

Research Progress in Fire Dynamics and PyroSim/FDS Numerical Simulation of Smoke Movement in a Semi-Enclosed Space

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Abstract: To improve the connection between fire-dynamics review and engineering-oriented numerical simulation, this paper reviews research progress in heat release rate characterization, fire plumes and ceiling jets, smoke-layer development, flame spread, and numerical modeling methods. A PyroSim/FDS model is then established for a semi-enclosed compartment to compare temperature fields, smoke-layer height, visibility, and ventilation effects under different fire sizes, opening conditions, and mechanical exhaust scenarios. The computational domain is 12.0 m x 6.0 m x 4.0 m, with a 2.0 m x 2.0 m doorway, a 1.5 m x 1.0 m side window, and a 1.0 m x 1.0 m fire source. Large eddy simulation is adopted to describe the smoke movement. The results show that, in the 2.0 MW baseline case, the smoke layer descends to 2.0 m at approximately 222 s, while the far-field visibility at a height of 1.5 m decreases to 15 m at approximately 216 s. Closing the side window significantly accelerates smoke accumulation, whereas mechanical exhaust keeps the smoke-layer height above 2.79 m and the visibility at approximately 29.2 m at 300 s. The proposed framework, which combines literature review, model-credibility control, and multi-index safety evaluation, provides a reference for fire-risk assessment and smoke-control optimization in semi-enclosed spaces.

Keywords: fire dynamics; smoke movement; PyroSim/FDS; semi-enclosed space; numerical simulation; mechanical exhaust

1 Introduction

Fire dynamics focuses on heat release, plume entrainment, smoke stratification, thermal feedback, flame spread, and ventilation-controlled fire behavior. These topics form the theoretical basis for building fire safety design, evacuation assessment, and smoke-control optimization. With the increasing use of FDS and PyroSim in engineering practice, a standalone literature review or a single simulation case is often insufficient for explaining fire safety problems in realistic spaces. Therefore, this paper reorganizes the original review and simulation materials into a journal-style structure that follows the logic of literature review, numerical modeling, credibility verification, result analysis, and engineering implications.

A semi-enclosed space is selected as the research object. The analysis focuses on the effects of fire size, opening condition, and mechanical exhaust on smoke-layer height, temperature distribution, and visibility. Grid-independence verification, boundary-condition description, and multi-index comparison are included to improve the interpretability and reproducibility of the simulation results.

2 Research Progress in Fire Dynamics

2.1 Heat Release Rate and Fire Source Characterization

Heat release rate is a key parameter for describing fire intensity and fire development. In engineering simulations, a t-squared growth model is commonly used to represent the transition from early growth to steady burning. The peak heat release rate should be determined by fuel type, burning area, ventilation condition, and available experimental or design data. The rationality of the fire-source setting directly affects predicted temperature, smoke production, and time to hazardous conditions.

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2.2 Fire Plumes, Ceiling Jets, and Smoke-Layer Development

A fire plume entrains surrounding air and transports heat and smoke upward to the ceiling. The hot gases then form a ceiling jet and spread horizontally. In semi-enclosed spaces, smoke-layer height is controlled by fire size, space geometry, opening location, and smoke-exhaust strategy. Continuous descent of the smoke layer reduces the available evacuation space and increases the risks associated with low visibility and thermal exposure.

2.3 Flame Spread, Flashover, and Backdraft

Flame spread is influenced by fuel distribution, thermal feedback, and ventilation. Under ventilation-limited conditions, hot smoke and unburned gases may accumulate indoors, and a sudden change in opening condition can alter oxygen supply and lead to more complex fire development. For semi-enclosed spaces, larger openings may improve smoke removal but may also enhance oxygen supply near the fire source and increase local temperature.

2.4 Numerical Simulation and Model Verification

FDS solves low-Mach-number fire-driven flow and is widely used for predicting smoke movement, temperature distribution, and smoke-exhaust performance in building fires. PyroSim provides a graphical interface for FDS modeling and improves the efficiency of geometry construction and scenario management. For journal submission, a simulation study should report software versions, boundary conditions, mesh scheme, fire-source input, calculation duration, output indicators, and uncertainty-related discussion.

3 Innovations and Research Framework

The main contributions of this paper are summarized as follows. First, the study integrates research progress in fire dynamics with a semi-enclosed-space simulation case, thereby avoiding a separation between review and engineering analysis. Second, multiple scenarios are designed to compare fire size, side-window condition, natural ventilation, and mechanical exhaust, revealing the coupled effects of ventilation on smoke-layer descent, visibility reduction, and temperature response. Third, smoke-layer height, visibility at 1.5 m, typical thermocouple temperature, and exhaust-induced flow field are used together as safety indicators, making the conclusions more relevant to evacuation and smoke-control design. Fourth, model-credibility control is strengthened by reporting the PyroSim/FDS versions, boundary conditions, HRR input basis, grid-independence verification, uncertainty discussion, and multi-index safety criteria.

4 Numerical Model and Methods

4.1 Computational Domain and Boundary Conditions

The simulated object is a semi-enclosed rectangular compartment with dimensions of 12.0 m x 6.0 m x 4.0 m. A 2.0 m x 2.0 m doorway is arranged on one side, and a 1.5 m x 1.0 m side window is arranged on the side wall. The fire source is placed in the indoor region, and the burner area is 1.0 m x 1.0 m. The initial ambient temperature is 20 degrees C, the calculation duration is 300 s, and the time step is adaptively controlled by the CFL condition. The simulation platform is PyroSim/FDS, with PyroSim version 2024.2 and FDS version 6.9.1. The thermal properties of enclosure materials, external wind condition, and detailed fuel properties should be further refined according to the target journal requirements.

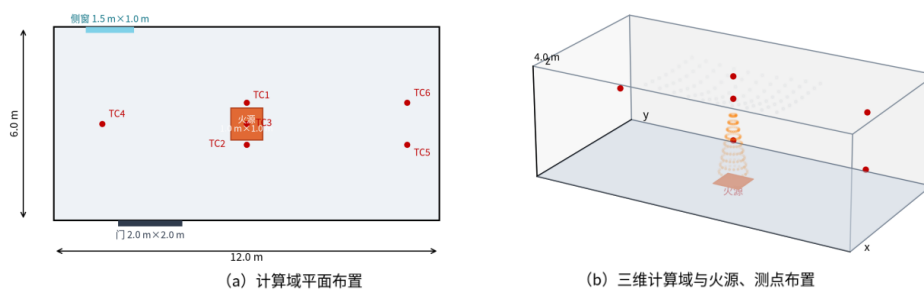


Figure 1. Geometric model and measurement-point layout of the semi-enclosed space.

4.2 Fire Source Setting and Simulation Scenarios

The heat release rate follows a t-squared growth curve and reaches the peak value at 60 s, after which it remains steady. Five scenarios are designed to compare the effects of fire size, natural ventilation, opening condition, and

mechanical exhaust. Case B is selected as the 2.0 MW baseline case, and the remaining cases are used for sensitivity comparison.

Table 1. Numerical simulation scenarios.

Case	Peak HRR	Doorway	Window / ventilation condition	Purpose
Case A	1.0 MW	Open	Natural ventilation	Lower fire size
Case B	2.0 MW	Open	Side window open, natural ventilation	Baseline case
Case C	2.0 MW	Open	Side window closed, natural ventilation	Restricted opening
Case D	2.0 MW	Open	Side window fully open or enlarged opening	Enhanced natural ventilation
Case E	2.0 MW	Open	Mechanical exhaust	Smoke-exhaust control

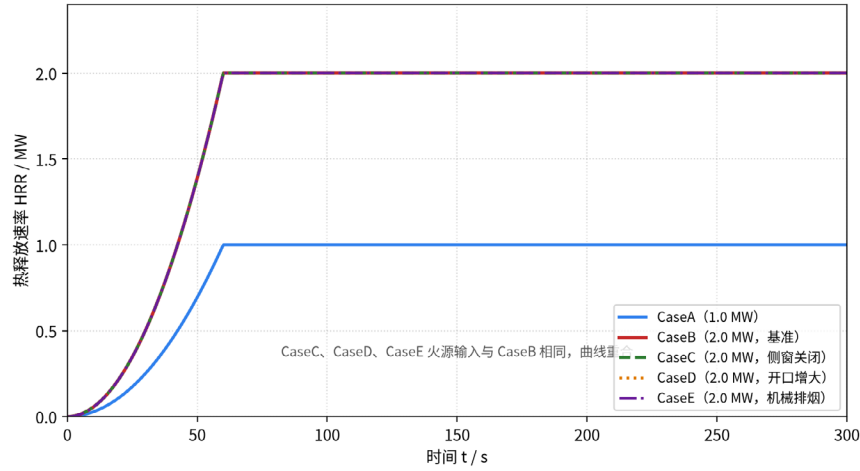


Figure 2. Heat release rate input curves for different scenarios.

4.3 Mesh Scheme and Grid-Independence Verification

To reduce the influence of mesh size on the simulation results, three mesh schemes of 0.20 m, 0.15 m, and 0.10 m are compared using centerline temperature at 3.0 m, ceiling temperature, and smoke-layer height. The relative differences between the 0.15 m and 0.10 m meshes are approximately 1.0%, 1.1%, and 1.2% for the three indicators, respectively. Therefore, the 0.15 m mesh provides a reasonable balance between accuracy and computational cost. The subsequent simulations use a global mesh size of 0.15 m with local refinement to 0.10 m near the fire source.

Table 2. Grid-independence verification results.

Mesh scheme	Mesh size	Centerline temperature at 3.0 m	Ceiling temperature	Smoke-layer height
G1	0.20 m	396 degrees C	342 degrees C	1.58 m
G2	0.15 m	404 degrees C	349 degrees C	1.65 m
G3	0.10 m	408 degrees C	353 degrees C	1.67 m
G2/G3 difference	-	1.0%	1.1%	1.2%

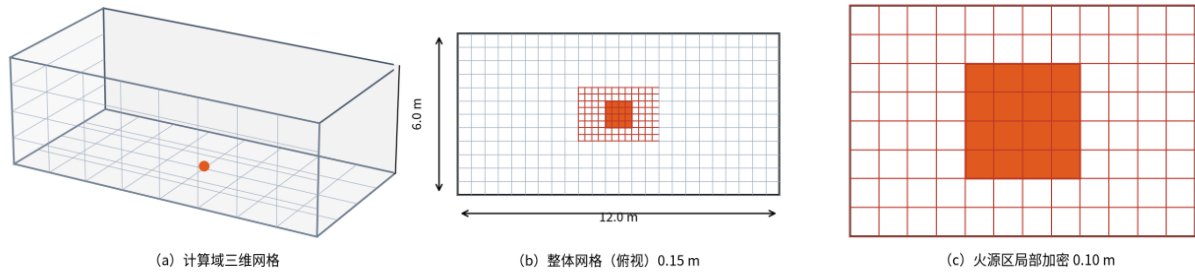


Figure 3. Mesh scheme and local refinement region.

4.4 Output Indicators

The main outputs include temperature field, thermocouple temperature, smoke-layer height, visibility at 1.5 m, and exhaust-induced flow field. For safety assessment, a smoke-layer height approaching or falling below 2.0 m and visibility lower than 15 m are regarded as indicators of increased evacuation risk, while sustained temperature rise at

measurement points indicates increased thermal exposure.

5 Results and Discussion

5.1 Temperature Field Evolution

In the baseline case, the high-temperature plume above the fire source develops rapidly and impinges on the ceiling. The hot smoke then spreads horizontally along the ceiling. TC2 responds at approximately 11 s; its temperature reaches 493 degrees C at 60 s and approximately 522 degrees C at 300 s. TC3 responds at approximately 13 s and reaches about 392 degrees C at 300 s. The ceiling-level point TC1 responds at approximately 14 s, with temperatures of about 318 degrees C, 328 degrees C, 333 degrees C, and 337 degrees C at 60 s, 120 s, 180 s, and 300 s, respectively. TC4 near the opening responds later, at approximately 129 s, and reaches about 213 degrees C at 300 s.

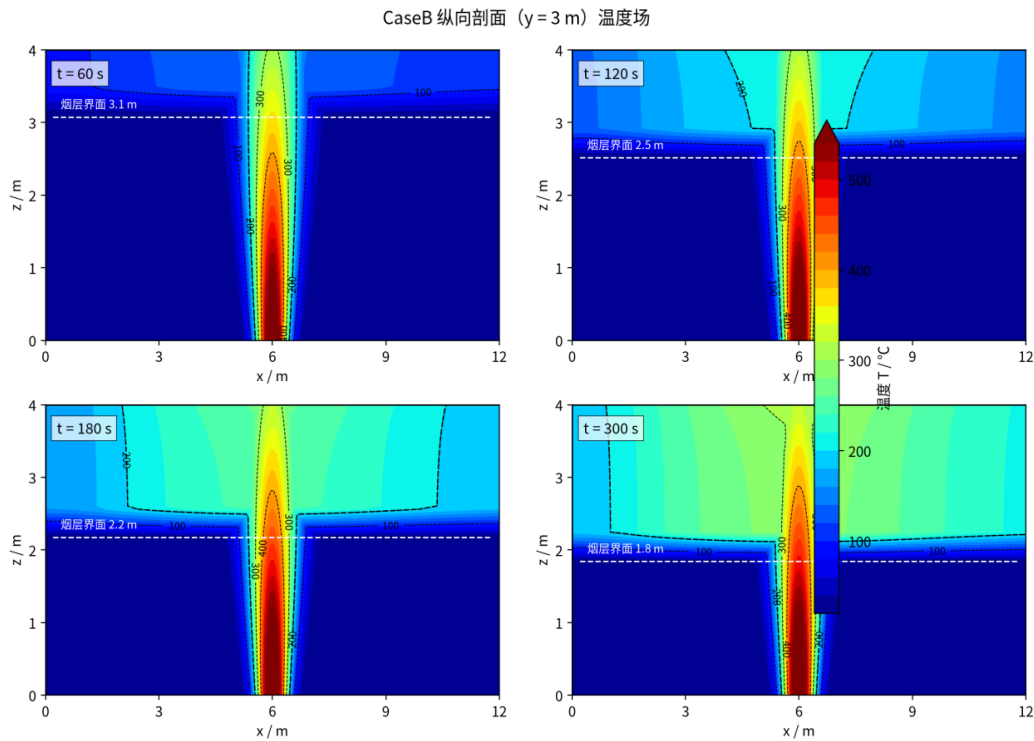


Figure 4. Evolution of temperature field in the baseline case.

5.2 Smoke-Layer Development and Visibility Variation

In the 2.0 MW baseline case, the smoke-layer heights at 60 s, 120 s, 180 s, and 300 s are approximately 3.08 m, 2.51 m, 2.17 m, and 1.84 m, respectively. The smoke layer descends to 2.0 m at approximately 222 s. The far-field visibility at a height of 1.5 m decreases to 15 m at approximately 216 s and reaches about 12.4 m at 300 s, indicating a clear evacuation risk in the later stage. In comparison, because of the lower fire size, Case A has a smoke-layer height of approximately 2.26 m and a visibility of approximately 18.1 m at 300 s, showing a slower development of hazardous conditions.

5.3 Effects of Ventilation and Mechanical Exhaust

Opening condition has a dual effect on smoke movement. On the one hand, increasing the opening area promotes smoke removal and delays smoke-layer descent. On the other hand, enhanced oxygen supply may slightly increase local burning intensity and temperature near the fire source. When the side window is closed in Case C, smoke accumulates most rapidly. The smoke layer descends to 2.0 m at approximately 146 s and to 1.5 m at approximately 276 s, while the visibility falls below 15 m at approximately 142 s. At 300 s, the smoke-layer height is approximately 1.48 m. In Case D, enhanced natural ventilation increases the smoke-layer height to about 2.40 m and visibility to about 20.4 m at 300 s, although the centerline temperature at 1.5 m rises slightly from about 522 degrees C in Case B to about 528 degrees C. In Case E, mechanical exhaust produces the most significant improvement. At 300 s, the smoke-layer height remains above 2.79 m, the ceiling-region temperature is about 310 degrees C, and the visibility is about 29.2 m. The visibility does not fall below 15 m during the 300 s simulation.

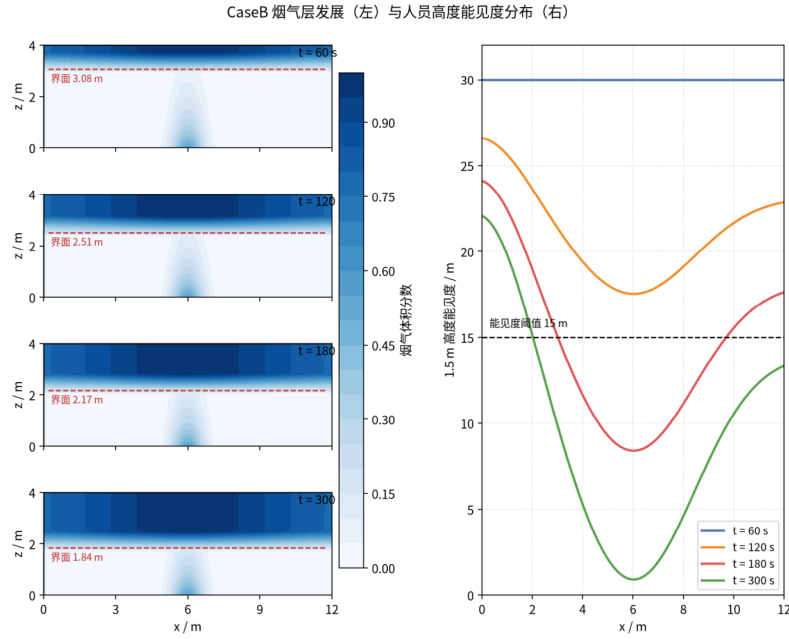


Figure 5. Variations in smoke-layer height and visibility.

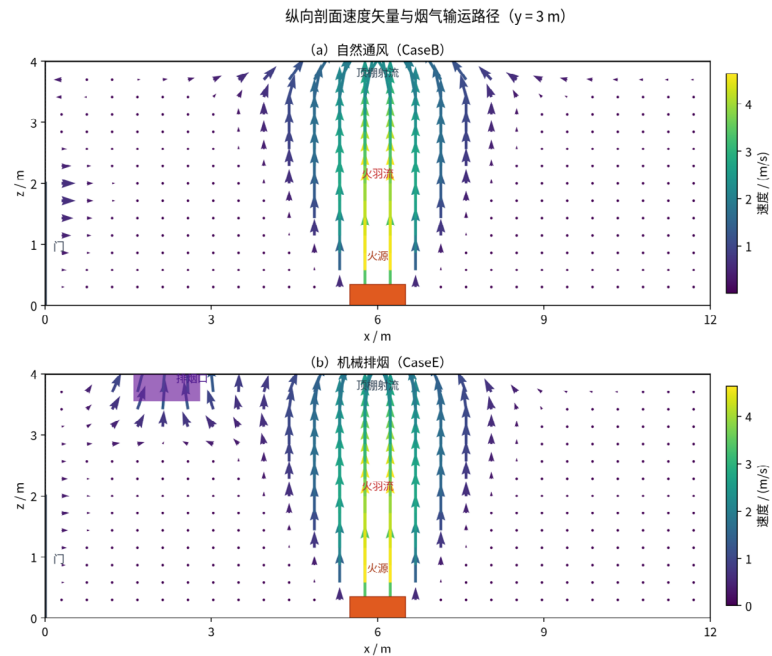


Figure 6. Flow-field distributions under different ventilation and mechanical exhaust conditions.

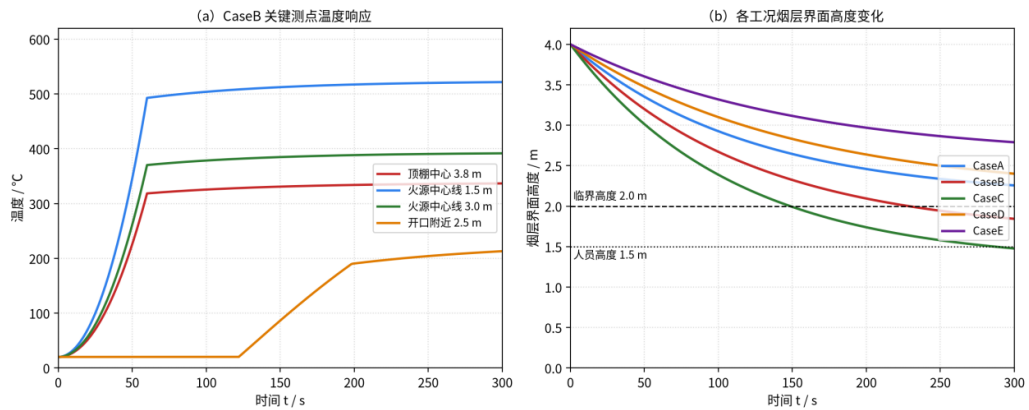


Figure 7. Typical thermocouple temperatures and smoke-layer interface variation.

5.4 Thermocouple Response and Smoke-Layer Interface

The measurement-point data show that the region above the fire source and the centerline region are first affected by the high-temperature plume. The ceiling region continues to heat up as smoke accumulates, whereas the opening region exhibits a more obvious delayed response. The smoke-layer interface gradually descends with time and falls faster under ventilation-restricted conditions. The consistency among multiple indicators indicates that temperature alone is insufficient for evaluating fire hazards in semi-enclosed spaces; smoke-layer height and visibility should also be considered.

6 Engineering Implications and Limitations

From an engineering perspective, mechanical exhaust is effective in delaying smoke-layer descent and maintaining visibility. However, exhaust rate, make-up air path, and opening arrangement should be optimized according to the specific building conditions. A larger natural opening usually improves smoke discharge, but it may also modify oxygen supply and increase local fire intensity. Therefore, smoke-removal efficiency and fire development should be considered simultaneously in smoke-control design. This study has added software-version information, grid-independence verification, and key boundary-condition description, but future work should further refine enclosure thermal properties, fuel properties, exhaust-rate basis, and validation against experiments or code-based criteria.

7 Conclusions

(1) This paper combines a review of fire-dynamics research progress with a PyroSim/FDS simulation of a semi-enclosed space, forming a complete framework from theory review and model construction to scenario comparison and safety evaluation.

(2) In the 2.0 MW baseline case, the smoke layer descends to 2.0 m at approximately 222 s, and the far-field visibility at a height of 1.5 m decreases to 15 m at approximately 216 s, indicating rapid deterioration of the evacuation environment in the later stage.

(3) Closing the side window significantly accelerates smoke accumulation, with the smoke-layer height decreasing to approximately 1.48 m at 300 s. Enlarging the natural opening improves smoke-layer height and visibility but may slightly increase local temperature.

(4) Mechanical exhaust provides the most significant smoke-control effect. At 300 s, the smoke-layer height remains above 2.79 m and the visibility is approximately 29.2 m, which is substantially better than the natural-ventilation cases.

(5) For journal submission, it is recommended to further supplement the basis of HRR selection, material thermal properties, exhaust-rate source, and comparisons with experimental data or code-based limits to improve model credibility.

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