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Numerical Simulation of Smoke Spread and Occupant Evacuation for a College Dormitory

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Abstract

The student dormitory building is a highly crowded place with dense houses and many students. Moreover, there is no automatic sprinkler system in the building, which will seriously threaten lives in case of fire. In view of the above problems, a fire model is established based on block a of a school dormitory, and fire sources are set in the two most unfavorable positions. The smoke flow and the temperature variation at the eight evacuation exits are studied under the above conditions, so as to obtain the available safe evacuation time TASET in case of fire in the dormitory building. Based on the simulation results of fire smoke diffusion, an evacuation model is established to simulate the evacuation under the above different cases, analyze the evacuation path and time, and then calculate the required safe evacuation time TRSET. The research shows that in the simulation cases, it is difficult for all personnel to evacuate within a safe time.

Keywords

Dormitory Fire; Evacuation; Smoke Flow; Pyrosim; Pathfinder.

1. Introduction

With the development of China's higher education, the demand for student dormitories in Colleges and universities is expanding. Student dormitory buildings with huge construction area and complex structure and function have appeared one after another. The increasingly complex student dormitory building also brings many fire hazards. In addition, there is no mechanical ventilation in the building. In case of fire, the smoke diffusion direction may be consistent with the evacuation direction, which is easy to cause personnel suffocation. Therefore, the risk and harmfulness of fire in student dormitory and the law of personnel evacuation in fire should be considered.

n the 1970s, Professor H.W. Emmons of Harvard University established the regional simulation theory of building fire based on the principles of mass conservation, momentum conservation, energy conservation and chemical reaction, marking the beginning of human beings taking fire as a dynamic system and using physical and chemical principles to understand the evolution process of the system, creating a precedent for fire scientific research [1]. In terms of personnel evacuation, Bryan, an American scholar, found the return behavior in a fire investigation in Maryland in 1956, which became one of the milestones in the study of crowd behavior in fire [2]. China's related research started late, but developed rapidly. In 1989, the State Key Laboratory of fire science, University of science and technology of China was established. The laboratory first proposed a new field, area and network simulation method and developed a comprehensive model combined with the field area simulation method [3]. In the study of personnel evacuation, Chen Tao and others considered the impact of personnel behavior and fire development on evacuation; The lattice gas model is used to simulate the evacuation dynamics, and the composite fire evacuation model CFE is developed to reveal the dynamic characteristics of traveler congestion and its relationship with pedestrian density [4,5]. Dr.

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Zhang Peihong of Northeastern University used adaptive fuzzy neural network (ANFIS) to realize fuzzy reasoning for the decision-making process before the start of evacuation action, and solved the problems of insufficient data and excessive data noise about evacuation behavior [6]. With the development of computer technology, fire and personnel evacuation simulation develop rapidly. For example, the National Institute of standards and Technology (NIST) developed the fire dynamic simulation software FDS in the 1980s and the regional model CFAST model for calculating multi room fire and smoke spread in the 1990s [7,8]. At present, more than 20 models for building personnel evacuation have been developed, mainly including evanet4, wayout, steps, exit, etc. [9]. In recent years, computer numerical simulation has become the main method of related research [10].

In this paper, two different fire source locations are selected to simulate fire smoke and personnel evacuation respectively, and the available safe evacuation time is calculated based on the simulation results T_{ASET} and necessary safe evacuation time T_{RSET} provides a reliable basis for fire fighting in school apartments and personnel evacuation in case of fire.

2. Project Background

The geometric model is established based on the main structure of dormitory building. The building is 113 meters long and 74 meters wide, with a total construction area of 24650 square meters , a storey height of 3m and six floors. The structure is regular, divided into A1, A2, A3 and A4, of which A4 is 5 floors. There are 8 evacuation stairs and 8 exits. In addition, on the first floor of A4 building, there is a fire truck passageway with a width of 7m and a height of 6m. The location of evacuation stairs and exits on the first floor of the apartment is shown in Figure 1.

According to the most unfavorable principle, two rooms are selected as the ignition position, and all persons are in the dormitory building when the fire occurs. The fire ignition position are the laundry room on the 1st floor of Building A4 and a room on the 1st floor of Building A1, as shown in Figure. 1. The smoldering stage of fire is ignored in the paper.

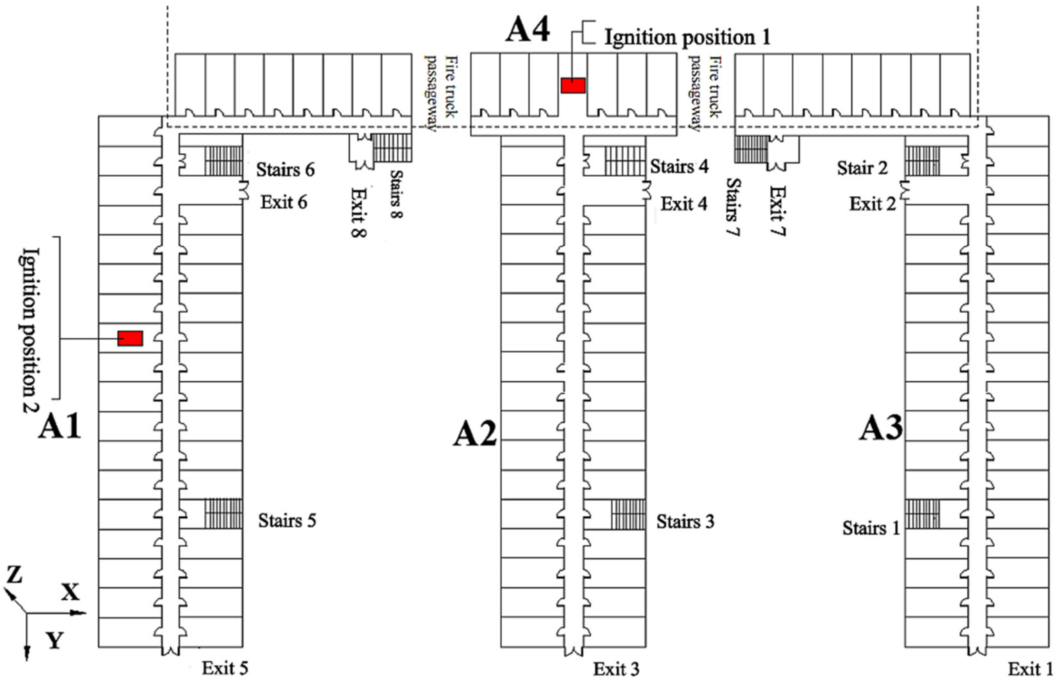

Figure 1. Distribution of stairs and exits on the 1st floor

3. Simulation and Analysis of Fire Smoke Diffusion

3.1. Model Establishment

Fire dynamic simulation software Pyrosim could be used to simulate and predict the flow of smoke, carbon monoxide and other toxic gases in the fire, the temperature of the fire field, and the distribution of smoke concentration [11]. The principle is to use the mixed fraction combustion model and the large eddy turbulence model LES (Large Eddy Simulation) to obtain the transient flow field, and calculate a set of Navier-Stokes equations describing the thermally driven low-speed flow through numerical methods. The basic equations are as follows [12].

Continuous equation

$$\frac{\partial \rho}{\partial t} + \bar{u} - \nabla \rho = -\rho \nabla \bullet \bar{u} \tag{1}$$

Grouping equation

$$\frac{\partial \rho Y_1}{\partial t} + \bar{u} \bullet \nabla \rho Y_1 = -\rho Y_1 \nabla \bullet \bar{u} + \nabla \rho D \nabla Y_1 + m_1''' \tag{2}$$

Momentum equation

$$\frac{\partial u}{\partial t} + \bar{u} + \omega + \nabla H = \frac{1}{\rho}((\rho - \rho_\infty)g + \bar{f} + \nabla \bullet \bar{\tau}_{ij}) \tag{3}$$

Energy equation

$$\frac{\partial}{\partial t}(\rho h) + \nabla \rho h \bar{u} = \frac{dp}{dt} + q''' - \nabla \bar{q} + \Phi \tag{4}$$

Velocity divergence

$$\nabla \bullet \bar{u} = \frac{1}{\rho c_p T}(\nabla \bullet k \nabla T + \nabla \bullet \sum_1 \int c_{p,1} dT \rho D_1 \nabla Y_1 - \bar{q_r} + q''') + (\frac{1}{\rho c_P T} - \frac{1}{P_0})\frac{dp_0}{dt} \tag{5}$$

State equation

$$P_0(t) = \rho RT \sum_1 Y_1 / M_1 \tag{6}$$

The simplified geometric model of the apartment building is established in the ratio of 1:1 to the actual. The 3D model diagram is shown in Figure 2. The ignition point area is set to 2 m*3 m, the power is 2000 kW/m^2, the simulation time is 480s, and the combustion reaction material is polyurethane. The grid boundary is connected to the outside atmosphere, the outside temperature is 20°C, the pressure is standard atmospheric pressure, and the oxygen mass fraction is 23.24%. There is no mechanical ventilation and automatic sprinkler system.

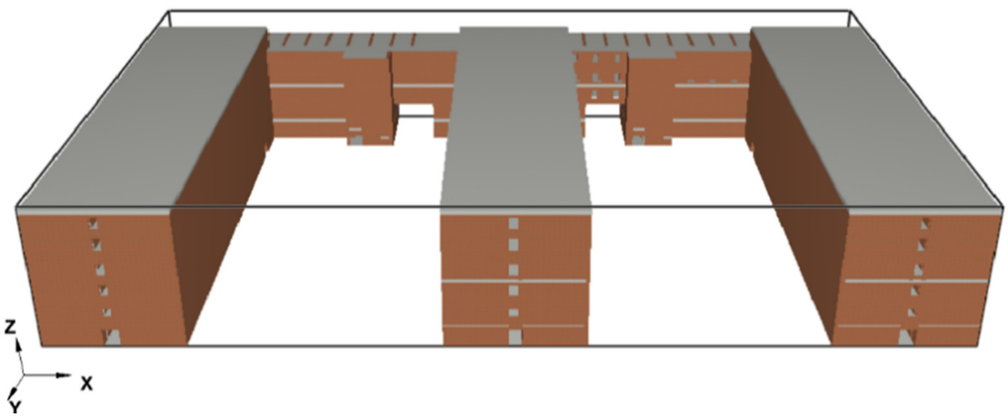

Figure 2. 3D model of the building

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3.2. Simulation Results and Analysis of Smoke and Dust Movement

By analyzing the simulation results, we can get the time when the smoke and dust reaches each exit and staircase in different cases, as shown in Table 1.

Table 1. Arrival time of smoke to exits and stairs

Arrival time of smoke/s	Exit1	Exit2	Exit3	Exit4	Exit5	Exit6	Exit7	Exit8
Ignition position 1	-	-	25.5	3.9	-	-	-	-
Ignition position 2	-	-	-	-	14.9	4.3	-	38.9
	Stairs1	Stairs2	Stairs3	Stairs4	Stairs5	Stairs6	Stairs7	Stairs8
Ignition position 1	135.4	121.9	25.5	3.9	179.1	112.3	43.7	85.9
Ignition position 2	255.5	229.9	227.5	162.3	14.9	4.3	187.2	38.9

-: No smoke arrives within the calculation time.

It can be seen from Table 1 that when the fire ignition position is 1, the smoke and dust quickly diffuses to exit 4 and stairs 4, exit 3 and stairs 3. When the ignition source is located at 2, the smoke and dust quickly diffuses to the exit 6 and the stairs 6, the exit 5 and the stairs 5, and the exit 8 and the stairs 8. There is no smoke and dust at other exits within the calculated time, indicating that these exits are safe to pass under the fire. In addition, from the simulation results, it can be seen that the smoke and dust at other stairways can only diffuse through layers 3, 4 and 5, and does not enter the lower layer within the calculation time. Figure. 3 shows the distribution of smoke and dust at 480 s of ignition position 2. It can be seen that building A1, where the fire brake out and some adjacent buildings A4 are full of smoke, and there are only smoke on floors 3, 4 and 5 in other buildings.This phenomenon is mainly due to the smoke impact effect and fire passage, so that the horizontal diffusion of smoke and dust on floors 1 and 2 of building A4 is blocked by the external wall, and can only diffuse upward through floors 3, 4 and 5, which greatly delays the diffusion speed of smoke and dust to other outlets.

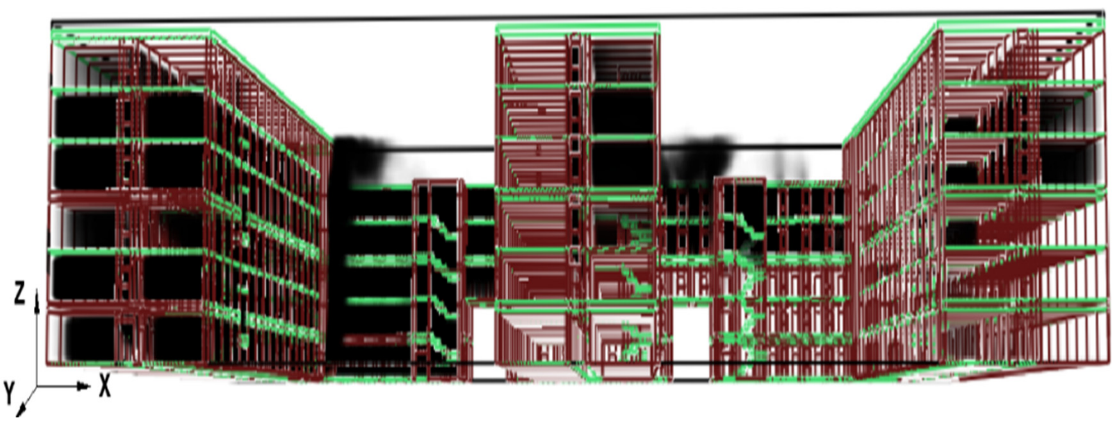

Figure 3. Smoke position distribution, 480s, Ignition position 2

3.3. Simulation Analysis of Temperature Field

In case of fire, personnel need to escape from the above 8 exits. Due to the different fire locations, the temperature of each exit changes differently. If the escape exit is not selected properly, it may endanger life due to the high temperature. In order to scientifically select personnel escape exits, the temperature changes of 8 exits (1.5m high on the floor, close to the height of human chest) within 480s under two cases were detected in the simulation process. The temperature changes of the eight exits with time are shown in Figures 4 and 5, respectively.

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In order to ensure the safe escape of personnel, it is necessary to determine the relationship between temperature and human tolerance time. Table 2 shows the corresponding relationship between air temperature and endurance time proposed in Japanese refuge design [13].

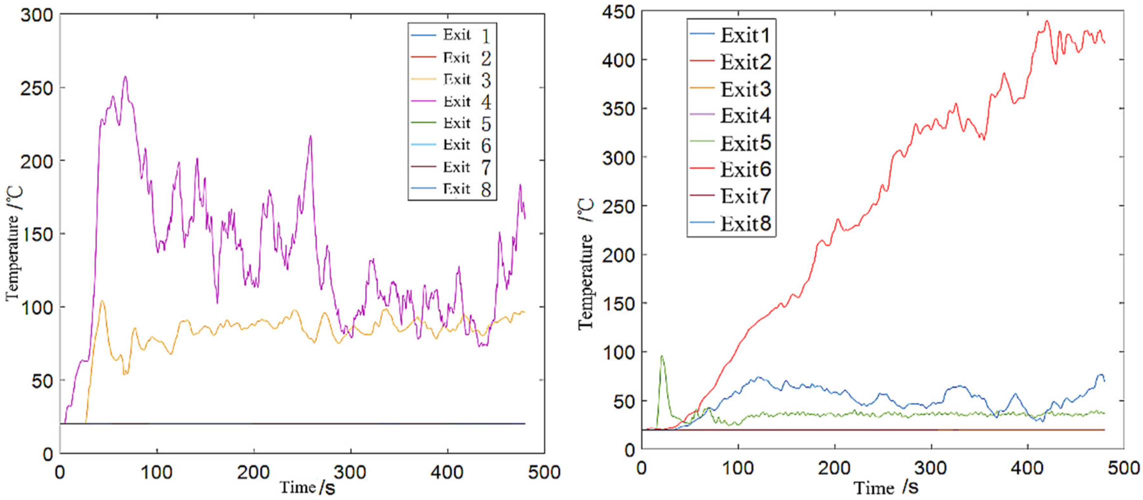

Figure 4. Exit temperature change when the ignition position is 1 and 2

Table 2. The corresponding relation between the critical time and air temperature

Air temperature (°C)	Critical time (min)	Air temperature (°C)	Critical time (min)
50	>60	130	15
70	60	200~250	5

It can be seen from Figure 4 and 5 that the temperature near the ignition position increases rapidly when a fire occurs. By analyzing the smoke diffusion and temperature field distribution, combined with the time and temperature division given in Table 2, the following evacuation scheme can be obtained: When the fire position is 1, do not escape from exit 4. When the fire position is 2, do not escape from exit 6.

3.4. Determination of Available Safe Evacuation Time

In case of building fire, whether people can evacuate safely mainly depends on two characteristic time indicators: available safe evacuation time T_{ASET} and required safe evacuation time T_{RSET}. The basic condition for safe evacuation is T_{ASET}>T_{RSET}.

The dynamic simulation of smoke and dust shows that when the fire is at position 1, the thick smoke fills the A2 building at 440.2s; When the fire is at position 2, the thick smoke fills the A1 building at 379.2s. At this time, dense smoke and high temperature will endanger the lives of stranded personnel. The available safe evacuation time T_{ASET} of buildings under two fire cases can be determined, as shown in Table 3.

Table 3. T_{ASET} of two cases

Ignition position	T_{ASET}/s
1	440.2
2	379.2

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4. Personnel Evacuation Simulation

4.1. Model Establishment

Pathfinder is a personnel emergency evacuation simulation system developed by American Thunderhead engineering company. The motion environment of the system is a complete three-dimensional triangular mesh design environment. A set of parameters are set for each person, and the independent motion of each person is simulated respectively. The evacuation process of dormitory personnel is simulated by Pathfinder software [14].

Table 4. Simulated persons' attributes

Category	Young Man	Young woman	Middle aged men	Middle aged women
Age	18-35	18-35	35-60	35-60
Speed (m·s-1)	1.51	1.30	1.39	1.25
Diameter (m)	0.463	0.424	0.473	0.449
Quantity	2458	152	9	7

According to the most unfavorable principle, a total of 2626 people are set in the dormitory building in case of fire. See Table 4 for different attribute classifications of people at different age levels. Considering that emergency exits 1, 3 and 5 are closed daily, the opening and closing states of emergency exits under different cases are simulated respectively. Based on the simulation results of fire smoke diffusion, the setting of evacuation path is shown in Table 5. Select steering mode during simulation.

Table 5. Evacuation cases

Ignition position	Emergency Exit	Path setting
1	Open	Exit 4 and stairs 4 on the first floor are impassable
	Closed	Exit 1, 3, 4, 5 and stairs 4 on the first floor are impassable
2	Open	Exit 6 and stairs6 on the first floor are impassable
	Closed	Exit1, 3, 5, 6 and stairs 6 on the first floor are impassable

The Pathfinder model is shown in Figure 5.

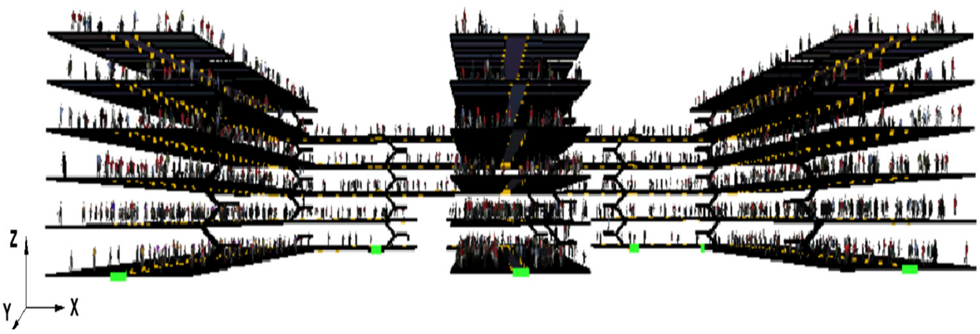

Figure 5. Evacuation model

4.2. Calculation Method of Evacuation Time

In case of fire, except for the personnel near the fire location, other personnel generally do not start evacuation immediately. According to the research, the required safe evacuation time TRSET includes several sections, which can be simplified into three stages: alarm time (T_{det}), response time (T_{pre}) and personnel evacuation action time (T_{move}), as shown in equation (7) [15].

$$T_{RSET} = T_{det} + T_{pre} + kT_{move} \tag{7}$$

-K is the safety factor. Based on the SFPE fire protection engineering manual, K =1.1. [16]

Since the student apartment building is equipped with automatic fire alarm device, and the personnel in the building live so long that they are very familiar with the internal situation of the building. In this paper, the alarm time T_{det} = 60s, preparation time T_{pre}=30s.

4.3. Simulation and Calculation of Evacuation Time

The simulation results show that the congestion is serious during the evacuation process, and the congestion occurs in and near the stairwell. See Table 6 for evacuation time and congestion time during evacuation.

In order to better illustrate the evacuation process, the changes of the number of people staying in the building with time under four cases are given, as shown in Figure 6.

Table 6. Evacuation time of different cases

Evacuation scene		Evacuation time/s	Per congestion time/s	Max congestion time /s	Per evacuation time /s
Ignition position 1	Emergency Exit open	313.03	47.27	141.83	119.66
	Emergency Exit closed	397.78	73.35	206.78	170.14
Ignition position 2	Emergency Exit open	302.03	52.67	101.83	122.44
	Emergency Exit closed	390.53	60.34	132.20	151.25

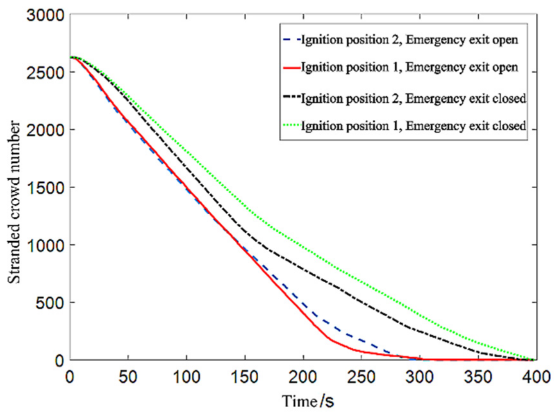

Figure 6. Number of evacuees in the building over time of four cases

The simulated total evacuation time is the personnel evacuation action time (T_{move}). The personnel required safe evacuation time T_{RSET} can be calculated according to equation (7), and the comparison with available safe evacuation time T_{ASET} is shown in Table 7.

Table 7. Contrast between T_{RSET} and T_{ASET} of four cases

Evacuation scene		T_{ASET}/s	T_{RSET}/s
Ignition position 1	Emergency Exit open	440.2	434.33
	EmergencyExit closed	440.2	527.56
Ignition position2	EmergencyExit open	379.2	422.23
	EmergencyExit closed	379.2	519.58

It can be seen from Table 7 that when the fire is at position 1 and the emergency exit is open, T_{ASET} is slightly greater than T_{RSET}, and T_{ASET} is less than T_{RSET} in other cases. Combined with the basic conditions of safe evacuation, it can be seen that in case of fire in student domitory building, people will face great evacuation pressure, especially when the emergency exit is not opened, people will be seriously threatened.

5. Conclusion

In this paper, Pyrosim is used to simulate the domitory building fire, and the available safe evacuation time T_{ASET} is obtained. Based on the fire smoke simulation results, Pathfinder is used to simulate the personnel evacuation of the domitory building, and calculate the required evacuation time T_{RSET}. Comparing and analyzing T_{RSET}, and T_{ASET}, the following conclusions are drawn.

(1) In case of fire in the dormitory building, it is difficult to evacuate for all personnel at safe time, but opening the emergency exit can significantly reduce T_{RSET} and reduce the impact of fire.

(2) When the fire is at position 1, T_{ASET} is 440.2s. When the emergency exit is opened, T_{RSET} is 434.33 s, slightly less than T_{ASET}. When the emergency exit is closed, T_{RSET} is 527.56 s, much greater than T_{ASET} and does not meet the safety evacuation conditions.

(3) When the fire is at position 2, T_{ASET} is 379.2s. When the emergency exit is open, T_{RSET} is 422.23s. When the emergency exit is closed, T_{RSET} is 519.58 s, which is much greater than T_{ASET} and does not meet the safety evacuation conditions.

(4) When the fire is at position 2, the time for the fire to develop into a dangerous state is shorter than that of position 1, and the risk is greater, so it needs to be prevented and controlled.

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