Technical Sciences
Academy of Romania
www.jesi.astr.ro

Journal of Engineering Sciences and Innovation
Volume 10, Issue 3 / 2025, pp. 285 - 292

E. Civil Engineering and Transport Engineering

Received ***17 May 2025*** *Accepted* ***16 September 2025***
Received in revised form ***30 July 2025***

Analysis of the operation of natural-organized ventilation systems used as a smoke removal solution for a logistic warehouse using CFD simulations

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Abstract. This case study aims to analyze the efficiency of smoke extraction systems based on naturally organized draft, implemented as a technical solution for a logistics warehouse, using computer simulations with PyroSim software. The primary objective is to evaluate the performance of the smoke ventilation system activated during a fire scenario through organized natural draft, with a focus on smoke stratification and movement, temperature evolution inside the space, and the maintenance of visibility — key factors in ensuring user safety and enabling a prompt firefighting response.
The research involves simulating multiple fire scenarios to identify and assess the influence of ventilation opening placement in various positions, as well as the sizing and configuration of fresh air inlets.
The findings demonstrate that, under specific conditions, naturally organized ventilation systems can maintain tenable environments for occupant evacuation and damage mitigation by limiting fire spread, offering a cost-effective alternative to mechanical systems.
Furthermore, the study provides valuable design insights and performance benchmarks to assist engineers and fire safety professionals in enhancing fire protection strategies.

Keywords: smoke extraction; computer simulations; fire safety.

1. Introduction

Ventilation of spaces plays a crucial role in fire control as well as in limiting the consequences of fires. In fire safety engineering, ventilation is not merely an architectural feature, but a dynamic factor that influences the combustion process, the accumulation of smoke and hot gases, and the survivability of occupants. The impact of ventilation systems is particularly significant in large-volume structures

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containing substantial amounts of combustible materials, such as logistics warehouses.
Modern logistics warehouses have a high density of materials packaged in paper, cardboard, or flammable plastics, which makes them extremely vulnerable to the rapid development of fires. One of the critical aspects of fire safety is the efficient removal of smoke, which ensures a safe environment for evacuation, limits fire spread, and facilitates firefighting operations.

2.Metodology

2.1 Structural characteristics

The building under analysis has dimensions of 49 m x 53.5 m x 12.35 m, with a built area of 2,621.5 m² and a volume of approximately 32,375 m³. The structure is constructed using reinforced concrete frames, enclosed perimetrally with sandwich-type thermal insulating panels, while the interior partitions are made of AAC masonry and gypsum board walls on metal framing. The primary function of the building is the storage of automotive subassemblies, serving simultaneously as a logistics base.

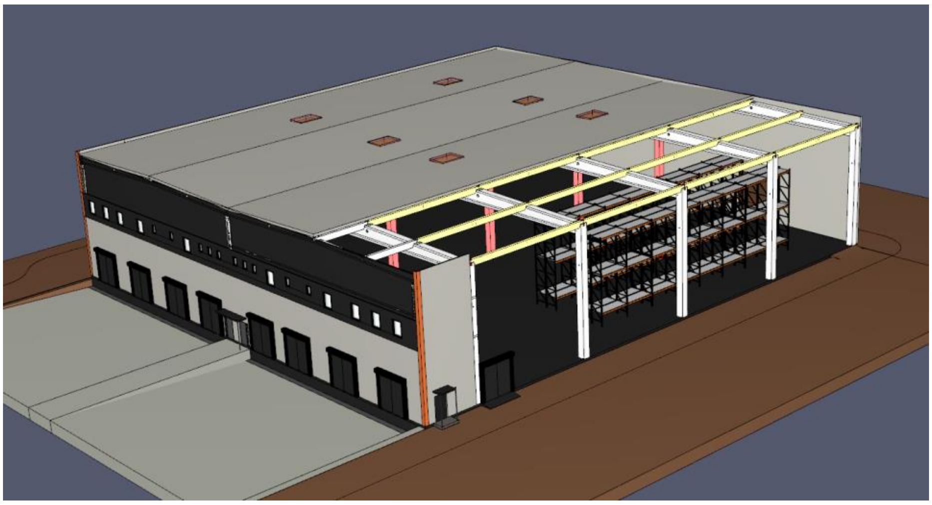

Fig. 1. The model of analyzed building.

The packaging of the stored parts is done using plastic film and cardboard boxes, which are palletized and stacked on metal racks.

2.2 Simulation parameters

To perform the simulations, a fire was modeled as originating in the materials stored on the bottom shelf of a storage rack. The fire parameters were defined based on the research conducted by McGrattan, K. [1]; specifically, test number 20 was used as a reference. This test involved the combustion of four plastic containers filled with paper pieces, placed on two wooden pallets. The maximum heat release rate recorded during the test was 2,319 kW, as indicated in Figure 2.

Table 2: Summary of test results.

Test No.	Item	No. Items	Initial Mass (kg)	Final Mass (kg)	ΔH_{O_2} (MJ/kg)	Peak HRR (kW)	Total Energy (MJ)	Time to Peak (min)	ΔH (MJ/kg)	CO Yield	CO_2 Yield	Soot Yield
1	Box #1	1	8.00 ± 0.02	0.25 ± 0.02	13.6 ± 0.4	328 ± 15	116 ± 4	4.7 ± 0.2	15.0 ± 0.5	0.035 ± 0.001	1.50 ± 0.05	0.0015 ± 0.0003
2	Box #1	2	16.00 ± 0.02	0.45 ± 0.02	13.6 ± 0.4	481 ± 21	236 ± 8	4.9 ± 0.2	15.2 ± 0.5	0.036 ± 0.001	1.51 ± 0.06	0.0010 ± 0.0005
3	Box #1	4	32.00 ± 0.02	0.66 ± 0.02	13.6 ± 0.4	944 ± 40	479 ± 15	3.3 ± 0.2	15.3 ± 0.5	0.034 ± 0.001	1.51 ± 0.05	0.0005 ± 0.0003
...												
20	Bin #1[a]	4	52.84 ± 0.02	3.64 ± 0.02	13.1 ± 0.7	2319 ± 155	1028 ± 61	2.6 ± 0.2	20.9 ± 1.2	0.019 ± 0.001	1.82 ± 0.07	0.0093 ± 0.0015
...												

Fig. 2. Tests results [1].

For the simulation, the fire source was placed on one of the rack shelves with a surface area of 1.2 m², and a heat release rate per unit area (HRRPUA) of 1,900.82 kW/m², reaching a peak HRR of 2,319 kW. A rapidly developing fire scenario was modeled, with a growth phase extending to the point of full development—corresponding to a flashover at t = 15 seconds. A t^2 fire growth model was selected instead of the standard time-temperature curve, due both to computational constraints and the specific focus of the simulation. The primary objective was to evaluate the efficiency of the building's smoke ventilation system, based on the accumulated smoke volume and the temperature within the smoke layer, without quantifying additional parameters.

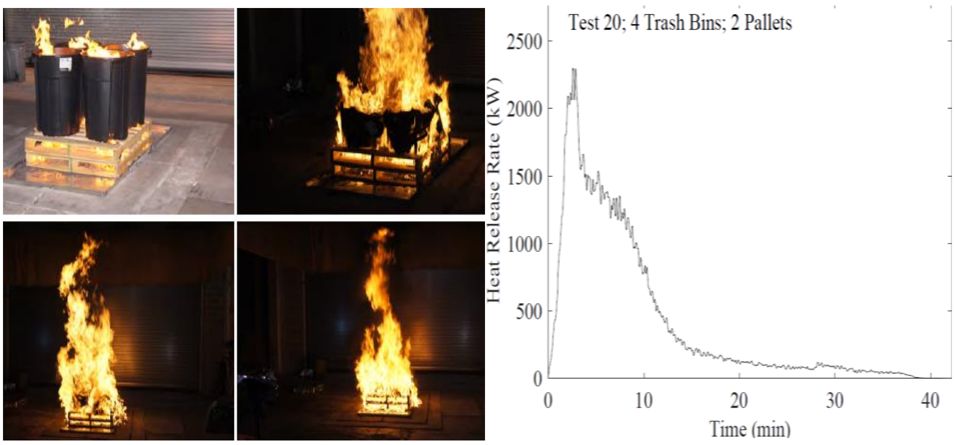

Fig. 3. Images captured during test and the resulting development graph [1].

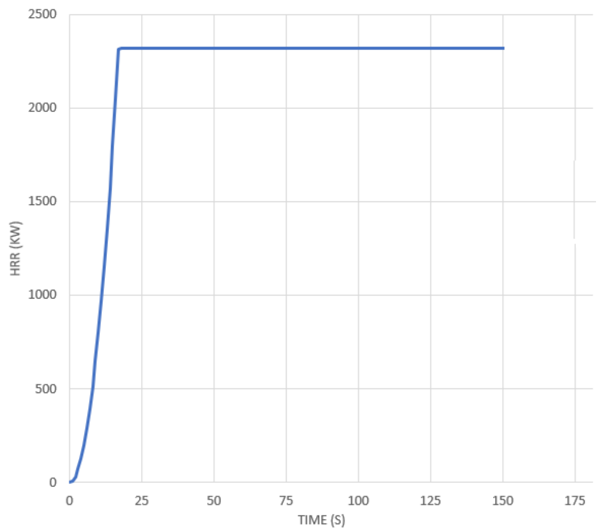

Fig. 4. Fire development graph.

The total duration of the simulations was 150 seconds, with an ambient temperature of 25 °C. The global computational domain was divided into 8 interconnected subdomains, with a general mesh cell size of 0.4 m. In the region surrounding the fire source, the mesh was refined, resulting in a cell size of 0.2 m. The boundary conditions for the simulation were set to atmospheric conditions.

Two simulations were conducted, Scenario A, in which the smoke vents remained closed throughout the entire simulation period and Scenario B, in which the vents were opened following a command triggered by a smoke detector located near the fire source. Upon activation, the vents remained fully open, providing the maximum available area for smoke extraction.

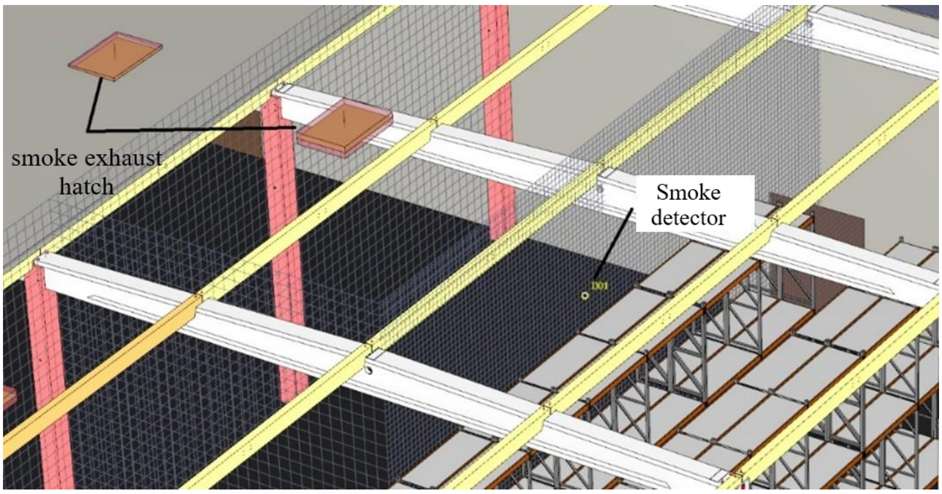

Fig. 5. Location of smoke exhaust hatches, smoke detectors and mesh refinement.

Smoke ventilation was ensured through roof-mounted vents with full opening capability, each measuring 1.8 x 2.5 m, corresponding to an opening area of A = 3.65 m². To comply with current regulatory standards, specifically, the requirement of a minimum ventilation surface area equal to 1% of the ventilated space, 8 such vents were installed. The smoke detector activated automatically upon detecting the presence of smoke, which occurred approximately 10 seconds after the start of the simulation.

To monitor the temperature evolution within the analyzed space, thermocouples were placed at various heights in the vicinity of the fire source, as well as at ceiling level, both above the fire and in adjacent areas.

3. Simulation results

The comparative analysis of the CFD simulation results reveals clear differences in fire development between the two scenarios tested. Temperature profiles recorded by thermocouples, the amount of heat released, smoke layer height, and internal pressure serve as direct indicators of the effectiveness of the smoke ventilation systems.

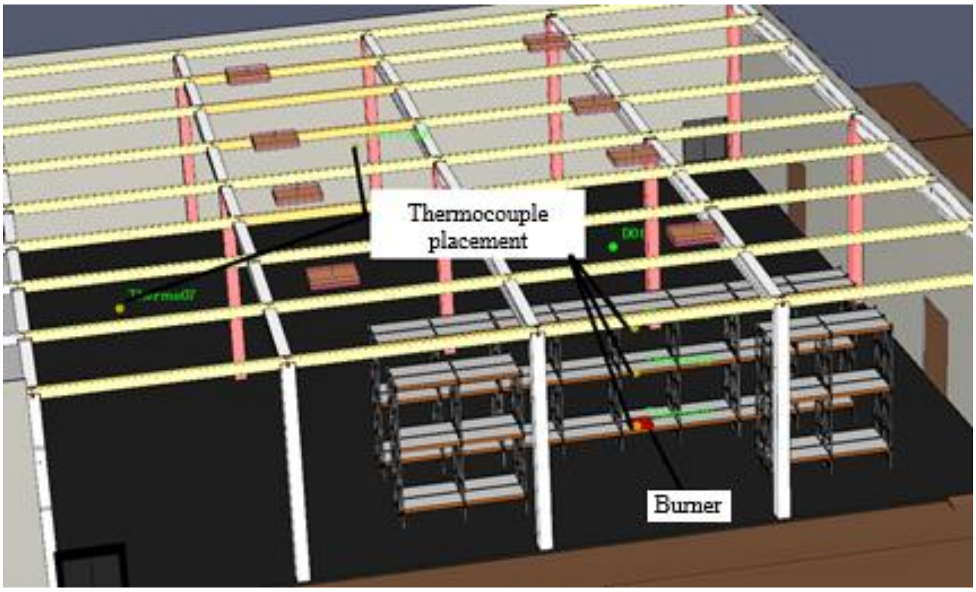

Fig. 6. Thermocouple placement.

An analysis of the temperature evolution shows a similar trend in both scenarios regarding the ceiling-level temperatures; however, a key difference lies in the temperature increase observed in the immediate vicinity of the fire source. In Scenario B, the opening of the smoke vents allows for the intake of fresh air into the combustion zone, thereby promoting fire development. As a result, higher temperatures were recorded during the third phase of the simulation.

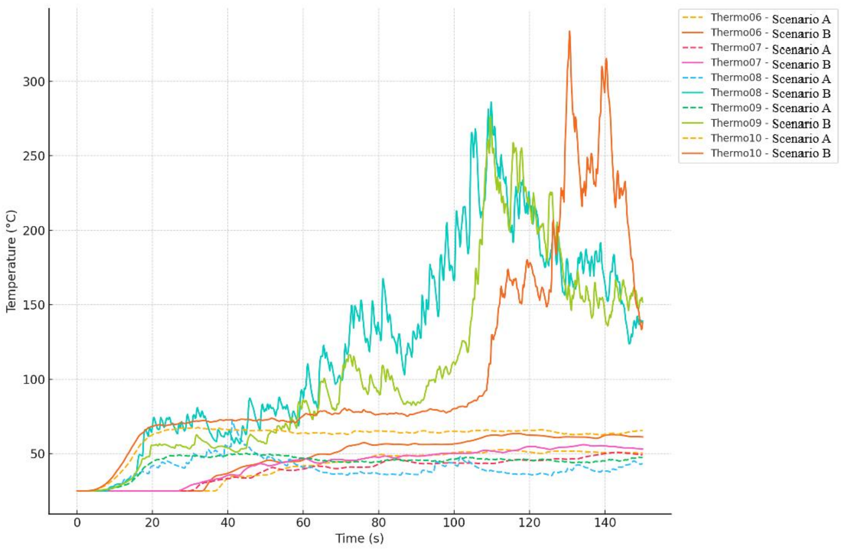

Fig. 7. Comparative graph of temperature evolution.

This observation is further supported by the data on heat release. Scenario B exhibited an increase in the heat release rate, reflecting the natural progression of fire development in a ventilated environment. In contrast, the amount of smoke accumulated within the space was significantly higher in Scenario A, primarily due to the absence of a means for smoke evacuation and the occurrence of incomplete combustion, which is typically associated with substantial smoke production.

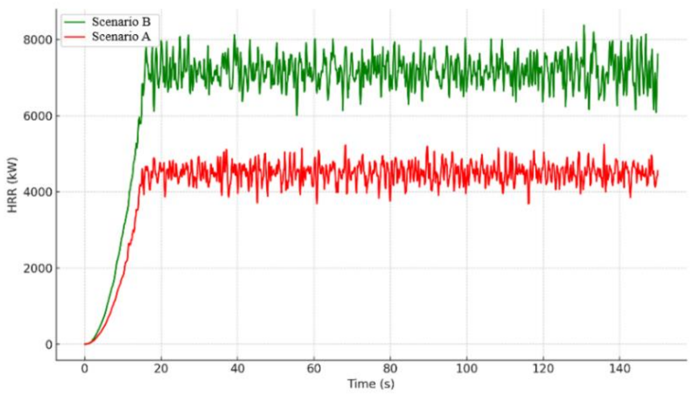

Fig. 8. Heat release rate comparison.

Examining the accumulated smoke volume reveals a distinct difference between the two scenarios in Scenario A, the smoke layer descended to a height of approximately 4.3 meters above the floor. In Scenario B, the smoke layer stabilized at about 5.4 meters, highlighting the effectiveness of the roof-mounted smoke vents in facilitating smoke extraction from the space.

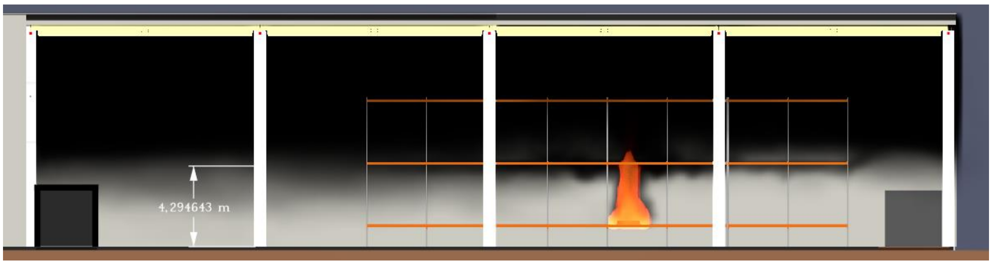

Fig. 9. Comparison of smohe layer height.

These findings align with established fire safety principles concerning the management of smoke and hot gases. The early activation of ventilation vents significantly improves control over smoke stratification, reduces heat accumulation at ceiling level, and enhances visibility in lower zones. These improvements are critical for supporting safe evacuation, minimizing structural damage, and facilitating effective firefighting operations.

4. Conclusions

Naturally organized ventilation systems can significantly improve smoke control when integrated with fire detection, signaling, and alarm systems, enabling early-stage activation during the initial phases of a fire. The results of this study indicate that the prompt opening of ventilation openings contributes to limiting the accumulation of smoke and hot gases beneath the ceiling, reduces smoke migration to adjacent spaces, and facilitates the safe and effective evacuation of occupants.

Although the simulation covered only two scenarios and considered a limited set of parameters, the data obtained supports the necessity of equipping buildings with smoke ventilation systems.

To extend and strengthen these conclusions, further research is recommended to address the following aspects:

- Evaluation of ventilation system performance under fire conditions, monitoring a wider range of parameters;
- Quantification of toxic gas concentrations in each scenario to assess the risks posed to occupants and emergency responders;
- Monitoring visibility levels and temperatures along evacuation routes;
- Exploring the efficiency of hybrid systems that combine natural ventilation with mechanical solutions, particularly for escape routes or spaces with complex geometries.

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