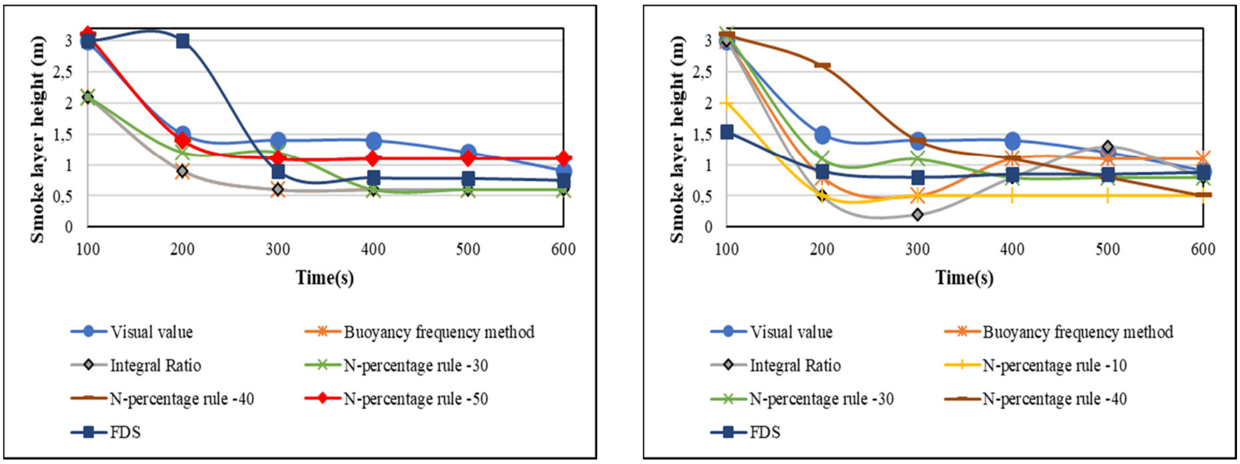
Figure 5. Comparison between simulated and experimental results for cases Tunnel 1 (A) and Tunnel 2 (B).



(A) (B)

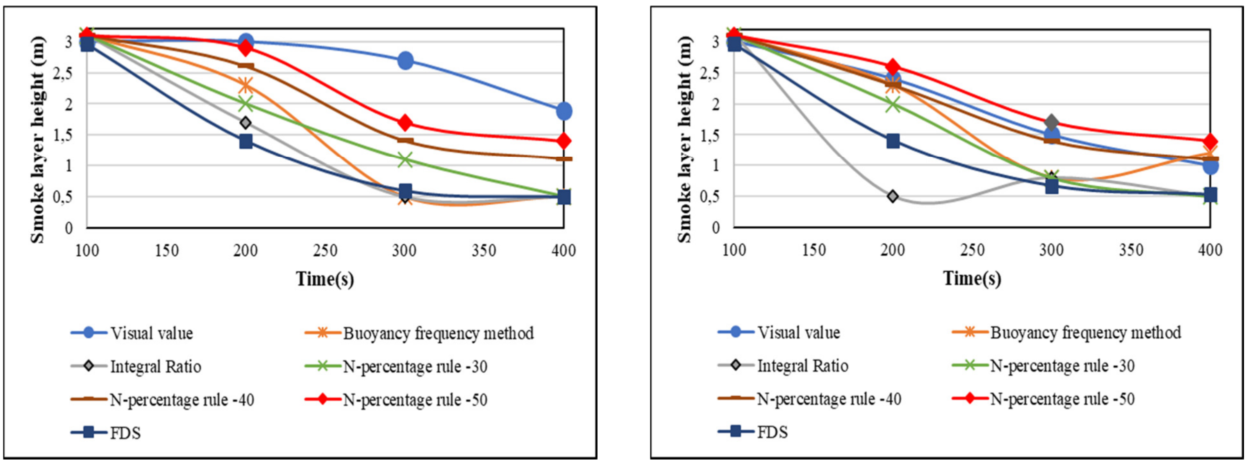
Figure 6. Comparison between simulated and experimental results for cases Tunnel 3 (A) and Tunnel 4 (B).

Figures 7 and 8 present the transient smoke layer height obtained in the present work by applying the different methods (N-percentage rule, Integral Ratio, Buoyancy Frequency, FDS-standard) in comparison to the experimental data (visual value) of Lai et al. (2013) for the cases Building TC1, Building TC3, Building TC5 and Building TC6. The scattered behavior is repeated for those cases, but with less oscillation relatively to the tunnel fire scenario.



(A) (B)

Figure 7. Comparison between simulated and experimental results for cases Building TC1 (A) and Building TC3 (B).



(A) (B)

Figure 8. Comparison between simulated and experimental results for cases Building TC5 (A) and Building TC6 (B).

Figures 9 present the transient smoke layer height obtained in the present work by applying the different methods (N-percentage rule, Integral Ratio, Buoyancy Frequency, FDS-standard) in comparison to the experimental data (visual value) of Li et al. (1999) for the Atrium. The scattered behavior is repeated for this case, but also with less oscillation relatively to the tunnel fire scenario.

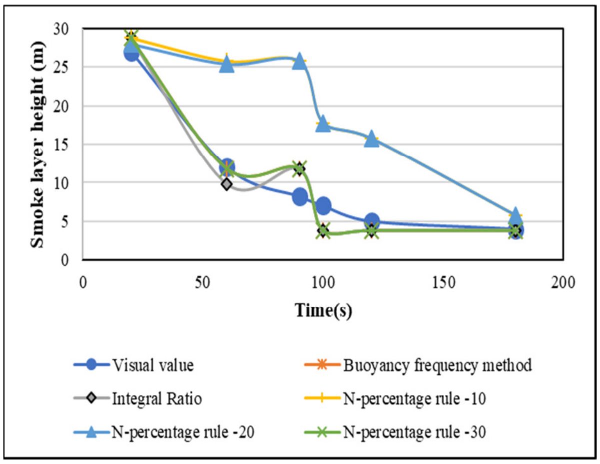


Figure 9. Comparison between simulated and experimental results for case Atrium.

Table 04 provides the mean relative deviation and the standard deviation data for each fire scenario (tunnel, building and atrium) and mathematical method (N-percentage rule, Integral Ratio, Buoyancy Frequency, FDS-standard) For each method, column A provides the mean relative error between the experimental data and the numerical results for each fire scenario, and column B provides its standard deviation. It is observed in this table that all methods present comparable relative errors (ranging between 20% and 30% in general), while the standard method available in FDS presented results slightly better than the others methods. Notwithstanding, the N-percentage rule showed the second better accuracy when N was set as 30, implying that this method is a good candidate to be further developed.

Table 4. Mean error and standard derivation for each case.

Scenario	Buoyancy Frequency Method		Integral Ratio		N-Percentage - rule (N = 10)		N-Percentage rule (N = 20)		N-Percentage rule (N = 30)		N-Percentage rule (N = 40)		N-Percentage rule (N = 50)		Standard FDS	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Tunnel 01	13%	0.02	21%	0.03	43%	0.04	22%	0.03	9%	0.03	42%	0.06	51%	0.06	18%	0.03
Tunnel 02	27%	0.03	32%	0.03	15%	0.06	28%	0.06	48%	0.07	24%	0.06	33%	0.05	1%	0.04
Tunnel 03	44%	0.04	50%	0.02	23%	0.07	12%	0.02	7%	0.03	57%	0.07	58%	0.06	8%	0.03
Tunnel 04	21%	0.03	23%	0.03	72%	0.13	21%	0.12	14%	0.04	31%	0.07	54%	0.08	20%	0.01
Building TC 1	45%	0.73	45%	0.73	16%	0.54	53%	0.50	34%	0.56	5%	0.76	5%	0.9	5%	0.9
Building TC 3	20%	0.79	33%	0.87	3%	0.81	49%	0.70	22%	0.85	4%	0.9	34%	0.6	34%	0.66
Building TC 5	44%	1.08	49%	1.09	55%	1.18	46%	1.15	41%	1.08	25%	0.98	16%	0.84	51%	1.06
Building TC 6	7%	0.9	43%	1.08	43%	1.19	28%	1.17	29%	1.10	1%	1.0	16%	0.79	36%	1.07
Atrium 1	4%	8.35	7%	8.34	125 %	9.13	125 %	9.13	4%	8.35	245%	10.0 9	242%	9.92	30%	8.25

5. CONCLUSIONS

This paper presented an assessment of four methods to obtains the transient smoke layer height using virtual thermocouple readings (temperatures) from numerical simulations in the software FDS.

Three fire scenarios were simulated to obtain the temperatures reading from the floor to the ceiling (the vertical temperature profile) of each configuration. The scenarios considered here were: tunnel fire (4 cases varying HRR and temperature profile), building fire (4 cases varying the virtual thermocouple positions), and atrium fire. First, each case was simulated in FDS in order to obtain the temperature readings (at positions covering the entire room height, from the floor to the ceiling). Then, temperature readings were using as inputs in each method to obtain the smoke layer height. The methods tested were: N-percentage rule (varying the N parameter: 10,20,30,40 and 50), Integral Ratio, Buoyancy Frequency, and standard method available in the software FDS.

The general behavior with the different methods was quite similar for all fire scenarios, showing that there is not a most accurate method for any fire scenario, while all methods agreed qualitatively with the experimental transient smoke layer heights. The mean relative error between numerical and experimental smoke layer heights ranged between 20% and 30% for all methods, which is acceptable considering the complexity of this phenomenon. Despite that, the standard method of FDS returned relative errors slightly smaller than the other methods. The second most accurate method was the N-percentage rule, with N=30, showing the importance of a good choice for the N parameter when applying that method.

The continuity of this research is focused on testing those methods for a wider range of fire scenarios and developing a new method to compute the smoke layer height that must consider physical properties of the fire scenarios as inputs (e.g., HRR, surface area, ventilation factor), besides the transient temperature profiles.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE