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INFLUENCE OF ASPECT RATIO AND WALL TEMPERATURE ON SMOKE EXHAUSTION IN A PRE-CHAMBER OF A SMOKE-PROOF STAIRCASE.

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Abstract. *In fire events, the major death cause is the intoxication due to inhalation of the released gases. Since there are difficulties related to smoke control in fires, it is essential that the designed structures is able to promote exhaustion and prevent the spread of these harmful gases. This study uses the computational fluid dynamics (CFD) to model the stratified flow in pre-chambers of smoke proof staircases. The combustion in a compartment attached to the pre-chamber was modeled using the Flamelet model so that the smoke could be generated. This study analyzed the influence of the pre-chamber aspect ratio, for a constant volume, as well as the wall temperature on the exhaust of combustion gases, varying from 25 °C. The results obtained show that the variation of aspect ratio, between width and height of the pre-chamber, can affect the smoke exhaustion. In the pre-chambers with lower aspect ratio, a short-circuit path was noted, in which the smoke is directed to the outlet duct just after the entrance, promoting a 15% improvement in the exhaustion of smoke from the pre-chamber as compared to the reference configuration. For pre-chambers with higher aspect ratio, a higher absolute smoke exhaustion was also observed, however, a greater volume of smoke was retained in the environment and a higher smoke volume reaches the exit door, which impairs the air quality on escape routes. Regarding the variation of the wall temperature, the results show that, for a positive variation of 7 °C, there was less exhaustion of toxic gases by the outlet duct, about 1.5%, as there was a loss of stratification effects and, consequently, a greater diffusion of gases. For higher temperatures, with a positive variation of 17 °C, there was a behavior similar to the previous one, with a worsening of approximately 0.5% in smoke exhaust when compared to the reference, with the effects analyzed in this situation are similar to the previous case. The difference in smoke exhaust for the stairs is due to the loss of stratification effects with the temperature increase on the walls, as the atmospheric air inside the pre-chamber exchanges heat with the wall. Therefore, the results of the variation of the aspect ratio are more expressive than the variation of the temperature in the wall.*

Keywords: *Combustion, Computational fluid dynamics, Smoke exhaustion, Pre-chamber smoke flow.*

1. INTRODUCTION

There are in history examples of tragedies resulting from security problems. When it comes to fire safety, there are major recent cases occurred in Brazil, such as the "Fire at the Kiss Nightclub", which occurred in Rio Grande do Sul in 2013, or the case of the "Ninho do Urubu fire at Training Center", which occurred in Rio de Janeiro in 2019. In both cases, experts report that the main cause of death was poisoning by inhalation of gases resulting from combustion. Which is in agreement with Olson et al. (2014) when reporting that the burning of organic and inorganic materials generates a number of different toxins. When inhaled, these toxins can bring consequences such as thermal damage to the airways, impairment of the respiratory tract, asphyxia and toxic systemic effects that, depending on the intensity and duration of inhalation can lead to morbid cases. Therefore, the smoke control in fire events on closed environments is of great relevance concerning safety and prevention of fatalities related to this type of event. The set of factors that result in a fatal victim in the fire usually involves, in addition to the incapacitation that the smoke causes with suffocation, reduce the visibility of escape routes and generate a panic feeling that impairs rational actions that could prevent fatalities.

Application of computer analysis techniques has become essential to better understanding the behavior of smoke in the rooms. Thus, Xue et al. (2001), Jones (1983), Doung (1990), Dembsey et al. (1995) and several authors tried to perform studies and create models to reproduce the experiments and better understand the behavior of smoke through

computational fluid dynamics (CFD). Because a confined space fire is a complex phenomenon, as combustion, turbulence and heat transfer need sub models to describe the behavior of the mixture or fluids (XUE et al., 2001).

Regarding the safety measures that must be adopted in fire situations, there is the Technical Standard 10/2013 from the military fire department of the state of Espírito Santo, Brazil (CBMES, 2013). It deals with emergency exits in buildings, and due to the size of the building, it is necessary for it to have a particular type of emergency stairway, called enclosed smoke-proof stairway (EPF). Besides its particular dimensioning characteristics, according to the standard, this type of stairs must have access through pre-chambers that have the main purpose of retaining and promoting the exhaustion of the smoke generated by the fire.

Although Technical Standard 10/2013 specifies the required characteristics for both the pre-chamber and for the air inlet and smoke outlet openings, this problem still lacks studies that better elucidate the efficiency of this natural exhaust system, in terms of minimum acceptable smoke flow to ensure that the smoke does not accumulate in the pre-chamber and subsequently invade the stairwell. Parameters related to the geometry of the pre-chamber and the dynamics of the fire can influence this capacity.

2. METHODOLOGY

The numerical modeling that represents a fire situation depends on the identification of the variables with the greatest influence on the phenomenon, and for this, the modeling validation was used through comparison with experimental data, obtained by Steckler et al. (1982), during the execution of a controlled fire indoors. At that time, temperature and velocity data were collected on the centerline of the door opening. Fig. 1 shows the experimental arrangement, representing the confined environment dimensions, the gas outlet opening position, the burner position and the used sensors.
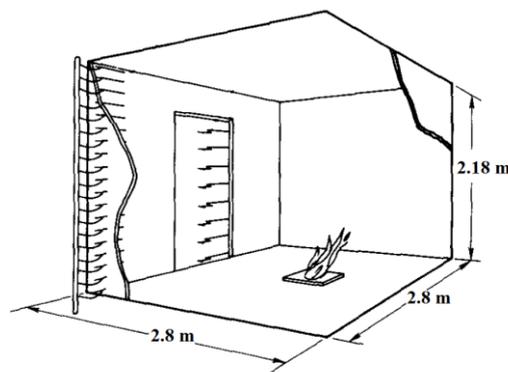

Figure 1 – Experimental setup. Steckler et al. (1982).

The numerical modeling of combustion starts from the definition of which model to use, and after a characteristics survey, the chosen combustion model was the Flamelet model. According to Palies (2020), Flamelet models considers a large number of chemical species by solving only two transport equations, in addition to providing information on smaller radicals such as CO and OH, also considering the turbulent fluctuations of the flow through density probability functions (PDF). A characteristic of Flamelet combustions is the dependence of a chemical reactions library as input data, as well as restrictions such as the need for constant pressure throughout the domain and that there is no premix of fuel and oxidizer in the system. As characteristic of the flow, Schmidt and Prandtl numbers equal to 0.7 were used. Radiation was modeled using the Direct Transfer Radiation Model (DTRM). The validation simulations resulted in a representation of the fire that will be then adapted and implemented in the pre-chamber.

The study used a numerical approach to the smoke flow in an Enclosed Smoke-proof Stairway (EPF) pre-chamber, defined by Technical Standard 10/2013 of the fire department in the state of Espírito Santo, and for this purpose, the Ansys CFX® 16.0 application was used. The standardized geometry was a parallelepiped, 4.0 m long by 2.0 m wide and a ceiling height (height) of 2.8 m. The entrance and exit doors of the pre-chamber have are 1.0 m wide and 2.1 m high, centered on their respective walls. One door was considered as smoke inlet (Inlet 1) and the other was considered as an opening (Opening 1: smoke or clean air inlet or outlet), both in an always open configuration to represent the worst possible scenario. The clean air inlet (Inlet 2: close to the floor) and the smoke outlet opening (Opening 2: close to the ceiling) were placed on one of the sidewalls, each with an area of 1 m² and dimensions of 0.5 m x 2.0 m. At the openings, atmospheric pressure was considered. Initially, the other surfaces were considered as adiabatic walls and with non-slip conditions. Fig. 2a indicates the geometry used in the simulations.

The gases inside the pre-chamber come from the combustion of methane (CH_4) that is exposed to atmospheric air, composed of 21% oxygen (O_2) and 79% by nitrogen (N_2), in a pre-chamber coupled to an external combustion room, symbolizing the corridors of a building, as Fig. 2b. At inlet 2, atmospheric air is introduced at a speed of 0.1 m/s with an ambient temperature, which was considered 298 K, and an oxidizer mixture option was enabled. For the determination of

thermal and fluid dynamic properties, the ideal mixture model was considered, the properties being calculated based on the weighting of the mass fraction of each component, the buoyancy model used 1.2 kg/m³ as reference density. In addition, the effects of natural convection that couple the equations of momentum and energy were considered when enabling, in the numerical model, the term of the buoyant force that results from the difference in specific mass between the fluids, this property being a function of temperature. For heat transfer, only the thermal energy transported due to the temperature difference between the fluids at the inlets was considered, disregarding the thermal energy generated by the viscous friction. The turbulence model used was the k-epsilon. The convergence criterion adopted was the root mean square value of the residuals (RMS) equal to 1×10^{-4}. The entire study used a compressible ideal gas approach to the flow and steady state simulations.
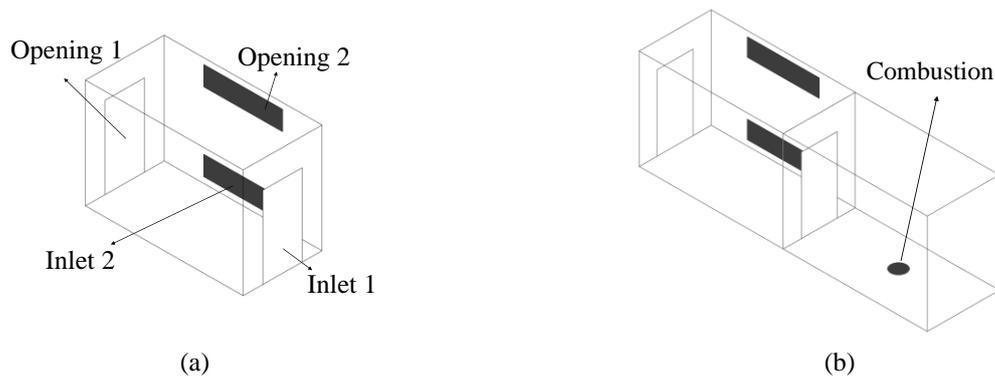

(a)

(b)

Figure 2 – Simulations tridimensional model. (a) Pre-chamber. (b) Pre-chamber coupled external combustion room.

The mesh test was performed to evaluate the independence of the results in relation to the number of nodes, as shown in Fig. 3, in which the opening velocities were measured as a function of the number of nodes. The results showed that for the mesh of 625215 nodes, for access to the stairs (opening 1), there was a percentage variation of 0.145% in relation to the more refined mesh, while for the smoke output (opening 2), a variation of 0.088% were presented. In relation to temperature, a continuous behavior is perceived, with negligible variations and already containing plausible results. Therefore, the adopted mesh, with 625215 nodes, guarantees the precision of the results at a plausible computational cost.
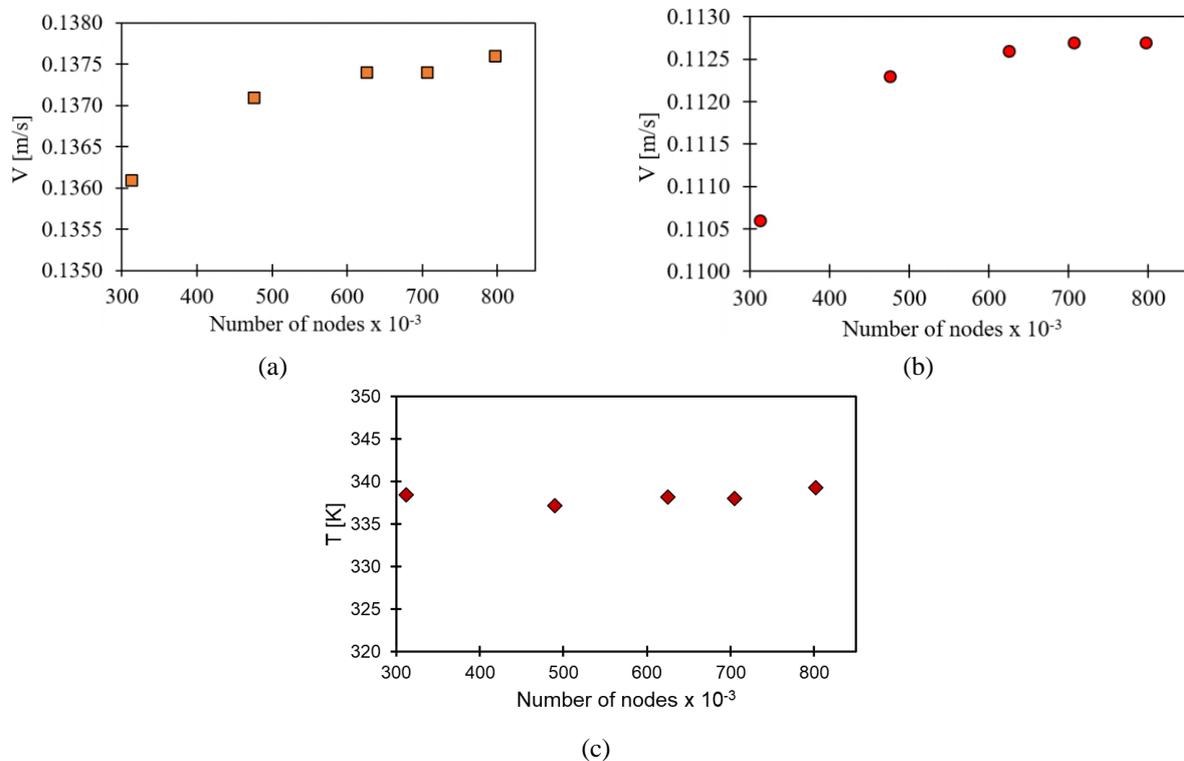

(a)

(b)

(c)

Figure 3 – Mesh test. (a) Mean velocity opening 1; (b) Mean velocity opening 2; (c) Ceiling temperature in the center of pre-chamber.

Motivated by the number of possible situations in a fire, the study simulations were separated into two cases. The standardized geometry of the pre-chamber was used to obtain reference values, so simulations were carried out that explored the influence of a positive variation of 7 and 17 K in the temperature of walls 1 and 2 (Fig. 4a) on the smoke exhaust. In addition to simulations that evaluated the influence of a positive variation in the aspect ratio of the pre-chamber on smoke exhaustion. The aspect ratio was defined as the ratio of length (y) to width (x) of the pre-chamber, Fig. 4b, and was applied so that a constant volume equal to the reference value was maintained. For this purpose, variations in width and length were defined, resulting in aspect ratio values equal to 1.53 and 1.12. It is noteworthy that the simulations of temperature variation and aspect ratio are independent of each other, because when varying one of the parameters, the other remained constant.
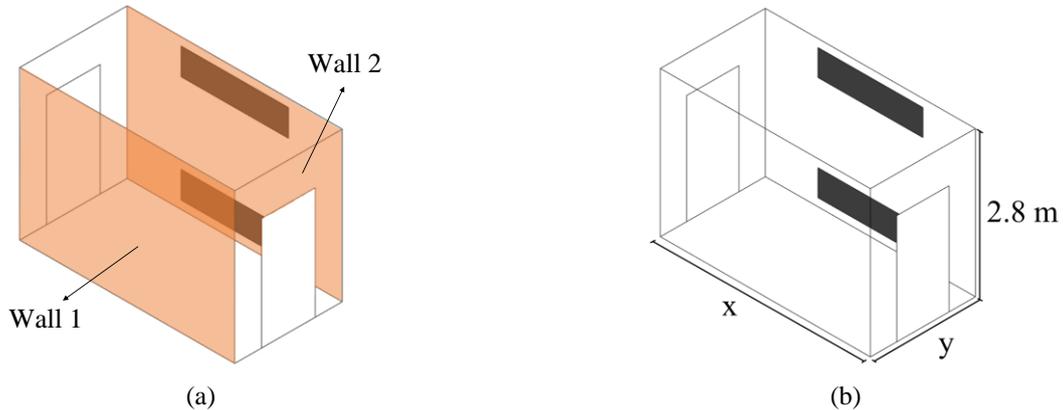

(a)   (b)

Figure 4 – Analysis parameters represented on 3D model geometry.
(a) Temperature affected walls; (b) Aspect ratio variables (y = width, x = length).

3. RESULTS AND DISCUSSION

The results obtained by the validation were displayed in the graphic form in Fig. 5. It also shows the experimental results of Steckler et al. (1982) and the results of the simulation performed by Xue et al. (2001). It is observed that there was a discrepancy between the experimental results and simulated results, but the data obtained are in agreement with solutions in the literature.

At Figure 5a, the height of the door between 0 m and 0.8 m, a simulated behavior similar to the experiment is perceived. Between 0.8 m, 1.2 m there was a greater discrepancy in the results. In the final portion of the door, above 1.2 m, a temperature is still not in agreement with the experiment. Already in Figure 5b, the simulation behavior is similar to the experiment, however, there is a discrepancy in the results obtained, in which the beginning of the door contains lower speed values and the end of the door contains higher values, when compared to the experiment. In relation to literature data, it is possible to see closer values. Such behavior can be explained through flame modeling, as turbulent combustion models may be unable to predict velocity and temperature, as they are the result of complicated interactions between the fire plume and the air intake. Another crucial factor for the simulation is the modeling of the chemical interaction, since the chemical kinetics of the experiment is not known.
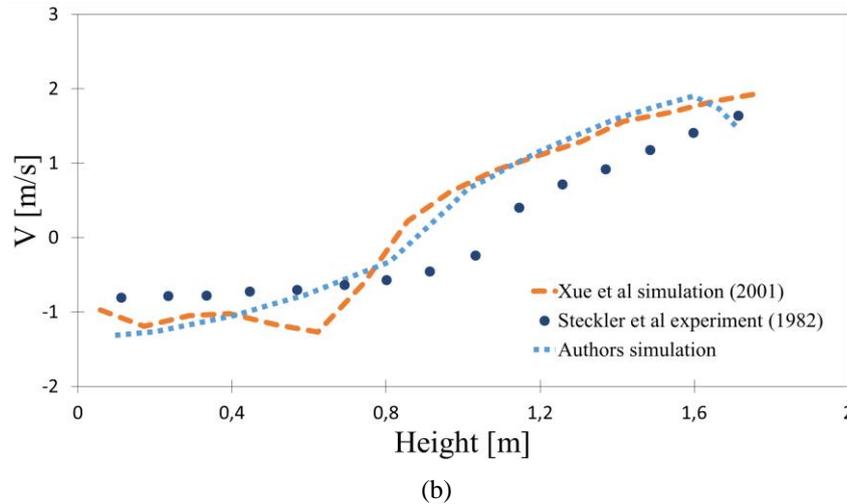

(a)

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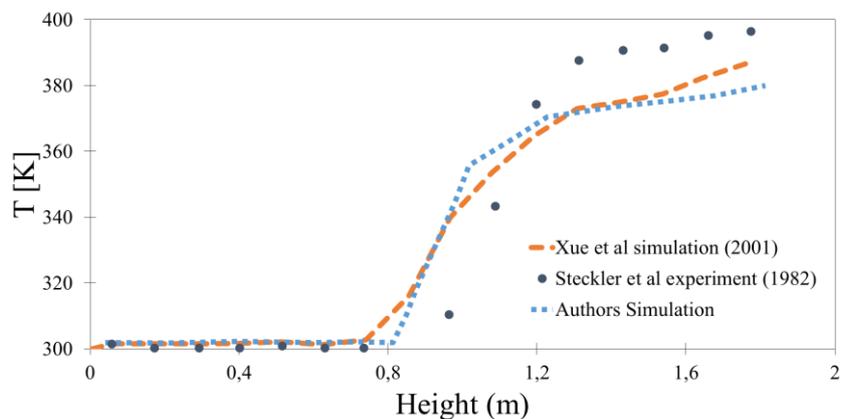
Figure 5 – Combustion modeling results. (a) Door's centerline temperature comparison. (b) Door's centerline velocity comparison.

For analyzing the results, the CO_2 flow was adopted as a parameter for checking the efficiency of the pre-chamber, since the other gases resulting from combustion are in negligible proportions in relation to the carbon dioxide. Thus, in Tab. 1, the results of CO_2 mass flow rates are presented in the openings for each of the simulated wall temperatures and their percentage changes in relation to the reference values.

Table 1. Openings mass flow and influence of wall temperature on pre-chamber CO_2 exhaust.

Temperature of the wall (K)	Opening 1 (Access to stairs)			Opening 2 (Output duct)		
	CO_2 mass exhaust flow x 10^{-3} (kg/s)	Percentage of CO_2 exhaustion (%)	Percent variation in relation of reference (%)	CO_2 mass exhaust flow x 10^{-3} (kg/s)	Percentage of CO_2 exhaustion (%)	Percent variation in relation of reference (%)
298 (ref.)	0.62	36.28	-	1.08	63.72	-
305	0.49	37.76	1.48	0.81	62.24	-1.48
315	0.62	36.73	0.45	1.06	63.27	-0.45

As can be seen in Tab. 1, the percentage of CO_2 in the mass flow exhaust for a temperature of 298 K (ref.) was 36.28% for opening 1 (access to stairs) and 63.72% for opening 2 (outlet duct). These values were adopted as a reference to evaluate the variation of smoke output flows in relation to the change in the thermal and geometric parameters. For the cases referring to the change in wall temperature, the variation in the percentage of the outflow mass in relation to the reference was equal to or less than 1.48%, with a small increase in quantity of toxic gases arriving at the stairs. Fig. 6 shows the concentration distribution results in the pre-chambers with different wall temperatures.
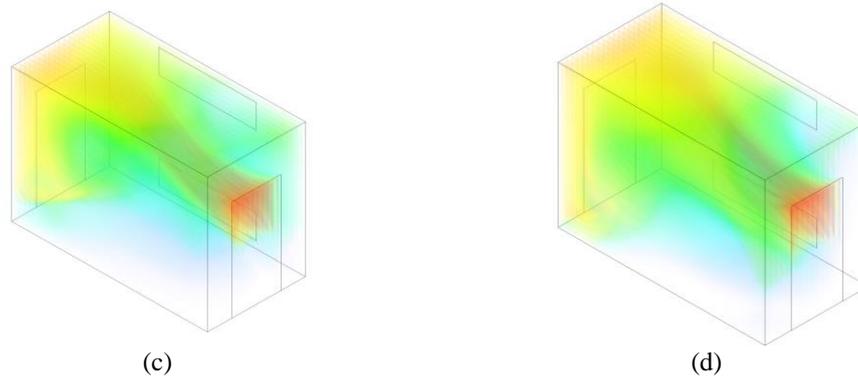

(a)   (b)

(c)   (d)
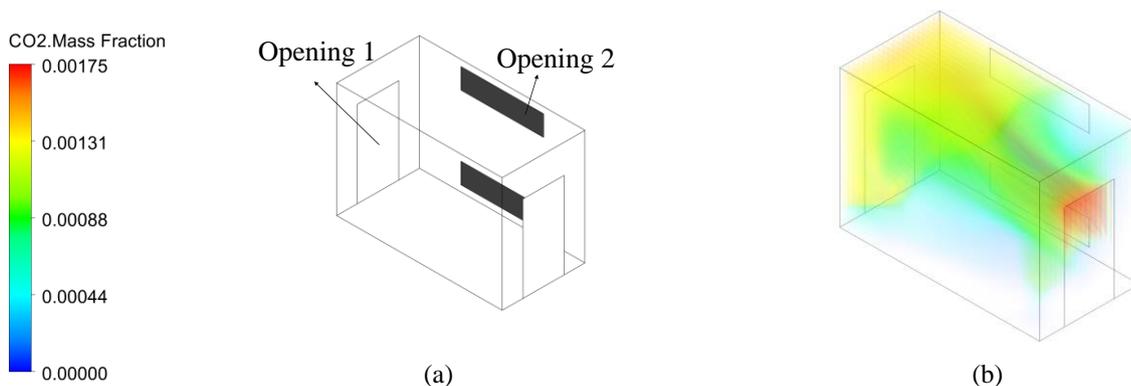
Figure 6 – CO_2 mass fraction for different wall temperatures.
(a) Analyzed openings; (b) T = 298 K; (c) T = 305 K; (d) T = 315 K.

The difference in smoke exhaust for the stairs is due to the loss of the stratification effects with the increase in the temperature of the walls, as the atmospheric air is at a temperature of 298 K inside the pre-chamber and exchanges heat with them. This phenomenon causes the temperature to increase inside the pre-chamber, facilitating the diffusion of smoke and obtaining higher concentrations of toxic gases near the door. It is possible to see in Fig. 6b and 6c, that the highest concentrations of toxic gases contain their favored passage through the central region of the enclosure, promoting higher concentrations of CO_2 in the region close to opening 1 (access to the stairs) and lower concentrations in opening 2 (gas outlet duct). Thus, the temperature variation of the walls is a parameter of possible fire situations, which in this case, despite the increase in the amount of smoke that arrives at the stairs, small variations occurs. Therefore, this parameter can be negligible when compared to another, like aspect ratio.

In Tab. 2 the results of CO_2 mass flow rates are presented in the openings for each of the simulated aspect ratios and their percentage variations in relation to the reference values.

Table 2. Openings mass flow and influence of aspect ratio on pre-chamber CO_2 exhaust.

Aspect Ratio (AR)	Opening 1 (Access to stairs)			Opening 2 (Output duct)		
	CO_2 mass exhaust flow x 10^{-3} (kg/s)	Percentage of CO_2 exhaustion (%)	Percent variation in relation of reference (%)	CO_2 mass exhaust flow x 10^{-3} (kg/s)	Percentage of CO_2 exhaustion (%)	Percent variation in relation of reference (%)
2.00 (ref.)	0.62	36.28	-	1.08	63.72	-
1.53	0.27	21.92	-14.36	0.95	78.08	14.36
1.12	0.26	20.33	-15.95	0.98	79.67	15.95

Tab. 2 presents the results in terms of CO_2 mass flow of leaving the pre-chamber in both Opening 1 and Opening 2. Note that the reference values, for the 2.00 aspect ratio, are equivalent to the values shown in Table 1, as it is the standardized pre-chamber, with dimensions of 4 m in length, 2 m in width and 2.8 m in height. The aspect ratio equal to 1.53 corresponds to a pre-chamber 3.5 m long and 2.29 m wide, and the results show an improvement of 14.36% in the amount of CO_2 that gets access to the escape route. For an aspect ratio equal to 1.12, being 3 m long and 2.67 m wide, this improvement reaches 15.95%. There is a variation of less than 2% when comparing the percentage of smoke that non standardized pre-chambers exhaust (AR = 1.53 and AR = 1.12), which indicates that there is a tendency to increase the exhaustion efficiency as the aspect ratio decreases. Future works can explore the variation between 2.00 and 1.53 aspect ratio, aiming to analyze this influence.
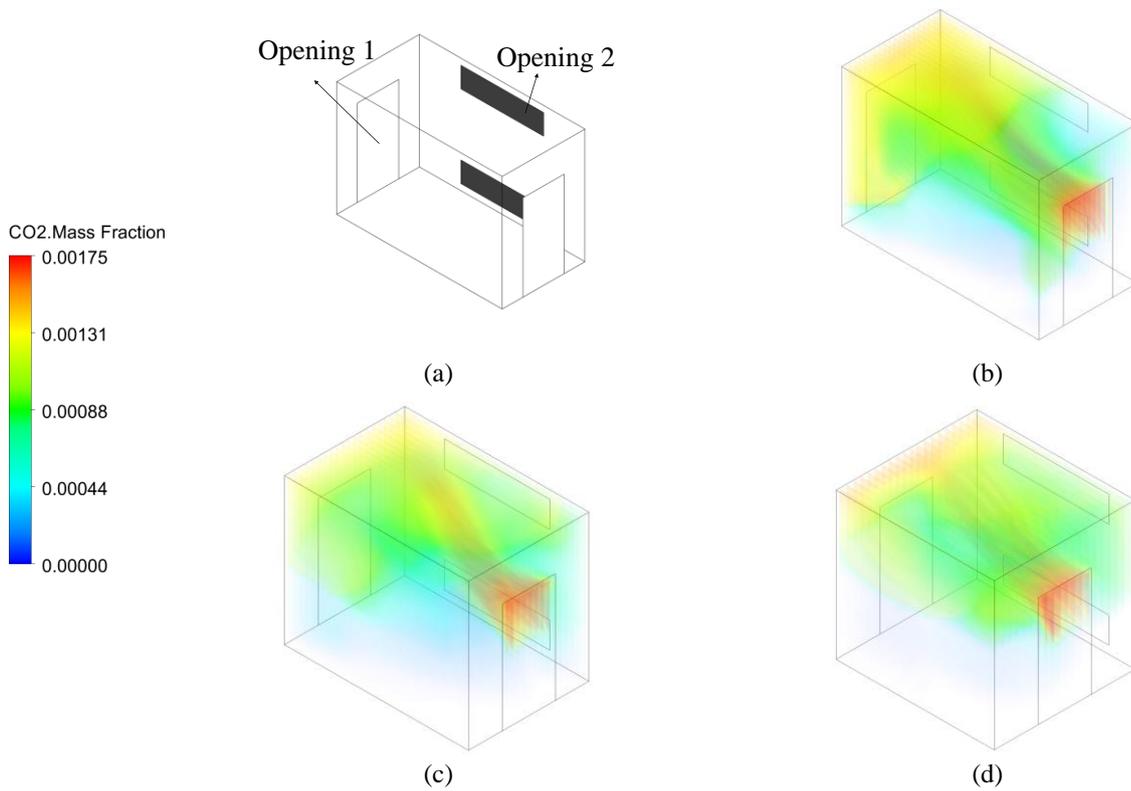
Figure 7 – CO_2 mass fraction distribution for different aspect ratio (AR) of the pre-chambers.
(a) Analyzed openings; (b) AR = 2.00; (c) AR = 1.53; (d) AR = 1.12.

Fig. 7 shows how the mass distribution of gases coming from combustion takes place when they enter the pre-chamber. It is noticed that the change in the aspect ratio brings a different path for the gases until they reach the exhaust duct, since the increase in the aspect ratio makes the doors closer, thus causing the smoke to have to travel a shorter path until reaches the exit to the stairs.

When comparing the data presented in Tab. 2 with the respective geometries in Fig. 7, it can be seen that a pre-chamber with a lower aspect ratio can exhaust, in terms of absolute values, approximately 1 kg/s of CO_2, as well as the pre-chamber with a larger aspect ratio. However, its great length allows longer recirculation for the gases, providing greater diffusion of smoke into the fresh air and thus causing a greater leakage of CO_2 to access the stairs, which is harmful in emergencies.

Both the pre-chamber with aspect ratio of 1.53 and 1.12, presented approximately 15% more exhaustion of gases from combustion. It is noteworthy that, in terms of absolute values, exhaustion through the smoke outlet duct has shown a little worsening. On other hand, the aspect ratio variation presented a severe change in smoke that gains access to emergency exit, with a 0.35 kg/s less smoke difference between aspect ratio of 2.00 and 1.53, which affect directly at the 15% ratio previously commented.
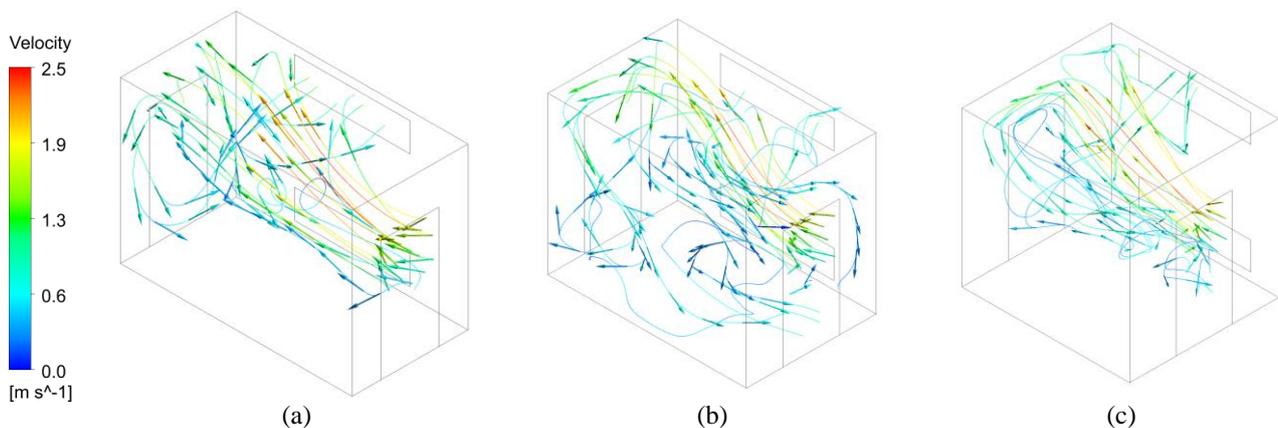

Figure 8 – Flow paths inside the pre-chamber for different aspect ratios.

(a) AR = 2; (b) AR = 1.53 (c) AR = 1.12.

In Fig. 8, the preferential flow path can be seen, which is towards the exit door, but there are interactions with the fresh air stream, coming from the inlet duct, which force a change in the flow direction of the smoke towards the exit duct. The pre-chamber with an aspect ratio equal to 0.65 showed greater recirculation in its interior, whereas the pre-chamber with an aspect ratio equal to 0.89 shows higher flow velocities, which lead the flow to collide with the upper part of the exit opening wall and return to the interior of the pre-chamber.

Although the present study has achieved satisfactory results, it is necessary to better elucidate the boundary conditions inherent to fire situations. Obtaining knowledge about the material that will be burned and the procedure that will take place in the flame is essential to understand the dynamics of fire. However, these situations in buildings contain many variables and possible burners of different types of composition, which can release other types of gases that are toxic to humans, such as hydrogen cyanide, carbon monoxide and hydrogen chloride. Thus, the composition of the burned gases becomes a difficult variable to find results closer to the real ones. The aspect ratio of the pre-chamber is a point to be explored in future work, as a trend towards improvement in the exhaustion efficiency for the studied geometries was presented, however different configurations may present optimization limits for an ideal smoke exhaustion. It is noteworthy that for the simulation, the doors (opening 1 and entry 1) were always open and, in a real case, they are fire resistant doors that only allow the entry of toxic gases when open, in addition to withstanding high temperatures for a period.

4. CONCLUSION

The present study shows that the stratified flow inside the pre-chamber is affected by changes in geometric characteristics and by thermal issues of the environment, regarding to exhaustion of toxic gases. With the present study, it was possible to conclude that the variations of geometric aspects influenced more abruptly the smoke exhaustion through the pre-chamber, since it observed significant improvements in the efficiency of the compartment. As for wall temperature variations, the results proved to be less expressive when compared to the aspect ratio, having little influence on the final objective of the pre-chamber, since this parameter is difficult to control. Further studies will be focused on implementing better boundary conditions that can more faithfully represent real fire situations, and changes in other geometric parameters, in order to find a more efficient compartment for exhausting smoke.

5. ACKNOWLEDGEMENTS

6. REFERENCES

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7. RESPONSIBILITY NOTICE