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Optimization research on smoke prevention and exhaust system for air-bearing membrane structure buildings

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ABSTRACT
Due to its advantages in energy conservation, emission reduction and recyclability, air-supported membrane structure (ASMS) has been widely implemented in various applications, including large stadiums, conference centers, warehouses and temporary buildings. Compared to traditional building, the structural and material properties of ASMS are special which significantly affect smoke diffusion and flow behavior during fire scenarios. Moreover, the design methods for smoke management system of ASMS buildings are still lacked and further research is required. In this study, a numerical model of a coal storage bin was built. The impact of several key design parameters, including such as height of natural smoke vent, fire source location and makeup air methods, on the performance of ASMS building`s smoke management system were evaluated. Gas temperature, CO concentration, visibility, smoke exhausting quantity, critical pyrolysis temperature and critical heat radiation intensity were selected as evaluation indexes. The results indicated that better natural smoke exhaust efficiency was achieved when the natural smoke vents were located at the height between 80% and 100% of the building's total height. Setting natural makeup air vent in the wall of smoke bay 3 can achieve the best cooling effect. However, compared to natural makeup air, the natural smoke exhaust efficiency of mechanical makeup air was much better. When the rate of mechanical makeup air reached 120% of the required natural smoke exhausting quantity, it has significant improvements in temperature reduction, visibility and natural smoke exhausting quantity which are crucial for ensuring safe evacuation during fire events. These findings provide a design refer for enhancing fire protection and construction practices in ASMS buildings.

Keywords: air-supported membrane structure, smoke management system, fire numerical simulation

1. Introduction

Air-bearing membrane structure building shows its unique charm in the field of modern architecture with its unique advantages. The emergence of inflatable membrane structure building marks a revolution in construction technology. Although its start in China is late, its unique advantages and gradually improved characteristics make it occupy an important position in modern construction [1-4]. The light weight of inflatable membrane structure building is one of its significant advantages.

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Membrane structure buildings are made of lightweight materials, which have significant weight advantages over traditional building structures, reducing infrastructure and structural loads, and lowering overall costs [5-8]. The long life of inflatable membrane structure buildings is based on the characteristics of the membrane material used. This composite material has excellent mechanical properties, high strength and aging resistance [9-10], and the reasonably designed structure ensures a safe service life of up to 50 years, making it an ideal choice for long-term buildings. In addition, air-bearing membrane structure buildings are characterized by self-cleaning, large span and good structural process [11-13].

The building smoke prevention and exhaust system is a very important part of the building, which is one of the most important measures to ensure the safe evacuation of people in case of fire. In order to ensure that the smoke can be discharged in time when there is a fire inside the building, and to prevent the spread of smoke from affecting the evacuation of people and rescue work [14-17]. Building smoke control and exhaust system can effectively control the spread of smoke in the event of fire to protect the safety of personnel. Therefore, the optimization of building smoke control and exhaust system is particularly important [18-20].

The study aims to evaluate the impact of key factors—such as height of natural smoke vent, fire source location and makeup air methods—on the performance of ASMS building`s smoke management system through numerical simulation. Gas temperature, CO concentration, visibility, critical pyrolysis temperature, critical heat radiation intensity and smoke exhausting quantity were selected as evaluation indexes. It is organized as follows: Chapter 2 introduced theory and design parameters of smoke management system in ASMS buildings. In chapter 3, a numerical model of a coal storage bin was built. Chapter 4 presented the analysis and results which is divided into four parts. Chapter 4.1 introduced the evaluation indexes in this study. Chapter 4.2 focused on the impact of height of natural smoke vents on smoke exhausting quantity and visibility. In chapter 4.3, the influence of number of natural smoke vent openings and natural makeup air vent openings on natural smoke exhaust efficiency was researched. Chapter 4.4 studied the influence of different fire source location on smoke spread and indoor temperature and compared the impact of different makeup air methods on the smoke exhaust effect and cooling effect. Finally, Section 5 summarized the key findings from the simulation results.

2. Theory and Design Parameters

In the construction of ASMS buildings, mechanical pressurization ventilation system was used to rapidly inflate the ASMS. When the indoor pressure increases to about 300 Pa, the mechanical exhaust system is turned on to maintain the stability of the ASMS building through the air volume difference. When a fire occurs in the building, the mechanical pressurization ventilation system should continue to work to avoid excessive fire temperature that causes the gas film surface to burn, resulting in structural collapse and entrapment of personnel. Meanwhile, the smoke management system should be opened in time to help exhaust smoke and evacuate personnel.

The smoke management system is divided into smoke protection system and smoke exhaust system. Smoke protection system includes natural ventilation system and mechanical pressurization ventilation system. The smoke protection system supplies air to the room to prevent the fire smoke from spreading to the area where people gathers. The smoke exhaust system includes natural smoke exhaust system, mechanical smoke exhaust system and makeup air system. The first two are through the setting of windows, the use of fans and other ways to naturally or mechanically exhaust smoke to the outside. Makeup air system includes natural makeup air system and mechanical makeup air system. It is usually opened when a fire is detected and it is used to help exhaust smoke and prevent negative pressure. For ASMS buildings, mechanical pressurization ventilation system is usually used to inflate the gas film structure. The mechanical smoke exhaust system needs to install smoke vents, smoke exhaust ducts and smoke exhaust fans at the top of building, the construction is difficult. Therefore, the ASMS building generally use natural smoke exhaust system.

However, in practical engineering, most ASMS buildings are not really equipped with natural smoke exhaust system because of cost savings. Therefore, when the ASMS building adopts natural smoke exhaust method, the performance effect of the its smoke management system is not clear, and the research on its performance effect is still lacking. Therefore, further research is required.

Before studying the impact of many factors on the performance of smoke management system of ASMS building, it is necessary to calculate the relevant parameters according to the code to ensure the effectiveness of the model`s smoke management system. Such as the minimum clear height, fire heat release rate, smoke plume mass flow rate and smoke exhausting quantity of each smoke control zone, etc. The relevant parameters mentioned in the article are shown in Table 1.

Table 1. Relevant parameters

Nomenclature			
Q	heat release rate (KW)	Q_c	the convective part of the heat release rate, $Q_c = 0.7Q'$ (KW)
ρ_∞	density of air (kg/m^3)		
C_P	specific heat capacity of air $kJ/(kg \cdot K)$	M_ρ	plume mass flow rate (kg/s)
T_∞	the temperature of the room when fire occurs, 293K	H_q	minimum clear height (m)
		H'	building height (m)
D^* / δ_x	grid density in the direction of the diameter of the fire source (m)	a	fire growth factor (KW/s^2)
		V	the volume of exhaust (m^3/s)
Z	the height of the fuel surface to the bottom of the smoke layer (m)	g	gravitational acceleration (m/s^2)
Z_1	flame limit height (m)	t	time required for the fire to develop to a stable stage (s)
k	the ratio of air inlet to smoke outlet		
K	heat transfer factor in flue gas	k	the ratio of air inlet to smoke outlet
ΔT	difference between average temperature of smoke layer and ambient temperature (K)	A_0	area of make-up air (m^2)
		A_v	smoke exhaust area (m^2)
T_f	the temperature of film surface, ℃	T_c	the temperature at minimum clear height, ℃
T_s	absolute temperature of the smoke layer	q	heat radiation flow
F_s	the radiation Angle coefficient between the smoke and the fuel	q_f	heat radiation generated by the flame thermal radiation
σ	postman constant, $5.67 \times 10^{-11} kW/(m^2 \cdot K^4)$	ε	the emissivity of the smoke layer
R	the distance of the fuel from the center of the fire	q_s	heat radiation generated by the smoke layer
C_v	flow coefficient of natural exhaust vent	C_0	intake flow coefficient

The minimum clear height H_q is the height from the lower edge of the smoke layer to the indoor floor:

$$H_q = 1.6 + 0.1 \cdot H' \tag{1}$$

H_q, minimum clear height, m; H', building height, m;

When a fire occurs, there are four stages of fire development: initial stage, growth stage, fully-developed stage and declining stage. Among them, fire in fully-developed stage is the most vigorous and the burning intensity is the largest. The formula for calculating the fire heat release rate is:

$$Q = a \cdot t^2 \tag{2}$$

Q, the heat release rate of fire source; t, time required for the fire to develop to a stable stage, s; a, fire growth factor, this article takes fast fire 0.044 kW/s^2;

The axisymmetric plume is the plume that does not contact the surrounding walls or obstacles and is not disturbed by the air flow. This plume conform to the smoke characteristics of large space structure when fire occurs, so the axisymmetric plume model is selected for simulation. The mass flow rate of the plume is calculated as follows:

$$Z > Z_1, M_\rho = 0.071 Q_c^{\frac{1}{3}} Z^{\frac{5}{3}} + 0.0018 Q_c \tag{3}$$

$$Z << Z_1, M_\rho = 0.032 Q_c^{\frac{3}{5}} Z \tag{4}$$

$$Z_1 = 0.166 Q_c^{\frac{2}{5}} \tag{5}$$

Q_c, convection part of heat release rate, generally $Q_c = 0.7Q$, kW; Z, height from fuel surface to bottom of smoke layer, m; Z_1, flame limit height, m; M_ρ, plume mass flow rate, kg/s;

As shown in Figure 1, the study divided five 60m x 30m smoke bays, each equipped with independent smoke management systems. Each smoke bay specifies the quantity of smoke exhausting and the calculation of the quantity is shown in formula (6), (7) and (8). In the event of a fire, smoke detectors within the affected zone activates the system which automatically opens the natural smoke vent and engages makeup air system to facilitate smoke exhaust. Due to the axial symmetry of the model, the fire source was set in bay 1, 2, 3, corner zone and wall-side zone respectively.

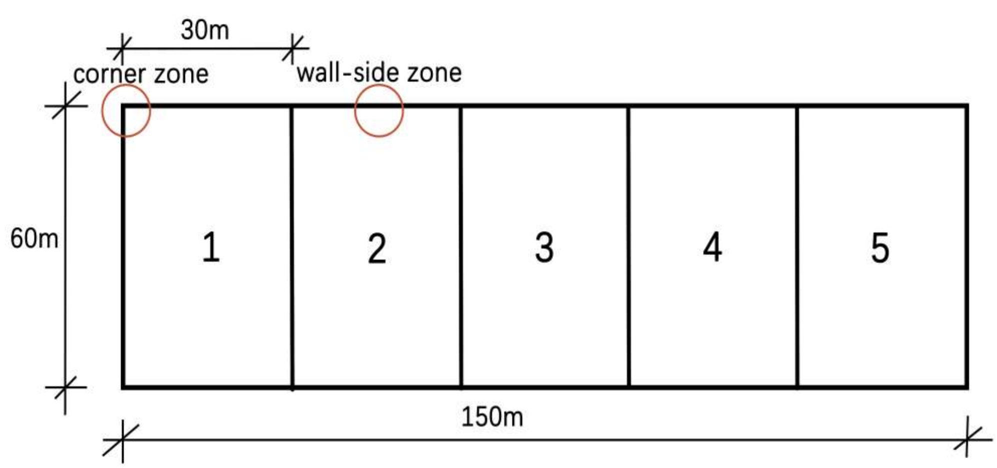


Fig. 1. Diagram of smoke bay

Calculating the difference between the average temperature of the smoke layer and the ambient temperature ΔT. According to ΔT, calculating the smoke exhausting quantity of each zone:

$$\Delta T = KQ_c / M_\rho C_\rho \tag{6}$$

$$T = T_0 + \Delta T \tag{7}$$

$$V = M_\rho T / \rho_0 T_0 \tag{8}$$

ΔT, difference between average smoke layer temperature and ambient temperature, K; T_0, the ambient temperature, 293K; K, heat transfer factor in smoke; $K = 1.0$ when mechanical smoke exhaust is used; $K = 0.5$ when natural smoke exhaust is used.

The cross-sectional area of natural smoke vent required is calculated:

$$A_v C_v = \frac{M_\rho}{\rho_0}\left[\frac{T^2 + \left(A_v C_v / A_0 C_0\right)^2 T T_0}{2 g d_b \Delta T T_0}\right]^{\frac{1}{2}} \tag{9}$$

A_v, area of natural smoke vent, m^2; A_0, area of natural makeup air vent, m^2; C_v, flow coefficient of natural smoke vent, 0.6; C_0, intake flow coefficient, 0.6; M_ρ, plume mass flow rate, kg/s.

In addition, the calculation formula of heat radiation flow on the gas film surface is cited to judge whether the gas film surface is burned through. The formula for calculating the heat radiation flow is as follows:

$$q = q_s + q_f = \varepsilon \times \sigma \times T_s^4 \times F_s + \frac{Q}{12\pi R^2} \tag{10}$$

q, the heat radiation flow of film surface, kW/s^2; q_s, heat radiation generated by the hot smoke layer, kW/s^2; q_f, heat radiation generated by the flame thermal radiation, kW/s^2; ε, the emissivity of the hot smoke layer; T_s absolute temperature of the smoke layer; σ, postman constant, $5.67\times10^{-11}\mathrm{kW}/(m^2\cdot K^4)$; F_s, the radiation angle coefficient between the hot smoke layer and the fuel; R, the distance of the fuel from the center of the fire.

According to the above formula, the important design parameters of smoke management system, such as the area of natural smoke vent and the required smoke exhausting quantity, can be calculated. It lays a foundation for next research. In chapter 3, the numerical model of ASMS coal storage bin will be established.

3. Numerical Model

Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) software developed by the National Institute of Standards and Technology (NIST) specifically designed to simulate fire. FDS has a wide range of applications in fire research and fire safety engineering. FDS uses the Large Eddy Simulation (LES) method to solve the conservation equations of mass, energy and momentum in each grid cell and the gas state equation to provide high-precision simulation results. In addition, FDS can realize the functions of fire dynamic simulation, smoke flow and diffusion, heat conduction and radiation, and evacuation simulation. The use process of FDS software is shown in Figure 2.

As shown in Figure 3, the numerical model of a coal storage bin with dimensions of $150\mathrm{m}\times60\mathrm{m}\times27.7\mathrm{m}$ was built. In order to balance the simulation accuracy and computational resources, it is necessary to select the mesh size in the simulation. The characteristic diameter of the fire was calculated using the formula (11):

$$D^* = \left(\frac{Q}{\rho_\infty C_P T_\infty \sqrt{g}}\right)^{\frac{2}{5}} g \tag{11}$$

Q, heat release rate of the fire source, according to GB 51251-2017, when the height of building is greater than 8m, it is considered as a no-spray building and the heat release rate of building without spray is 20MW; ρ_∞, air density, 1.29 $\mathrm{kg/m^3}$; C_P, specific heat capacity of air, 1.007 $kJ/(kg\cdot K)$; T_∞, indoor temperature when a fire occurs, 293K; g, the acceleration of gravity, 9.8 $\mathrm{m/m^2}$.

Dimensionless numbers D^*/δ_x represents the mesh density in the direction of the fire source diameter. The larger the value, the finer the mesh size, but correspondingly, the longer the calculation time is required. Normally, the value of D^*/δ_x ranges from 4 to 16. The mesh size was 0.5m~2m. As shown in Figure 4, the study carried out the mesh independence analysis. Selecting the point T_5 above the fire source as the detection point and measuring its temperature change. Compared to mesh sizes of 1m and 2m, the 0.75m mesh provides more refined data, capturing more accurate temperature changes. Considering both computational efficiency and accuracy, the selected mesh size for this study was $0.75m \times 0.75m \times 0.75m$, resulting in a total of 756000 grid cells.

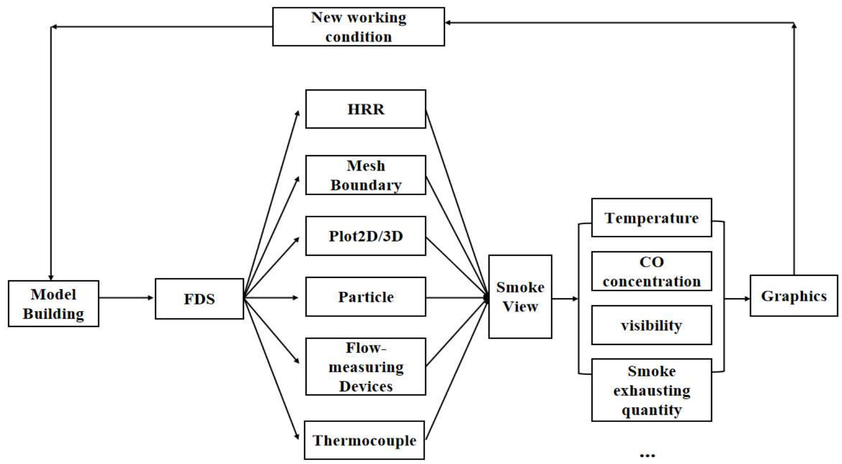


Fig. 2. FDS software use process

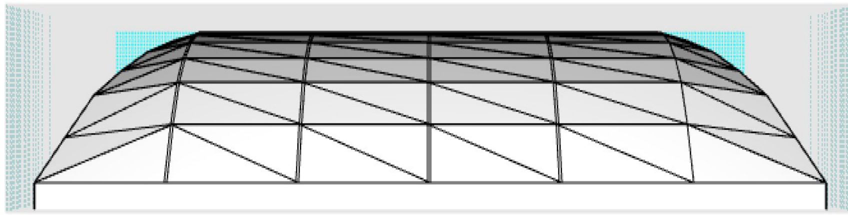


Fig. 3. Model of a coal storage bin

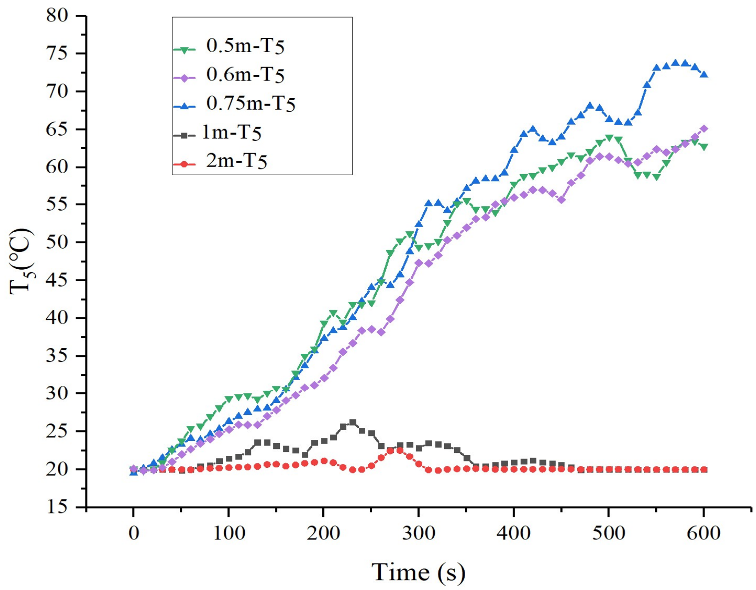


Fig. 4. Mesh independence analysis

4. Analysis and Results

4.1. Evaluation index

According to "SFPE", common evaluation indexes used for building fire simulation are temperature, CO concentration and visibility. In addition, for the consideration of building fire safety and personnel evacuation, the critical pyolysis temperature of the gas film, the critical heat radiation intensity and the smoke exhausting quantity are also adopted as evaluation indexes to evaluate the performance of the ASMS building smoke management system. Table 2 shows the evaluation indexes and limitation values.

Table 2. Evaluation indexes

Evaluation Indexes	Critical value
Gas temperature	≤60 ℃
CO concentration	≤500 ppm
Visibility of the air layer below the clear height	5m, small space
	10m, large space
Critical pyolysis temperature	260 ℃
Critical heat radiation intensity	20kW/m^2
Smoke exhausting quantity	55.8 m^3/s

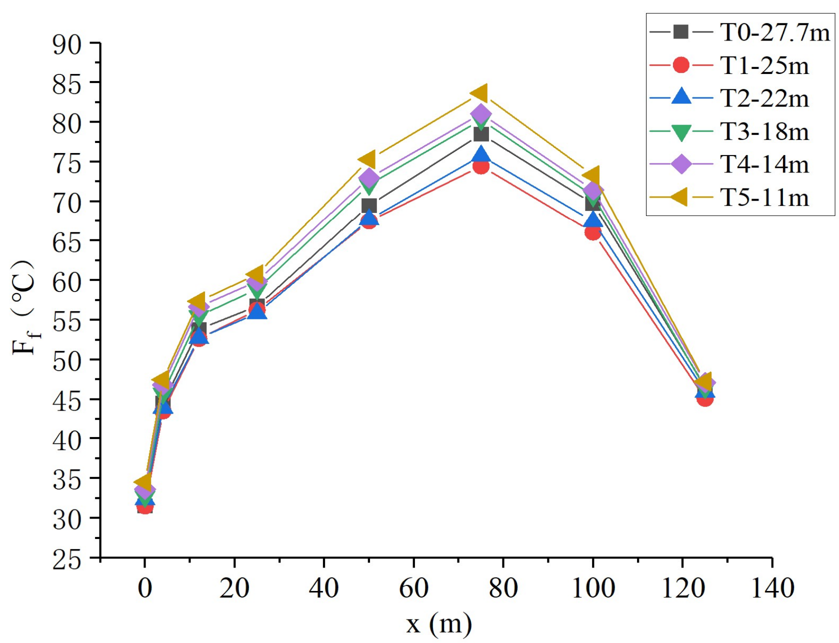
When a fire occurs, the temperature near the fire source rises first. As the smoke spreads upward, it accumulates at the top of the building, raising the temperature of the ceiling. According to the flow characteristics of flue gas, it is known that these two regions are the regions with the largest temperature change. Therefore, it needs to focus on the analysis of these two regions. Among them, gas temperature is used to evaluate the temperature near the minimum clear height T_c in order to ensure the safety of personnel evacuation. Critical pyrolysis temperature and critical heat radiation intensity are used to evaluate the temperature of film surface T_f in order to ensure the safety of the building structure after the fire. In the simulation, the study probes the numerical value of each index by setting the detection thermocouple point, 3D slice.

4.2. Heights of natural smoke vents

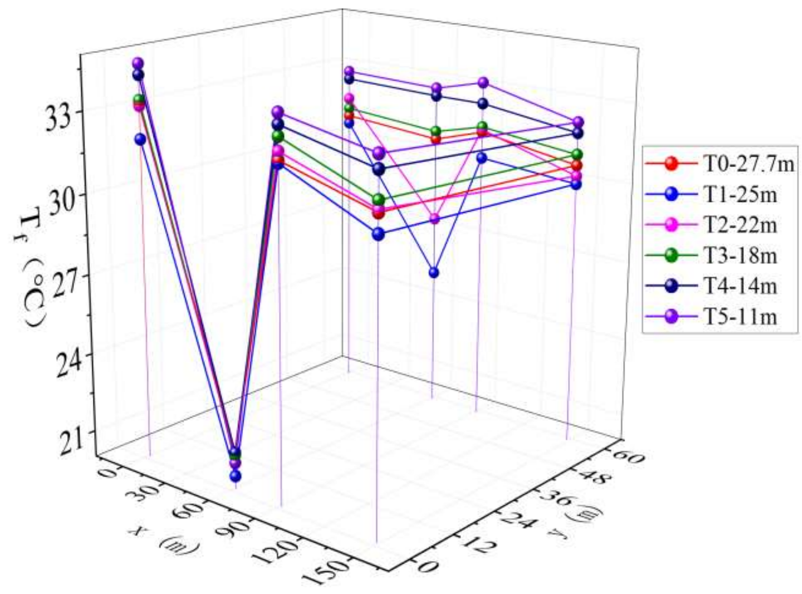
In order to study the influence of natural smoke vent height on smoke exhausting quantity and visibility, natural smoke vents were set at different heights. Fire source was set in bay 3 and natural makeup air method was adopted. Working conditions F0~F5 respectively correspond to natural smoke vent heights of 27.7m, 25m, 22m, 18m, 14m and 11m. Their coordinates are (x=60m, y=30m, z=27.7m), (x=60m, y=22m, z=25m), (x=60m, y=16m, z=22m), (x=60m, y=10m, z=18m), (x=60m, y=6m, z=15m), (x=60m, y=4m, z=11m).

Figure 5 revealed the impact of height of natural smoke vents on cooling. In Figure 5(a), when the height of natural smoke vent is 25m, the temperature of film surface T_f and the temperature at minimum clear height T_c are the lowest. T_f and T_c rose when natural smoke vent height decreased and reached highest when natural smoke vent was set at 11m, T_f is 83.6℃and T_c is 34.7℃, respectively. It can be concluded that T_f does not reach the critical pyrolysis temperature of 260℃ and T_c also does not reach the gas temperature of 60℃, both of which meet the safety requirements.

In Figure 5(b), there are some obvious inflection points where the temperatures are much lower than other detection points. That is because the detection points were set at the position of mechanical pressurization ventilation fan.



(a)



(b)

Fig. 5. (a) film surface temp at different heights; (b) temp at 4.4m at different heights

Smoke exhausting quantity peaks which is 45 m^3/s when natural smoke vent is set at 25m, but it reduces as vent height decreases. This phenomenon occurs because smoke from a fire ascends to the ceiling where it forms a smoke layer. Positioning vents near the ceiling improves smoke exhaust, prevents accumulation and weakens the convective heat transfer between high temperature smoke and the roof surface. When the vents are lowered away from the ceiling, the time required for the smoke layer to descend to the lower vent increases and the smoke exhausting quantity reduces. However, Figure 6 shows that the quantity of smoke exhausting is less than required 55.8 m^3/s when natural smoke exhaust and natural makeup air are adopted.

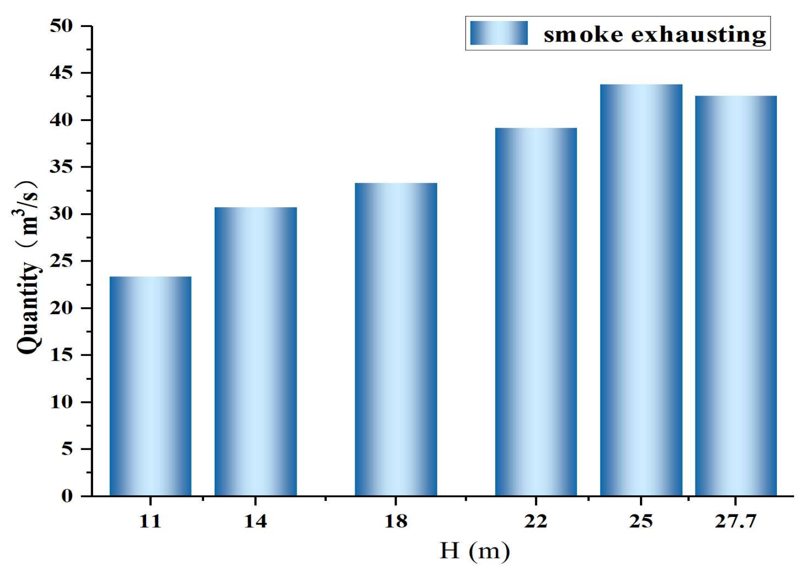


Fig. 6. smoke exhausting quantity varied with different smoke vent heights

As mentioned in Chapter 4.1, for large space buildings, the visibility of 10m should be guaranteed within the minimum clear height range after a fire occurs. Figure 7 illustrates the visibility at the fire source 600s after ignition under F0 to F5 working conditions. The black line in the simulation result figure represents the dividing line of 10m visibility, higher than the black line represents visibility less than 10m, lower than the black line represents visibility more than 10m.In case F0, when the natural smoke vent is positioned at 27.7m, the visibility at 4.4m is optimal and the area covered by the 10m visibility is the largest. As the height of the natural smoke vent decreases, visibility progressively worsens and the 10m visibility coverage diminishes, reaching it lowest point in condition F5, where natural smoke vent height is 11 m. To ensure effective smoke exhaust and visibility, it is recommended that the natural smoke vent should be positioned at 80% to 100% of the total height.

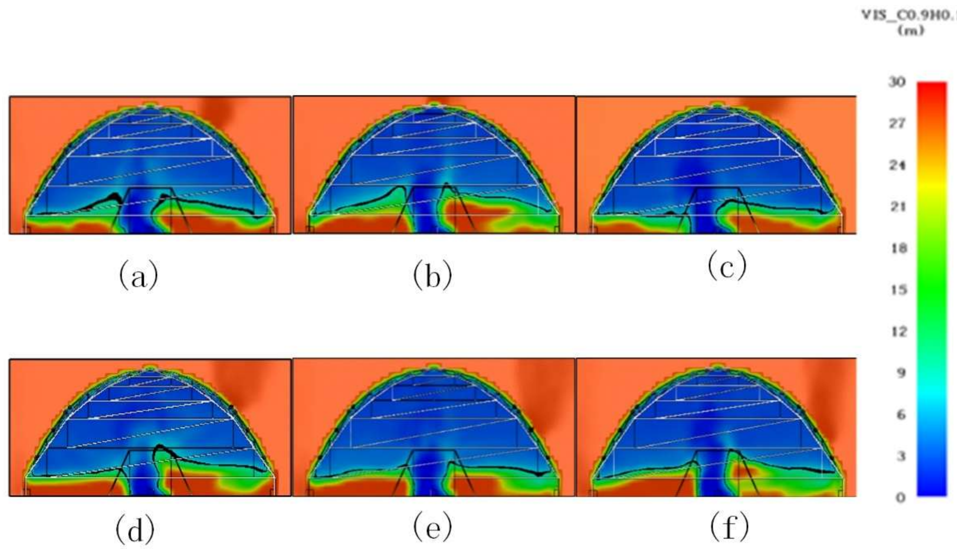


Fig. 7. (a) ceiling jet flow under an unrestricted ceiling, the visibility of 4.4m height plane when vent is set at 27.7m; (b) 25m; (c)22m; (d)18m; (e) 14m; (f)11m

According to the above conclusion, when the natural smoke vent is set at 11m, T_f and T_c are the highest, the smoke exhausting quantity is the lowest and the visibility is not good. Therefore, the working condition F5 which the natural smoke vent is set at 11m, is selected as the most adverse working condition for CO concentration analysis. In Figure 8, the simulation results reveals that during fully-developed stage, the carbon monoxide (CO) concentration at the minimum clear height can reach up to 250ppm which is far below the critical dangerous concentration of 500ppm. This suggests that, under the most adverse conditions, the CO concentration at the minimum clear height in ASMS buildings remains within a safe range. Consequently, this study will not prioritize CO concentration as a primary research index.

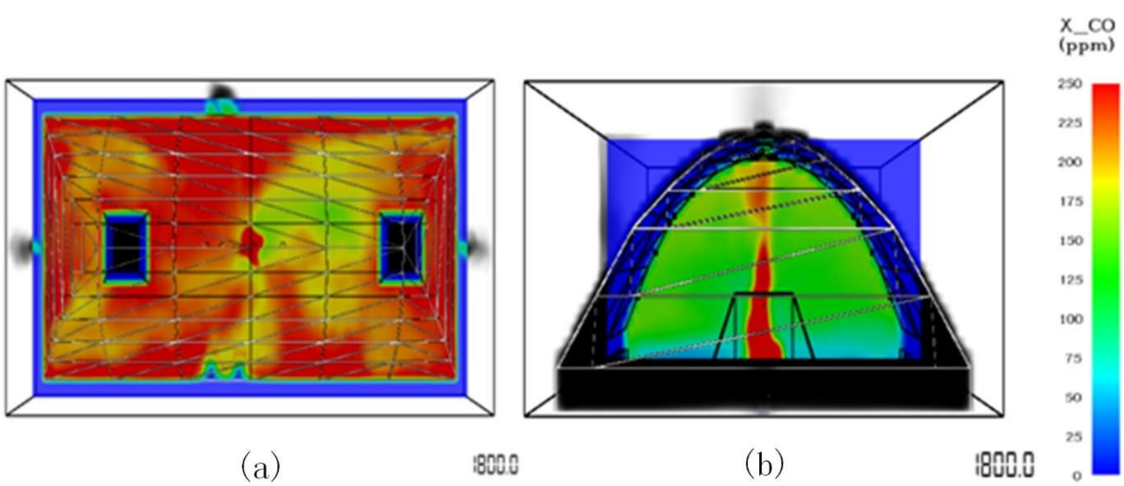
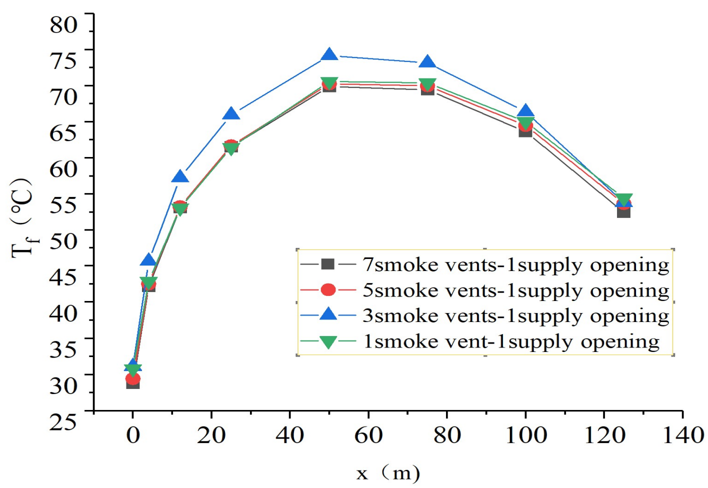


Fig. 8. (a) plot of CO concentration at 4.4m plane; (b) CO concentration map at fire source location

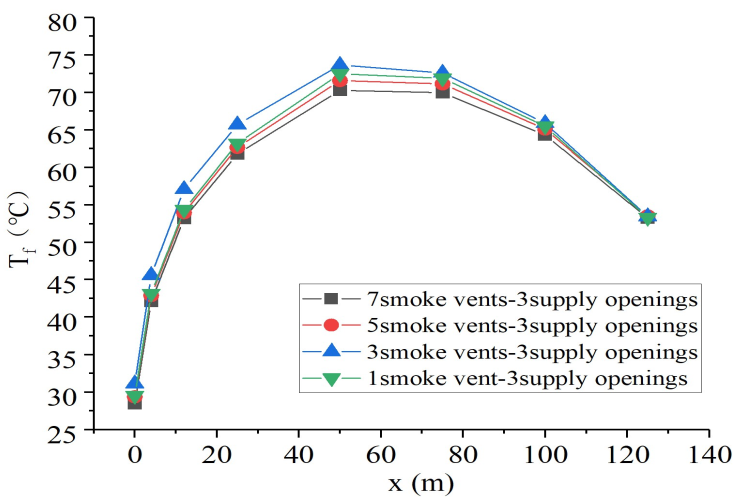
4.3. Number of smoke vent and makeup air vent openings

This section will analyze the impact of the number of natural smoke vent openings and natural makeup air vent openings on smoke exhausting quantity and cooling effect. Too many openings will affect the stability of the air-supported membrane structure, which will not be described in this paper. Therefore, in this study, the natural smoke vent was positioned at height of 27.7m and four kinds of openings were tested: single, three, five and seven. Three kinds of openings are selected for natural makeup air vent: single, three and five.

As shown in the Figure 9, when the number of natural makeup air vent opening is kept constant and seven-opening configuration of natural smoke vent is adopted, is the lowest at 55.4℃ while the is the highest at 58.9℃when three-opening configuration of natural smoke vent is adopted. When the number of natural smoke vent openings remains constant, increasing the number of makeup air vent openings results in a reduction in, though the decrease is relatively small. Figure 10 illustrates that the quantity of smoke exhausting increases as the number of openings increases. However, the smoke exhausting quantity is still less than the required 55.8m^3/s.



(a)



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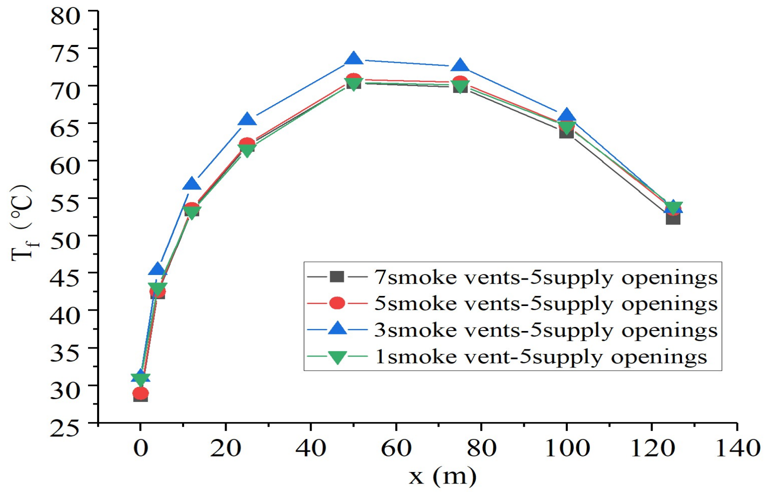


(c)

Fig. 9. (a) 1 supply opening - different natural smoke vents; (b) 3 supply openings - different natural smoke vents; (c) 5 supply openings - different natural smoke vents

Figure11 shows the visibility within the minimum clear height height plane under the conditions of a single natural makeup air vent and four natural smoke vent openings 600s after the fire. As shown in Figure 11(d), when seven-opening configuration smoke vent is adopted, the 10m visibility covers the largest range area while the three-opening configuration covers the smallest. With fewer natural smoke vent openings, the smoke accumulates at the top and cannot be discharged in time. As the smoke layer reaches a certain thickness, it begins to descend along the wall which reduces visibility around the perimeter. With more natural smoke vent openings, a significant quantity of smoke exhausting is directly discharged from the top, improving the visibility coverage.

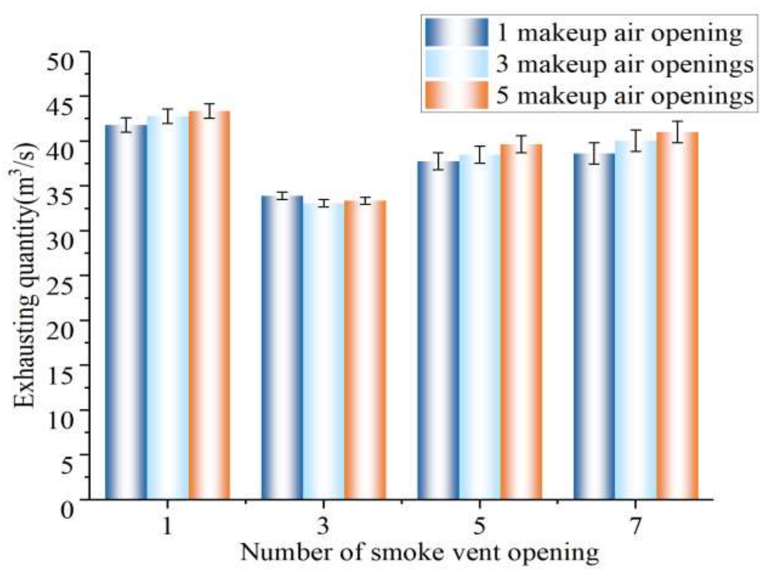


Fig. 10. the smoke exhausting quantity under different natural smoke vent and natural makeup air openings

In conclusion, increasing the number of natural smoke vent openings and makeup air vent openings has a significant impact on the cooling, visibility and smoke exhaust efficiency but smoke exhausting quantity does not reach the requirement. Combined with the conclusion of chapter 4.2, it can be concluded that by using natural smoke exhaust and natural makeup air, the smoke exhausting quantity of ASMS building does not reach the required quantity of smoke exhausting.

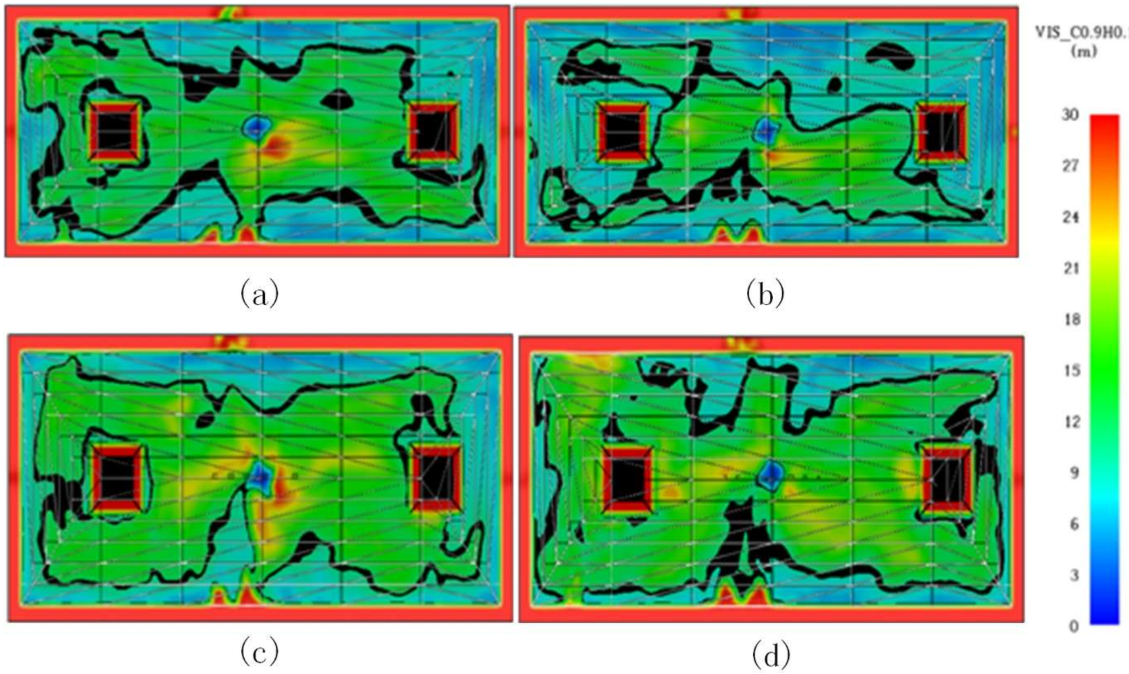


Fig. 11. (a) visibility at the minimum clear height at 600s when a single-opening natural smoke vent is adopted; (b) three-opening vent; (c)five-opening vent; (d) seven-opening vent

4.4. Different fire source location and makeup air method

In this chapter, the influence of fire source position and different makeup air methods on smoke exhaust was studied. As shown in Figure 12, since the building follows an axisymmetric model, the fire sources are set in smoke bay 1, 2 and 3. Taking into account the axisymmetric plume and constrained plume, fire sources are also set at corner zone and wall-side zone ,a total of five types of working conditions: A, B, C, D and E. Case A0 to A5 respectively represent different conditions:A0 without makeup air and A1~A5 corresponding to setting natural makeup air vent in the wall of bay 1,2,3,4 and 5.Similarly, B0 to B5, C0 to C5, D0 to D5, and E0 to E5 follow the same configuration. The working conditions are shown in Table 3.

As shown in Figure 12, the results indicate that T_f is far lower than the critical pyrolysis temperature of 260℃ which can be considered safe. Compared to cases without natural makeup air, Case A with natural makeup air shows an average temperature reduction ΔT 4.4℃, ΔT_B is 2.4℃, ΔT_C is 3.3℃, ΔT_D is 1.2℃ and ΔT_E is 2.3℃.

The temperature comparison results in Table 4 indicate that setting natural makeup air vent in the wall of bay 3 can achieve the best cooling effect. In ASMS buildings, T_f remains within safety limits regardless of where the natural makeup air vent is set. Figure 12 and Figure 13 illustrate when a fire occurs in bays 1, 2 and 3, the drop of T_f is significantly improved in the presence of makeup air compared to conditions without natural makeup air. The average temperature reduction ΔT for Case A is 2.9℃, for Case B is 4.1℃ and for Case C is 3.7℃.

Table 3. Different working conditions of smoke exhausting and makeup air

working condition	HRR (MW)	Fire source	Position of makeup air vent	Position of smoke vent
CaseA0	20	Bay3	No	Bay3
CaseA1			Bay1	
CaseA2			Bay2	
CaseA3			Bay3	
CaseA4			Bay4	
CaseA5			Bay5	
CaseB0	20	Bay2	No	Bay2
CaseB1			Bay1	
CaseB2			Bay2	
CaseB3			Bay3	
CaseB4			Bay4	
CaseB5			Bay5	
CaseC0	20	Bay1	No	Bay1
CaseC1			Bay1	
CaseC2			Bay2	
CaseC3			Bay3	
CaseC4			Bay4	
CaseC5			Bay5	
CaseD0	20	Corner zone	No	Bay1
CaseD1			Bay1	
CaseD2			Bay2	
CaseD3			Bay3	
CaseD4			Bay4	
CaseD5			Bay5	
CaseE0	20	Wall-side zone	No	Bay3
CaseE1			Bay1	
CaseE2			Bay2	
CaseE3			Bay3	
CaseE4			Bay4	
CaseE5			Bay5	

Table 4. Temperature comparison results

Working conditions	Temperature of film surface	Temperature at 4.4m
Case A	A2<A3<A5	A4<A5<A1
Case B	B4<B3<B2	B4<B3<B1
Case C	C1<C2<C3	C3<C2<C1
Case D	D3<D4<D5	D1<D5<D2
Case E	E3<E1<E5	E5<E4<E3

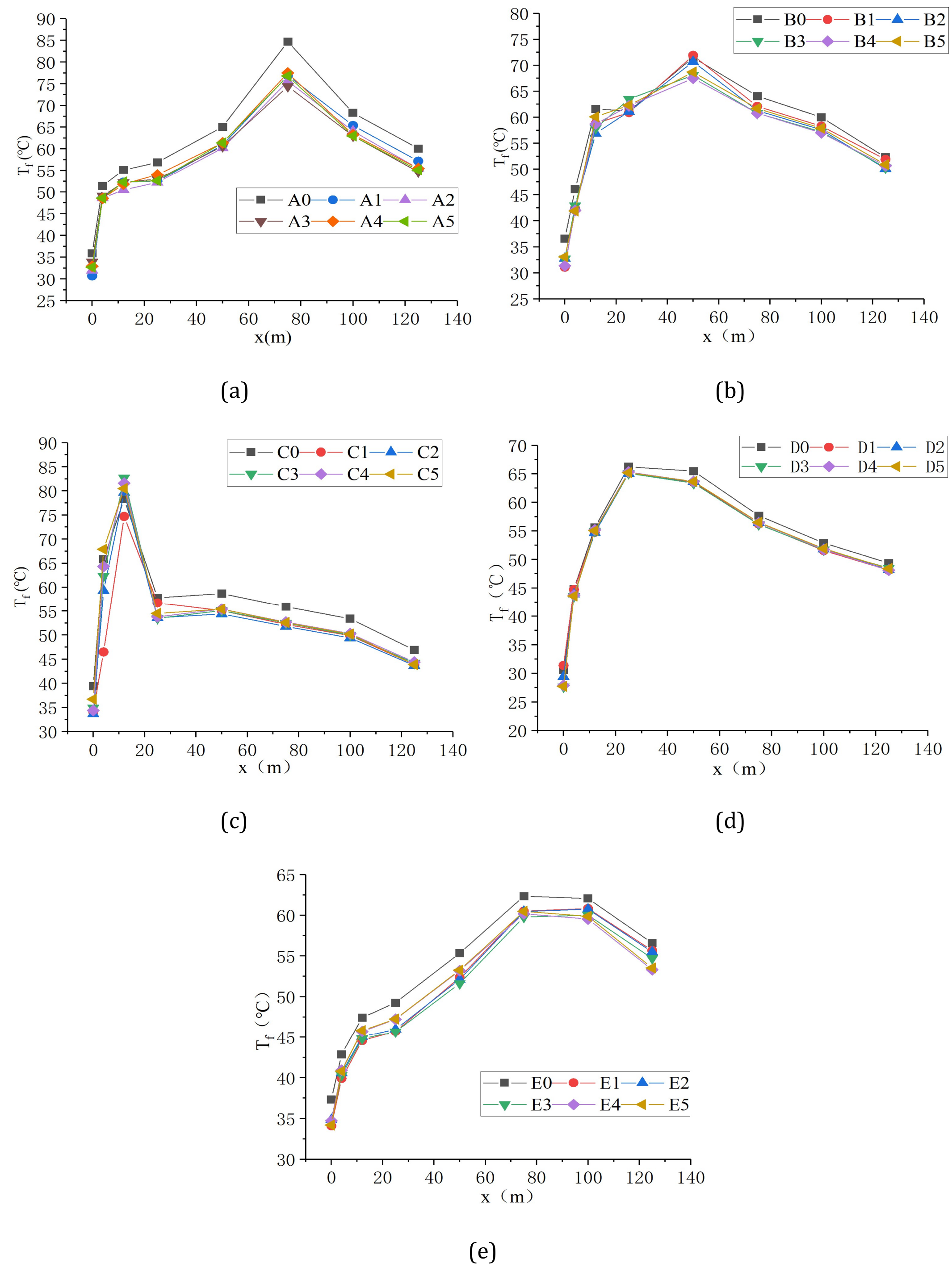
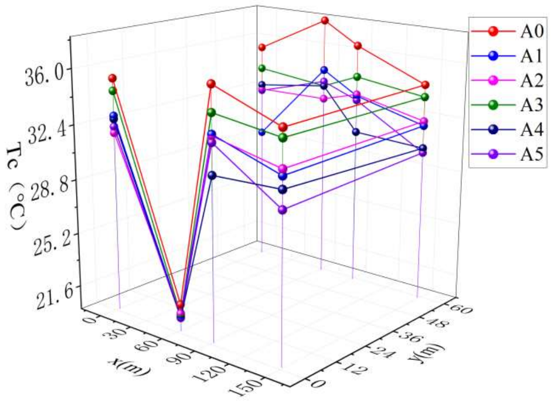


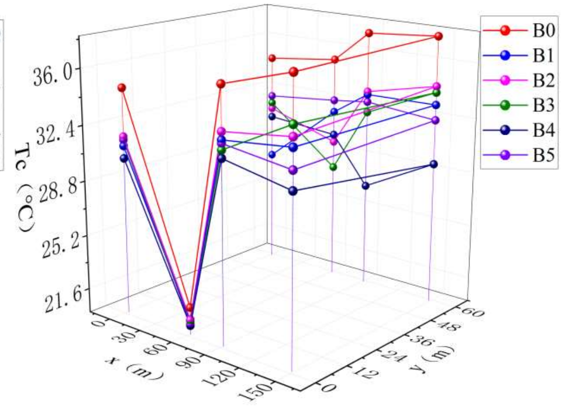
Fig. 12. (a) shows the cooling effect of different natural makeup air vent positions on T_f when bay 3 is on fire; (b) fire in bay 2; (c) fire in bay 1; (d) fire in the corner zone; (e) fire in the wall

However, as shown in Figure 13 (d) and Figure 13 (e), when a fire occurs in corner zone or wall-side zone, localized high temperature can reach up to 240℃.Although this temperature does not exceed the critical pyrolysis temperature of 260℃, there still present a risk. According to formula (10), the heat flux q in the corner area is 33.17 KW/m^2 which surpasses the critical heat radiation intensity of 20 KW/m^2 where the gas film will melt. To prevent the surrounding gas film from melting and burning due to fires in corners or along walls, the safe distance can be obtained by calculating, R=5.2m. Considering a safety factor of 1.2, the recommended safe distance is 6.2m.

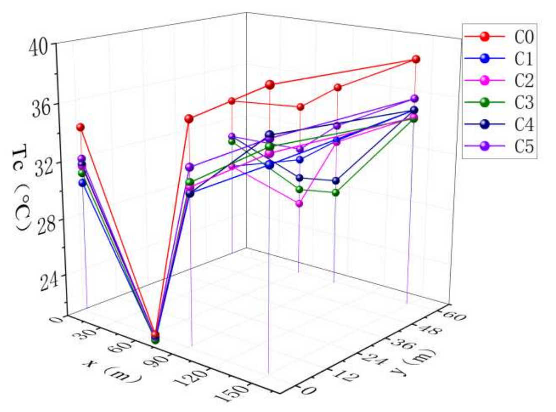
Due to the large number of working conditions, the following Figure 14 only shows the visibility map of CaseA. The results indicates that visibility improves when the natural makeup air vent is set. Figure 14 illustrates that visibility decreases in a circular pattern, with higher visibility in the center and lower visibility towards the boundary. The mixed wind of mechanical pressurization ventilation and natural makeup air blows high-temperature smoke upward, forming a thickened layer beneath the ceiling and walls. Some of the smoke is expelled through the natural smoke vent while the remainder moves slowly along the ceiling and settles on the wall, leading to reduce visibility around the periphery. According to Table 5, visibility is notably better when natural makeup air vent is set in the wall of bay 3 and bay 4.



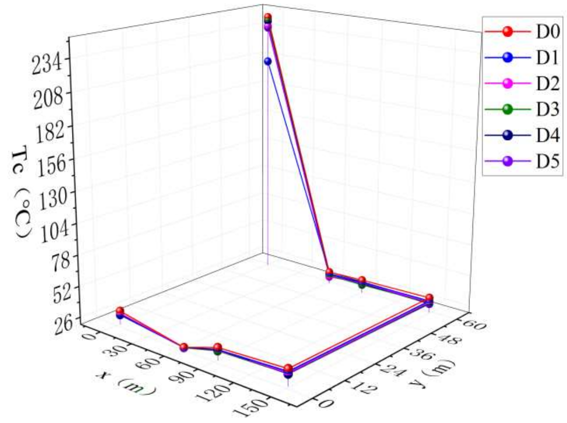
(a)



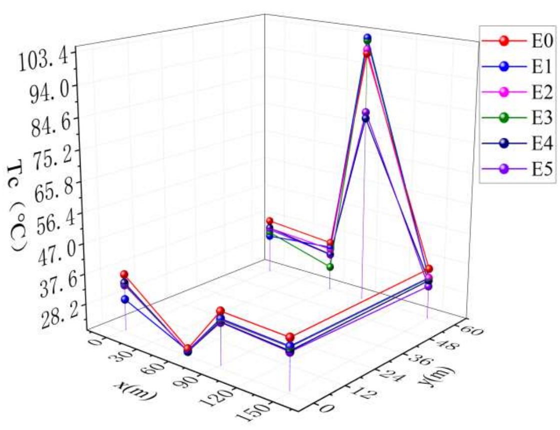
(b)



(c)



(d)



(e)

Fig. 13. (a) shows the temperature change of different natural makeup air vent positions on the minimum clear height when bay 3 is on fire; (b) fire in bay2; (c) fire in bay 1; (d) fire in the corner; (e) fire in the wall-side

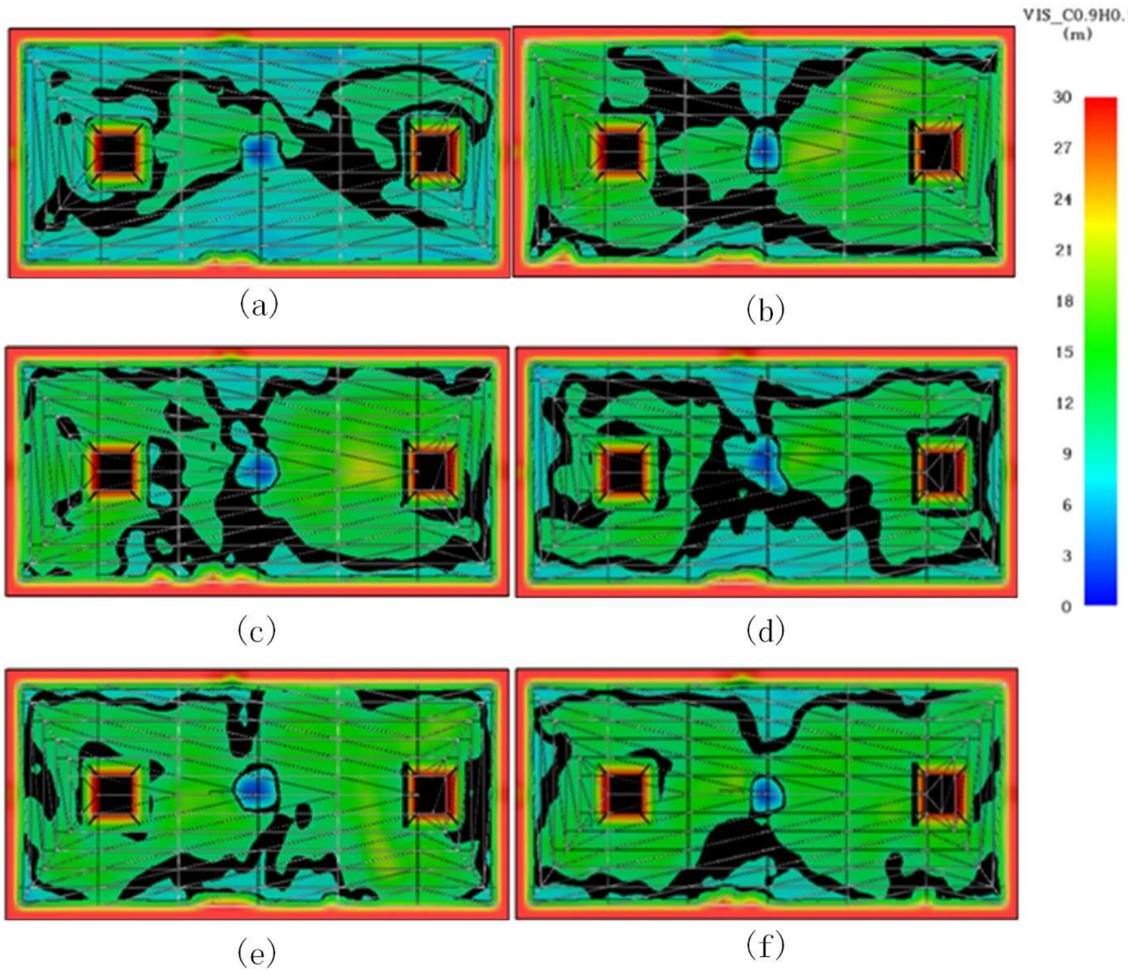


Fig. 14. (a) At 600s, the visibility of Case A0 minimum clear height plane; (b) Working condition A1; (c) Case A2; (d) Case A3; (e) Case A4; (f) Case A5

Under the same natural smoke vent openings, the smoke exhaust effect of natural makeup air and mechanical makeup air was compared. Selecting 4 kind rates of mechanical makeup air, 50%, 80%, 100%, 120%. Among them, mechanical makeup air rate refers to the proportion of makeup air quantity to the required smoke exhausting quantity. The effects of two makeup air methods on T_f and T_c, smoke exhausting quantity and visibility were analyzed. As shown in Figure 15, the cooling effect of natural makeup air is similar to 50% mechanical makeup air, ΔT_f is only 0.1℃ and ΔT_c is 0.5℃. As the mechanical makeup air rate increases, the cooling effect becomes more pronounced and T_f and T_c reaches the lowest when mechanical makeup air rate reaches 120%. It can be concluded that T_f is well below the critical pyrolysis temperature of 260℃ and T_c also does not reach the gas temperature of 60℃, both of which meet the safety requirements.

Table 5. Visibility results contrast

Conditions	Visibility
Case A	A4>A2>A5>A1>A3>A0
Case B	B1>B3>B4>B2>B5>B0
Case C	C3>C1>C2>C5>C4>C0
Case D	D4>D5>D3>D2>D1>D0
Case E	E5>E4>E3>E2>E1>E0

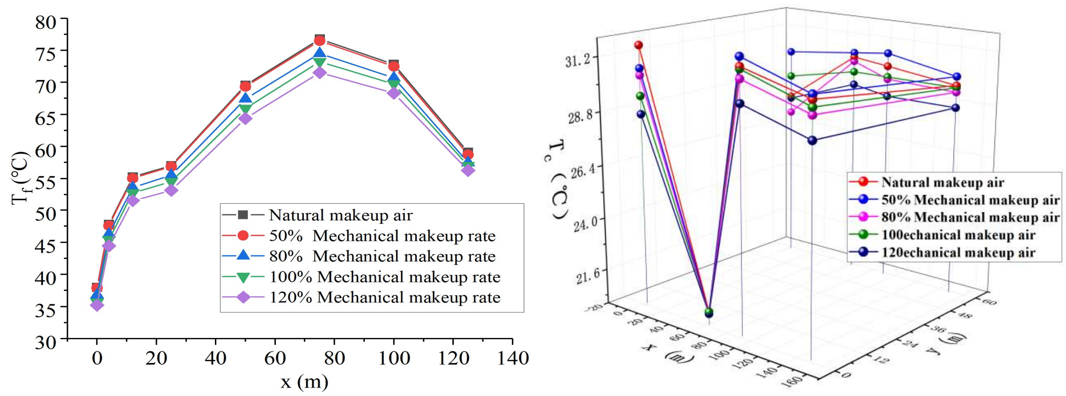


Fig. 15. (a) Temperature change of T_f under natural and mechanical makeup air;

(b)Temperature change of T_c under natural and mechanical makeup air

The study also examined the effect of varying natural smoke vent openings on changes in smoke exhausting quantity. Figure 16 shows that as the mechanical makeup air increases, the smoke exhausting quantity gradually rises. When the mechanical makeup air rate is low, the number of natural smoke vent opening has a limited impact on the smoke exhausting quantity. At 50% mechanical makeup air, the smoke exhausting quantity is approximately 35m^3/s. As the mechanical makeup air increased to 120%, the quantity rises and stabilizes around 70m^3/s. As shown in Figure 17, the increase in mechanical makeup air leads to a significant improvement in visibility. With a 50% mechanical makeup air, visibility in the central area is maintained above 10m, but the surrounding area cannot be guaranteed. When the rate of mechanical makeup air is increased to 100% and 120%, visibility near the wall also improves and meets the safety requirements.

Therefore, it can be concluded that natural smoke exhaust and mechanical makeup air method should be adopted for the smoke management system of ASMS buildings, so that all evaluation indexes, especially the smoke exhausting quantity, can meet the safety requirements.

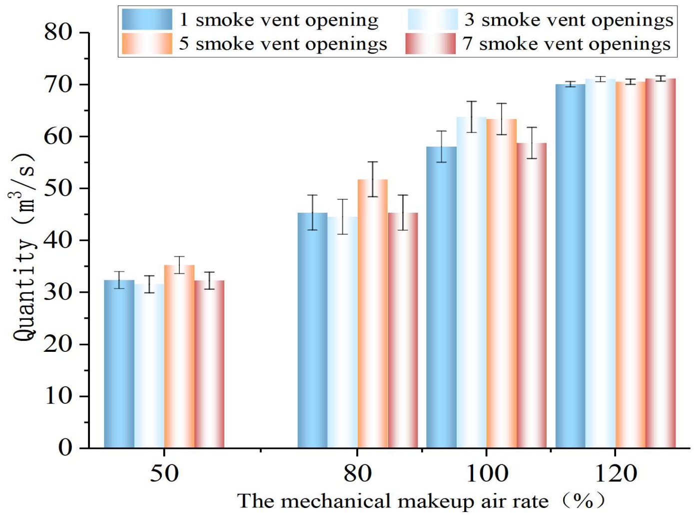


Fig. 16. Exhausting quantity of different natural smoke vents under different mechanical makeup air rate

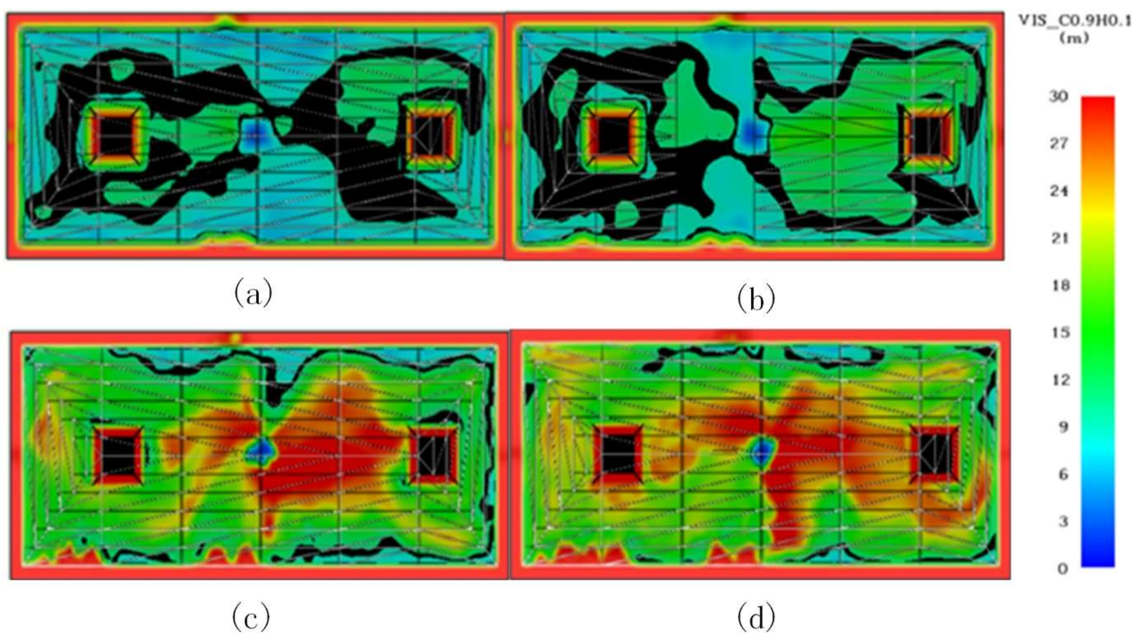


Fig. 17. (a) 600s, the visibility at the minimum clear height at 50% mechanical makeup air; (b) 80% mechanical makeup air; (c) 100% mechanical makeup air; (d) 120% mechanical makeup air

5. Conclusion

This study used the Fire Dynamics Simulator (FDS) to establish a numerical model of a coal storage bin and researched the impact of several key factors included the natural smoke vent height, the number of smoke vent openings and makeup air methods on the performance of ASMS building`s smoke management system. The primary results of the study are followed:

1) In the event of a fire, smoke ascends towards the ceiling, creating a stratified smoke layer. Positioning natural smoke vents at 25m can achieve best smoke exhaust efficiency and visibility. Based on the simulation results, it is recommended that natural smoke vents should be positioned between 80% and 100% of the building`s total height to maximize exhaust efficiency.

2) Increasing the number of natural smoke vent openings and natural makeup air vent openings has a significant improvement in cooling effect and visibility. However, it can be concluded that by using

natural smoke exhaust and natural makeup air, the smoke exhausting quantity of ASMS building does not reach the required quantity of smoke exhausting.
3) Setting natural makeup air vent in the wall of bay 3 can achieve the best cooling effect. In fire scenarios involving corner zone or wall-side zone, there is a risk of air-supported membrane melting. Based on the formula and the application of safety factor, the recommended safe distance is 6.2m.
4) When the rate of mechanical makeup air reached 120%, improvements in visibility, temperature, and smoke exhausting quantity were obtained. It can be concluded that natural smoke exhaust and mechanical makeup air should be adopted for the smoke management system of air-bearing membrane structure buildings so that it can meet the safety requirements.

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