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Numerical Fire Simulation: Key Tools in Fire Safety for Modern Engineering

Simulare numerică a incendiului: instrumente cheie în securitatea la incendiu pentru ingineria modernă

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Abstract. Fire simulation is a crucial tool in modern engineering for improving fire safety in constructions, especially in complex compartmental designs. It provides practical insights into structural fire behavior, the impact of combustible materials, and fire development, aiding in the formulation of effective fire safety measures. PyroSim, a graphical interface based on the Fire Dynamics Simulator (FDS), simplifies the creation and management of complex fire models. It supports file imports from AutoCAD DXF and DWG formats, offers background options from GIF, JPG, or PNG drawings, and includes tools for creating and validating multiple meshes. These simulations are essential for obtaining comprehensive data on various fire-related properties, such as temperatures, gas concentrations, smoke volume, pressures, and more, to ensure alignment with real-world conditions.

Key words: Fire simulation, Modern engineering, 3D modeling, PyroSim, Combustible materials.

1. Introduction

Fire simulation stands is indispensable within modern engineering, playing a very important role in ensuring the safety of buildings in the face of potential fire hazards [1]. In a multitude of contexts, especially when dealing with structural designs, fire simulation is a pragmatic tool necessary to gain insights into fire dynamics. It facilitates the comprehension of how flames interact with various structural components, the influence of combustible materials within confined spaces, and the progression of a fire event [2].

Linked with this indispensable field lies PyroSim, a globally used tool for making well-informed decisions regarding fire safety in building design [3]. Developed as a graphical interface built upon the Fire Dynamics Simulator (FDS) framework, PyroSim stands as a must in managing intricate fire models [4]. AutoCAD

DXF and DWG files can be imported, where 3D objects are meticulously recognized as obstacles.

Furthermore, PyroSim empowers users with the ability to import images in GIF, JPG, or PNG formats, which is important giving the possibility for very fast model tracing directly over these imported images [5]. Beyond these capabilities, PyroSim integrates tools designed to facilitate the creation and validation of multiple meshes, offering multiple advantages: parallel processing to enhance model resolution, fine-tuning of mesh geometries to reduce cell counts and resolution time, and the ability to adjust resolution levels across distinct areas of interest [6].

The path to a successful fire simulation, however, lies in the fidelity of the obtained results [7]. To this end, fire simulation programs provide comprehensive statistical insights into the behavior of various combustible materials and substances in fire scenarios [8,9]. This tool is used with dexterity by fire safety specialists, endowing them with mathematically data encompassing a variety of fire-related parameters, including temperatures (both air and surfaces), concentrations (of oxygen, combustion gases, and smoke), visibility (intricately tied to smoke levels), pressures within distinct spaces, and the interplay of temperature and pressure fields [10,11].

2. Building Design

To transform the building plans into a three-dimensional model, the SketchUp program was employed. Consequently, a three-dimensional model was successively created for each level of the building (basement, ground floor, 1st floor, 2nd floor, 3rd floor, 4th floor).

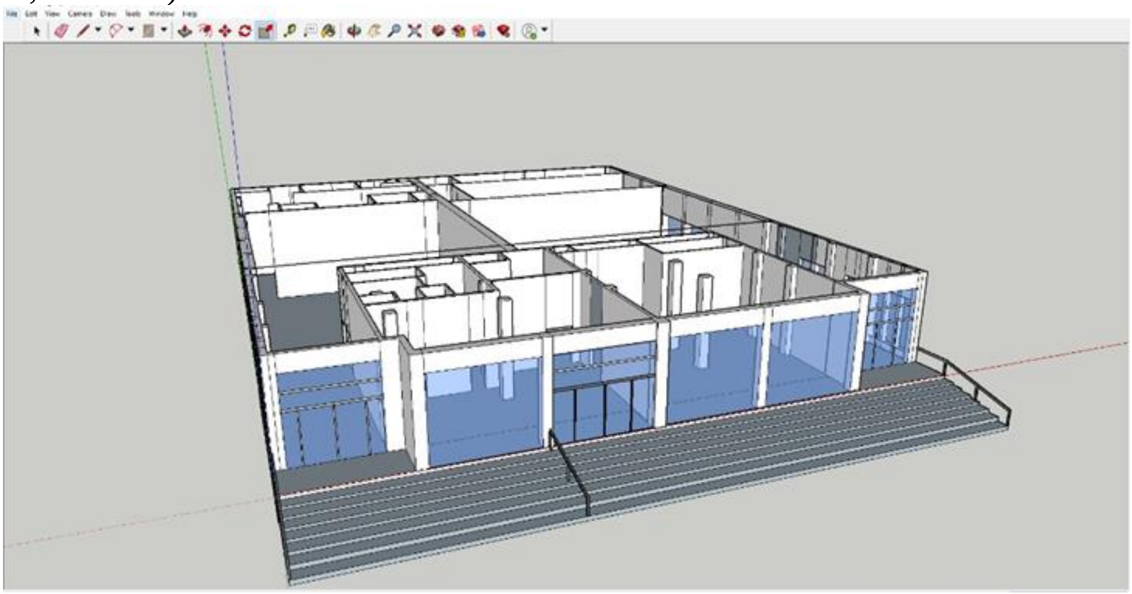

Figure 1 - 3D Ground Floor

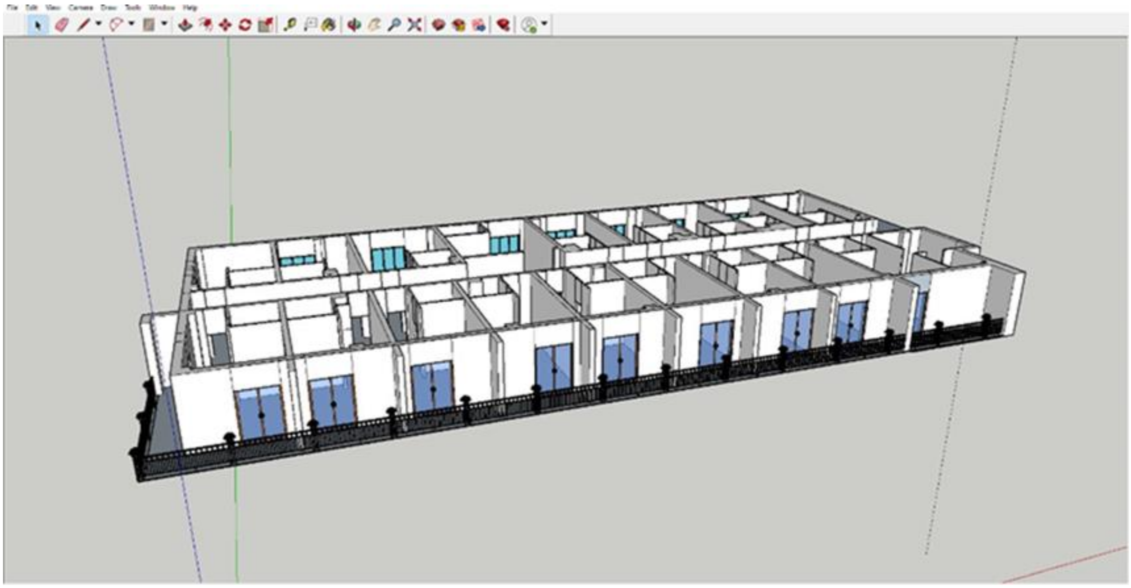

Figure 2 - 3D Current Floor

Figure 3 - 3D Hotel

In the end, by superimposing these models, the overall shape of the entire building was obtained, which was then introduced into the PyroSim program to perform the fire simulation. Introducing the building's shape into PyroSim enabled the creation of a detailed virtual environment for simulating fire behavior inside it.

3. Fire Simulation in a Room on the Hotel's Top Floor

The fire simulation was conducted on the upper floor of the hotel, situated on a concrete floor, with the hotel's structure composed of 25 cm thick BCA masonry exterior walls and 10 cm thick BCA masonry interior walls.

Space dimensions:
Length – 39.55 m
Width – 16.80 m
Height – 3.00 m
Usable area – 664.44 m^2
Volume – 1993.32 m^3

The top floor of the hotel comprises 18 accommodation rooms and a main hallway. Each accommodation room on this floor exhibits the following characteristics, as per Table 1:

Table 1

Accommodation Room Characteristics

Space	Usable Area (sqm)	Combustible Material	Mi(kg)	Qi(Mj/kg)	Sq(Mj)	Qi(Mj/sqm)
Accommodation Room	19.38	Wood	200.00	18.40	3680.00	349.03
	Textiles	50.00	16.75	837.50		
	PVC	80.00	21.80	1744.00		
	Other materials	30.00	16.75	502.50		

3.1. Fire Initiation

The ignition source originates at the bed level, 0.4 m above the floor, with minimal smoke production initially. This situation can be explained by the limited amount of combustible material consumed, and the flame initially dominates due to the presence of a substantial amount of oxygen in the room. The source of fire initiation is attributed to open flame work execution without adhering to fire prevention and extinguishing rules and measures.

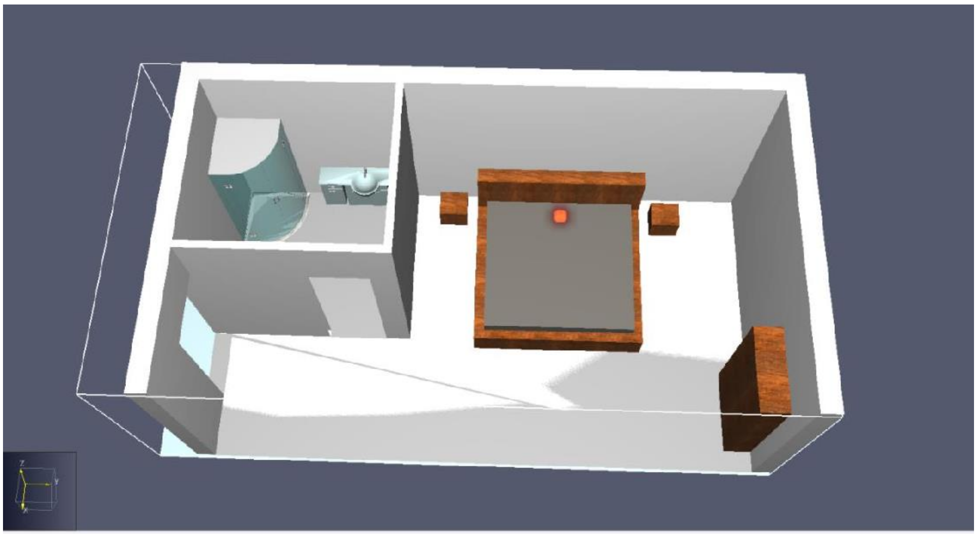

Figure 4 - Fire Initiation

3.2. Fire Development

The flames predominantly spread horizontally rather than vertically because there are no combustible materials above the initial flames to sustain upward combustion. This slowing of fire propagation upwards occurs as there is no available fuel at the upper part of the room. As the fire develops, the smoke becomes denser than in the initial stage. Smoke naturally accumulates at the room's upper part, rising due to heat and density differences. The hot gases and smoke accumulating beneath the ceiling form a hot layer at the room's upper part. This hot layer gradually thickens as the fire progresses. It thermally affects and influences the materials at its level through radiant and convective heat transfer. The elevated temperatures in the hot layer can lead to material deterioration and increase the fire's spread risk.

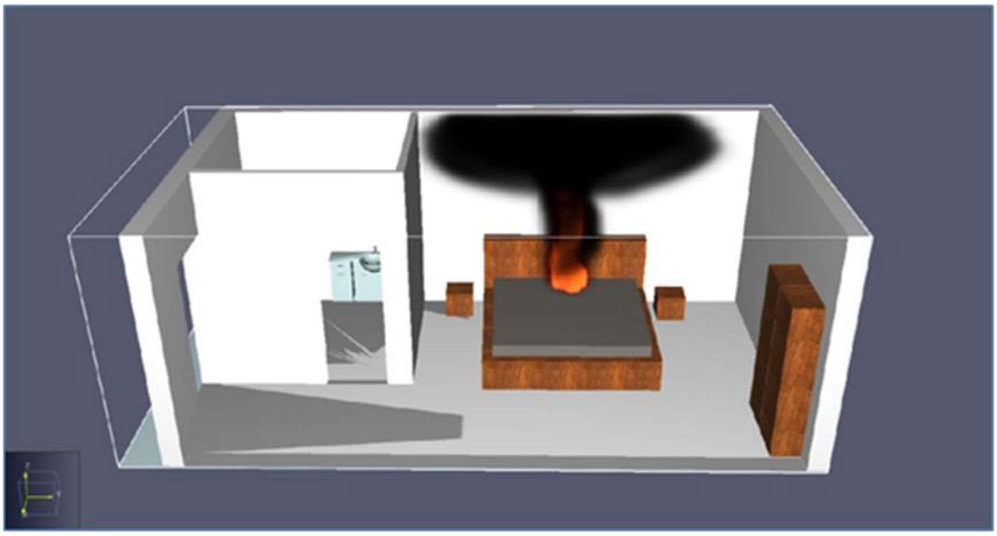

Figure 5 – Fire Development

3.3. Smoke Generation

Materials such as plastics, textiles, and wood used in furniture manufacturing can release a substantial amount of dense smoke in the event of a fire. As the fire progresses, the smoke can spread throughout the room, a phenomenon called "flooding" (see Figure 6). Smoke and toxic gases generated during material combustion tend to rise towards the upper part of the room. As the fire continues to burn, the smoke becomes extremely dense, and if not vented out of the room, it can occupy a significant portion of the room's volume. Smoke release from the burning area significantly reduces visibility inside the space. This diminished visibility impacts the safe evacuation of people inside and delays emergency service intervention actions. Firefighters responding to such fires aim to establish access routes to the fire and extinguish it from the interior. However, smoke becomes an obstacle to achieving this objective. In such a situation, when there is an external oxygen supply, the danger of a phenomenon called "backdraft" arises.

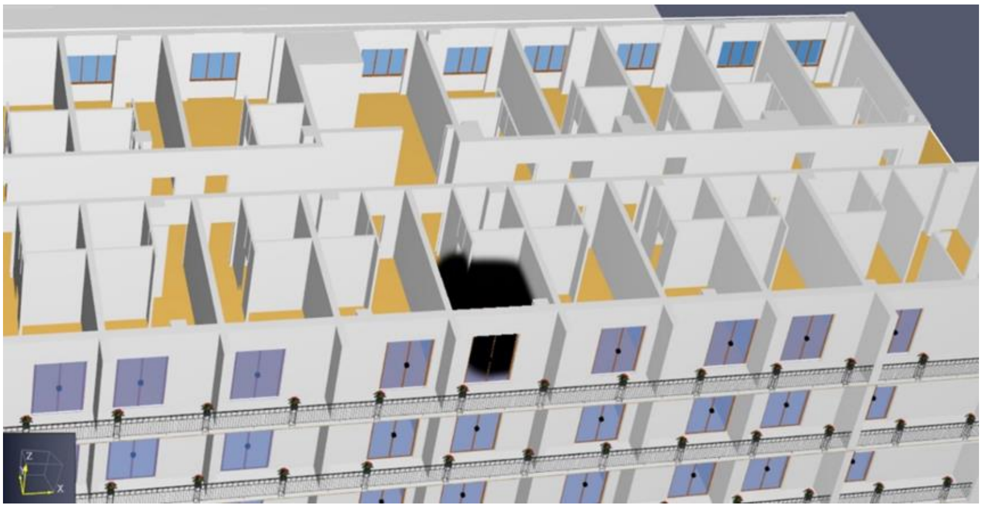

Figure 6 - Initial Smoke Release

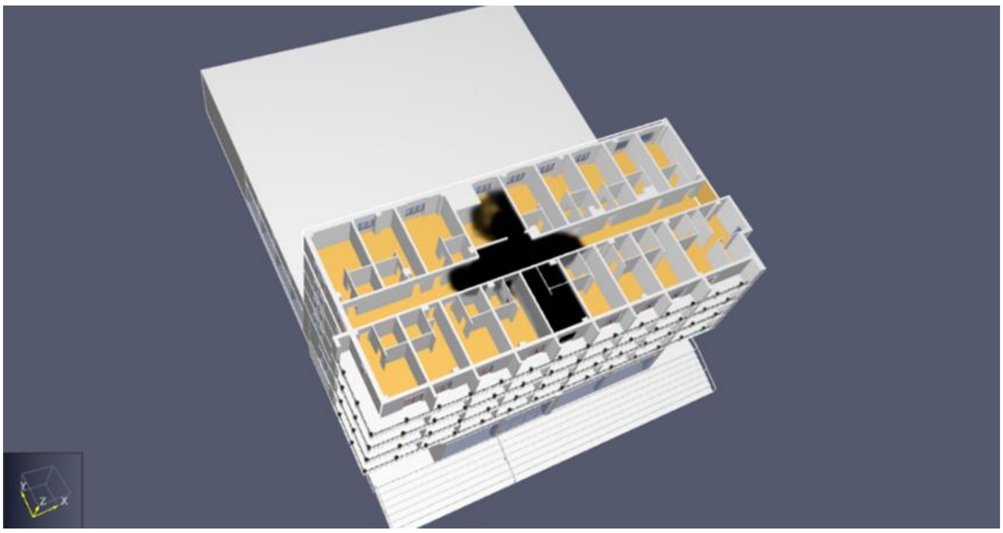

Figure 7 - Smoke Release in the Hallway and Adjacent Rooms

By running the simulation, it becomes apparent that after 50 seconds, smoke spreads and covers the entire floor area (see Figure 8). Observing the simulation, one can see how smoke gradually rises and spreads throughout the room before uniformly spreading over all areas of the floor.

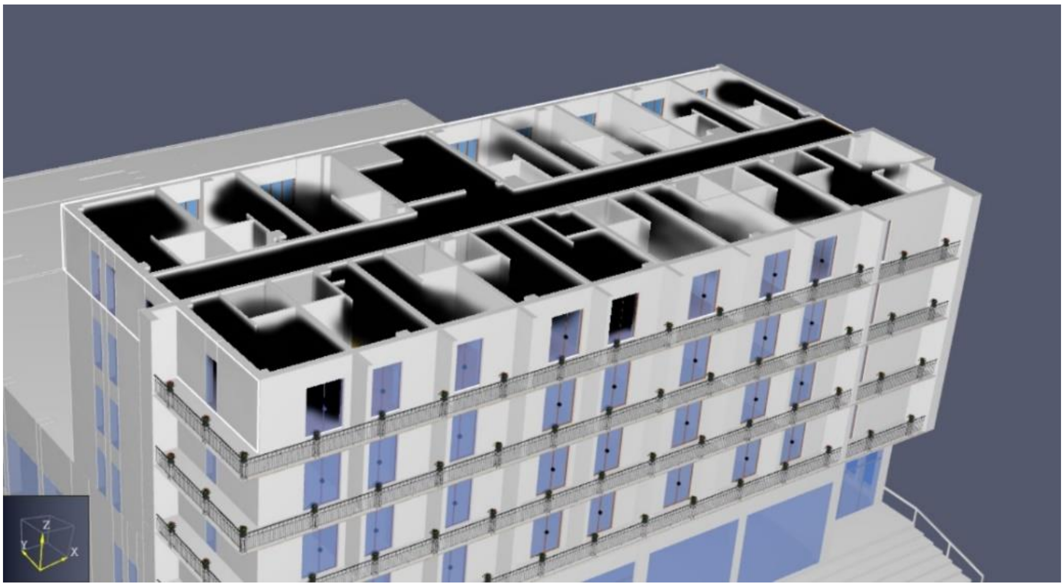

Figure 8 - Smoke Release Across the Entire Floor

3.4. Temperature Distribution

To monitor temperature distribution during a fire, both 3D section visualization and 2D section visualization were employed. These methods allow for observing and understanding how temperature propagates within the room, evolves over time, and is influenced by specific fire factors.

3.4.1. 3D Section Visualization

In the 3D section visualization, temperature is represented on a three-dimensional model of the room. This provides a three-dimensional perspective of how heat and elevated temperatures spread in space. High-temperature zones can be identified, and the way they move and expand during the fire's progress can be tracked. The three-dimensional visualization offers a more complete and detailed picture of temperature distribution inside the fire.

During the fire, temperatures recorded inside the space are very high. In the focal area, measurements show that temperatures can reach up to 720 °C (as per Figure 9).

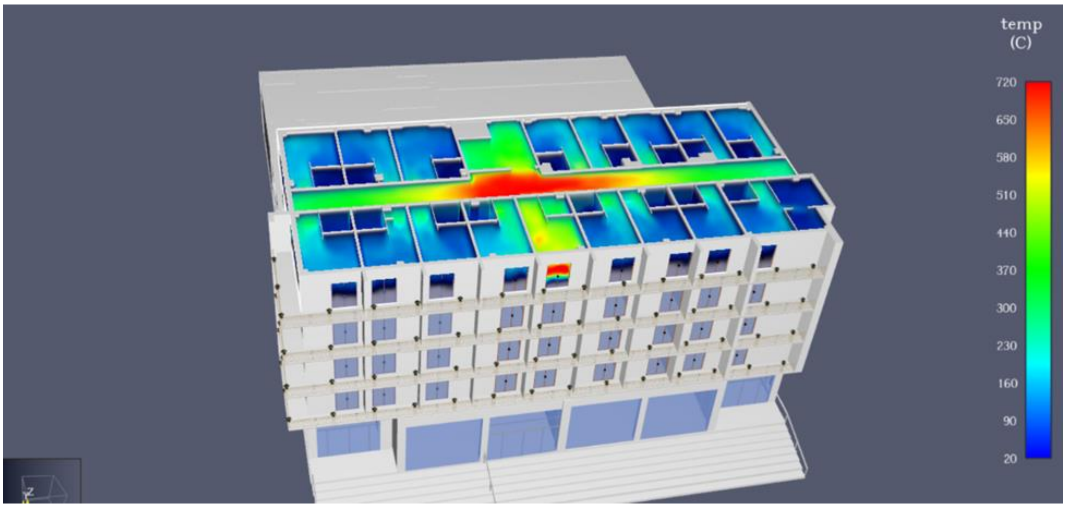

Figure 9 - Vertical Temperature Distribution

With the help of the three-dimensional visualization, it's possible to see temperature values at all points along the floor. It's observed that high temperatures ranging from 20°C to 720°C are recorded, even up to the ceiling level (as measured on the vertical plane). In the hallway, the highest temperatures are recorded, ranging from 240-720 °C. These elevated temperatures indicate an intense fire in the hallway, resulting from the strong combustion of combustible materials and the presence of a substantial amount of oxygen, facilitating temperature increase in this space.

3.4.2. 2D Section Visualization

On the other hand, in the 2D section visualization, temperature is represented in a two-dimensional plane. This plane can be either a horizontal or vertical section of the room. By obtaining these sections, high-temperature areas and how they propagate in a specific direction can be more clearly highlighted. The 2D section visualization can provide a more detailed view of temperature variations in different parts of the room, aiding in identifying areas with the greatest fire propagation risk.

A horizontal section can be useful for observing how heat propagates through different layers of the room. This can reveal temperature variations between different levels and assist in evaluating the risk of fire spreading upwards or downwards. For example, high-temperature areas can be identified at the top of the room, indicating that smoke and heat accumulate there.

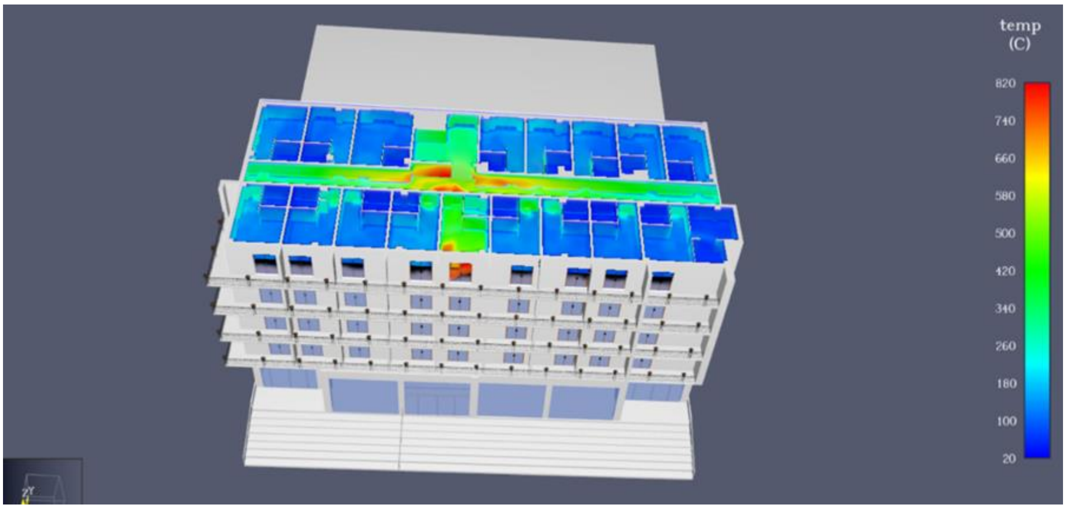

Figure 10 - Horizontal Temperature Distribution

The horizontal section is located at the top level and serves to monitor the distribution of heat released at the ceiling level. This allows for an approximation of the fire resistance time of the ceiling. At a height of 3 meters, high temperatures ranging from 500 ºC to 820 ºC are recorded (see Figure 10). The temperature from the focal area rapidly spreads horizontally at the ceiling level. This phenomenon results from the accumulation of hot gases and smoke from the combustible materials in the hotel room. Smoke and particles generated during combustion initially spread horizontally, gradually occupying the entire ceiling area.

Both three-dimensional and two-dimensional visualizations are valuable tools for monitoring and understanding temperature behavior during a fire.

3.5. Visibility on the Floor Level

Visibility represents an observer's ability to identify an object against the background at a certain distance. In the context of occupant safety, visibility is often used as an essential requirement.

Reduced visibility due to dense smoke can create significant difficulties in safely evacuating people from a building or in locating and fighting the fire by firefighters. Figure 11 illustrates the visibility capacity of occupants across the entire top floor of the hotel. It shows how smoke can spread and affect visibility in various areas of the floor during a fire.

As smoke spreads horizontally, it can be observed that areas closer to the focal point exhibit reduced visibility. In these areas, dense smoke and particles resulting from the combustion of combustible materials can limit visibility to a few meters ahead (between 0 and 9 m). As one moves away from the focal point and approaches lateral and opposite areas, visibility may improve.

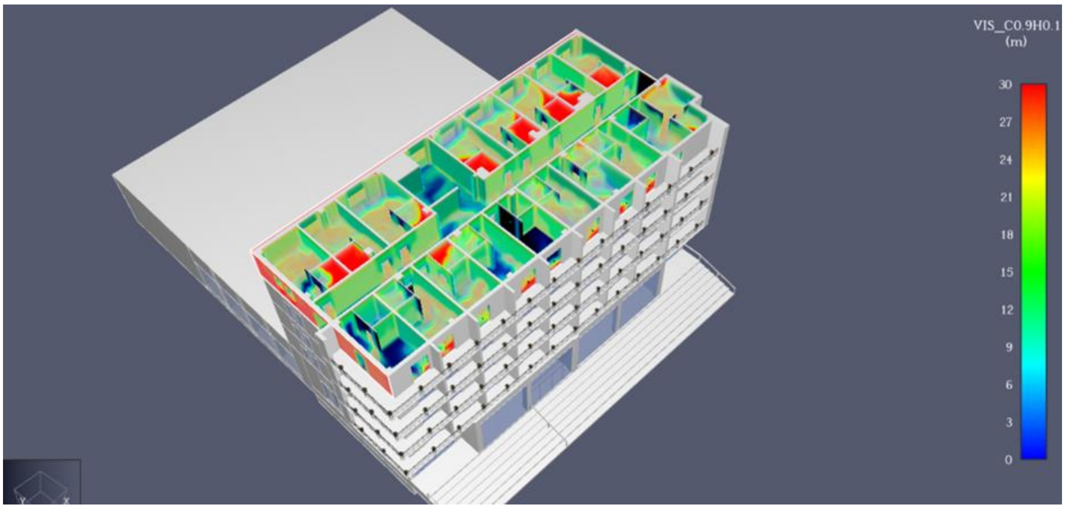

Figure 11 - Visibility on the Floor Level

In light of the identified visibility deficiencies in Figure 11, the following measures are necessary to ensure safe evacuation:

Verification and reevaluation of the lighting system: It is essential to check the proper functioning of emergency lighting and general lighting in critical areas and on evacuation routes. If deficiencies are found or if the light is not sufficiently intense, adjustments or replacements should be made to ensure optimal visibility during a fire.

Proper placement of evacuation signage: Evacuation signs must be placed in visible locations at an appropriate height and in sufficient numbers to guide guests and staff to emergency exits. Existing signage visibility should be checked, and additional signs should be added where necessary.

Obstacle removal: Careful inspection of every area of the hotel is required to identify and eliminate any obstacles that could hinder visibility or access to evacuation routes. This may include furniture, equipment, or any other objects that could block sightlines or pathways to exits.

Review of the evacuation plan: The hotel's evacuation plan needs to be reviewed and updated following the fire simulation and the identification of visibility-related issues. Ensure that the plan is clear, easy to understand, and includes precise instructions regarding evacuation routes and assembly points.

Implementing these measures will contribute to improving visibility in the hotel in the event of a fire and will enhance the effectiveness of evacuation.

4. Conclusions

In conclusion, fire simulation represents an indispensable tool in modern engineering and the fire safety of buildings [12]. Through simulations, a deeper understanding of the fire behavior of load-bearing structures, combustible materials, and the destructive effect of fire is obtained, providing guidance for the implementation of the most suitable fire safety measures [13].

The use of the SketchUp program to transform building plans into three-dimensional models allows for a detailed representation of each level of the building, facilitating fire simulation and evaluation of its behavior inside the structure [14]. Superimposing the obtained shapes for each level and introducing them into the PyroSim program enables precise fire simulation in a virtual environment [15].

The fire simulation conducted on the upper floor of the hotel, with the initiation source being open flame work execution without adhering to fire prevention and extinguishing rules and measures, highlighted the danger posed by plastics, textiles, and wood in generating dense smoke and its propagation throughout the room [16].

For monitoring temperature distribution during a fire, multiple measurement plans were used, both horizontal, allowing visualization of temperature distribution in space, and vertical, crossing the focal point and providing temperature information in that area [17].

Visibility is an essential requirement in ensuring occupant safety in the event of a fire. Reduced visibility due to dense smoke can create significant difficulties in safely evacuating people and in firefighters' intervention in locating and extinguishing the fire [18].

In conclusion, fire simulation and visibility assessment are crucial tools in ensuring the fire safety of buildings, providing essential information for the development and implementation of effective fire prevention and protection measures [19].

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