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Analysis of the Fluid Dynamic Behavior of a Smoke-Proof Enclosed Staircase Under Fire

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Abstract. Fire analysis through computational modeling enables the improvement of both current legislation and fire protection and fighting techniques. This paper presents an investigation of the fluid dynamics behavior of a Smokeproof Enclosed Staircase (FP) in a fire situation, using computational modeling with the commercial software Fire Dynamics Simulator (FDS), developed by the National Institute of Standards and Technology (NIST). The FP stairway was sized according to the specifications of standard NBR 9077:2001. Through simulations, it becomes possible to understand smoke behavior in fire situations, especially inside the stairway and the safety antechamber, in addition to enabling the development of mitigation measures applicable to existing buildings. The results obtained indicated that, although the FP stairway meets the dimensions required by NBR 9077, its performance can be improved. It was observed that smoke tends to concentrate in the safety antechamber, with effective drainage.

Keywords: Smoke-proof enclosed staircase, fire, computational modeling, visibility, temperature.

1. Introduction

Every building or structure is subject to fire situations during its use, which can be triggered by various factors acting simultaneously or independently. Due to the complexity of these events, experimental analysis of structures under fire conditions is often costly. Therefore, alternative analysis methods have been developed to simulate these situations more realistically.

In this context, the use of computer fire simulation stands out. Using specialized software, it is possible to obtain numerical responses regarding the behavior of structures subjected to temperature variations and smoke development in different environments.

This work aims to obtain the temperature profile and visibility level generated by commercial software, based on mathematical and fluid mechanics models. The purpose is to verify the correct applicability of an enclosed, smoke-proof staircase, constructed of reinforced concrete, located in the Vertentes Suítes Hotel building in Conselheiro Lafaiete, Minas Gerais. The building is intended for lodging services, and the staircase was designed according to the requirements of NBR 9077[3].

2. Methodolgy

This article is divided into two main stages: the three-dimensional modeling of the Vertentes Suítes Hotel building, located in Conselheiro Lafaiete, Minas Gerais, and the computer simulation to determine the level of visibility in fire situations.

Initially, the theoretical foundations necessary to support the work and understand the research topic were developed. Based on the literature consulted, testing and evaluation methods for damaged structures were applied. Based on this data, the building was modeled using information from available projects, including the "as-built" architectural design. This information allowed the virtual creation of the building using CAD software.

In the second stage, the building model was imported from AutoCAD into PyroSim, where a randomly estimated fire was simulated. The simulation was conducted using FDS (Fire Dynamics Simulator) software,

which allowed for the analysis of the temperature profile and smoke propagation. Some important criteria were adopted in the computational modeling:

a) Floors unaffected by the fire were considered single volumes, without detailing the interior spaces.

b) The building dimensions in the simulation correspond approximately to those of the original design.

c) The fire load used was defined according to Brazilian standards for the type of occupancy.

The analysis focused on fire behavior in an enclosed smokeproof stairwell, providing information on smoke propagation, areas of greatest visibility, and safest evacuation routes.

The following resources were used to perform the analysis:

- Notebook
- Fire Dynamics Simulator (FDS) software
- Smokeview software
- AutoCAD software
- PyroSim software

The simulated environment corresponds to the Vertentes Suítes Hotel building, designed to meet the requirements of NBR 9077[3] and Technical Instruction 08 of the Minas Gerais Military Fire Department, considering its occupancy as a lodging service. The building has 10 floors, the top floor being the water tower, all consisting of a reinforced concrete structure (pillars, beams, and slabs).

The fire simulation was based on information from the architectural design, with a reproduction of the typical floor—considered standard for the building. The architectural plans were used to create the fire representation and were later imported into PyroSim, which converts CAD files into a graphical interface compatible with FDS. This approach allowed the development of a complete three-dimensional model of the building.

Figure 1 shows the modeled building, ready for simulation.

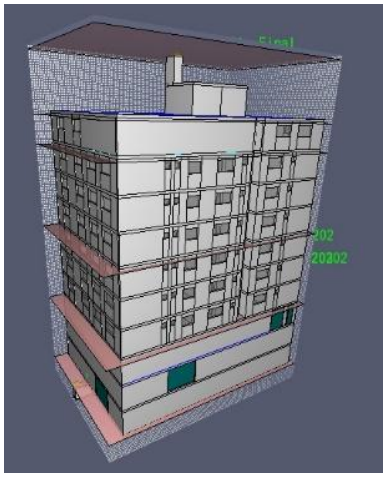


Figure 1: Simulation-ready environment
Source: (Authors, 2025)

At Vertentes Suítes Hotel, the main activity is the provision of lodging services, classified as B-1 – Hotels in General. According to NBR 14432 [2], the specific fire load is 500 MJ/m², representing the energy available and released during the combustion of the elements present in the building.

In the software used for the simulation, it is possible to add elements called "burners," which are responsible for starting the fire. One of these burners was positioned inside one of the rooms on the building's standard floor, as illustrated in Figure 2 below.

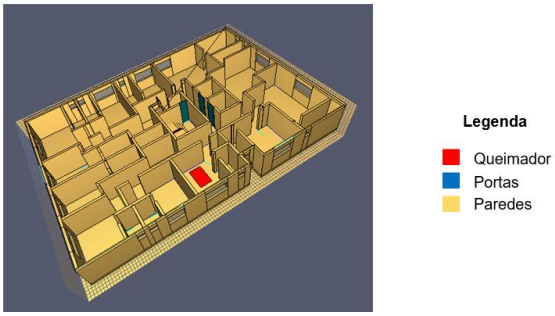


Figure 2: Burner location on the 6th Floor
Source: (Authors, 2025)

It is essential to exercise caution when setting the values assigned to the burner, as excessively high values can significantly influence fire development. In the case of this specific burner, a fire load corresponding to approximately 0.01% of the total load defined for the location where the fire began was applied.

According to Rodrigues [10], it is necessary to use the normative value of the specific fire load, as shown in Equation 01, to convert the units from MJ/m² to MW, assuming a total simulation time of 600 seconds.

$$Q = (Af \times q)/500 \qquad \text{EQ (01)}$$

Where:

Q = fire load, in MW;

Af = affected floor area, in m²;

q = fire load, in MJ/m².

Equation 01, mentioned above, allows you to convert the fire load values defined by the standards into the units used by the FDS software[8]. To ensure the thermal stability of the simulation, all building materials were considered inert, ensuring that the walls would not undergo significant changes due to heat fluctuations. This approach focused primarily on analyzing smoke dynamics and evaluating the ventilation effectiveness of the building's enclosed stairwell. Furthermore, it was determined that the elevator doors would remain closed during the fire, indicating that they would not be used as an escape route or ventilation.

In the software, calculation cells, known as meshes, define the simulation refinement parameters. They represent the number of cells applied to the model, determining the size of the finite volumes to be simulated. The maximum number of cells used depends on both the computer hardware configuration and the characteristics of the system under study.

Simulations aimed at evaluating the surface temperature of materials and fire dynamics do not require a large number of cells. For these simulations, factor values of 3, 4, and 5 are assigned to the cells.
A 25-centimeter cell size was adopted, applied to an area larger than that occupied by the building. This allowed observation of smoke development in the interior spaces and its dispersion to the exterior.

To simulate the oxygen supply to the fire, openings called "open vents" were created, allowing communication between the interior and exterior environments. The area of these openings is directly related to the volume calculated by the computer during the fire simulation.

Finally, to visualize visibility over time, a "slice" was created and positioned on the floor under study—the location where the main damage was observed.

Below are the main parameters configured for material characterization and the characteristics of the environment to be simulated in the software, already complying with the units of measurement used by the Pyrosim system:

Material Characteristics: Concrete.
- Density: 452 kg/m³
- Specific Heat: 1,758 kJ/(kg.K)
- Conductivity: 13,956 W/(m.K)
- Emissivity: 0,9

Simulated Environment Characteristics:
- Ambient Temperature: 20 °C
- Ambient Pressure: $1{,}01325 \times 10^5$ Pa
- Relative Humidity: 40,0%
- Absorption Coefficient: $5{,}0 \times 10^4$ 1/m

A simulation was performed with a maximum time of 600 seconds. The various interactions performed by the application until the end of the entire simulation totaled approximately 120 hours, performed on a computer with two processing cores and 2.0 Gigahertz.

3. Results and Discussions

To better represent the simulation results, the results will be presented in two parts. The first part will present the results for the building as a whole, demonstrating its overall impact, and the second part will present the specific results for the floor where the fire started.

After the simulation, it was possible to obtain global value profiles for the entire building, as shown in Figure 3. The temperature variations are shown on the right and the visibility variations for the structure as a whole are shown on the left after 5 minutes of simulation.

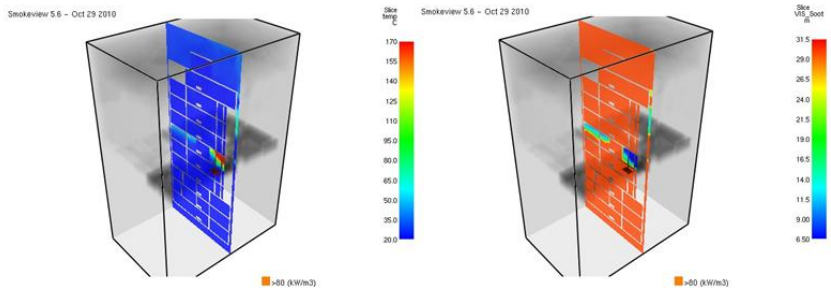


Figure 3: Global result of analysis performed by FDS after 5 minutes of simulation.
Source: (Authors, 2025)

It can be observed that after 5 minutes of fire, the temperature varied little on the floor where the fire started, with only a high temperature initially. Regarding the visibility profile, it can be seen that it is already spreading to other areas of the building, but the smoke is still settling on the floor, already reaching the antechamber area leading to the stairwell, but still with good visibility for possible movement within the floor. It is worth noting that, as observed in Figure 3, after the initial 5 minutes of fire, only the floor where the fire started experienced visible variations in the demonstrated temperature and visibility profiles.

Figure 4 presents the temperature and visibility results of the Global analysis after 10 minutes of simulation.

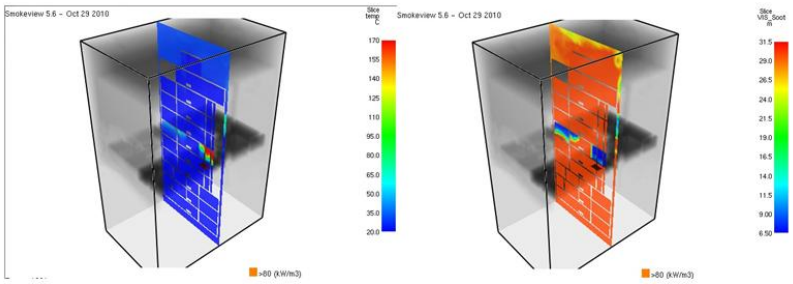


Figure 4: Global result of analysis performed by FDS after 10 minutes of simulation.
Source: (Authors, 2025)

Figure 4 shows that after 10 minutes of fire, the temperature on the floor varied little compared to the initial 5 minutes. Regarding the visibility profile, it can be observed that the smoke had practically settled across the entire floor, resulting in low visibility for evacuation situations across the floor as a whole. Comparing the 5-minute and 10-minute simulations, it can be seen that only the floor where the fire started experienced visible variations in temperature and visibility. To better interpret the results shown in Figures 3 and 4, thermocouples were placed in the antechamber accessing the 6th Floor stairwell to obtain accurate values for temperature variation only.

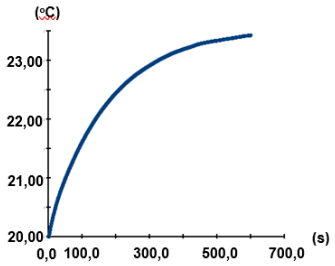


Figure 5: Temperature Variation on the 6th Floor.
Source: (Authors, 2025)

In Figure 5 above, it can be seen that there was already a temperature variation in the safety antechamber located on the 6th floor, already exceeding 3°C. However, this is still a very low value, demonstrating once again that the fire that started in a room on this floor had little effect on the antechamber accessing the stairwell.

Considering the temperature variation represented in Figure 5 above, it was pertinent to evaluate the specific results for the 6th floor, the focus of the fire. Figure 6 shows the results of the analysis performed on the 6th floor after one minute of simulation. For the following figure, consider the temperature variation on the left and the visibility variation on the right.

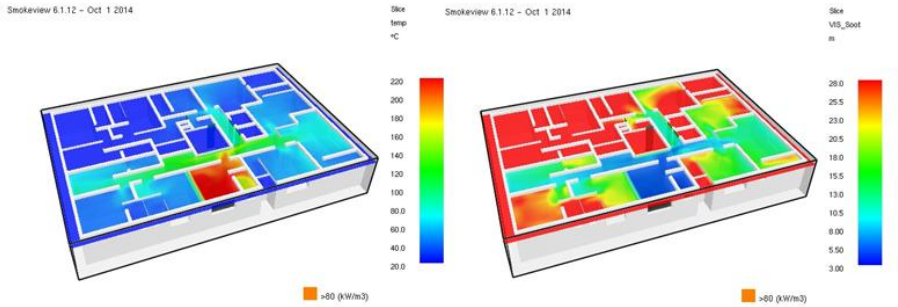


Figure 6: Result of analysis performed by FDS after 1 minute of simulation.
Source: (Authors, 2025)

During the first minute, it can be seen that practically the entire area where the fire started is already above 200°C, and the temperature is already rising in the floor's circulation corridor. It is worth noting that for simulation purposes, the doors of all rooms were assumed to be open. Regarding the visibility profile, it can be seen that in this first minute, the compartment where the fire started is already completely filled with smoke, thus having a visibility level well below that permitted by the standard, and the smoke is already beginning to settle in the other areas of the floor.

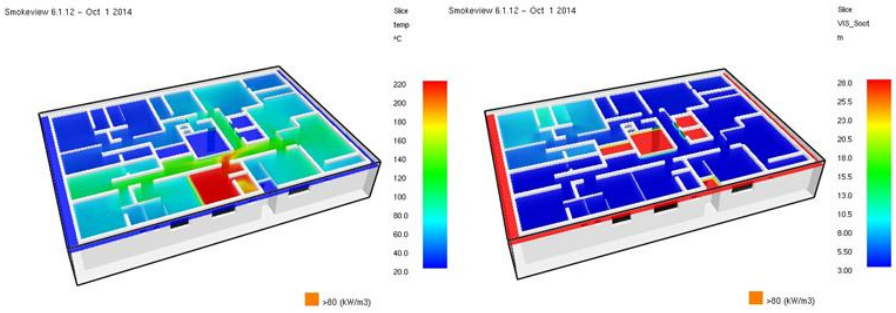


Figure 7: Result of analysis performed by FDS after 10 minutes of simulation
Source: (Authors, 2025)

In Figure 7 above, after 10 minutes, the temperature variation profile again shows little variation compared to the previous results, demonstrating the stabilization of the temperature variation. Regarding the visibility profile, it can be seen that the entire pavement now has a low visibility rate.

To further interpret the results, three thermocouples were placed on the floor where the fire started to record temperature and visibility variations across the floor. These thermocouples were installed at three different points on the floor: one in the antechamber leading to the stairwell, another in the hallway, and another in the bedroom where the fire started.

Figure 8 summarizes the thermocouple results.

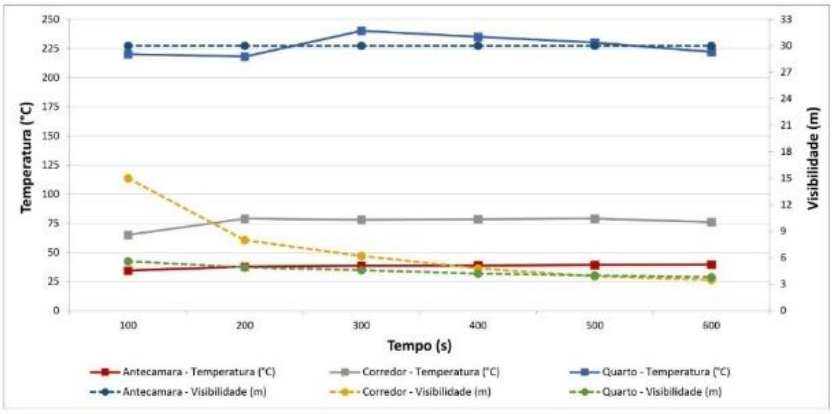


Figure 8: Temperature and Visibility Variation over Time on the Pavement Where the Fire Started.
Source: (Authors, 2025)

It can be seen that the antechamber leading to the stairwell exhibited temperature fluctuations, but maintained good visibility throughout the simulation. This is due to the presence of air inlet and outlet ducts, which ensure adequate ventilation. This stability demonstrates the stairwell's effectiveness in fire situations.

Figure 8 shows that both temperature and visibility remained virtually constant throughout the 10-minute simulation, with only a slight increase in temperature. This stable visibility reinforces the importance of ventilation ducts in maintaining safe conditions in the antechamber.

In the corridor, there was significant temperature fluctuation in the first few minutes, stabilizing after about 5 minutes. This demonstrates the concrete's excellent performance in fire situations. Visibility, however, progressively decreased, indicating smoke accumulation and making evacuation difficult.

In the room where the fire started, the situation was most critical: the temperature remained high from the start, with little fluctuation, and visibility was low and decreasing, reaching practically zero. Finally, the stairwell access antechamber showed low temperature and constant visibility, compared to the ambient temperature defined in the simulation. These results reinforce the need for protected stairwells with ventilated antechambers in large buildings, especially in fire and panic situations.

4. Conclusions

After obtaining the simulation results, it was concluded that the use of software to visualize the dynamics of fires in structures is of great importance, as it provides us with clues about how the structure behaves in a fire situation.

The simulation using the FDS was effective, allowing us to visualize the fire's behavior and the effectiveness of the use of the Smoke-Proof Enclosed Staircase (FP) in a fire situation.

The Smoke-Proof Enclosed Staircase (FP) helps evacuate smoke from the environment, thus facilitating the escape of the building's occupants, as well as facilitating access for the Fire Department to begin fighting the fire.

The results of the overall analysis using the FDS showed that temperature and visibility variations were notable on the floor where the fire started, being less evident on the other floors.

The results confirm that after just one minute of simulation, the temperature and visibility profiles are significantly altered in the compartment where the fire started. Temperature and visibility variations were also observed in the corridor.

During the 10-minute simulation, changes in visibility profile were observed throughout the simulated floor. Between 100 seconds and 600 seconds of simulation, it was possible to observe little variation in the temperature profile in the corridors, antechamber, and bedroom, but significant variation in visibility in the corridor.

Within the antechamber leading to the stairwell, visibility remained constant due to the presence of air inlet and outlet ducts within it, demonstrating the importance and efficiency of using this type of staircase in buildings.

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Authorship statement. The authors confirm that they are solely responsible for the authorship of this work, and that all material that has been included here as part of this work is the property (and authorship) of the authors, or has the permission of the owners to be included.

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