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NUMERICAL SIMULATION OF STRATIFIED FLOW IN A PRE-CHAMBER OF SMOKE-PROOF STAIR

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Abstract. *One of the greatest difficulties in a fire is in the smoke control , and it is fundamental that structures designed to promote exhaustion and prevent the spread of these harmful gases work properly. The present study uses computational fluid dynamics to model the stratified flow in smoke proof stairs chambers, in order to evaluate the effects of the variation of measures stipulated by technical norm on the exhaustion of smoke. We analyzed the changes in the distance between the ceiling and the smoke outlet and the aspect ratio of the smoke outlet as well. The results showed that there is no significant variation in the smoke exhaust flow when the distance between the ceiling and the smoke outlet increase, but there are negative implications regarding the efficiency of the chamber when the aspect ratio of the same opening increase, the exhaust flow being more sensitive to the change of this geometric parameter.*

Keywords: *fire control, computational fluid dynamics, smoke exhaust, natural convection, smoke proof stairs chamber.*

1. INTRODUCTION

One of the greatest difficulties in a fire is the control of the smoke emitted by the flame, since the gases and particulate matter emitted can be harmful to the health, being able to cause illnesses or asphyxia, and this is one of the main cause of deaths in fires (Dueñas- Laita et al., 2010).

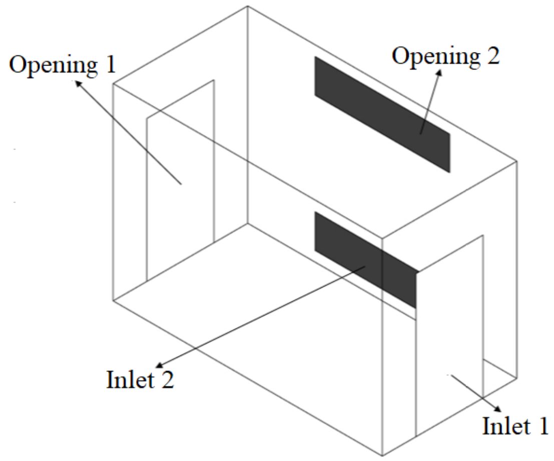
According to technical standard 10/2013, elaborated by the military fire department of the state of Espírito Santo (CBMES, 2013) that specify emergency exits in buildings, as a function of the size of the building, it has to have a particular type of emergency staircase called a smoke-proof enclosed stair. According to the standard, in addition to their design features this type of stair must have access through antechambers that have the main purpose of retaining and promoting the exhaustion of the smoke generated by the fire. In addition to the access and exit doors, the antechamber must have an opening for clean air intake near the floor, and another opening for smoke exit, near to the ceiling.

Mandatory dimensions for antechamber construction are stipulated in the standard, as well as the geometric relationships and maximum and minimum distances between the entrance, exit and openings for entry of clean air and smoke outlet. However, in a real building, there may be changes in these dimensions that may affect the performance of smoke exhaustion in the antechamber. In this way, the present study aims to evaluate, using computational fluid dynamics (CFD), the impact of two modifications made on the opening of smoke output on the flow in the antechamber: the distance from the ceiling and the aspect ratio (height:width).

2. METHODOLOGY

The simulations were performed with Ansys® CFX 16.0 software. The geometry used was a parallelepiped, 4 m long by 2.0 m wide and 2.8 m high. The entrance and exit doors of the antechamber were 1.0 m wide and 2.1 m high, centralized in their respective walls. One door was considered to be a smoke inlet (Inlet 1) and another was considered to be an opening (Opening 1: entrance or exit of smoke or clean air). In one of the side walls were placed the entrance of clean air (Inlet 2: near the floor) and the opening smoke exit (Opening 2: near the ceiling), each with an area of 1 m². Initially both windows (clean air entrance and smoke exit) had dimensions 0.5 m x 2.0 m, and then the smoke exit window dimensions were changed.

The study simulations were separated into two cases. In the first case, the monophasic flow of air as ideal gas, at 25º C, was simulated, in steady state regime. Then, the effect of natural convection, which coupled the equations of momentum and energy, was considered to determine the buoyancy force that results from the density difference between the fluids. Density is a function of temperature in the ideal gas model adopted. For the heat transfer only the thermal energy transported due to the temperature difference between the fluids in the inlets was considered, despising the thermal energy generated by the viscous friction. The κ–ε turbulence model was used. The openings were considered at atmospheric pressure and the other surfaces were considered as adiabatic walls with non-slip conditions. The convergence criterion adopted was the average quadratic value of the residuals (RMS) of 1×10^{-4}. Fig. 1 shows the geometry and boundary conditions used.



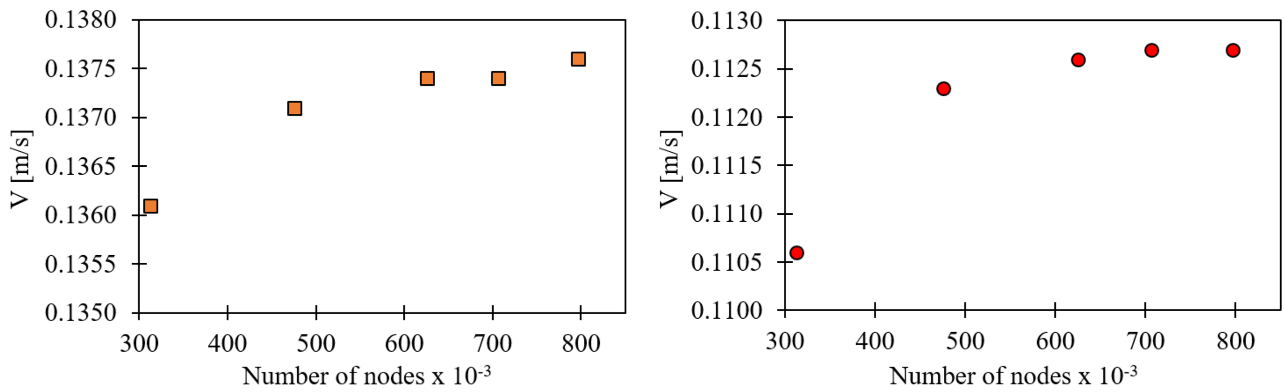
(a)

Region	Prescribed temperature (ºC)	Prescribed normal speed (m/s)
Inlet 1	65	0.1
Inlet 2	25	0.1
Opening 1	-	-
Opening 2	-	-

(b)

Figure 1. Details of the simulated configuration. (a) Geometry; (b) Contour conditions.

A grid independence test was performed (Fig. 2), comparing the velocities in the openings as a function of the number of nodes. The results were independent of the mesh for the test with more them 625215 nodes. For the access to stairs (opening 1), the percentage variation for this mesh in relation to the most refined one was 0.145%, while for the smoke exit (opening 2) the variation was 0.088%. Thus, the mesh adopted had 625215 nodes, in order to guarantee the accuracy of the results at plausible computational cost.



(a) (b)

Figure 2. Mean velocity for different computational meshes. (a) Opening 1; (b) Opening 2.

The disposition of the openings and dimensions to be treated below are shown in Fig. 3. According to technical standard 10/2013, the maximum distance (h) allowed between the ceiling and the smoke exit should be 0.15 m. In addition, the same standard requires 0.84 m² as minimum area for each opening and, when rectangular, it should have a maximum aspect ratio of 1:4. This ratio is called the aspect ratio β and can be calculated by Eq. (1).

$$\beta = \frac{y}{x} \tag{1}$$

where y is the height and x is the width of the smoke exit window. Therefore, the distance h = 15 cm was used, stipulated by the norm, an area equal to 1 m² with dimensions of y = 0.5 m and x = 2.0 m, obeying the 1:4 aspect ratio. These features were used as reference to evaluate the effects of the changes in h dimension and aspect ratio over the flow. In the sequence, simulations were performed with the distances h equal to 0.20 m, 0.25 m and 0.30 m, maintaining the aspect ratio of 1:4. Other simulations were performed by changing the aspect ratio to 1:1.77 and 1:1, keeping constant the distance h = 15 and area. Finally, a comparative analysis was carried out to verify the effects of such geometric changes in the smoke exhaust flow, the main parameter that determines the efficiency of the smoke proof chamber.

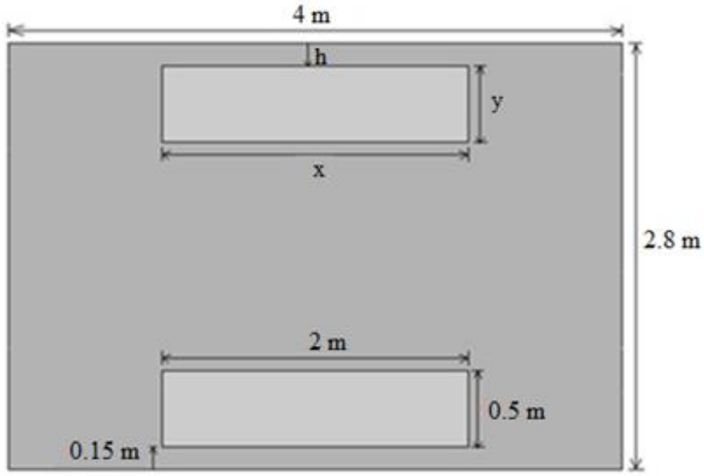


Figure 3. Variable dimensions of smoke exit window and other chamber dimensions.

In the second case, the two-phase flow was implemented with the addition of the smoke, having the same ideal gas properties to compose the mixture between the fluids present inside the chamber. For the determination of thermal and fluid dynamics properties, the ideal mixing model was considered, and the properties calculated based on the weight fraction of each component. In addition, the same contour and geometry conditions of the first case, presented in Fig. 1, were adopted. However, it was necessary to establish the smoke mass fractions at the entrances, with Inlet 1 being the entrance region for smoke originating of the fire, where a mass fraction of smoke equal to 1 was assumed to model the most critical case in the fire, while Inlet 2 was considered only the entrance of clean air, to promote the exhaustion of smoke from the interior of the chamber.

According to Foust et al. (2011), the diffusion coefficient of the smoke in the mixture can be calculated by the Lennard-Jones model and, for the assumed conditions, the determined value was $2{,}424 \times 10^{-5}$ m²/s. The Schmidt number, ratio between the momentum and mass diffusivity was 0.9.

3. RESULTS AND DISCUSSION

3.1. First case: air flow

Tab. 1 presents the results of the mass flow in the openings for each simulated condition in relation to the distance h.

Table 1. Mass flow in the openings and percentage variation in relation to the reference case (h = 15 cm).

h (cm)	Opening 1 (stair access)		Opening 2 (smoke exit)	
	Mass flow (kg/s)	Variation (%)	Mass flow (kg/s)	Variation (%)
15 (ref.)	0.80	-	1.13	-
20	0.77	-3.75	1.10	-2.65
25	0.74	-7.5	1.08	-4.42
30	0.73	-8.75	1.07	-5.3

It is worth to point out that all the mass flow in opening 1 were entering the chamber, while in the opening 2 the flow was leaving the chamber. In order to assure mass conservation it was necessary that the clean air enters the chamber through the opening 1, since the mass flow out of the opening 2 was larger than the mass flow from the inlets 1 and 2.

It is noticeable that the increase in distance h resulted in a decrease in the mass flow rate in opening 2 and opening 1, due to the decrease in the stratification effect, since the increased distance resulted in a lower driving force promoted by buoyancy due natural convection. It is possible that by increasing h by 5 centimeters, the variation in the mass flow rate was not enough to compromise the efficiency of the chamber since, for the established conditions, the reduction was less than 3%. It is noticed that there is a relation between the increase of h and decrease of the flow, but this relation is not so impacting for the functioning of the chamber, being observed a reduction of 5.3% when the dimension *h* is twice the reference value, the more critical case evaluated in this study.

Tab. 2 presents the mass flow rates of each opening for different aspect ratios of the smoke exit window (opening 2) and their corresponding dimensions.

Table 2. Mass flow in the openings and percentage variation in relation to the reference (β = 1:4).

Dimension (m)		β	Opening 1 (stair access)		Opening 2 (smoke exit)	
y	x		Mass flow (kg/s)	Variation (%)	Mass flow (kg/s)	Variation (%)
0.5	2.0	1:4 (ref.)	0.80	-	1.13	-
0.75	1.33	1:1.77	0.72	-10	1.06	-6.1
1	1	1:1	0.66	-17.5	1.00	-11.5

Again, it should be stated that all the mass flow in opening 1 were entering the chamber, while in the opening 2 it was leaving the chamber. When the aspect ratio β of the opening 2 (smoke exit) is modified, it is perceived that the mass exhaust flow decreases in both openings. For the aspect ratio of 1:1.77, there was a significant decrease in the mass flow rate of exhaustion. This decrease is relevant when the aspect ratio increases, since the vertical dimension *y* (Fig. 3) tends to increase and, consequently, the effects of the stratified flow that favor the exhaust flow in the opening 2 decrease. Thereby, recirculation of the warmer fluid occurs inside the chamber, which may represent a greater difficulty in the exhaustion of the smoke in a real fire situation. This may still cause a smoke exit through the opening 1, which cannot occur in this kind of system, since the chamber purpose is to prevent the entrance of smoke to the stairs, protecting this escape route in a fire situation.

Fig. 3 shows the behaviour of the fluid as the aspect ratio increases. The largest recirculation can be perceived mainly by the difference in fluid velocity distribution between Fig. 3 (a) and 3 (c). Based on the results, it was possible to perceive a greater influence in the reduction of the mass flow rate output when the aspect ratio β was modified in smoke exit window. In the case of real buildings, it is interesting to note that many projects may have constructive limitations that can alter both aspect ratio and distance *h*. Although preliminary and in need of refinement in the model and boundary conditions used, this study helps the understanding of the tolerance criteria that can be adopted in the evaluation and approval of a building that uses a smoke-proof enclosed stair.

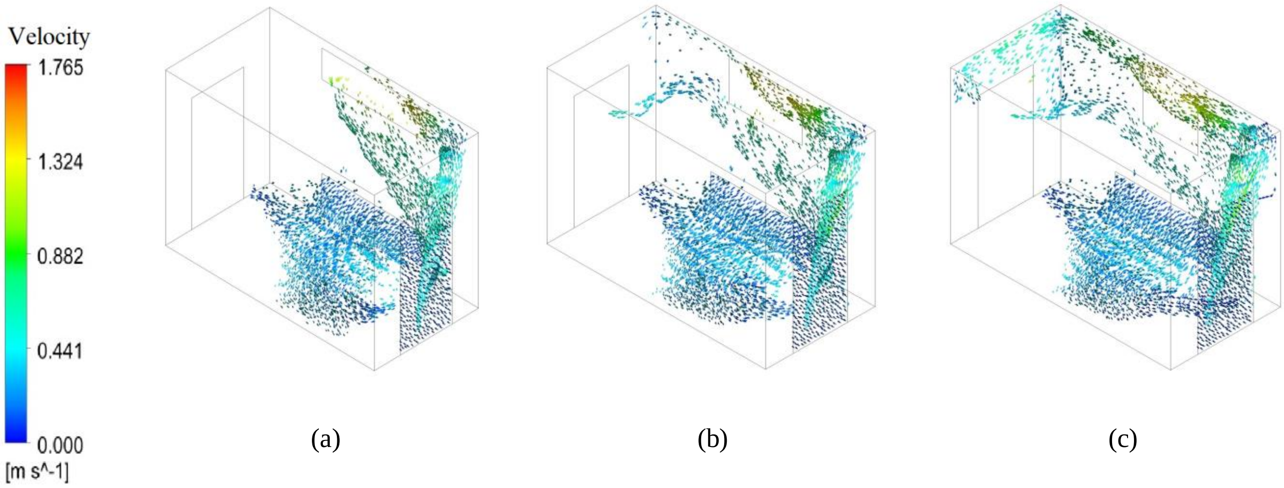


Figure 4 – Influence of aspect ratio on smoke dispersion on the chamber. (a) β = 1:4; (b) β = 1:1.77; (c) β = 1:1.

3.2. Second case: flow of air-smoke mixture

Moving closer the analysis of the actual situation, that the mixture inside the chamber is composed of air and smoke, the mass flow rates of smoke exhaustion were assessed in the stair access (opening 1) and in the smoke exit window (opening 2), in order to relate the variation of this flow as a function of the modification of the geometric parameters, distance h and aspect ratio β.

It is noted that, as in case 1, to respect the conservation of flow mass, a net inlet flow through opening 1 (access to stairs) was necessary. However, when looking at the velocity distribution in this opening, as shown in Fig. 5, it was verified that in the lower part of the access door, the fluid enters the chamber and in the upper part the fluid leaves it. Since the mass fraction of smoke increases with the height (stratification) when the smoke flow is evaluate in this opening, there is smoke output for the stair, which is not the desirable behaviour for the chamber.

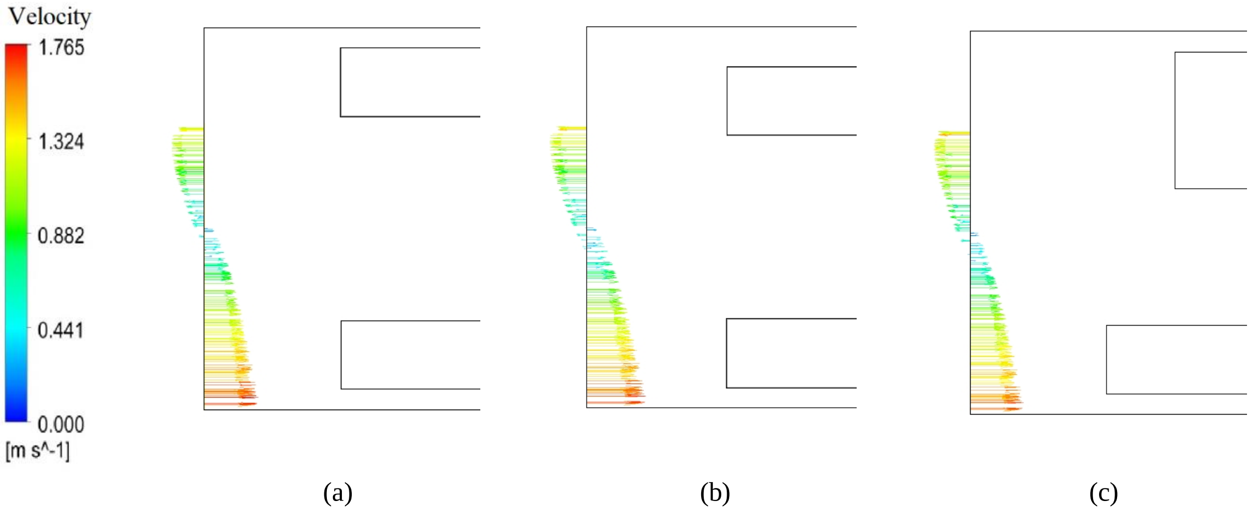


Figure 5 – Behaviour of the flow of the mixture in relation to the stair access door (opening 1).
(a) Reference (h = 15 cm and β = 1:4); (b) h = 30 cm and β = 1:4; (c) β = 1:1 and h = 15 cm.

Tab. 3 presents the results of the smoke mass flow rates at the openings for each simulated distance and their percentual variations in relation to the reference values.

Table 3. Smoke mass flow rates at openings and percentual variations in relation to the reference (h = 15 cm).

h (cm)	Opening 1 (stair access)			Opening 2 (outlet duct)		
	Mass exhaust smoke flow (kg/s)	Percentage of smoke exhaustion (%)	Percent variation in relation of reference (%)	Mass exhaust smoke flow (kg/s)	Percentage of smoke exhaustion (%)	Percent variation in relation of reference (%)
15 (ref.)	0.02027	9.29	-	0.1979	90.71	-
20	0.01850	8.41	-0.88	0.2014	91.59	0.88
25	0.01927	8.72	-0.57	0.2017	91.28	0.57
30	0.02368	10.73	1.44	0.1970	89.27	-1.44

As can be seen in Tab. 3, the percentage of smoke leaving the chamber for the distance h = 15 cm and β = 1: 4 stipulated by Technical Rule 10/2013 of the military fire department of the state of Espírito Santo (CBMES, 2013) was 9.29% for opening 1 (access to stair) and 90.71% for opening 2 (outlet duct). These percentage values were adopted as reference to evaluate the variation of the mass flow rate of smoke leaving the chamber in relation to the changes in the geometric parameters evaluated. For all cases referring to distance h, the percentage variation of mass leaving the chamber in relation to the reference is insignificant for both openings, since this variation is lower than the numerical percentage error of the study.

Regarding the evaluation and approval of chamber projects, the results indicate that the rules related to the distance h needs to be reviewed by the norm, since when the maximum allowed distance *h is doubled*, there were no relevant implications in the main objective of the chamber, which would avoid the emission of smoke for the stair (opening 1). From a practical point of view, in structures where there are constructive limitations, the change in distance h may be necessary, and alterations of up to 15 cm would not be impacting to the point of reproach the project, as evidenced in Tab. 3.

Tab. 4 presents the results of the smoke mass flowrates at the openings for each β and their percentage variations in relation to the reference case.

Table 4. Smoke mass flowrates at openings and percentage variations in relation to the reference (*β* = 1: 4).

β	Opening 1 (Access to stair)			Opening 2 (Smoke exit window)		
	Mass exhaust smoke flow (kg/s)	Percentage of smoke exhaustion (%)	Percent variation in relation of reference (%)	Mass exhaust smoke flow (kg/s)	Percentage of smoke exhaustion (%)	Percent variation in relation of reference (%)
1:4 (ref.)	0.02027	9.29	-	0.1979	90.71	-
1:1.77	0.02286	10.39	1.10	0.1972	89.61	-1.10
1:1	0.04487	20.37	11.08	0.1754	79.63	-11.08

The aspect ratio (β) analysis is analogous to the one carried out for the distance *h*. The percentages of smoke in the exhaust flow are 9.29% for opening 1 (access to stair) and 90.71% for opening 2 (smoke exit window). For *β* = 1:1.77, the percentage change in relation the reference is insignificant for the openings, because it is less than the numerical error stipulated as acceptable for this work. However, for *β* = 1:1 the effects are more relevant, since the percentage variation of smoke through the openings was 11.08%. Associated with this value, about 20.37% of the mass flow of smoke is exhausted to the stair, which may compromise the efficiency of the chamber and the route of escape in a real fire situation. This behaviour was already expected, since, when the aspect ratio increases, the stratification effects decreases, because the distance y increases while the distance x decreases (Fig. 3). This promotes a greater recirculation of the mixture inside the chamber, resulting in a longer residence time for the smoke, that when submitted the advective and diffusive transport mechanisms, will have greater scattering in the interior of the chamber and consequently will reach the exit to the stair (opening 1) with greater concentration.

With regard to the aspect ratio (*β*), the study indicates that the limitation imposed by the Technical Norm 10/2013 of the CBMES, is indeed relevant for the performance of the antechamber, since the mass flow of smoke exhaustion is more sensitive to the variation of this parameter, when compared to distance *h*. However, as criteria of approval of chambers projects, the norm lacks better investigation on different aspect ratios, since it was evidenced in this study that for *β* = 1:1.77, the effects are not significant. It is also worth mentioning that the results were obtained independently for each parameter because, during the simulations, the distance *h* was modified and the aspect ratio (*β*) was maintained according to the norm. For the simulations in which the aspect ratio (*β*) was changed, the distance *h* was fixed. To get results in which the parameter variations occur simultaneously, it is necessary to perform a larger set of simulations.

To better understand the results, it is essential to investigate the fluid dynamics behaviour inside the domain. Since the main objective of the chamber is to avoid smoke escape for the stair, Fig. 6 shows the distribution of the smoke mass flow through opening 1 comparing the most critical cases for distance *h* and aspect ratio (*β*) with the reference case.

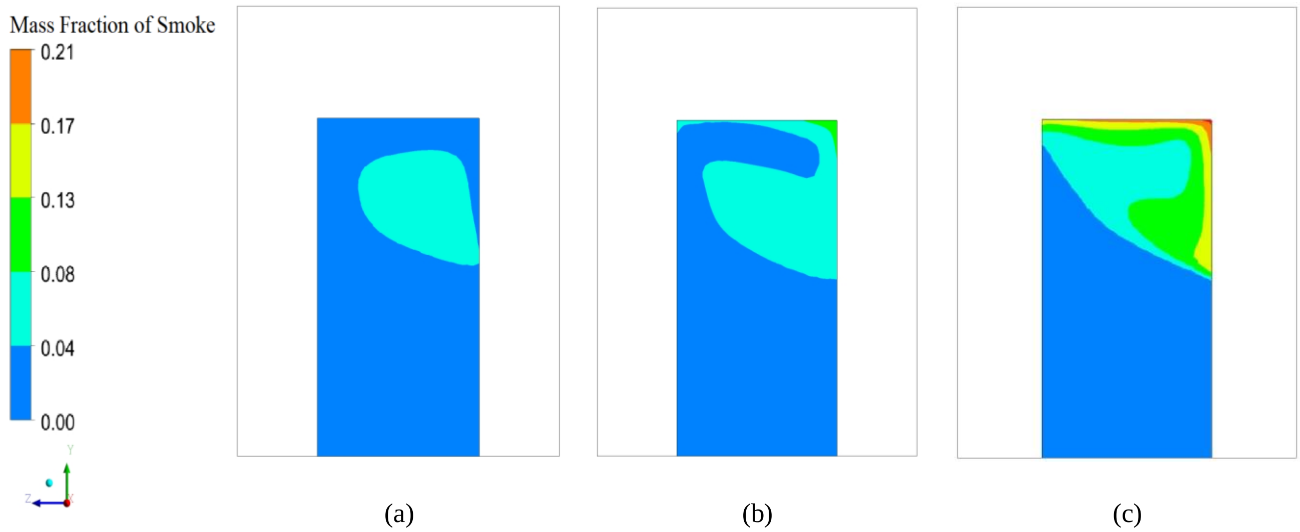


Figure 6 - Smoke concentration distribution in the stair access door (opening 1).
(a) Reference (*h* = 15 cm and *β* = 1:4); (b) *h* = 30 cm and *β* = 1:4; (c) *β* = 1:1 and *h* = 15 cm.

It was found that the maximum percentage of smoke exhaustion in the reference ranges from 4 to 8%, while for the largest distance h this value ranges from 8 to 13%. Already for the case of β = 1:1, the maximum fraction of smoke is between 17 and 21%. As expected already, the distribution of smoke in opening 1 for the three cases occurs asymmetrically, concentrating in the upper right corner. This happens by fact that the smoke exit window is located perpendicular to the right of the plane visualized in Fig. 5 and due to the effects of the stratification, the exhaust smoke accumulates in the upper region of the contour.

Since there is dispersion of one fluid in the other, which in this case would be smoke in air, the greater the circulation of the smoke inside the chamber, the larger its diffusion in the environment and the evasion of the mixture through the opening 1 will present higher concentrations of smoke. Due to the modification of the parameters (distance h and β), there was a decrease in the use of stratification effects, which favored the recirculation of the mixture in the chamber. This can be observed in Fig. 6, where the smoke concentration increased in the upper boundary of the door for the most critical cases, evidencing that when the recirculation occurs, the smoke occupy a larger region in the chamber.

Another crucial factor for the analysis is the residence time of the smoke in the chamber, since when there are recirculations inside the chamber, the residence time of the smoke increases and consequently favors the dispersion of that in the air. This effect is harmful to the aims of the chamber, since high percentages of smoke in the mixture can reach the stair. In contrast, for best chamber operation, it is desired that the flow streams be in short-circuit. In which a large part of the stream lines of the flow, when entering the chamber, are immediately directed towards the smoke exit window to be released to the external environment.

When analyzing Tab. 3 and 4, it was possible to perceive a greater influence in the cases for the aspect ratio, being observed a considerable percentage of smoke exhausted by the stair access door (opening 1). This can be observed in Fig. 5, where concentrations were in the range of 17 to 21% for the critical case of the aspect ratio. However, for the maximum distance h, the concentrations were in the range of 8 to 13%. This effect is directly related to the behaviour of the stratification in the domain, which is more sensitive to changes in the aspect ratio.

Even if the present study has achieved satisfactory results, it is necessary to better elucidate the contour conditions inherent to fire situations, such as air and smoke inlet flows, smoke inlet temperature and wall temperatures. In addition, the distribution of smoke and the inlet velocities also influences the flow path, since if a higher concentration of smoke occurs at the top of the door, it will facilitate the exhaustion of the mixture by short-circuit. On the other hand, when the smoke inlet is concentrated at the lower part of the door, it will provide a longer residence time of the mixture and its exhaustion will depend exclusively on the effects of stratification.

4. CONCLUSION

The present study demonstrated that the stratified flow inside the antechamber is affected by the changes in the geometric characteristics in the opening for smoke exit. Although, it is a preliminary investigation, the results for the simplest case demonstrated that the aspect ratio has greater influence on the decrease of the smoke exhaust than the increase in of the distance h. For the case where the air/smoke flow was implemented, the variation of the smoke flow to the openings was not dependent on the distance h, and again, the aspect ratio showed significant implications in the smoke exhaustion. Further studies will focus on the implementation of boundary conditions that may better represent the actual fire situation.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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7. RESPONSIBILITY NOTICE