



Experimental Study Of Fire Propagation On The Facade Of A High-Rise Building With Internal Vertical Void (Patio)

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Key words

Building fire,
Façade fire,
High-rise building,
Internal patio,
Chimney effect,
Smoke propagation.

Abstract

This study presents an experimental investigation of fire and smoke propagation through a window opening facing an internal patio (vertical void) in a high-rise building (HRB). Experiments were carried out on a 1:4 scale model composed of two superimposed compartments of identical dimensions (1.23 m × 1.23 m × 2.0 m). Each compartment was equipped with a front window (0.25 m × 0.25 m), while a door measuring 0.50 m × 0.25 m was installed only on the left side of the lower compartment. Two configurations were analyzed: a building with an internal patio (CIAP) and a building without a patio (CISP). Using kerosene as the fire source, a comparative analysis of smoke and hot gas propagation was performed. In the CIAP configuration under windless conditions, the patio acted as a vertical shaft, promoting rapid upward movement of smoke and hot gases to the upper level within 82 seconds. A maximum temperature of 65 °C was recorded in the upper compartment after 400 seconds, accompanied by dense smoke accumulation and reduced visibility. In contrast, the CISP configuration, exposed to ambient airflow, limited the vertical spread of smoke and hot gases, with the upper compartment reaching a maximum temperature of only 39 °C. These results highlight the significant influence of internal patios on chimney effects and emphasize their critical impact on vertical fire propagation in high-rise buildings.

Received:07.07.2025

Accepted: 04.11.2025

Published online: 08.12.2025

How to cite this article: Falina Manassé, I., Onguene Mvogo, P., Enone Ellah, C. R., El-Kebir Iya, A., Tegawendé Zaida, J., & Mouangue, R. (2025). *Experimental study of fire propagation on the façade of a high-rise building with internal vertical void (patio)*. *MJ Engineering Sciences*. 1(2), 117–127. <https://doi.org/10.63156/mjes08>

1. Introduction

A façade represents the outermost envelope of a building and forms the interface between the indoor spaces and the external environment [1]. In high-rise buildings, internal patios or vertical voids are often incorporated into architectural designs to enhance natural lighting and ventilation [2]. However, during a fire event, such spaces can unintentionally act as vertical channels that promote the rapid upward movement of hot gases and smoke. Façade fires therefore represent a major safety concern, as they can spread over the entire height of a building within a short period, particularly in dense urban environments [3].

When a fire occurs inside a compartment, the combustion products, including hot gases and smoke, may escape through openings such as doors and windows. If an internal patio is present, these gases can be drawn into the void, potentially intensifying the vertical transport of heat and smoke in complex ways. Despite its architectural benefits, the role of an internal patio in fire propagation remains insufficiently understood, especially in terms of its contribution to stack-driven flow and smoke transfer between floors.

Several studies have examined smoke movement and heat transfer in vertical shafts. Marshall [4] used a reduced-scale experimental model to investigate air entrainment and smoke propagation in vertical enclosures, showing that combustion products tend to rise along shaft boundaries. Klote and Milke [5] analyzed chimney effects and provided analytical principles for predicting smoke movement in vertical spaces. Chow and Hung [6] investigated high-rise buildings with internal patios in Hong Kong and evaluated related fire safety issues, including the feasibility of protected or fire-resistant patios. Zukoski [7] further explored the interaction between smoke and air in shafts and its impact on heat transfer.

The importance of buoyancy-driven flow and stack effects in high-rise fires has also been demonstrated in real and simulated fire scenarios. Madrzykowski et al. [8] analyzed a fatal fire incident in a residential building, in which the opening of a door and subsequent window breakage led to a sudden and violent spread of hot smoke, resulting in the deaths of three firefighters. Shui-Bo et al. [9] numerically investigated fire propagation caused by the chimney effect in patios and concluded that obstructions, such as window shades, may significantly increase heat accumulation and enhance fire spread. Rockett [10] established an early relationship for the mass flow rate of hot gases escaping through openings, while Onguene et al. [11] highlighted the influence of opening size on fire behavior. Meskéoulé et al. [12] emphasized the impact of door and window positioning on combustion dynamics, and Upeka et al. [13] as well as Yousef et al. [14] demonstrated the critical role of wind speed and direction in modifying façade fire propagation patterns. Duny [15] showed that the presence of a façade above an opening limits air entrainment, increases buoyancy forces and intensifies the upward movement of hot gases.

While these studies provide valuable insight into fire dynamics in vertical and façade environments, a direct experimental comparison between high-rise building models with and without internal patios remains limited. The lack of controlled comparative experimental data represents a significant gap in the literature.

The main objective of the present study is therefore to experimentally investigate and compare the propagation of smoke and hot gases through the façade of a high-rise building under two configurations: one with an internal patio (CIAP) and one without a patio (CISP). This comparative analysis is based on a 1:4 scale physical model. Specifically, the study aims to determine whether the presence of a patio mitigates or exacerbates the vertical transfer of smoke and heat to the upper floors, and to quantify the resulting temperature variations and smoke behavior in each case.

2. Material and methods

2.1. Experimental set-up

The experimental domain in which the experiments were conducted is a small-scale 1/4 building with dimensions $L \times W \times H$: 1.23 m \times 1.23 m \times 2.0 m. It consists of two compartments of equal size; one located above the other. Each room has a front window, with dimensions 0.25 m \times 0.25 m. A door measuring 0.50 m in height and 0.25 m in width was inserted only on the left side of the lower room (Figure 1).

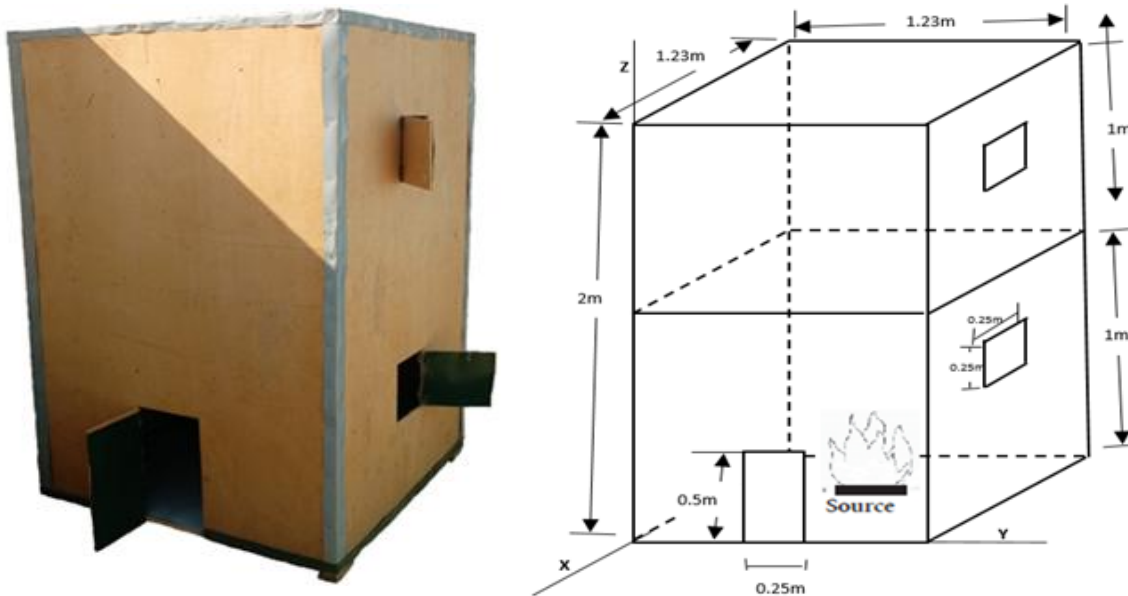


Figure 1: Experimental domain under the CISP configuration.

This compartment layout was adopted for both the lower and upper floors in order to illustrate the possible spread of smoke and hot gases from the lower floor to the upper floor through the façade. The structure was constructed using plywood panels with a thickness of $e = 0.015$ m, a density of 800 kg/m^3 , and a thermal conductivity of $0.20 \text{ W/m}\cdot\text{K}$.

Placed at the center of the lower room ($Z = 0$), the fire source consisted of a cylindrical pan with a diameter of 0.13 m, into which a mass (M) of 100 g of kerosene, with a calorific value (CV) of $46,000 \text{ kJ/kg}$, was introduced to represent the heat load for the experiments.

To experimentally study the external propagation of hot gases and smoke escaping through the window of a high-rise building, the experimental domain was used in two configurations. The CIAP configuration represented the building with a patio measuring $1.23 \text{ m} \times 0.70 \text{ m} \times 2.0 \text{ m}$ (Figure 2), while the CISP configuration represented the building without a patio (Figure 1). The cladding was not modified, as the same thermal conductivity was maintained for both configurations.

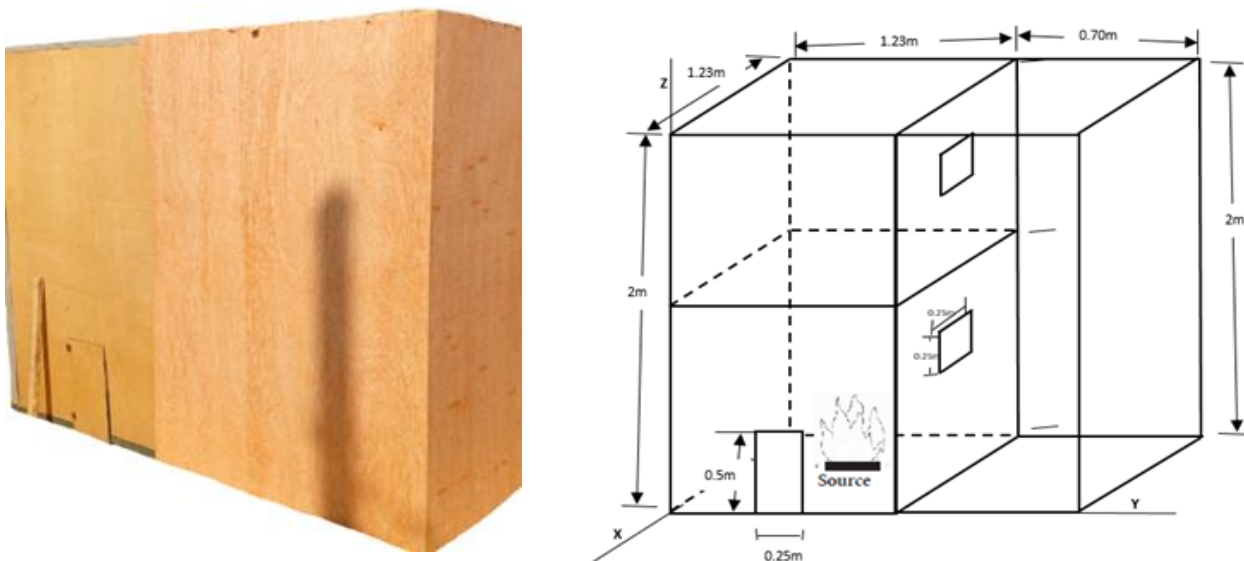
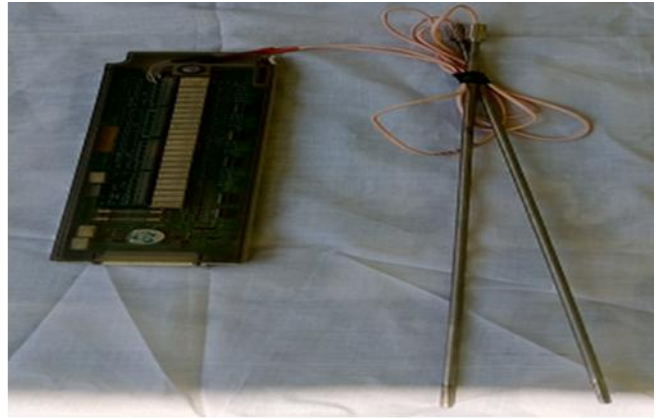


Figure 2: Experimental domain under the CIAP configuration.

The temperatures of the hot gases inside the compartments, as well as those escaping to the outside, were automatically recorded using a data acquisition system, which ensured continuous and reliable monitoring of the thermal behavior during each experiment. This system consisted of a data acquisition and switching unit connected to a computer and a 40-channel multiplexer equipped with thermocouples, as shown in Figures 3A–B.



A



B

Figure 3A–B: Experimental data acquisition system used for temperature measurements: (A) data acquisition and switching unit with computer (Agilent 34970A) and (B) 40-channel multiplexer with connected thermocouples.

The temperature measurements were obtained using seven type-N thermocouples, all connected to the acquisition system. These thermocouples were installed both inside the compartments and outside along the front façade in order to capture the temperature variations at different vertical levels. Their exact positions, located just above and below each window opening, are illustrated in Figure 4.

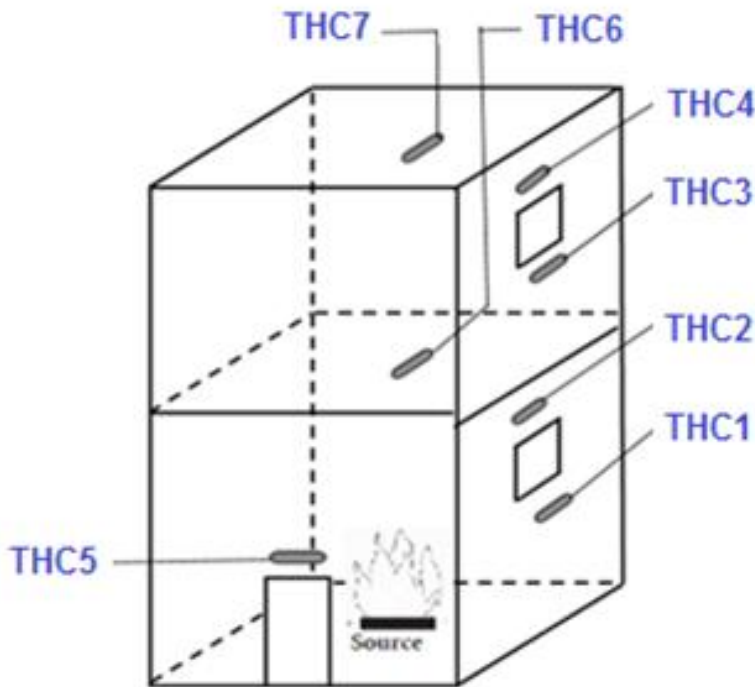


Figure 4: Location of thermocouples in the experimental area

To allow a clear spatial understanding of the measurement points, the precise locations of all thermocouples within the experimental domain are summarized in Table 1.

Table 1: Locations of thermocouples in the experimental range

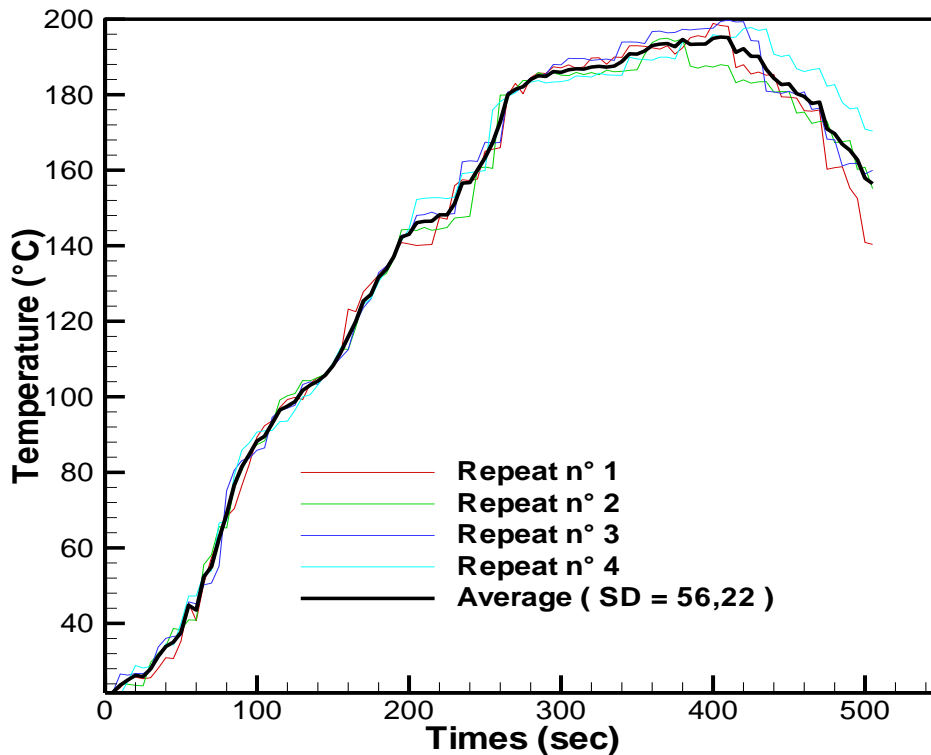
| Thermocouples | X(m) | Y(m) | Z(m) |
|---------------|------|------|------|
| THC1 | 0.61 | 1.23 | 0.32 |
| THC2 | 0.61 | 1.23 | 0.74 |
| THC3 | 0.61 | 1.23 | 1.32 |
| THC4 | 0.61 | 1.23 | 1.74 |
| THC5 | 1.23 | 0.61 | 0.46 |
| THC6 | 0.61 | 0.61 | 0.85 |
| THC7 | 0.61 | 0.61 | 1.85 |

The experimental protocol consisted of preheating the fuel (kerosene) placed in the pan until it reached its flash point, after which the fire was ignited using matches and the pan was positioned at the center of the lower compartment. The data acquisition system was activated simultaneously to measure and record the parameters at 5-second intervals. This process was maintained until the fuel had completely burned. The wind speed was measured using an anemometer positioned at a height of 2 m. During all the tests, only the two windows (in the upper and lower compartments) were kept open, while the door remained closed.

3. Results and Discussion

In order to demonstrate the repeatability of the experiments carried out under identical conditions, each fire scenario was repeated four times, and only the average value of these repetitions was used in the analysis. The repeated temperature profile recorded by the selected THC 6 thermocouple is presented in Figure 5.

It can be observed that the data dispersion is almost identical for all repetitions, indicating good consistency of the measurements, with an acceptable mean deviation and a standard deviation of $SD = 56.22$.

**Figure 5:** Repeatability of temperature measurements in the lower compartment recorded by thermocouple THC 6.

3.2. Comparative results for CIAP and CISP configurations

The temperatures recorded by the thermocouples located on the front façade and at the upper floor, obtained from the CIAP and CISP configurations, were compared. A visual method was also used to observe and compare the hot smoke ejected outside the lower compartment. The combustion time varied between 8 and 9 minutes for the different tests performed.

3.2.1. Analysis of the CIAP configuration (with patio)

The fire ignited on the ground floor after a few seconds, and hot smoke spread from the window into the patio, reaching the opening of the upper floor after 82 seconds. The patio acted as a vertical shaft, allowing hot smoke to spread rapidly towards the upper level. This situation can be considered a typical case of the chimney effect, in which smoke and hot gases rise quickly from the lower level to the upper level through the patio.

The smoke not only propagated rapidly but also filled the entire patio. This flow of smoke resulted in poor visibility in the patio: the higher the gas concentration, the lower the visibility. After 400 seconds, a maximum temperature of 65 °C was recorded inside the upper compartment.

3.2.2. Analysis of the CISP configuration (without patio)

In the configuration without a patio, the façades of both floors were exposed to ambient air and natural ventilation. Although wind has a significant effect on fire spread, the natural wind speed in this case varied between 0 and 0.3 m/s, which was not sufficient to completely prevent the vertical propagation of smoke. Figure 6A shows the smoke flow (in light blue) along the façades at wind speeds ranging from 0 to 0.3 m/s, allowing hot smoke to rise towards the upper floor.

However, when the wind speed increased from 0.3 to 1 m/s, the distribution of hot gases and smoke became strongly influenced by the ambient airflow (Figure 6B). Under these conditions, wind did not favor the vertical spread of smoke to the upper floor. This can be explained by the fact that a higher wind speed (e.g., 1 m/s) provides sufficient momentum to counteract the upward movement of smoke and hot gases. As a result, the flame is redirected and tends to follow the side edges of the horizontal projection, promoting lateral spread rather than vertical propagation. The maximum temperature recorded inside the upper compartment was 39 °C.



A



B

Figure 6A-B: Hot smoke propagation along the façade at different wind velocities: (A) between 0 and 0.3 m/s and (B) from 0.3 to 1 m/s.

Figures 7A and 7B show the different temperatures recorded by the thermocouples positioned along the front façade as a function of height from the lower stage to the upper stage, at 200 s and 350 s, respectively, for both the CIAP and CISP configurations.

In the case of the CIAP configuration (with patio and no external wind), when smoke and hot gases are ejected through the window into the patio, they are drawn directly into the upper zone. As a result, the thermocouple THC 3, located at the entrance of the upper-storey window, reaches a temperature of approximately 45 °C. It is also observed that the THC 1 thermocouple, installed below the lower-storey window (fire source compartment), maintains an ambient temperature of about 26 °C. This indicates that, in the event of a fire, the chimney effect mainly affects the upper levels, while the lower zones remain relatively protected.

In contrast, for the CISP configuration (without patio), the results shown in Figures 7A and 7B (CISP) demonstrate that ventilation plays a significant role in limiting the vertical spread of smoke and hot gases to the upper floor. In this case, the THC 3 thermocouple located at the upper floor window entrance remains close to the ambient temperature of approximately 26 °C.

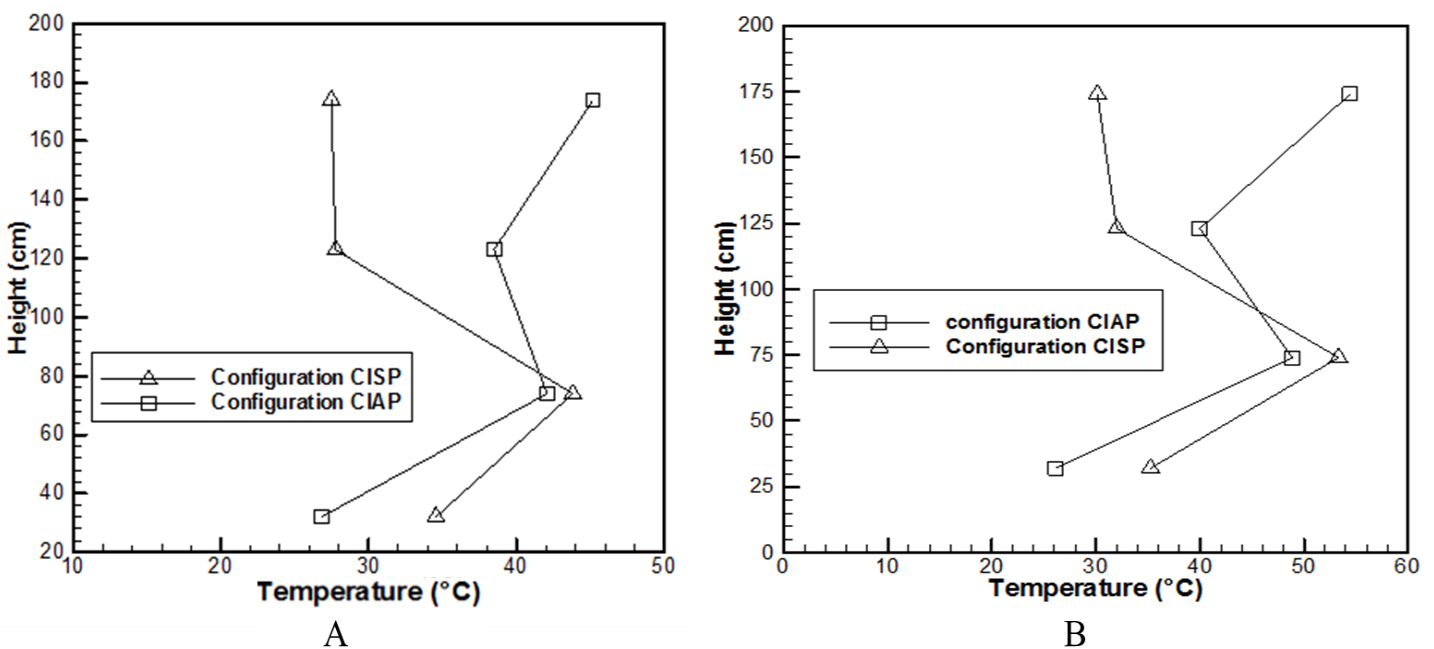


Figure 7A-B: Smoke temperature distribution along the front façade at different times: (A) at 200 s and (B) at 350 s.

Figures 8A–D present the temperature distribution of smoke and hot gases along the façade and inside the upper storey for both configurations. In the CIAP configuration (with patio), the reference case resulted in the fastest vertical propagation of smoke and hot gases to the upper floor through the patio. The absence of external wind appears to provide highly favorable conditions for buoyancy forces to drive the upward movement of smoke along the façade.

The accumulation of heat causes smoke to be drawn into the upper storey, where the gas concentration increases with time, leading to a maximum temperature of 65 °C reached within 82 seconds.

For the CISP configuration (without patio), Figures 8C and 8D show that the presence of wind above the opening (window) of the lower compartment significantly reduces smoke propagation to the upper floor. The maximum temperature recorded by thermocouple THC 7 inside the upper storey is limited to 39 °C. A noticeable change in the temperature profile is observed under windless conditions, confirming the strong influence of ventilation on fire dynamics.

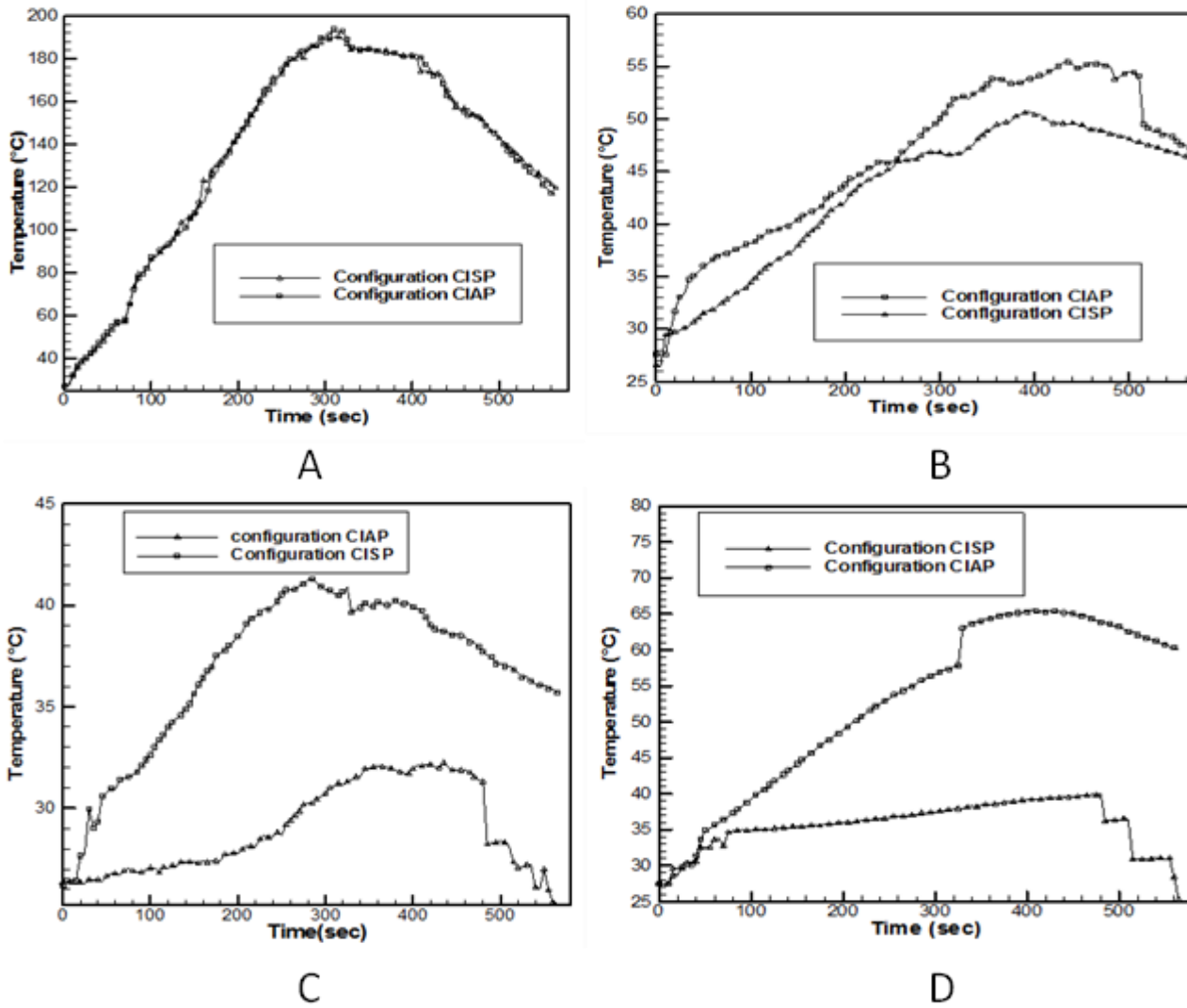


Figure 8A–D: Temperature distribution of smoke and hot gases at different locations along the façade and inside the building for the CIAP and CISP configurations: (A) inside the lower stage, (B) at the lower-stage outlet, (C) at the upper-stage inlet, and (D) inside the upper stage.

To further quantify the differences between the two configurations, a comparative analysis of the maximum temperatures recorded at key locations (lower floor, lower outlet, upper inlet, and upper storey) was performed. The results of this analysis are summarized in Table 2.

Table 2: Comparison of temperatures for CIAP and CISP

| | T_{\max} inside the lower stage. THC 6 (°C) | T_{\max} at lower stage outlet. THC 2 (°C) | T_{\max} at upper stage inlet. THC 3 (°C) | T_{\max} inside the upper stage. THC 7 (°C) |
|------------|---|--|---|---|
| CIAP | 193.87 | 55.43 | 44.24 | 65.99 |
| CISP | 190.35 | 50.69 | 32.09 | 39.95 |
| ΔT | 3.45 | 4.74 | 12.15 | 26.04 |
| Error (%) | 1.810 | 8.552 | 27.448 | 39.991 |

Thermocouples THC 3 and THC 7 recorded temperature differences of 27% and 38%, respectively, between the CIAP and CISP configurations. In addition, the temperature of smoke and hot gases in the upper compartment remained significantly higher in the absence of wind, corresponding to the CIAP configuration.

4. Conclusion

The objective of this study was to conduct an experimental investigation of the behavior of smoke and hot gases escaping from the openings of a high-rise building under two different configurations: the CIAP configuration (with patio) and the CISP configuration (without patio). A comparative analysis was performed in order to better understand the influence of the presence of a patio in a high-rise building during a fire event. Following a series of small-scale (1/4 scale) experimental tests, the results revealed that, in the CIAP configuration, smoke and hot gases escaping to the outside become partially trapped within the patio. The smoke particles contained in the combustion products exhibit a strong obscuring power, significantly reducing visibility and potentially complicating rescue and evacuation operations. In the absence of wind, the vertical propagation of smoke and hot gases towards the upper floor is accelerated, and a maximum temperature of 65 °C is reached. In the CISP reference configuration, the presence of wind above the opening of the lower compartment proves to be more effective in delaying, and in some cases preventing, the vertical spread of smoke and hot gases toward the upper floor. As a result, the maximum temperature is reduced by $\Delta T = 26.04$ °C compared to the CIAP configuration. This indicates that the horizontal projection of the façade can have a positive effect on limiting vertical fire spread, as smoke and heat are redirected laterally. In other words, the vertical propagation of smoke is inhibited at relatively higher wind speeds.

In the present study, the patio dimensions and window openings were not varied, heat release rate (HRR) measurements were not performed, and no toxicity analysis of the generated smoke was carried out. Future work will therefore focus on conducting additional tests by modifying the patio geometry and opening configurations to further investigate their influence on fire and smoke propagation.

Acknowledgements

The authors would like to express their gratitude to the heads of the Doctoral Training Unit of Engineering Sciences and the Doctoral School of Fundamental and Applied Sciences at the University of Douala.

Financial supports

No funds, grants, or other financial support was received for conducting this study or for preparing this manuscript.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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