fire

MDPI

Article

Indoor Fire Simulation in Low-Rise Teaching Buildings Based on BIM–FDS

Mengkai Liu * **and Guoquan Wang**

Department of Engineering Management, Wuhan University of Science and Technology, Wuhan 430074, China
* Correspondence: mengkailiu@wust.edu.cn

Abstract: School buildings gather a large number of underage students, and the disastrous consequences of fire in such buildings are very serious, which is one of the key concerns of society in fire prevention and control. This study takes a "[" type kindergarten teaching building as the background and constructs a BIM–FDS building fire simulation model to reveal the fire smoke dispersion law under the coupling of the typical building structure and fire protection systems. The results show that the stairwells on both sides of the "[" type building are the main channels for the diffusion of fire smoke, and the asymmetry of the stairwell structure will cause apparent differences in the diffusion of smoke. Using the natural smoke exhaust in the stairwells of low-rise buildings does not aggravate the spread of smoke in the building and is conducive to smoke emissions. The high-pressure water mist system is superior to the water spray system in fire extinguishing and controlling room temperature. While it reduces smoke exhaust performance, it does not adversely affect personnel evacuation. This study systematically reveals the law of diffusion of fire smoke from "["-type teaching buildings, which can support the design of similar building structures, ventilation, fire protection, and the formulation of fire escape plans.

Keywords: fire; building information modeling; fire dynamics simulator; kindergarten; low-rise building; high pressure water mist; natural smoke exhaust

Citation: Liu, M.; Wang, G. Indoor Fire Simulation in Low-Rise Teaching Buildings Based on BIM–FDS. *Fire* **2023**, *6*, 203. https://doi.org/10.3390/fire6050203

Academic Editors: Song Lu, Changcheng Liu, Guohui Li and Paweł Wolny

Received: 12 April 2023
Revised: 5 May 2023
Accepted: 12 May 2023
Published: 14 May 2023

1. Introduction

Building fire is one of the most common sudden social security incidents. According to the U.S. Fire Administration report, fires caused 3515 deaths and 16,600 injuries in the United States in 2019 [1]. In general, fires have the characteristics of suddenness, rapid process development, and severe catastrophic consequences. The probability of successfully escaping trapped people is affected by the response speed and evacuation efficiency of themselves and rescuers. Children and students are one of the more vulnerable groups in society. Their ability to make emergency judgments and active ability in a fire emergency is severely lacking, significantly reducing their probability of successful escape. For example, in 2001, a fire broke out at night in a kindergarten in Jiangxi, China, killing 13 children and injuring one [2]. Therefore, for kindergartens and other places where children concentrate, practical fire safety emergency plans should be made to improve the protection ability and rescue efficiency for young children in disaster scenarios. A complete fire safety emergency plan should follow the unique fire laws of each type of building to be practical and targeted. Therefore, studying the fire law of specific buildings is of great significance.

The evolution process of building fires is affected by many factors, such as building structure characteristics, building materials, and fire protection systems. When formulating building fire emergency plans, copying other engineering data is impossible. It is necessary to carry out particular relevant research to determine the potential fire evolution characteristics of specific buildings to effectively improve disaster protection and mitigation. At present, the research on the fire development process and smoke diffusion law mainly adopts physical and numerical model experiments [3]. Physical model experiments consume a lot of labor and material costs in operation, and environmental parameters such as temperature, wind speed, and air humidity cannot be accurately set. Therefore, numerical simulation has become the primary way to study building fire characteristics. The numerical model mainly includes the zone model, network model, and field model. The field model describes the fire development process by calculating the change of these state parameters with time [4]. As a classical field model simulation software, FDS is widely used to study the smoke and heat transfer process in fire and the effect of the water spray system. In recent years, the advantages of BIM technology in life cycle management and data sharing have become increasingly prominent, and the combination of BIM and professional emergency management software has become particularly important. Fire simulation can be realized by relying on the simulation method in the "BIM+" framework, setting the initial simulation information, using computer program algorithms, and displaying the simulation process and results visually. For example, Schatz designed a serious game based on BIM to explore human behavior in fire evacuation [5]. Wang proposed a dynamic fire escape path planning method based on BIM [6]. In addition, BIM can correct deviations between 3D and 2D drawings, visualize building surroundings and facility locations in 3D, and improve differences when using traditional 2D fire management tools [7]. BIM not only supports 3D visualization, but its models also contain architectural information such as building materials and quantities. Fire trends are closely related to building materials, and these parameters are critical for simulation [8].

Building fire is a fire in an indoor space with unique evolution characteristics due to its structural characteristics. The horizontal and vertical structures inside the building have various forms, which form a unique indoor space, thus affecting the evolution of fire and the law of smoke diffusion. For example, the rectangular configuration contributes better to smoke ventilation design than the square and triangular configurations [9]. Kerber's physical experiments concluded that smoke takes less time to fill buildings with smaller aspect ratios (R/H) [10]. The smoke will accumulate at the closed end of the L-shaped and annular corridors and the corner of the corridor, forming an escape danger area, while the T-shaped corridor will not form a similar area [11]. The stack effect in shafts such as elevator shafts and stairwells can accelerate smoke propagation in tall buildings [12]. The concave building structure can increase the longitudinal propagation of fire and smoke, increasing the level of danger on the upper floors of the building [13].

The design of building fire protection systems is an essential part of fire emergency management. Water-based fire extinguishing systems are widely used as a relatively mature fire extinguishing technology in several locations, such as urban tunnels [14,15], warehouses [16], subways [17,18], and nuclear power plants [19]. According to the different particle sizes of sprayed water droplets, water-based fire extinguishing systems can be divided into water sprinkler systems (WSS) and fine water mist fire extinguishing systems (WMS) [20]. The traditional WSS mainly achieves the fire extinguishing effect by directly spraying and cooling the fire source. Water mist also has the same cooling effect, but its sprayed droplets are smaller in diameter, resulting in faster heat absorption and evaporation and a better cooling effect [21]. At the same time, the water mist will be suspended in the form of dense droplet particles around the ignition point, blocking the heat transfer from the fire source to the surrounding material [22]. The water vapor formed by evaporating droplets will also create a barrier around the ignition point, isolating oxygen from it [20,23].

WMS is an emerging fire extinguishing technology using water as the medium. It has the advantages of fast extinguishing speed and small water consumption and is widely used in several scenarios [24,25]. Jiang's study on the application of HPWMS in subway fires concluded that HPWMS could effectively suppress fire development and has better suppression of ambient temperature and CO concentration[18]. Liu studied the application of WMS and WSS in an indoor ventilation environment and concluded that the WMS has a shorter action time and better cooling effect, effectively reducing the risk of backfire [26]. Liu demonstrated the ability of fine water mist to bypass obstacles in complex indoor environments through half-size experiments [27]. Wang concluded that water mist curtains applied in narrow passages effectively hindered the early spread of smoke, and the CO concentration and smoke particles in the protected area were reduced to a large extent [28]. Ku studied the application of HPWMS in transformer fires to provide theoretical and technical references for the safe and stable operation of transformers [29]. The WMS nozzle parameters are critical for effective fire suppression in different application scenarios. Lee studied the application of WMS in a nuclear power plant electrical room and derived a power function relationship between the nozzle and fire source horizontal distance on fire suppression time [30]. Gui discussed the effect of nozzle characteristics parameters such as atomization cone angle, spray velocity, droplet size, and spray flow rate on fire suppression effectiveness in a naturally ventilated room [31]. Ku discussed the effect of different droplet velocities and nozzle flow rates on fire extension [29]. In addition to the aforementioned building fires, WMS still provides excellent fire suppression in restricted spaces with little water volume, such as vehicle and aircraft fires [32]. There are even a large number of applications in particular scenarios, such as oil and gas explosions [33], lithium battery fires [34], suppression of natural gas leaks [35], and jet fires caused by gas leaks [36]. However, WMS are currently less applied in densely populated public buildings such as school buildings, shopping malls, and office buildings, and targeted research on such buildings is necessary.

Although the cooling and extinguishing performance of the WMS are good, it cannot reduce the amount of smoke diffused in the room. The building smoke exhaust system can effectively reduce the smoke concentration. Common smoke extraction systems include mechanical and natural smoke extraction systems. Natural smoke exhaust is an unorganized natural smoke exhaust through building exterior windows or smoke exhaust windows without consuming mechanical power. It is the preferred smoke exhaust method for multi-story civil buildings. In multi-story buildings, vertical shaft structures such as stairwells and elevator shafts are the main stairwells for smoke diffusion. Using the natural smoke exhaust in stairwells can quickly discharge smoke and is conducive to smoke control. For example, Chen concluded in the smoke exhaust experiment of an office building that the maximum total smoke exhaust of stairwell windows is 7852 m^3, and the smoke exhaust capacity of the first-floor window is the largest at 2800 m^3 [37]. Through small-scale experiments, Ahn found that when all the stairwell windows were open, the time of smoke rising was prolonged [38]. However, using natural smoke exhaust in the stairwell will form a stack effect, increasing the risk of the upper building. For example, Su conducted a fire experiment on a residential building in Taiwan and concluded that the chimney effect could cause smoke to spread to the top floor of the building within 180 s [39]. In a 10-story residential building simulation, Philip showed that opening the fire doors reduced residents' available safe egress time (ASET) by 36% [40]. In addition, the effect of natural smoke exhaust often depends on the temperature difference between indoors and outdoors, the height difference between exhaust and air inlet, outdoor wind, and other factors. Therefore, whether the natural smoke exhaust method is used in the stairwell must be determined by the smoke diffusion simulation of a specific building.

Fire extinguishing and smoke exhaust are essential in building fire emergency management. It is challenging to simultaneously achieve fire extinguishing and smoke exhaust by relying solely on a single fire protection system. Multiple fire protection systems often need to be installed in buildings to work together. However, some studies have shown that the water mist system will reduce the smoke diffusion rate, destroy the stability of the smoke layer, and reduce the efficiency of the smoke exhaust system. Sun also found that the water mist system can effectively prevent the spread of smoke in the tunnel but does not work under mechanical ventilation [41]. The open doors and windows will increase the oxygen content of the fire and increase the fire. However, Zhou concluded that a lower mechanical exhaust rate (0.381 m^3/s)-assisted water mist system could shorten the fire extinguishing time [42]. Lee proposed that setting the activation temperature of the spray system below 85 °C can eliminate the activation time delay caused by the smoke exhaust system [43]. However, these studies mainly focus on the coupling effect of two fire protection systems in the same room. There are few studies on the influence of the spray system on the smoke exhaust system in the main evacuation path.

From the above, it can be seen that the building structure greatly influences the smoke diffusion law, and the research on the application of WMS is mostly focused on special-purpose buildings such as warehouses, subways, nuclear power plants, urban tunnels, etc. However, the research on applying WMS in low-rise buildings with complex internal structures, such as shopping malls and school buildings, is less. In addition, whether the use of natural smoke exhausts in the stairwell of low-rise buildings will aggravate the spread of smoke in the building or is beneficial to smoke emission requires the study of smoke diffusion in the building. Therefore, this study takes the actual single building of a kindergarten as the research object supported by BIM technology and uses the numerical simulation method to study the internal temperature and smoke diffusion law of the building under the joint action of the building structure, smoke exhaust system and spray system, and explores the smoke law in the stairwell of low-rise buildings, the fire suppression and smoke extraction performance of the fire protection systems, and the influence of the spray system on the smoke exhaust system in the main evacuation path. It strongly supports the fire protection system design, fire emergency plan, and emergency rescue of the kindergarten and similar building structures.

2. Research Methodology

2.1. Methods of FDS

The FDS (Fire Dynamics Simulator) is a fluid dynamics software developed by the National Institute of Standards and Technology for analyzing and simulating fire flames and smoke. The FDS uses large eddy simulation (LES) to show the flame propagation process and smoke diffusion path in fire scenarios. Since the FDS is open-access, it is widely used in fire research.

Pyrosim was developed based on the FDS, which provides a graphical user interface (GUI) for dynamic fire simulation. Based on computational fluid dynamics, the software can predict the movement, concentration, and temperature changes of toxic gases such as smoke and CO in the fire. Among many fire simulation software, Pyrosim is widely used in fire simulation because of its fast model establishment, convenient parameter setting, and location determination. Therefore, this paper chooses the Pyrosim software to simulate the fire of the model.

2.2. BIM-Based Simulation Framework

The accuracy of parameters such as building geometry, building material information, and fire source information is crucial to the numerical study of building fires. BIM integrates various information about the whole life cycle of the building and allows the numerical model to approximate the physical model as closely as possible. This study uses BIM as an information integration and visualization platform to establish a BIM–FDS-based fire simulation framework for building fire risk management. The overall framework is shown in Figure 1. The first step of the framework is to build the building model through the Autodesk Revit software and then import the building material information into the model to ensure the accuracy of the graphical and non-graphical information of the building model. In addition to the building model, fire origin information and detection equipment are equally important. Therefore, the second step is to import the Revit model into Pyrosim in DXF format and set the calculated fire parameters, grid parameters, and detection equipment in Pyrosim. Finally, the corresponding building's fire simulation results and detecting points data are obtained.

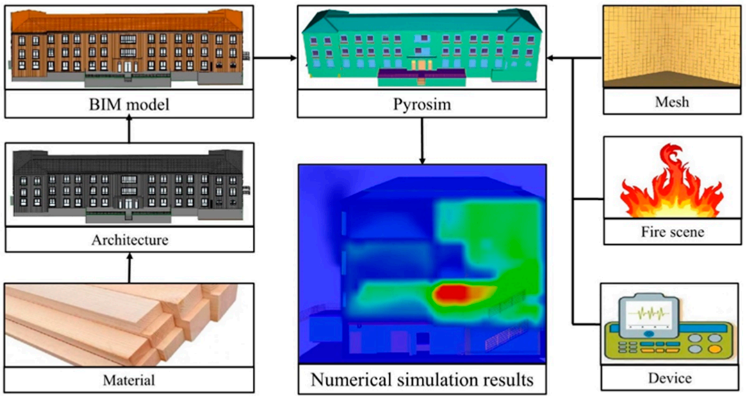

Figure 1. BIM–FDS integration framework.

3. Case Study

3.1. Fire Model Setting

This article takes a large kindergarten in Zhejiang Province, as an example. The kindergarten is "[" shaped, covers an area of 1466 m^2, with a building area of 3363 m^2, including three floors above ground and one underground floor, and the floor height is 4 m. The whole building can accommodate 240 students and 70 staff members. The first and second floors are mainly for teaching and activity areas, and the third is for the staff office area. The layout of the ground floor plan is shown in Figure 2.

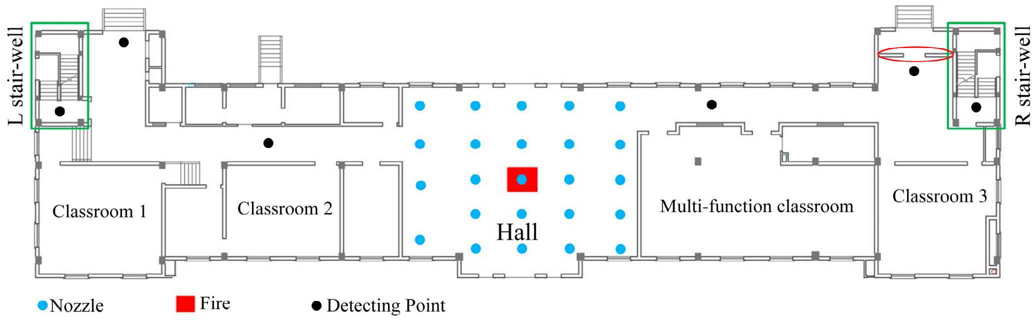

Figure 2. First floor layout plan.

3.1.1. Design of the Fire Scene

The lobby is an important public space in kindergartens. It is often used as an indoor playground or festival site, where many decorative materials are often laid out, posing a greater fire hazard. Therefore, this article assumes that the fire event is a Christmas tree made of PVC in the hall that catches fire due to a short circuit in the decorative lamp wire. It was during teaching hours at the time of the fire, and the door to the hall was closed. The development of early fires can be described using the t^2 model, the formula for which is as follows [44].

$$Q_f = \alpha t^2 \tag{1}$$

where Q_f is the heat release rate of fire, α is the fire growth coefficient, and t is the burning time.

In this paper, the fire source is set to fast fire with the power of 4 MW, and the growth coefficient is α = 0.047. Table 1 describes the main parameters of the model and sets the other parameters to the system defaults.

Table 1. Details of environment parameters.

Settings	Parameters
HRRPUA (kW/m^2)	4000
Burner size	1 m × 1 m
Soot yield (kg/kg)	0.07 [45]
CO yield (kg/kg)	0.04 [45]
EPUMO2 (kJ/kg)	13,100
Initial temperature (°C)	20
Initial pressure (Pa)	101,300
Humidity (%)	40
Simulation time (s)	500
Initial visibility (m)	30

3.1.2. Grid Resolution Analysis

The mesh size has a significant impact on the accuracy of numerical simulation results. The more precise the meshing in the fire model, the more accurate are the numerical simulation results, but it will lead to longer calculation time. The mesh size needs to be determined according to the characteristic diameter of the fire source (D^*) as follows [46]:

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

where D^* is a characteristic fire diameter, m; Q is the heat release rate of the fire, KW; ρ_∞ is the ambient air density, generally 1.204 kg/m^3; c_P is the specific heat capacity of ambient air, generally 1.005 kJ/(kg·K); T_∞ is the ambient air temperature, generally 293 K, g is the acceleration of gravity, generally 9.8 m/s^2.

This paper's fire source power is 4 MW, and the calculated D* is 1.67 m. The 0.06D*–0.25D* recommended by the National Institute of Standards and Technology is used to obtain a reliable calculation grid size range of 0.100–0.418 m. In this interval, the grid sizes of 0.1 m, 0.2 m, 0.3 m, and 0.4 m were selected for fire temperature simulation and comparative analysis. To save time, the simulation time was set to 300 s, and the results are shown in Figure 3. It can conclude that the temperature variation curve of the grid size of 0.4 m is different from the others, while the temperature deviation caused by the grid size of 0.3 m and 0.1 m is only 3%. Therefore, in the case of similar accuracy, to minimize the simulation time, this case selected the mesh size of 0.3 m × 0.3 m × 0.3 m.

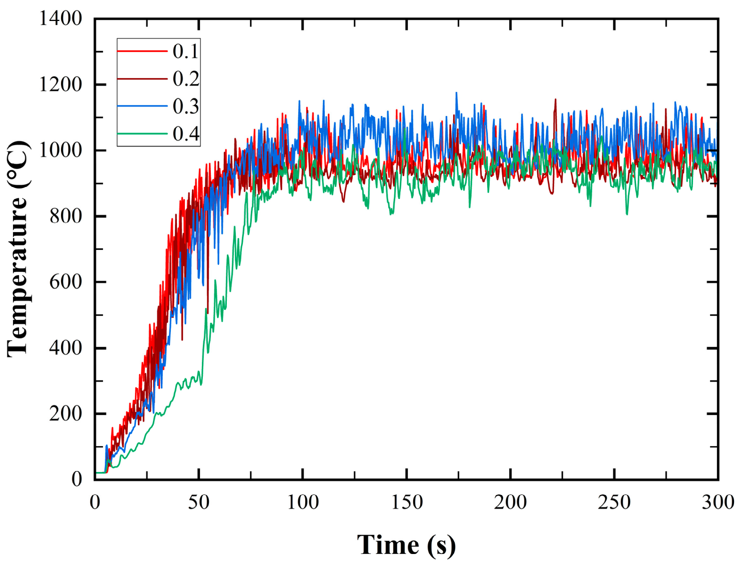

Figure 3. Comparison of temperature above the fire source among the four grid systems.

3.1.3. Configuring the Detecting Point

Most of the casualties during the fire are caused by smoke. The CO concentration, temperature, and visibility in the air are the key factors affecting the evacuation of the affected people. In order to obtain the diffusion path information of these three factors inside the building, 14 detecting points are set in this paper, and CO concentration, temperature, and visibility sensors are set at each detecting point. The National Health Commission of China has pointed out that the average height of Chinese adult men and women is 169.7 cm and 158.0 cm, respectively. Therefore, detecting points are set at the height of 1.7 m to better reflect the impact of smoke on the affected personnel. The elevation position of each detecting point is shown in Figure 4, and the plane position is shown in Figure 2.

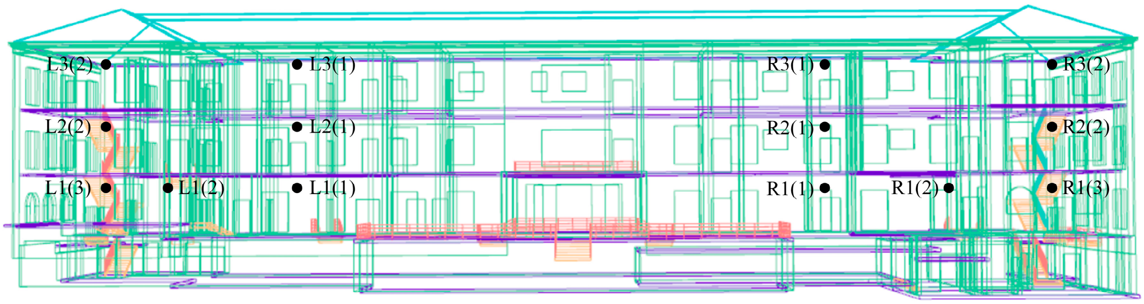

Figure 4. Distribution of detecting points.

3.2. *Scenarios of Simulation*

In this paper, HPWMS and WSS are used as the water-based fire extinguishing systems of the building, and assuming that only the sprinklers in the hall are triggered, other building locations are not reached. According to the relevant provisions of the architectural design of fire protection norms, the hall of the spray system layout is shown in Figure 2. The WSS parameters refer to the fire design drawings of the case model, and the HPWMS parameters are assumed based on the existing research in the review. The two parameters are shown in Table 2. Moreover, the activation time of the system is assumed to be the 50 s when the fire occurs.

Table 2. Spray system setting parameters.

Parameter	HPWMS	WSS
Operating pressure (MPa)	10	0.13
K-Factor	1.2	80
Jet velocity (m/s)	15	5
Median volumetric diameter (µm)	100	1000
Distribution	Constant	Constant
Spray cone angle	60°	60°

There are two different forms of window design in stairwells, fixed windows for lighting only and sliding windows for lighting and exhausting. In this paper, the above two kinds of windows are set in the stairwells on both sides of the case to study the influence of natural smoke exhaust on the smoke diffusion of such typical buildings.

HPWMS, WSS, sliding window, and fixed window are combined into four working conditions, as shown in Table 3. The influence of different water-based fire extinguishing systems and natural smoke exhaust system on fire and smoke will be obtained by comparing the detecting data of the four scenarios.

Table 3. Operating conditions.

Working Conditions	Sprinkler System	Window Type
Test 1	WSS	Fixed window
Test 2	WSS	Sliding window
Test 3	HPWMS	Fixed window
Test 4	HPWMS	Sliding window

4. Results and Analysis

4.1. Smoke Diffusion Law

The building structure will affect fire smoke during the diffusion process to form a unique smoke diffusion law. Figure 5 shows the smoke diffusion law of Test 1 within 500 s. In a short period after the fire, the fire layer and the top floor are the first to be affected by the smoke, followed by the middle floor. The two side stairwells are the main path of smoke spread, and the amount of smoke in the R stairwell is more than in the L stairwell. The same diffusion law was observed in the simulation results of the other three working conditions.

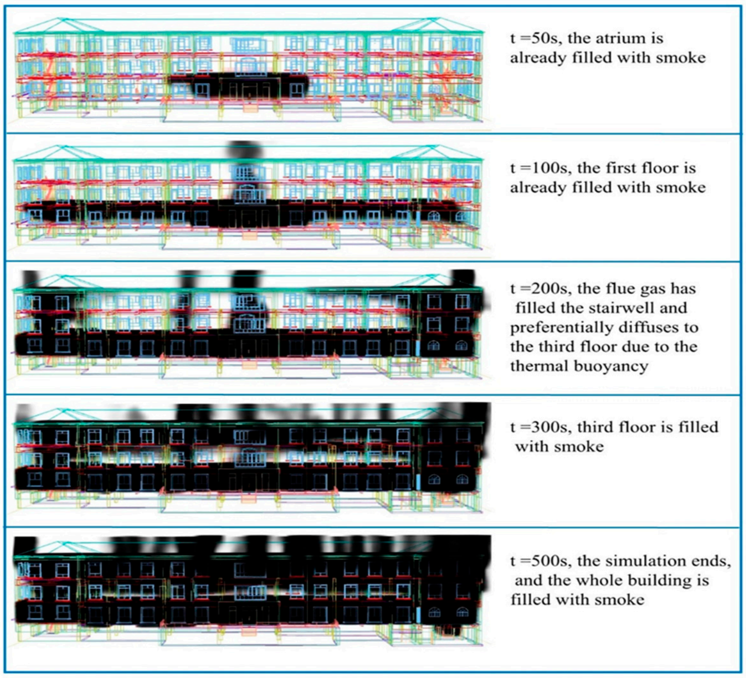

Figure 5. Smoke diffusion process (Test 1).

During the fire evacuation process, the maximum ambient temperature and CO concentration that the human body can withstand are 60 °C and 500 ppm, respectively, and the visibility should not be less than 10 m [47,48], exceeding which will pose a threat to the escape of affected persons. The time for one of the indicators to reach the critical value is the available safety egress time (ASET) under that indicator. The ASET corresponding to the air environment indicators at each detecting point was obtained statistically, as shown in Table 4. It can be seen that the difference in the ASET among the three indexes increases with the increase in smoke diffusion distance. Among them, the change in visibility is the fastest and most widely affected by smoke, which is the first factor threatening the escape of disaster victims. The CO concentration is second, and the temperature change is the slowest.

Table 4. ASET Statistics Details (Test 1).

Site	Detecting Point	Available Safety Egress Time (s)		
		CO Concentration	Temperature	Smoke Visibility
First floor	R1(1)	101	101	72
	L1(1)	93	97	76
	R1(2)	104	110	88
	L1(2)	NO *	NO	124
Stairwell	R1(3)	134	168	100
	L1(3)	NO	NO	124
	R2(2)	180	334	122
	L2(2)	NO	NO	126
	R3(2)	169	330	124
	L3(2)	NO	NO	132
Second floor	R2(1)	NO	NO	299
	L2(1)	NO	NO	392
Third floor	R3(1)	NO	NO	188
	L3(1)	398	NO	250

* NO—indicates that the critical value is not reached during the simulation period.

According to the data of the detecting points in the stairwells, the three data of each detecting point of the L stairwell are smaller than those of the R stairwell. The reason can be attributed to two points. First, two staircases in the building are located at the ends of each side of the stairwell. In case of a fire, smoke accumulates at the end of the stairwell, forming a hazardous area [11]. Second, the exits on both sides of the first-floor stairwell are set differently, as shown in Figure 2, using a red wireframe marker area. A wall is set at the right end of the stairwell exit to separate the interior from the exterior, which reduces the smoke extraction area and prevents the smoke from spreading outside in time, resulting in a large influx into the R stairwell. Therefore, when formulating fire emergency plans, teachers and students should try to avoid evacuation from the R stairwell.

4.2. Effect of HPWMS on Smoke Diffusion

This section selects the CO concentration and ambient temperature of Test 1 and Test 3 for quantitative comparative analysis.

4.2.1. Temperature

Figure 6 depicts the temperature change with time at 1 m above the fire source for Test 1 and Test 3 simulation conditions. It can be seen that the fire source has gone through three stages: 1. rapid growth stage; 2. attenuation stage; and 3. stabilization phase.

In the first stage, the temperature above the fire source continues to rise due to the intense combustion of combustibles. The sprinkler systems were activated after 50 s, but as the fire source was burning violently at this time, neither sprinkler system could immediately reduce the temperature around the fire source; hence, the temperature above the fire source continued to rise. The temperature curve of the two conditions at this stage tend to be consistent. In the second stage, the temperature above the fire source decreases due to the influence of the spray system. Under the action of HPWMS, the temperature in Test 3 decreased sharply at 82 s, and decreased to 68 °C at 132 s, and then entered the next stage. However, it is worth noting that the temperature curve shows obvious oscillation in the stage of 114 s–132 s. This is due to the decrease in fire temperature, resulting the decrease of evaporated droplets, which leads to a worse cooling and oxygen insulation effect. The temperature rises briefly and then decreases again, but the overall trend is downward. Under WSS, the temperature decreases slowly and enters the next stage after decreasing to 160 °C at 304 s. In comparison, HPWMS reduces the fire extinguishing time by 76.6%. In the third stage, the temperature above the fire source in both conditions fluctuates in a small range. The difference is that the temperature in Test 1 is stable at about 170 °C, while Test 3 is stable at about 75 °C.

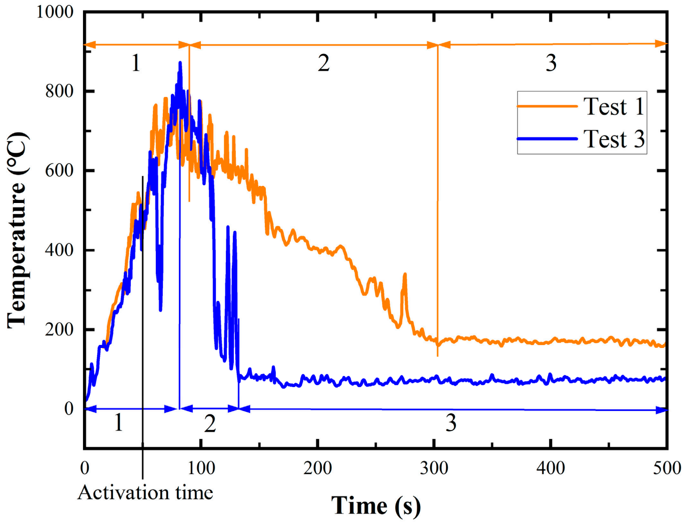

Figure 6. Temperature change at 1 m above the fire source during Test 1 and Test 3.

HPWMS shows a better effect than WSS in fire extinguishing; the cooling effect of HPWMS is also better for the ambient temperature of the first floor. Figure 7 shows the temperature distribution for the first floor at 400 s for the two working conditions. It can be seen that the temperature difference between the two conditions in the hall is enormous. Most of the Test 1 hall is about 100 °C higher than the Test 3 hall, and the temperature in the stairwell is also higher.

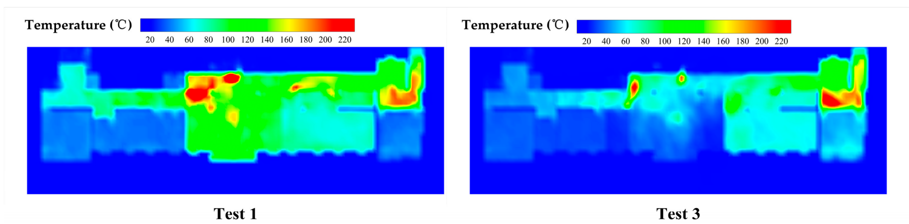

Figure 7. First floor temperature distribution during Test 1 and Test 3 at 400 s.

In summary, HPWMS has more advantages than WSS in extinguishing fire sources and controlling ambient temperature.

4.2.2. CO Concentration

As shown in Table 4, the CO concentrations at R1(2), R1(3), R2(2), and R3(2) exceeded the critical value during the simulation period. The CO concentration curves corresponding to these four detecting points are shown in Figure 8. It can be seen that the CO concentration is lower under the action of HPWMS, and the difference between the two conditions is the largest at R1(2). However, with the increase in smoke diffusion distance, the difference gradually decreases, but this inhibitory effect gradually decreases with the increase in smoke diffusion distance. This shows that HPWMS has a significant inhibitory effect on CO concentration, but this inhibitory effect gradually decreases with the increase in smoke diffusion distance, which indicates the limitation of the action range.

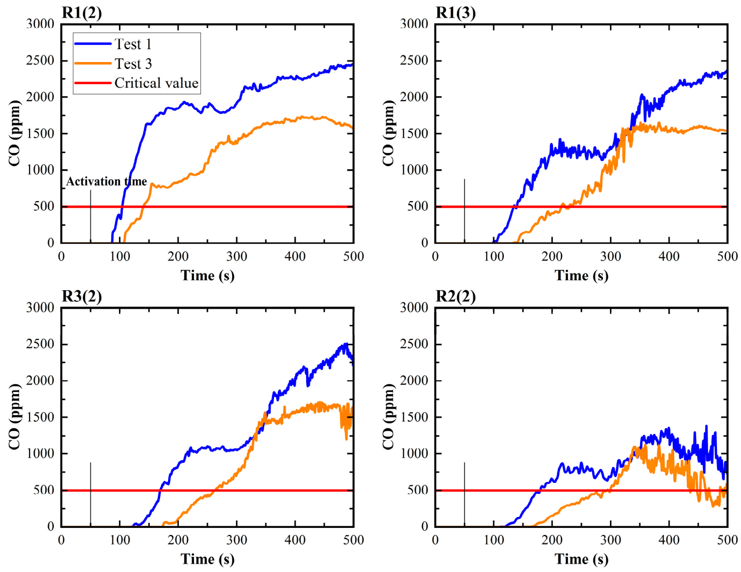

Figure 8. Variation in CO concentration during Test 1 and Test 3 at the following detecting points: R1(2), R1(3), R3(2) and R2(2).

It can also be seen from the change curve of CO concentration in Figure 8 that the CO concentration curve of Test 3 has a slower growth trend, which is due to the better cooling effect of HPWMS on the smoke, weakening the thermodynamic force of the smoke and slowing down the smoke diffusion rate. As shown in the CO concentration observed in Figure 9 (Test 1), the smoke has obvious stratification. Therefore, in the process of smoke diffusion into the stairwell, a small amount of smoke enters first, and when the smoke layer falls below the height of the door frame, a large amount of smoke enters the stairwell. Therefore, the CO concentration change curve shows a stepwise growth. However, the stability of the smoke layer in Test 3 is destroyed by HPWMS, as shown in Figure 9 (Test 3), which is consistent with the conclusions of Blanchard [49] and Morlon [50]. Therefore, the CO concentration curve will continue to rise and then tends to be stable.

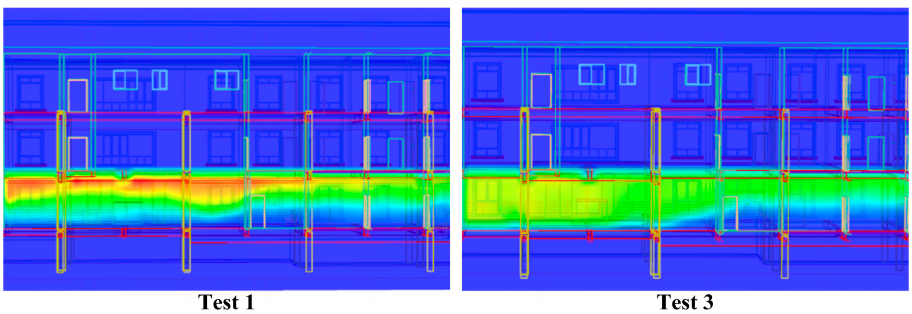

Figure 9. CO concentration distribution in the corridor during Test 1 and Test 3 at 200 s.

4.3. Influence of Natural Smoke Exhaust Systems on Smoke Diffusion

When sliding windows are used in stairwells, the stack effect has an important impact on the smoke diffusion. Therefore, the determination of the pressure neutral surface in the stack effect is crucial for studying the smoke diffusion law. The formula is as follows [51].

$$\frac{H_n}{H} = \frac{1}{1 + (T_S/T_O)(A_b/A_a)^2} \tag{3}$$

where H_n is the vertical distance from the neutral surface to the lower edge of the shaft, H is the height of the lateral opening of the shaft, T_S is the absolute temperature inside the shaft, T_O is the absolute temperature outside the shaft, and A_a, A_b are the areas of the upper and lower windows, respectively, and since this model uses uniform windows, the ratio is taken as 1.

The calculated height of the pressure-neutral surface of the model is 9.24 m, located at the bottom of the third floor. Therefore, in theory, the natural smoke exhaust system of the stairwell can reduce the impact of smoke on the second floor of the building. In the numerical simulation of this paper, the smoke distribution in the building under Test 1 and Test 2 also confirms this conclusion. As shown in Figure 10, under the condition of natural smoke exhaust in the stairwell, the smoke volume on the second floor of the building is significantly reduced, and most of the area is in a blank state without smoke. Based on the visibility curve shown in Figure 11, it can be concluded that the visibility during Test 2 in the second-floor corridor fluctuates within the safe range, in contrast to that observed in Test 1, and the visibility during Test 2 on the third floor decreased to the critical value later. From the above analysis, it can be concluded that using the natural smoke exhaust in the stairwell can significantly reduce the hazard of smoke to the middle floor and does not increase the amount of smoke on the top floor due to the stack effect.

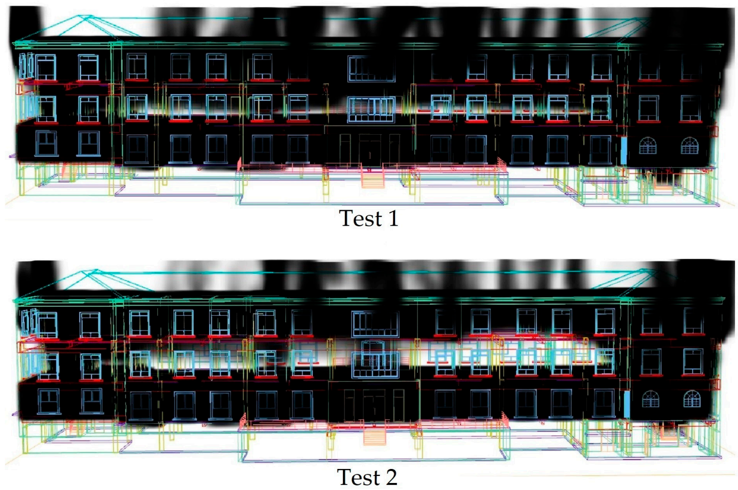

Figure 10. Comparison of smoke diffusion during Test 1 and Test 2 at 500 s.

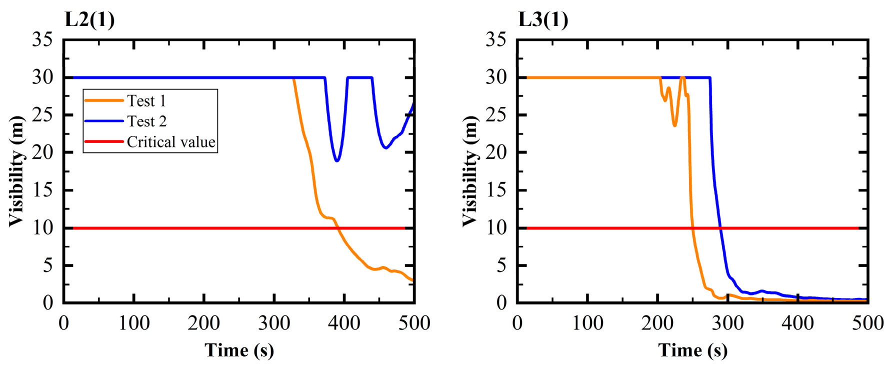

Figure 11. Visibility changes during Test 1 and Test 2 at the following detecting points: L2(1) and L3(1).

4.3.1. CO Concentration

The CO concentration data in the R stairwell are shown in Table 5. It can be seen that the CO concentration at each detecting point is reduced by more than 35% when the normally open sliding window is used in the stairwell. When only considering the influence of CO on evacuation, the ASET in the R stairwell increased significantly under the condition of the windows opening. The difference in ASET for the R3(2) is small due to the rapid diffusion of the smoke in the stairwell. In the fire, priority should be given to evacuating the affected people on the top floor. Therefore, from the above analysis, it can be concluded that the natural smoke exhaust in the stairwell has a good effect on reducing the CO concentration in the air and ensuring the evacuation safety of the affected people.

Table 5. Comparison of ASET under the effect of CO (Test 1, Test 2).

Point	Test	Average CO Concentration (ppm)	Degree of Reduction	ASET (s)	Difference Value (s)
R2(2)	1 2	613.03 358.02	41.60%	180 301	121
R3(2)	1 2	984.52 636.98	35.30%	169 203	34
R3(1)	1 2	148.92 80.68	45.82%	NO * NO	NO

* NO—indicates that the critical condition is not reached during the simulation period.

4.3.2. Temperature

The average temperature data calculated in detecting points in the corridors on the second and third floors during Test 1 and Test 2 have been collected in Table 6. Combined with the data of the corresponding detecting points in Tables 4 and 6, it can be seen that the ambient temperature of the top and middle floors of the building were less affected during the fire. In addition, the temperature difference between the two working conditions at each detecting point is small, which indicates that the natural smoke exhaust in the stairwell has a negligible effect on the temperature of the floor above the fire. Ahn explained this phenomenon in his research. He proved that opening a single window has little effect on the temperature of the stairwell. When the number of open windows exceeds five, the temperature of the stairwell will be significantly reduced [38].

Table 6. Average temperature of detecting points (Test 1, Test 2).

Detecting Point	Test 1	Test 2	Difference
R2(1)	30.56 °C	29.99 °C	0.57 °C
L2(1)	30.19 °C	30.05 °C	0.14 °C
R3(1)	35.22 °C	32.27 °C	2.96 °C
L3(1)	33.14 °C	31.22 °C	1.92 °C

4.4. Linkage Effect of the Fire Control System

HPWMS and natural smoke exhaust systems are active and passive fire-fighting facilities, respectively, which play different roles in different areas of the building and in different stages of the fire. The interaction between the two systems cannot be ignored. In the analysis of Section 4.2.1, HPWMS has a good cooling effect on the ambient temperature, as well as the ambient smoke. The temperature difference between smoke and air is the main driving force for smoke, while HPWMS will reduce the temperature difference between smoke and air, destabilizing the smoke layer and reducing the diffusion speed. Therefore, the efficiency of natural smoke exhaust will be reduced. As shown in the change in CO concentration on the third floor in Figure 12, the CO concentration of Test 3 and 4 (using HPWMS) was less than that of Test 2 before 300 s, but the CO concentration of Test 3 and 4 was higher than that of Test 2 after 300 s. At the end of the simulation, the concentration between Tests 3 and 4 with two different windows is similar. This shows that HPWMS has an inhibitory effect on the natural smoke exhaust. However, in the latter simulation stage, the CO concentration value in Test 4 is not significantly larger than that in Test 2, which indicates that the effect of HPWMS on natural smoke exhaust does not significantly increase the amount of smoke on the top floor in a low-rise building, such as the one evaluated in this study paper.

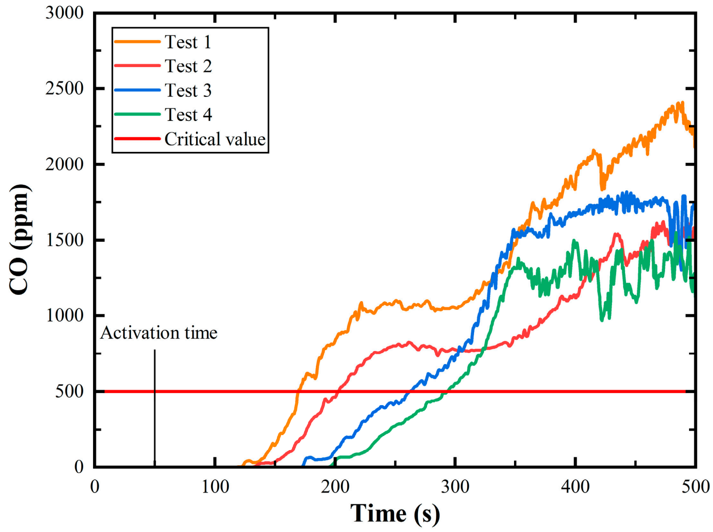

Figure 12. Variation of R3(2) CO concentration during Test 1, Test 2, Test 3, and Test 4.

Stairwells are the only way for the victims to escape, so the ASET in the stairwell is an important parameter to measure the disaster relief capacity of the fire system. Under the comprehensive consideration of CO concentration, temperature, and visibility conditions, the ASET in the R and L stairwells is shown in Figure 13. It can be seen that when the two systems are applied simultaneously, the ASET at each detecting point is increased by 50–77 s. Under this condition, the ASET at each point in Test 4 is higher than that in other conditions. HPWMS reduces the smoke temperature and slows down the diffusion rate, and has the best effect in increasing the ASET of the victims. The inhibiting effect of HPWMS on the natural smoke exhaust does not endanger the evacuation. In addition, the ASET of the L stairwell on the same floor is higher than that of the R stairwell, so the L stairwell should be the first choice when formulating the emergency plan.

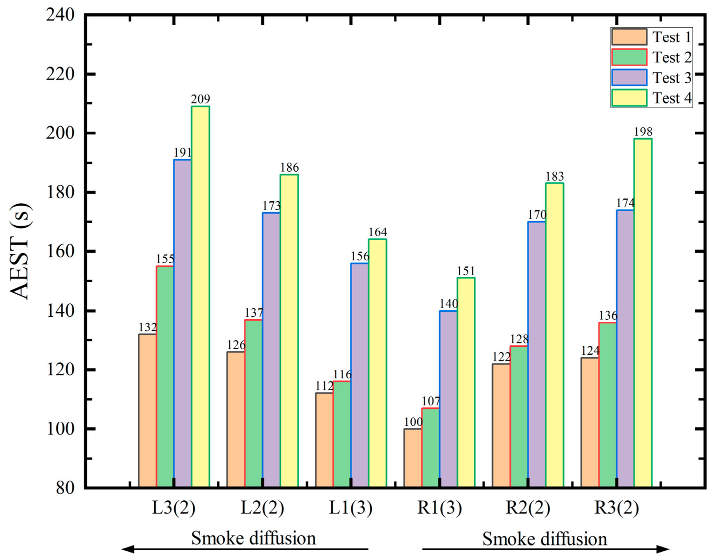

Figure 13. ASET comparison of each detecting point in the stairwell.

5. Conclusions

This study established a BIM–FDS fire simulation model based on the "["-type kindergarten building. Based on the results and analysis, the following conclusions are formulated:

1. This study verified the practical value of the BIM technology in emergency evacuation management for public buildings. A public building emergency evacuation manage-

ment model based on the BIM–FDS is established by combining accurate BIM building information data with a professional fire simulation program. The accurate smoke information and smoke diffusion law at each key node in the building evacuation path are obtained, which provides a basis for emergency management and better guides the emergency management that is difficult to predict and control.

2. This study obtained the unique smoke diffusion law in "]" buildings. In the "]" building, the fire smoke diffuses through the penetrating corridor to the stairwells on both sides and through the stairwells to the whole building. In the diffusion process, the fire source and the top layer are the most vulnerable to smoke, followed by the middle floor. In the case studied in this paper, the asymmetric building structure at both ends of the corridor causes different smoke exhaust areas on both sides, resulting in a large difference in the amount of smoke diffused upward, reflecting the important influence of building structure on the smoke diffusion law and the accurate guarantee of fine BIM models for fire simulation.
3. This study demonstrates the excellent performance of HPWMS in extinguishing fire and inhibiting smoke diffusion and stairwells' natural smoke exhaust ability. Comparing Tests 1 and 3 shows that HPWMS shortens the fire extinguishing time by 76.6%, reduces the smoke temperature and diffusion velocity, and reduces the average concentration of CO in the R stairwell by more than 60%. In low-rise buildings, using the natural smoke exhaust in the stairwell can timely discharge the smoke, reduce the threat of smoke to other floors, and will not increase the hazard of smoke to other floors.
4. This study demonstrates the negative effect of HPWMS on natural smoke exhaust and obtains the influence of this effect on smoke diffusion in buildings. HPWMS reduces the diffusion velocity and destabilizes the smoke layer, weakening the performance of natural smoke exhaust. However, in this case, the building floor is lower, and the difference between the natural smoke exhaust efficiency of Tests 2 and 4 is not obvious. Moreover, the ASET value at each staircase of Test 4 is the largest, which indicates that the combined effect of HPWMS and natural smoke exhaust can be more beneficial for fire evacuation.

In this study, the interior's fire load and furniture decoration aspects were simplified, and the influence of fire spread on the fire outcome was not considered. In addition, this paper does not carry out escape simulation for special groups such as young children and needs to be discussed in depth in the later stage.

Author Contributions: Conceptualization, M.L.; Data curation, G.W.; Methodology, M.L.; Software, G.W.; Formal analysis, G.W.; Investigation, G.W.; Visualization, G.W.; Supervision, M.L. Writing—original draft preparation, G.W.; Writing—review and editing, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this study are available on request to corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. USFA, Fire Risk in 2019. Available online: https://www.usfa.fema.gov/statistics/deaths-injuries/ (accessed on 14 December 2022).
2. SAWS. *Jiangxi Radio and Television Development Center Art Kindergarten Fire Accident*; China's Work Safety Yearbook: Beijing, China, 2002; pp. 456–457.
3. Lulea, M.D.; Iordache, V.; Nastase, I. Numerical Model Development of the Air Temperature Variation in a Room Set on Fire for Different Ventilation Scenarios. *Appl. Sci.* **2021**, *11*, 11698. [CrossRef]
4. Ji, J. *Fire Dynamic in High-Rise Building*; Science Press: Beijing, China, 2020; pp. 50–51.

5. Rüppel, U.; Schatz, K. Designing a BIM-based serious game for fire safety evacuation simulations. *Adv. Eng. Inf.* **2011**, *25*, 600–611. [CrossRef]
6. Wang, J.; Wei, G.; Dong, X. A dynamic fire escape path planning method with BIM. *J. Ambient Intell. Hum. Comput.* **2021**, *12*, 10253–10265. [CrossRef]
7. Chen, X.-S.; Liu, C.-C.; Wu, I.C. A BIM-based visualization and warning system for fire rescue. *Adv. Eng. Inf.* **2018**, *37*, 42–53. [CrossRef]
8. Shi, L.; Chew, M.Y.L.; Liu, X.Y.; Cheng, X.D.; Wang, B.; Zhang, G.M. An experimental and numerical study on fire behaviors of charring materials frequently used in buildings. *Energy Build.* **2017**, *138*, 140–153. [CrossRef]
9. Doheim, R.M.; Yohanis, Y.G.; Nadjai, A.; Elkadi, H. The impact of atrium shape on natural smoke ventilation. *Fire Saf. J.* **2014**, *63*, 9–16. [CrossRef]
10. Kaye, N.B.; Hunt, G.R. Smoke filling time for a room due to a small fire: The effect of ceiling height to floor width aspect ratio. *Fire Saf. J.* **2007**, *42*, 329–339. [CrossRef]
11. Tang, J.; Shi, B.m.; Chen, K. Numerical simulation of fire smoke flow in typical structure of building corridor. *J. Saf. Sci. Technol.* **2015**, *11*, 33–37.
12. Zhang, J.; Weng, J.W.; Zhou, T.N.; Ouyang, D.X.; Chen, Q.P.; Wei, R.C.; Wang, J. Investigation on Smoke Flow in Stairwells induced by an Adjacent Compartment Fire in High Rise Buildings. *Appl. Sci.* **2019**, *9*, 1431. [CrossRef]
13. Lu, X.X.; Shi, G.Y.; Song, S.Y. Investigation on the fire behaviour and propagation rule of fire overflow in the high-rise concave building structure. *Indoor Built Environ.* **2022**, *32*, 214–229. [CrossRef]
14. Li, J.; Li, Y.F.; Bi, Q.; Li, Y.; Chow, W.K.; Cheng, C.H.; To, C.W.; Chow, C.L. Performance evaluation on fixed water-based firefighting system in suppressing large fire in urban tunnels. *Tunn. Undergr. Space Technol.* **2019**, *84*, 56–69. [CrossRef]
15. Cheong, M.K.; Cheong, W.O.; Leong, K.W.; Lemaire, A.D.; Noordijk, L.M. Heat Release Rate of Heavy Goods Vehicle Fire in Tunnels with Fixed Water Based Fire-Fighting System. *Fire Technol.* **2014**, *50*, 249–266. [CrossRef]
16. Dasgotra, A.; Rangarajan, G.; Tauseef, S.M. CFD-based study and analysis on the effectiveness of water mist in interacting pool fire suppression. *Process Saf. Environ. Prot.* **2021**, *152*, 614–629. [CrossRef]
17. Li-wei, P.A.N.; Lo, S.M.; Guang-xuan, L.; Bei-hua, C. Experimental Study of Smoke Control in Subway Station for Tunnel Area Fire by Water Mist System. *Procedia Eng.* **2011**, *11*, 335–342. [CrossRef]
18. Jiang, Q.; Gao, S.; Kong, X.X. Application analysis of high pressure water mist fire extinguishing system in subway train. *Water Wastewater Eng.* **2020**, *56*, 76–80, 85. [CrossRef]
19. Lee, J. Numerical analysis on the rapid fire suppression using a water mist nozzle in a fire compartment with a door opening. *Nucl. Eng. Technol.* **2019**, *51*, 410–423. [CrossRef]
20. Yang, P.Z.; Liu, T.; Qin, X.A. Experimental and numerical study on water mist suppression system on room fire. *Build. Environ.* **2010**, *45*, 2309–2316. [CrossRef]
21. Santangelo, P.E.; Tarozzi, L.; Tartarini, P. Full-Scale Experiments of Fire Control and Suppression in Enclosed Car Parks: A Comparison Between Sprinkler and Water-Mist Systems. *Fire Technol.* **2016**, *52*, 1369–1407. [CrossRef]
22. Li, B.Q.; Liu, B.; Tang, L.G.; Zhao, S.; Chen, Y. Application Analysis of High Pressure Fine Water Mist Extinguishing Technology in Metro Vehicles. *Electr. Driv. Loco.* **2020**, *273*, 124–128. [CrossRef]
23. Yao, B.; Chow, W.K. Extinguishment of a PMMA fire by water spray with high droplet speeds. *Int. J. Therm. Sci.* **2005**, *44*, 410–419. [CrossRef]
24. Yu, H.Z. The Ceiling Height Limits for Water Mist Protection of Two Solid Combustible Fire Hazards in Open Environment. *Fire Technol.* **2021**, *57*, 163–187. [CrossRef]
25. Zhang, P.H.; Tang, X.; Tian, X.L.; Liu, C.; Zhong, M.H. Experimental study on the interaction between fire and water mist in long and narrow spaces. *Appl. Therm. Eng.* **2016**, *94*, 706–714. [CrossRef]
26. Liu, H.; Wang, C.; De Cachinho Cordeiro, I.M.; Yuen, A.C.Y.; Chen, Q.; Chan, Q.N.; Kook, S.; Yeoh, G.H. Critical assessment on operating water droplet sizes for fire sprinkler and water mist systems. *J. Build. Eng.* **2020**, *28*, 100999. [CrossRef]
27. Liu, Y.; Wang, X.; Liu, T.; Ma, J.; Li, G.; Zhao, Z. Preliminary study on extinguishing shielded fire with water mist. *Process Saf. Environ. Prot.* **2020**, *141*, 344–354. [CrossRef]
28. Wang, Z.; Wang, X.; Huang, Y.; Tao, C.; Zhang, H. Experimental study on fire smoke control using water mist curtain in channel. *J. Hazard. Mater.* **2018**, *342*, 231–241. [CrossRef]
29. Ku, Y.; Zhang, J.; Wang, Z.; Li, Y.; Yao, H. A Numerical Study on the Extinguishing Performances of High-Pressure Water Mist on Power-Transformer Fires for Different Flow Rates and Particle Velocities. *Fld. Dyn. Mater. Process.* **2021**, *17*, 1077–1090. [CrossRef]
30. Lee, J.; Moon, J. Numerical analysis of the effect of horizontal distance between a water mist nozzle and ignition source on reduction in heat release rate. *Ann. Nucl. Energy* **2020**, *144*, 107560. [CrossRef]
31. Gui, X.; Xue, H.; Hu, Z.; Cui, Z. Influence of Water Mist Nozzle Characteristic Parameters on Oil Pool Fire Extinguishing in Confined Space. *Arab. J. Sci. Eng.* **2023**, *48*, 3441–3454. [CrossRef]
32. Papa, R.; Andrade, C.R.; Zaparoli, E.L.; Santos, L.C.D. CFD analysis of smoke transport inside an aircraft cargo compartment. *J. Braz. Soc. Mech. Sci. Eng.* **2016**, *38*, 327–334. [CrossRef]
33. Li, G.C.; Pan, C.Y.; Liu, Y.P.; Zhu, X.L.; Ni, X.M.; Zhao, X.D.; Chen, G.X.; Wang, X.S. Evaluation of the effect of water mist on propane/air mixture deflagration: Large-scale test. *Process Saf. Environ. Prot.* **2021**, *147*, 1101–1109. [CrossRef]

34. Liu, T.; Liu, Y.; Wang, X.; Kong, X.; Li, G. Cooling control of thermally-induced thermal runaway in 18,650 lithium ion battery with water mist. *Energy Convers. Manag.* **2019**, *199*, 111969. [CrossRef]
35. Liu, Y.P.; Wang, X.S.; Zhu, P.; Li, G.C.; Ni, X.M.; Zhang, J. Experimental study on gas jet suppressed by water mist: A clean control technique in natural gas leakage incidents. *J. Cleaner Prod.* **2019**, *223*, 163–175. [CrossRef]
36. Liu, Y.P.; Shen, J.X.; Ma, J.; Li, G.C.; Zhao, Z.H.; Ni, X.M.; Wang, X.S. Laser-based measurement and numerical simulation of methane-air jet flame suppression with water mist. *Process Saf. Environ. Prot.* **2021**, *148*, 1033–1047. [CrossRef]
37. Chen, Y.B. Influence of layout of windows in the staircase on natural smoke exhausting. *Fire Sci. Technol.* **2015**, *34*, 1436–1439.
38. Ahn, C.-S.; Kim, D.-Y.; Park, C.; Kim, M.-W.; Kim, T.; Bang, B.-H.; An, S.; Yarin, A.L.; Yoon, S.S. Experimental and numerical study of smoke behavior in high-rise stairwells with open and closed windows. *Int. J. Therm. Sci.* **2020**, *157*, 106500. [CrossRef]
39. Su, C.H.; Lin, Y.C.; Shu, C.M.; Hsu, M.C. Stack effect of smoke for an old-style apartment in Taiwan. *Build. Environ.* **2011**, *46*, 2425–2433. [CrossRef]
40. McKeen, P.; Liao, Z. Numerical analysis on the hazards of open stairwell doors in high-rise residential buildings. *J. Build. Eng.* **2022**, *54*, 104561. [CrossRef]
41. Sun, J.Y.; Fang, Z.; Tang, Z.; Beji, T.; Merci, B. Experimental study of the effectiveness of a water system in blocking fire-induced smoke and heat in reduced-scale tunnel tests. *Tunn. Undergr. Space Technol.* **2016**, *56*, 34–44. [CrossRef]
42. Zhou, Y.; Bu, R.W.; Zhang, X.N.; Fan, C.G.; Gong, J.H. Performance evaluation of water mist fire suppression: A clean and sustainable fire-fighting technique in mechanically-ventilated place. *J. Clean. Prod.* **2019**, *209*, 1319–1331. [CrossRef]
43. Lee, J. Numerical analysis of how ventilation conditions impact compartment fire suppression by water mist. *Ann. Nucl. Energy* **2020**, *136*, 107021. [CrossRef]
44. Zhang, T.; Cao, D.; Lv, Z. Simulation Study on the Influence of Fire Partition on Curtain Wall Temperature in Super High-Rise Buildings in China. *Complexity* **2021**, *2021*, 4124049. [CrossRef]
45. Zhang, T. Simulation Study on Fire Visibility of Typical Floor Planes of Modern Super High-Rise Office Buildings in China. *Complexity* **2020**, *2020*, 8868522. [CrossRef]
46. Meng, N.; Hu, L.; Wu, L.; Yang, L.; Zhu, S.; Chen, L.; Tang, W. Numerical study on the optimization of smoke ventilation mode at the conjunction area between tunnel track and platform in emergency of a train fire at subway station. *Tunn. Undergr. Space Technol.* **2014**, *40*, 151–159. [CrossRef]
47. Xiao, M.F.; Zhou, X.H.; Pan, X.X.; Wang, Y.A.; Wang, J.; Li, X.L.; Sun, Y.S.N.; Wang, Y.M. Simulation of emergency evacuation from construction site of prefabricated buildings. *Sci. Rep.* **2022**, *12*, 2732. [CrossRef]
48. Wang, J.G.; Zhao, S.R.; Su, J.K. Influence of different smoke exhaust modes on personnel evacuation in subway station fire. *Fire Sci. Technol.* **2021**, *40*, 1141–1145.
49. Blanchard, E.; Morlon, R.; Parent, G.; Fromy, P.; Boulet, P.; Borgiallo, D. Experimental Study of the Interaction Between Water Sprays and Smoke Layer. *Fire Technol.* **2018**, *54*, 479–501. [CrossRef]
50. Morlon, R.; Boulet, P.; Parent, G.; Morlon, R.; Lechene, S.; Blanchard, E.; Rebuffat, C.; Fromy, P.; Vantelon, J.P.; Borgiallo, D. Study of De-stratification and Optical Effects Observed During Smoke/Mist Interactions. *Fire Technol.* **2015**, *51*, 1231–1248. [CrossRef]
51. Xu, Z.S.; Jiang, X.P. *Smoke Control Engineering*; China Machine Press: Beijing, China, 2011; pp. 2–3.