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# A SIMULATION METHOD FOR FIREPROOF SPACE DESIGN IN AVIATION AIRPORT TERMINALS

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**Abstract**
To scientifically design a fireproof space system for general aviation airport terminals, a simulation method was proposed by comparing smoke spread, temperature, visibility, and evacuation time. Taking the civil aviation airport of Luoyang, China as an example, four fire scenarios were set in the business and baggage areas through fire zoning, and the evolution of visibility and temperature under different scenarios was analysed. Then, the safe evacuation time and the available evacuation time under each scene were comparatively discussed, and the spatial optimization layout effect and the safety of personnel evacuation in the terminal on the fire scene were verified through simulations. Results show that the available safe evacuation time in the baggage area and business area increases from 401.5 seconds and 388.3 seconds to 524.2 seconds and 424.5 seconds, respectively, after the addition of the smoke control system and fire zones in the terminal. The required safe evacuation time in the event of a fire is 300 seconds, which is shorter than the available safe evacuation times. The obtained conclusions provide a novel method for developing efficient emergency evacuation strategies for airports.
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**Key Words:** Performance-Based Fire Protection Design, Fire Simulation, Emergency Evacuation

## 1. INTRODUCTION

Airports are regarded as the foundation of air transportation and are considered pivotal components of the aviation system, with terminals being classified as one of the most essential facilities within airports. With the rapid development of civil aviation, an increase in passenger throughput at airports has been observed, leading to escalating safety challenges for multifunctional airport terminals [1]. Terminals are recognized as not only primary gateways for passengers entering and exiting airports but as centralized hubs for activities such as waiting, shopping, and dining [2]. As a result, the safe operation of terminals is deemed essential for maintaining smooth airport operations and ensuring the safety of passengers [3]. Fires are identified as one of the most devastating hazards for airports. Due to the dense concentration of people, the widespread presence of electrical equipment, and the potential storage of flammable materials in certain areas, the risk of fire in terminals is significantly increased. In the event of a fire, rapid flame spread and smoke accumulation are likely to occur, substantially increasing the probability of large-scale casualties and property damage [4]. Whether individuals inside the terminal can be evacuated to safety within a limited time is considered a critical factor affecting aviation safety. Therefore, the scientific formulation of fire emergency evacuation strategies is viewed as a prerequisite for ensuring and improving the efficiency of personnel evacuation during emergencies.

However, traditional emergency evacuation drills are often influenced by factors such as participants' attitudes, scenario settings, skills and experience, and fatigue during the drills. These factors can lead to suboptimal drill outcomes and fail to accurately reveal the movement patterns of individuals evacuating from terminals under emergency conditions. Consequently, current study on emergency evacuation in terminals predominantly relies on simulation-based methods to develop evacuation strategies. Compared to actual drills, simulation-based approaches significantly reduce labour and financial costs while allowing repeated testing to evaluate the effectiveness of various strategies or plans. Nevertheless, simulations focused solely on evacuation strategies may fail to account for the variability of real-world disaster conditions, potentially resulting in significant deviations between simulated results and practical applications. To address these limitations, this study first applies performance-based fire protection design to airport terminals and simulates various fire scenarios. Subsequently, evacuation processes are modelled to analyse personnel movement and propose targeted improvements. These measures aim to provide a scientific basis for fire emergency management in terminals, ensuring maximum safety for occupants and minimizing losses caused by fires.

## 2. STATE OF THE ART

For studies on fire protection design, Jokinen et al. [5] used a calculation model and a simplified model to study four local fire scenes and analyse the fire safety of the steel structure of Nokia Go Center in Finland. Alasiri et al. [6] used the finite element model to simulate the nonlinear deformation, instability, and connection damage of buildings under the conditions of earthquake and subsequent fire; evaluated the influence of post-earthquake fire on steel frame buildings; and proposed the necessity of preventing the collapse of building structures by adding structural design or fire protection. D'Ovidio et al. [7] proposed a set of passive and active lithium fire prevention, detection, and mitigation measures in line with major international and national fire protection standards to minimize fire risk. Cantor et al. [8] presented a new standard fire curve to simulate the external wildfire caused by the burning of trees and bushes and to design and protect residential buildings at the junction of urban wilderness from natural wildfire. To sum up, the current study on fire protection design mainly concentrates on the traditional normative fire protection design, where the fireproof performance of structures is predicted and evaluated via simulation software. However, performance-based fire protection design is lacking, and few studies comprehensively consider fire protection design from the perspective of environmental factors.

In terms of studies on emergency evacuation, Lotero et al. [9] proposed a framework by combining fire simulation with the Ford–Fulkerson algorithm to quantify the risk and calculate the best evacuation path. Keykhaei et al. [10] proposed a situation-aware evacuation framework, which combined the A* search algorithm and the Bayesian inference method to significantly shorten the evacuation time. Sheeba and Jayaparvathy [11] presented a discrete-time Markov chain model to evaluate the evacuation time in this case by considering factors such as staircase confluence and floor congestion. Ilkhani et al. [12] determined the most suitable information content and form for tunnel emergency evacuation by evaluating the driver's response to variable information signs to reduce the possibility of catastrophic accidents and mitigate their consequences. The above results show that relevant scholars have mainly optimized the emergency evacuation process. Moreover, they used all kinds of simulation technologies and models to evaluate evacuation efficiency and explored the influencing degree and importance of factors such as evacuation path, exit layout, and emergency broadcasting. However, the optimization degree in personnel evacuation has been scarcely discussed from the angle of designing and improving disaster-stricken environments.

Given the limitations of the existing studies, this work performed fire zoning and a smoke control system was created based on performance-based fire protection design considering the fire protection factors of the terminal. In this way, the available safe evacuation time (*ASET*) in case of the fire in the terminal was lengthened. Then, the personnel evacuation time under fire scenes in the terminal was analysed via Pathfinder, and the feasibility of the proposed performance-based fire protection design was verified. This work is expected to provide a decision-making reference for improving the emergency evacuation efficiency in airport terminals.

The remainder of this paper is organized as follows: Section 3 describes the personnel evacuation criteria, the fire scene simulation and safety evacuation simulation under performance-based fire protection design, and the parameter setting rules. Section 4 comparatively analyses the *ASET* under multiple fire scenes and the results of the safe evacuation simulation. The final section summarizes the whole paper and draws relevant conclusions.

## 3. METHODOLOGY

### 3.1 Fire simulation scenes and parameter settings

Performance-based fire protection design is a building fire protection design method [13] that is based on fire safety engineering, sets fire safety objectives for specific buildings, and uses recognized analytical tools and methods for quantitative analysis to ensure that the design scheme meets fire safety performance requirements. PyroSim is a fire simulation software [14] that integrates FDS, simplifies fire scene modelling through a graphical interface, supports fire parameter configuration, and can provide three-dimensional visualization results of fire simulation. In this paper, fire scenes in the terminal were simulated using PyroSim after performance-based design.

In this study, the spatial layout structure of the terminal building in a civil aviation airport in Luoyang, China, was taken as an example for the simulation verification of the performance-based fire protection design method. Its planar model is as shown in Fig. 1.

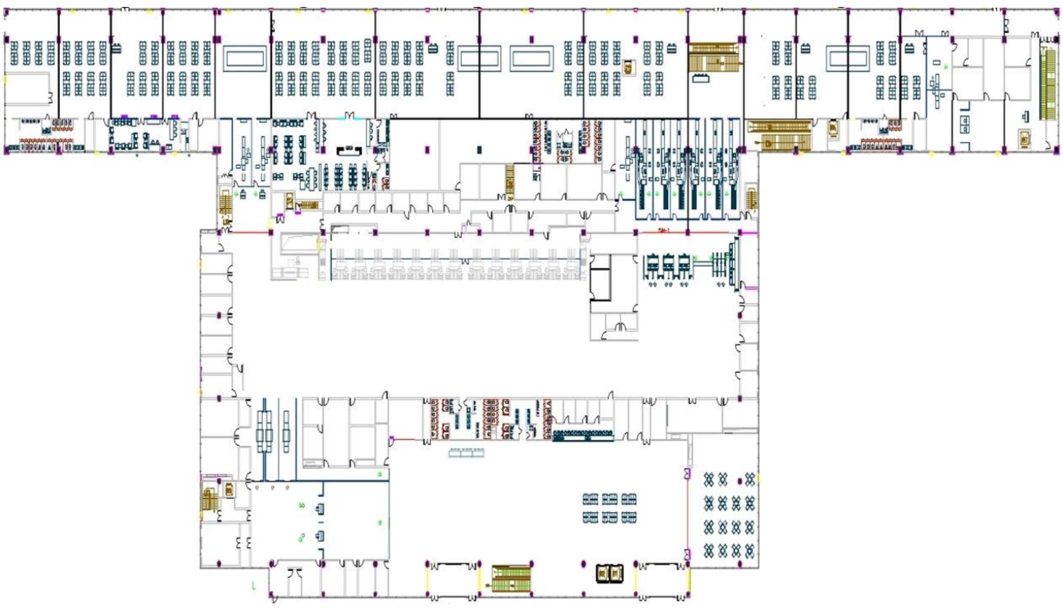

Figure 1: Planar model of departure lounge in the airport terminal.

**Fire zoning**: The terminal building selected in this study is a multi-story civil building with a fire resistance rating of Level I. The departure floor (part) (building area: about 9,479 m$^2$) of the terminal in the civil aviation airport in Luoyang was selected as the study object. As specified in Article 5.3.1 of *Code for Fire Protection Design of Buildings*, the maximum allowable building area of fire zones in single-story and multi-story civil buildings with a fire resistance rating of Level I is 2,500 m$^2$. When an automatic fire extinguishing system is arranged in the building, the area of a fire zone can be doubled. Hence, the maximum fire zone area on the departure floor in this terminal was finally determined as 5,000 m$^2$.

According to the data of relevant scholars [15], the areas of an airport terminal, which may be subjected to fires, include the baggage area, business area, dining area, and office area. According to relevant specifications, the office area is generally an independent fire zone, so two fire source points were set in this design. Fire source point 1 was located in the luggage area of fire zone 1, with the combustible substances in passenger baggage as burning substances. Fire source point 1 was set in the business area of fire zone 2, with combustible commodities stored in the business area as burning substances.

**Setting of smoke control zones**: According to Article 4.2.4 of the Standard, the smoke control zone area was set to 1,000 m² to ensure personnel safety during fires and meet performance design requirements.

A 1 m × 2 m smoke outlet was adopted in the PyroSim-based simulation, the wind speed at the smoke outlet was set to 5 m/s, and the effective smoke exhaust rate per hour in each fire control zone was 10 $m^3$/s, which was greater than the design requirement and met the wind speed requirement at the smoke outlet.

**Selection of heat release rate in case of fire**: Considering that the civil airport terminal, as a tall building, has many people, commodities, and baggage, having more combustible materials means greater heat of combustion and higher fire load, and thus greater damage caused by the fire [16]. Thus, the fire of baggage and commodities in the airport terminal should be the focus of fire prevention. In this study, the fire-induced heat release rate in the baggage area was set as 1 MW and that in the business area was 5 MW.

In the setting of fire scenes, relevant factors, such as the distribution of combustible materials in building space and the fire heat release rate, should be considered [17]. Four fire scenes were set in this design, as seen in Table I, by analysing the fire heat release rate, fire growth rate, and heat release in the airport terminal and considering the typical fire scenes in the airport terminal. With the assumption that automatic spraying failed, the fire in Scenes 1 and 3 naturally spread, without mechanical smoke exhaust; mechanical smoke exhaust was started within 90 s after the fire broke out on Scenes 2 and 4.

Table I: Settings of fire scenes.

| Scene number | Location of fire source | Fire heat release rate | Scene description |
|---|---|---|---|
| Scene 1 | Baggage area | 1 MW | Without smoke exhaust system |
| Scene 2 | Baggage area | 1 MW | With smoke exhaust system |
| Scene 3 | Baggage area | 5 MW | Without smoke exhaust system |
| Scene 4 | Baggage area | 5 MW | With smoke exhaust system |

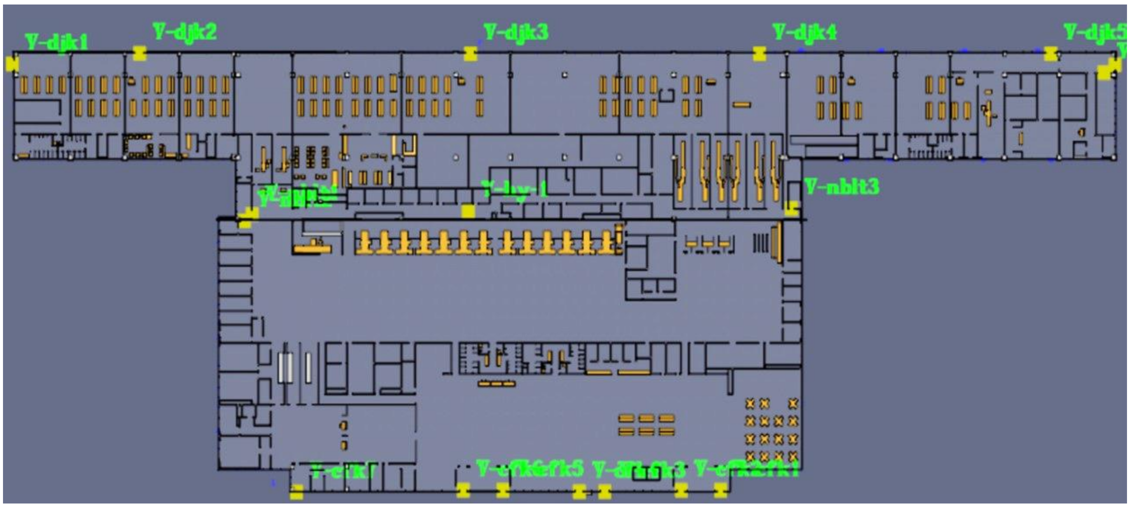


Figure 2: Fire model of check-in and departure lounge in the terminal.

A fire model (Fig. 2) was established by combining the environmental temperature, wind speed, and humidity according to the previously set relevant data, such as fire zoning, smoke control zones, the setting of the fire ignition position, the smoke exhaust rate, the maximum heat release rate of fire sources, airport terminal layout, and the physical properties of materials.

According to the characteristics of the site, all except the fire source were incombustible materials to facilitate simple calculation. Different fire zones were separated using a fire roller shutter. Considering the response time and action time required after the fire took place on the site, fire zones 1 and 2 were separated using obstruction, which would automatically appear through control 90 s after the fire broke out.

A 1 m × 1 m obstacle was adopted as the fire source. Thermocouples were arranged at each evacuation exit and above the fire source to detect indexes such as temperature and visibility, and the temperature at the evacuation exit of 60 ℃ or visibility < 10 m was set as the limit for safe evacuation.

### 3.2 Personnel evacuation simulation scenes and parameter settings

**Personnel evacuation criteria**: The personnel evacuation in the performance-based design is studied based on the safety evacuation criterion, which presents two concepts of time: *ASET* and required safety evacuation time (*RSET*). When *RSET* < *ASET*, the evacuation was safe, and vice versa [18]. Safety should be enhanced by improving the evacuation scheme or the fire protection design, e.g., increasing the mechanical smoke exhaust rate or adding safety evacuation exits. *RSET* refers to the time needed by all personnel within the building to evacuate to safe places. *ASET* means the time when fire spreads until human life is endangered or the time until the fire spreading throughout the surrounding environment exceeds the limit that can be tolerated by humans, as shown in Fig. 3.

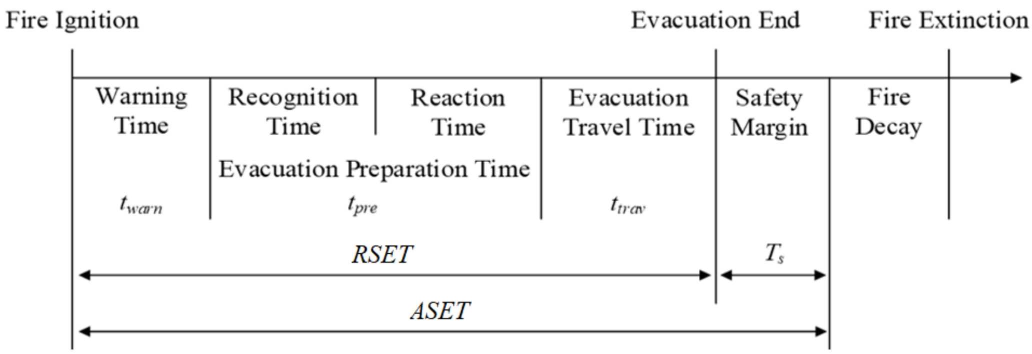


Figure 3: Personnel evacuation timeline.

The safety evacuation criteria are described as follows:

$$RSET + T_s \leq ASET \quad (1)$$

where *RSET* represents the total time spent by personnel in the building from starting evacuation until all are evacuated to the safe area; *ASET* denotes the time when the physiological or psychological limit of evacuated personnel is broken through; and $T_s$ represents the safety margin.

*RSET* is composed of the following three parts, as expressed by the following calculation formula:

$$RSET = t_{warn} + t_{pre} + k \cdot t_{trav} \quad (2)$$

where *k* is the safety factor, which is generally 1.2–1.5.

An automatic fire alarm system was installed in the terminal. According to the worst-case principle, the fire was discovered by the alarm system after burning for 30 s, that is, the alarm time set in this study was 30 s. In this study, therefore, the preparation time for personnel evacuation in case of a fire on the departing floor of the terminal was set to 1 min [19].

**Parameter setting**: Pathfinder is a personnel evacuation simulation software [20] that provides a graphical interface, simulates the evacuation process by combining physical and behavioural models, supports user-defined attributes and 3D visualization, and can be integrated with FDS for fire evacuation analysis. It has been widely used in design, evaluation and emergency management to help optimize evacuation schemes. In this study, the personnel evacuation process was simulated via Pathfinder.

The personnel evacuation efficiency in Pathfinder includes the following factors: personnel density, proportion of personnel, and their movement speed.

According to relevant data in recent years, the passenger throughput of this airport is nearly 10 million passengers, and the average daily use time is 20 h. Then the passenger flow at a certain moment of the day is about 2,070. Thus, the personnel density is 2,070/9,479, being approximately equal to 0.21 $m^2$/ person, which is only the design capacity in this study.

Based on the relevant conclusions [21], the proportion of airport terminal staff is as follows: 54 % are male and 46 % are female, of which 86 % are middle-aged, 2 % are young, and 12 % are old. This design refers to the above data, and the evacuation will be simulated by the following proportions: 40 % for middle-aged men, 40 % for middle-aged women, 15 % for old people, and 5 % for children.

In the existing evacuation simulation, the movement speed of adult men is 1–1.4 m/s, while that of adult women is usually 0.8–1.2 m/s and that of the elderly and children is 0.6–1 m/s [21]. In reference to the existing results, the movement speed of adult men was set to 1.2 m/s, that of adult women was 1 m/s, that of the elderly was 0.8 m/s, and that of children was 0.6 m/s.

**Establishment of the evacuation model**: An evacuation model was established according to the design drawing. First, considering the evacuation in case of a fire in the business area, no evacuation exit was shared between fire zones 1 and 2, in which personnel were evacuated separately. Evacuation was considered to be completed when people in the terminal ran outside the terminal through the boarding gate (outdoor by default), and evacuation was considered to be completed when people in the check-in hall ran to the door through the evacuation passage in the departure lounge (see-off passage by default).

## 4. RESULT ANALYSIS AND DISCUSSION

### 4.1 Fire scene simulation results and analysis

**Fire simulation in the baggage area**: Observing the changes in smoke and temperature in the process of fire simulation showed that the fire spread slowly at the beginning of the fire and began to spread rapidly after 150 s, but it did not expand to the adjacent fire zone, with overall good safety. Meanwhile, the smoke concentration in the presence of the smoke exhaust device was lower than that without any smoke exhaust device. The smoke changes in Scenes 1 and 2 are shown in Fig. 4, and the temperature changes in Scenes 1 and 2 are shown in Fig. 5.

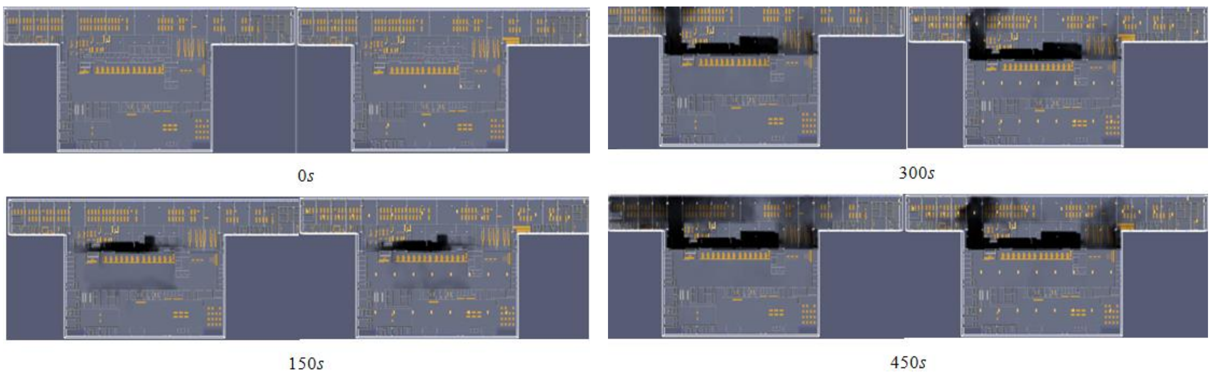


Figure 4: Smoke changes in Scenes 1 (left) and 2 (right).

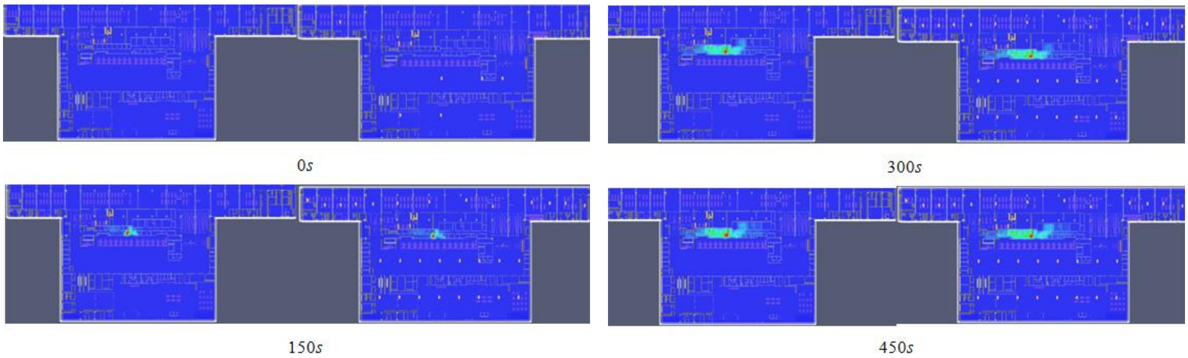


Figure 5: Temperature changes in Scenes 1 (left) and 2 (right).

Judging from the temperature change at the evacuation exit, the temperatures at boarding gate 2 and interior stair 2 were lower in the presence of the smoke exhaust device. The temperature changes at the evacuation exit in Scenes 1 and 2 and their comparison are shown in Fig. 6.

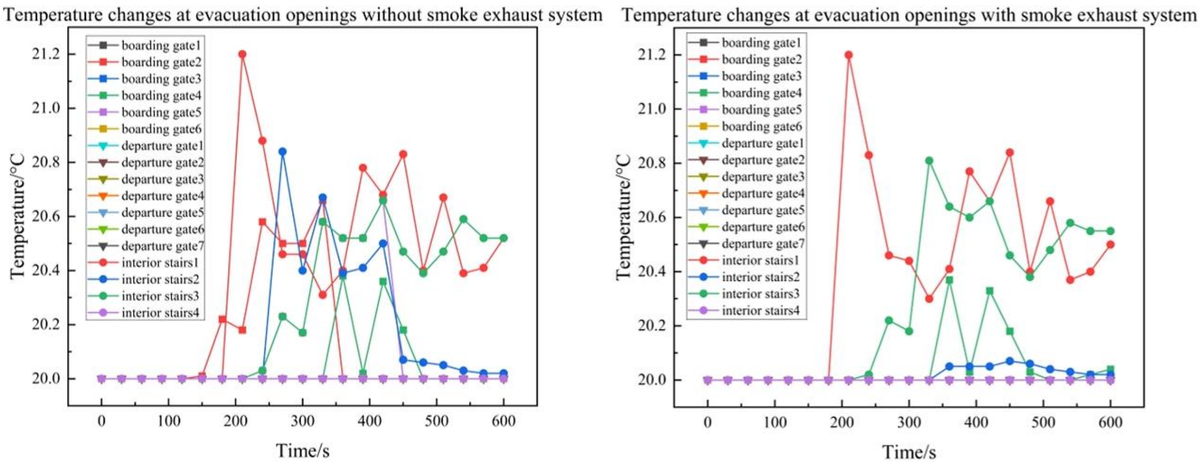


Figure 6: Temperature changes at evacuation exit in Scenes 1 (left) and 2 (right).

From the visibility changes at the evacuation exit, the visibility at the evacuation exit in the presence of the smoke exhaust device was higher than that without any smoke exhaust device on the whole. The visibility changes at the evacuation exit in Scenes 1 and 2 and their comparison are exhibited in Fig. 7.

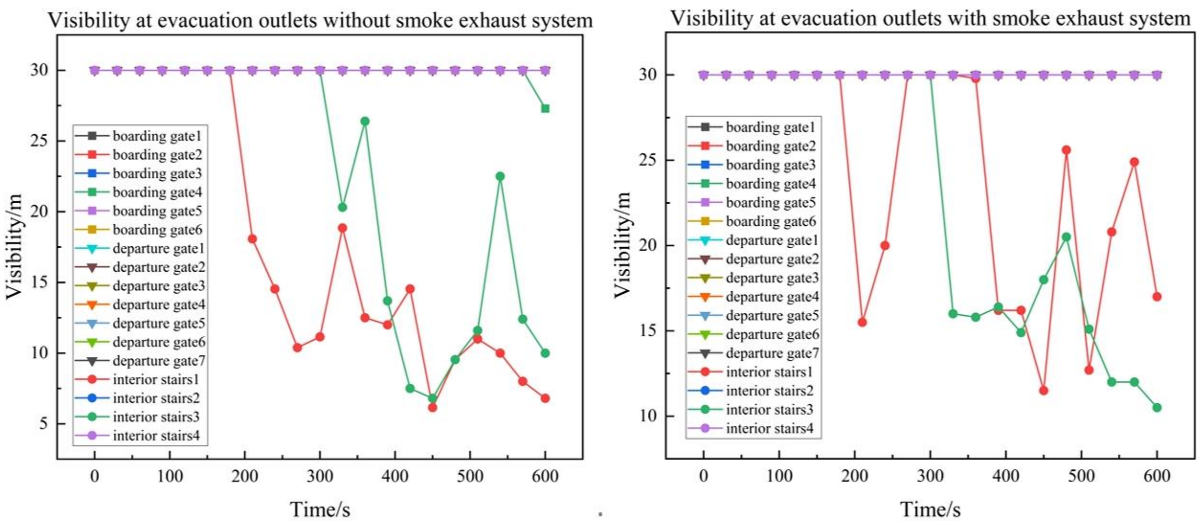


Figure 7: Visibility changes at the evacuation exit in Scenes 1 (left) and 2 (right).

**Fire simulation in the business area**: Observing the change process of smoke and temperature in the fire simulation showed that the fire spread slowly in the early stage due to the influence of fire development. The fire spread rapidly after 326 s, but the fire roller shutter was opened in 90 s, so the fire did not expand to the adjacent fire zone. The smoke changes in Scenes 3 and 4 are shown in Fig. 8, and the temperature changes in Scenes 3 and 4 are shown in Fig. 9.

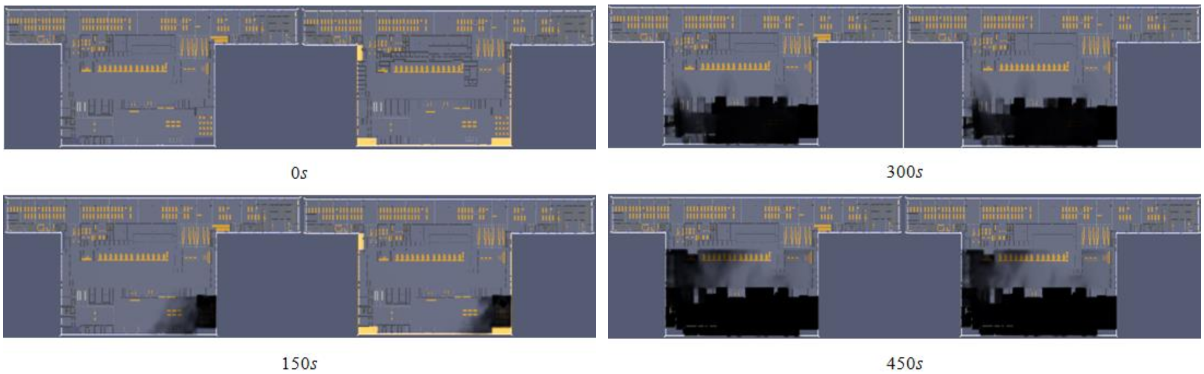


Figure 8: Smoke changes in Scenes 3 (left) and 4 (right).

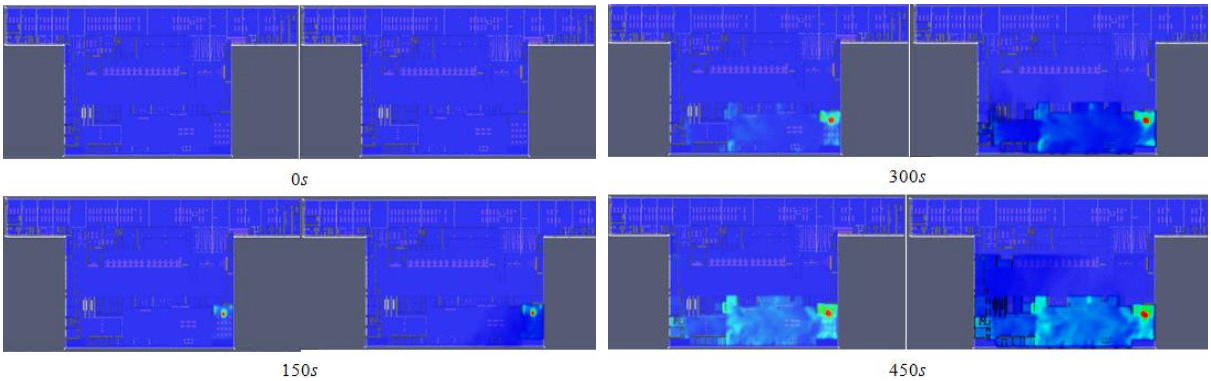


Figure 9: Temperature changes in Scenes 3 (left) and 4 (right).

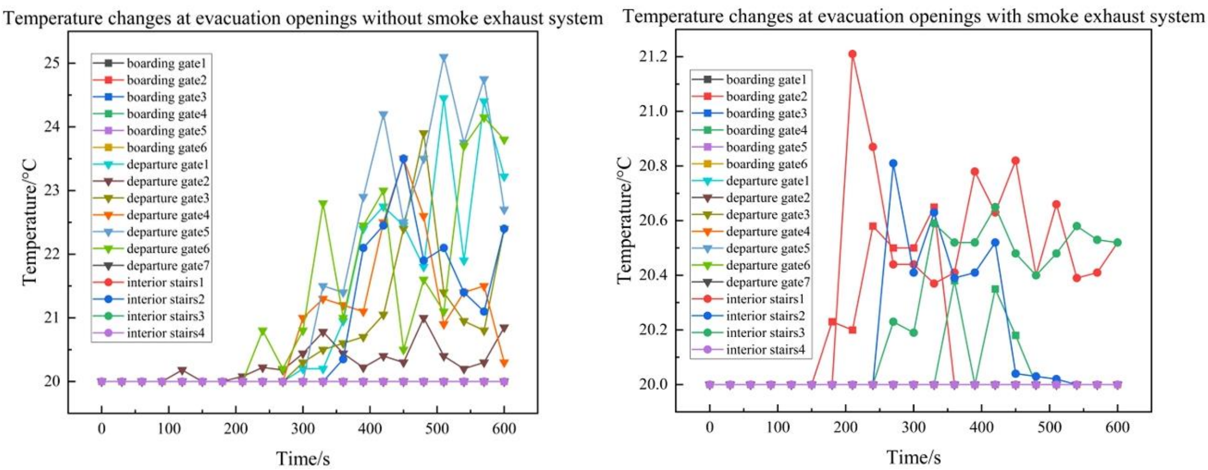


Figure 10: Temperature changes at the evacuation exit in Scenes 3 (left) and 4 (right).

A comparative analysis of temperature change data in Scenes 3 and 4 with and without smoke exhaust shows that when the fire smoke control and exhaust system was installed, the fresh air brought by the start of the smoke control and exhaust system in the early stage of fire development led to a faster temperature rise at the fire source. With the development of the fire, however, the temperature at the fire source when the smoke temperature and fire behaviour reached the maximum in the presence of the smoke exhaust system was evidently lower than that without any smoke exhaust system. The temperature changes at the evacuation exit in Scenes 3 and 4 and their comparison are displayed in Fig. 10.

Based on the visibility changes at the evacuation exit, the visibility at the evacuation exit with a smoke exhaust device was higher than that without the smoke exhaust device on the whole. The visibility changes at the evacuation exit in Scenes 3 and 4 and their comparison are shown in Fig. 11.

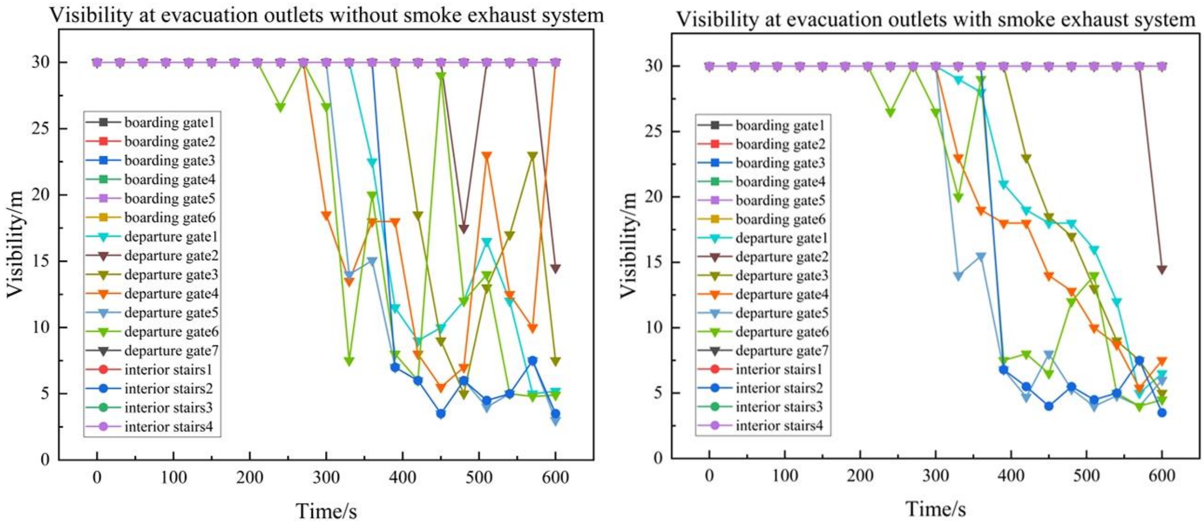

Figure 11: Visibility changes at the evacuation exit in Scenes 3 (left) and 4 (right).

According to the principle that safe evacuation cannot be carried out when the temperature is more than 60 °C or the visibility is less than 10 m, the *ASET* in four fire scenes is shown in Table II.

Table II: ASET under different scenes.

| **Scene number** | ***ASET*** **(s)** |
|---|---|
| Scene 1 | 401.5 |
| Scene 2 | 532.2 |
| Scene 3 | 388.3 |
| Scene 4 | 424.5 |

The *ASET* without smoke exhaust facilities was shorter than that with smoke exhaust facilities. Thus, considering the most unfavourable situation, the time spent in case of no smoke exhaust was taken as the basis for the comparison. Hence, the minimum *ASET* in case of any fire in the baggage area and business area was 401.5 and 388.3 s, respectively.

To sum up, adding the smoke exhaust system can relatively control the spread of smoke and temperature rise (especially the fire source temperature when the fire behaviour reaches the maximum), which helps mitigate the fire behaviour and increase the *ASET*. However, as a result of the suction effect of the smoke exhaust port, the smoke spreads faster in the early stage than that without smoke exhaust, which leads to the rapid decline of visibility near the smoke exhaust device, but the visibility in the presence of a smoke exhaust system is higher than that without any smoke exhaust system. Therefore, the smoke exhaust port should be as far away from the evacuation exit as possible. Meanwhile, the visibility is also controlled to some extent, thus improving the safety of the terminal fire protection design.

### 4.2 Personnel evacuation simulation results and analysis

The personnel evacuation scene after the fire is displayed in Fig. 12. Given the presence of equipment such as airport partitions and security desks, people must pass through multiple obstacles while evacuating, which greatly affected the evacuation time. Moreover, the people in the internal equipment room were relatively far away from the evacuation exit, thus resulting in a considerably long evacuation time.

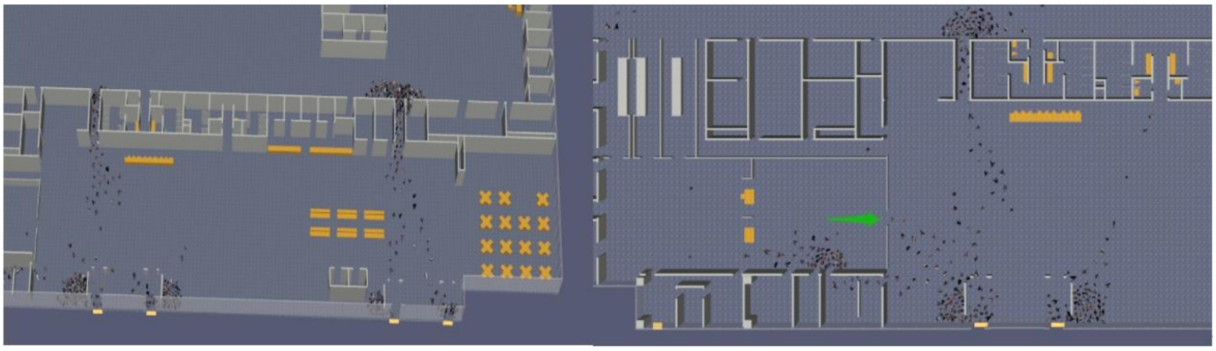

Figure 12: Personnel evacuation scene.

Through evacuation simulation analysis, the total time required for all individuals to evacuate to a safe zone in the event of a fire in the commercial area ($t_{trav}$) is 175 seconds. Considering the preset fire alarm activation time ($t_{warn}$) of 30 seconds and the evacuation preparation time ($t_{pre}$) of 60 seconds, a safety factor ($k$) of 1.2 is applied due to the sufficient buffer time allocated for alarm and preparation. Based on Eq. (2), the required safe evacuation time (*RSET*) for a fire originating in the commercial area is calculated to be 300 seconds. This satisfies the terminal's 5-minute evacuation safety principle, as it is less than the available safe evacuation time (*ASET*) of 388.3 seconds, thereby meeting safety standards and demonstrating the reliability of the design. In this study, Fire Zone 1 and Fire Zone 2 are configured with separate evacuation exits to avoid overlapping evacuation routes. Since the two fire sources – located in the baggage area and commercial area, respectively – are set in distinct fire zones, the required safe evacuation time for both scenarios is consistent. Thus, similarly, the required safe evacuation time for a fire in the baggage area is also 300 seconds, which is less than its available safe evacuation time of 401.5 seconds. This further verifies the reliability of the design, affirming that the performance-based fire protection design in this study is reasonable.

## 5. CONCLUSIONS

The departure level of the terminal building at Luoyang General Aviation Airport in China is selected as the subject of this study. PyroSim and Pathfinder software are utilized to simulate fire scenarios and evacuation processes, respectively. Based on performance-based fire protection design principles, four fire scenarios are established to analyse the variations in visibility and temperature under different conditions, thereby verifying the safety of the proposed design. The following conclusions can be drawn from this study:

(1) Based on performance-based fire protection design, the rational division of fire protection zones and the installation of a smoke exhaust system in the departure level of the terminal building can effectively contain the spread of fire during an incident. These measures also assist in facilitating the orderly evacuation of personnel, thereby enhancing the safety of the terminal and improving evacuation efficiency.

(2) The simulation of four fire scenarios using PyroSim software reveals that, with fire protection zones divided but no smoke exhaust system installed, the available safe evacuation

times for the baggage area and the commercial area are 401.5 seconds and 388.3 seconds, respectively. After the installation of a smoke exhaust system, the available safe evacuation times increase to 532.2 seconds and 424.5 seconds, respectively. This demonstrates that the addition of a smoke exhaust system can effectively extend the available safe evacuation time and enhance the fire safety of the terminal building.

(3) Personnel evacuation under fire scenarios in the terminal building was simulated using Pathfinder, resulting in a required safe evacuation time (*RSET*) of 300 seconds. According to the safety evacuation criterion $RSET + T_s \leq ASET$, it was concluded that with fire protection zones divided and a smoke exhaust system installed, the evacuation of personnel in all fire protection zones is safe. This validates the safety and rationality of the performance-based fire protection design proposed in this study.

In this study, the evacuation scenarios were set without considering the impact of different evacuation methods. In future, the team will comprehensively evaluate the effects of various evacuation methods on evacuation efficiency and time, aiming to obtain more accurate results regarding the optimization of building fire safety performance through performance-based fire protection design. These aspects will serve as directions for further exploration in this field.

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