Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 15, No. 2, 2025

Research on the Spread of Fire Smoke in High-rise Residential Kitchens Based on Pyrosim

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Abstract: In order to conduct in-depth research on the propagation law of pollutants caused by fire in different scenarios in the kitchen, this study took the 19-storey high-rise residential building as the object of numerical simulation analysis, studied the smoke propagation law of the high-rise residential kitchen, and verified the fire model by using the grid-independent and tracer gas experiment. The results show that when the smoke pipe is on fire, the smoke first spreads vertically in the smoke pipe, and then spreads horizontally from the mouth of the range hood to the surroundings, while when the electrical appliance is caught by short circuit, natural gas leakage and the oil pot is fired, the smoke first spreads horizontally on the floor where the fire source is located, and then spreads vertically through windows and stairs. The fire of oil smoke pipeline and natural gas leakage is the most harmful, followed by the fire hazard of electrical short circuit, and the fire of oil pan is significantly increased in the middle and late stages.

Keywords: High-rise residential; Pollutant propagation laws; Numerical simulation; Tracer gas experiment.

1. Introduction

With the acceleration of China's urbanization process, the land utilization rate has become higher and higher, leading to a sharp increase in the number of high-rise buildings. Among high-rise buildings, high-rise residential buildings account for a large proportion. High-rise residential buildings have a large fire load due to a large number of occupants, a lot of sundries in the corridors, and a large quantity of daily necessities in the rooms. Fires occur frequently in high-rise residential buildings, and the consequences are extremely serious.

There are studies on high-rise residential building fires from different dimensions at home and abroad. Existing studies mostly focus on single fire scenarios, with relatively few comparative analysis studies on different types of fires. The relevant research on kitchens mainly focuses on large commercial kitchens, and the research on kitchens in high-rise residential buildings is relatively scarce. However, kitchens in high-rise residential buildings are used frequently and have a high fire risk, so relevant research needs to be strengthened to fill the gap.

Tang Liqing [1] focused on a high-rise residential community in Beijing. By establishing a fire model and setting up 4 different fire scenarios for numerical simulation according to the principle of the most unfavorable situation, corresponding preventive management countermeasures, suggestions and measures were put forward. Zdzislaw Salamonowicz et al. [2] reconstructed the estimation numerical model. For the analyzed building cases, the study found that the rapid adoption of mechanical ventilation can shorten the operation time and improve the operation safety, providing a new idea for the ventilation design and fire prevention and control of medium and high-rise buildings. Li Dongxu et al. [3] focused on the problems in the fire protection design of civil high-rise buildings, such as the fire protection performance of the main structure, smoke prevention and smoke exhaust facilities, decoration materials, thermal insulation materials, and electrical equipment, which do not meet the specification requirements. It was clearly pointed out that in the fire prevention work, the importance of fire protection design must be emphasized. Rafat Al-Waked [4] studied different situations of whether a fire occurred in the atrium for two residential buildings connected by the atrium. The results showed that when a fire broke out in the atrium, the location of the fire had a significant impact on the air quality in the atrium. Zhang Jiangfeng [5] carried out numerical simulation taking a high-rise residential building as a typical research object. By simulating different fire conditions, a practical research scheme for the setting of refuge rooms in Class I high-rise residential buildings was provided. Wen Bo and Wang Xingmao [6] found through numerical simulation and analysis that under the condition of the same heat release rate, there were significant differences in the changes of the smoke obscuration rate in a single room due to different positions of the fire source. Guo Zidong [7] used the FDS simulation software, adopted the large eddy simulation method and the orthogonal experimental method to design the working conditions, and explored the influence of factors such as wind speed and cross-sectional size on the fire spread law of the oil fume duct. Chen Tuoqi [8] used the FDS software to analyze the temperature, visibility, CO concentration changes and smoke spread process in the kitchen, corridor and restaurant under the two smoke exhaust methods of natural and mechanical smoke exhaust for a specific restaurant model. Liu Xuhua [9] focused on the kitchens in the catering industry. From the four dimensions of the building's own fire protection, fire-fighting facilities and equipment, hazard sources, and safety management, a fire risk assessment index system and evaluation model suitable for this scenario were constructed, providing a powerful tool for accurate risk assessment. Hu Kangfei [10] deeply analyzed the causes and characteristics of fires in the smoke exhaust ducts of large kitchens and successfully designed a fire warning system specifically for the smoke exhaust ducts in kitchens, helping to detect fire hazards in advance and improve the prevention ability.

There are mainly two reasons for the occurrence of fires in high-rise residential buildings. The first is the ignition of flammable furniture. There are a large number of furniture in the residence, and the ignition speed is fast. Once ignited, it will cause large-scale combustion. The second is the kitchen fire. The kitchen not only has a large number of electrical appliances but also high power. For example, on January 10, 2022, when an old man in Guizhou was stir-frying in the kitchen at home, the range hood sucked in the flames at the moment of flipping the pan, and the flames ignited the exhaust duct along the oil dirt instantly [11]; on July 7, 2024, a fire occurred in a community in Chikan District, Zhanjiang, Guangdong. The main burning material was an induction cooker. Preliminary investigation found that the induction cooker caused the fire due to aging of the circuit [12]; on July 19, 2022, a gas leakage occurred in a household in Unit 6, Building 3, Huanyanli, Tianmu Town, Beichen District, Tianjin, resulting in the complete collapse of the outer walls on the south side of the households on the 4th to 6th floors. The accident eventually caused 4 deaths and 13 injuries [13]; on January 7, 2024, a fire suddenly broke out in the kitchen of a resident's home in Hanyang, Wuhan, and the cause was that the oil pan was heated for a long time, resulting in the oil temperature in the pan being too high and then catching fire [14].

Through the analysis of the above-mentioned daily use scenarios of the kitchen, it is found that if the staff does not operate properly or the facilities are not maintained properly, the fire accident of the oil smoke pipe is likely to occur; High-power appliances often used in the kitchen are prone to electrical accidents; Due to the frequent use of various fuels in the kitchen, such as gas, liquefied petroleum gas, diesel, etc., fire and explosion accidents caused by fuel leakage are very likely to occur [15]; When using the kitchen, improper oil temperature control, cooking operation errors, equipment failure, and combustibles next to the oil pan can easily cause oil pan fire accidents. Therefore, this paper mainly analyzes the distribution characteristics and propagation rules of smoke in high-rise residential kitchen fire accidents under four fire causes: smoke pipe fire, electrical short circuit, fuel leakage, and oil boiler fire.

2. Overview of the Basic Theories of Pyrosim Software and Its Research Objects

2.1. Control Equations

In a fire simulation, the mass conservation equation is used to track the mass change of various fluids in the scene, as shown in Eq. (1):

$$\frac{\partial \rho}{\partial t}+\nabla \cdot (\rho \vec{\upsilon})=0 \quad (1)$$

In the formula: ρ is the fluid density, t is the time, and $\vec{\upsilon}$ is the fluid velocity vector. $\frac{\partial \rho}{\partial t}$ represents the rate of change of density with respect to time, and $\nabla \cdot (\rho \vec{\upsilon})$ represents the net outflow rate of mass per unit volume.

According to the law of conservation of momentum, the momentum equation can be deduced as follows:

$$\rho \frac{\partial \vec{\upsilon}}{\partial t}+\rho (\vec{\upsilon}\cdot\nabla)\vec{\upsilon}=-\nabla p+\mu\nabla^2\vec{\upsilon}+\rho\vec{g} \quad (2)$$

In the formula: ρ is the fluid density, $\vec{\upsilon}$ is the fluid velocity vector, t is the time,

p is the pressure, μ is the dynamic viscosity, and $\vec{g}$ is the gravitational acceleration. t $\rho\frac{\partial \vec{\upsilon}}{\partial t}$ represents the rate of change of the fluid momentum with respect to time, and $\rho(\vec{\upsilon}\cdot\nabla)\vec{\upsilon}$ represents the change in momentum caused by the fluid flow (convective term). $-\nabla p$ represents the pressure gradient force, $\mu\nabla^2\vec{\upsilon}$ represents the viscous force, and $\rho\vec{g}$ represents the gravitational force.

According to the law of conservation of energy, convective heat transfer, and the absorption (or release) of heat by internal and external heat sources, the energy equation (3) can be obtained:

$$\rho C_p \frac{\partial T}{\partial t}+\rho C_p (\vec{\upsilon}\cdot\nabla)T=\nabla\cdot(k\nabla T)+q''' \quad (3)$$

In the formula: ρ is the fluid density, C_p is the specific heat capacity at constant pressure, T is the temperature, t is the time, $\vec{\upsilon}$ is the fluid velocity vector, k is the thermal conductivity, and q''' is the internal heat generation rate per unit volume. $\rho C_p\frac{\partial T}{\partial t}$ represents the rate of change of internal energy per unit volume with respect to time, and $\rho C_p(\vec{\upsilon}\cdot\nabla)T$ represents the change in internal energy caused by the fluid flow (convective term). $\nabla\cdot(k\nabla T)$ represents the change in heat flux caused by heat conduction, and q''' represents the internal heat generation due to processes such as combustion.

Species conservation equation:

$$\frac{\partial(\rho Y_i)}{\partial t}+\nabla\cdot(\rho\vec{\upsilon}Y_i)=\nabla\cdot(\rho D_i\nabla Y_i)+\dot{\omega}_i \quad (4)$$

In the formula: ρ is the fluid density, Y_i is the mass fraction of the i-th component, t is the time, $\vec{\upsilon}$ is the fluid velocity vector, D_i is the diffusion coefficient of the i-th component, and $\dot{\omega}_i$ is the production or consumption rate of the i-th component. The first term on the left - hand side of the equation, $\frac{\partial(\rho Y_i)}{\partial t}$ represents the rate of change of the mass fraction of the i-th component with respect to time. The second term, $\nabla\cdot(\rho\vec{\upsilon}Y_i)$ represents the change in the mass fraction of the i-th component caused by the fluid flow (convective term). The first term on the right - hand side,

$\nabla \cdot (\rho D_i \nabla Y_i)$ represents the change in the mass fraction of the i-th component due to diffusion. The second term, $\dot{\omega}_i$ represents the production or consumption of the i-th component due to processes such as combustion or chemical reactions.

2.2. Physical Model

In this paper, the object of fire simulation is an ordinary high-rise residential building in a certain area. The residential building has a total of 19 floors. Considering the locational advantage of the middle floors, compared with the ground floor and the top floor, the 12th floor, which is in the middle position, is more representative and can represent most of the floors. This is conducive to analyzing the law of the degree of fire spread under general circumstances and the impact of the fire on the upper and lower floors. The fire source is set in the kitchen on the 12th floor for the fire simulation. Due to the symmetry of the building, a kitchen is randomly selected. As shown in Figure 1, the kitchen of the household on the upper right is chosen as the fire source. This paper mainly studies the fire spread situation in the worst-case scenario and highlights the impact of internal factors in the kitchen on the fire. Therefore, the doors and windows of the entire high-rise residential building are always set to be open.

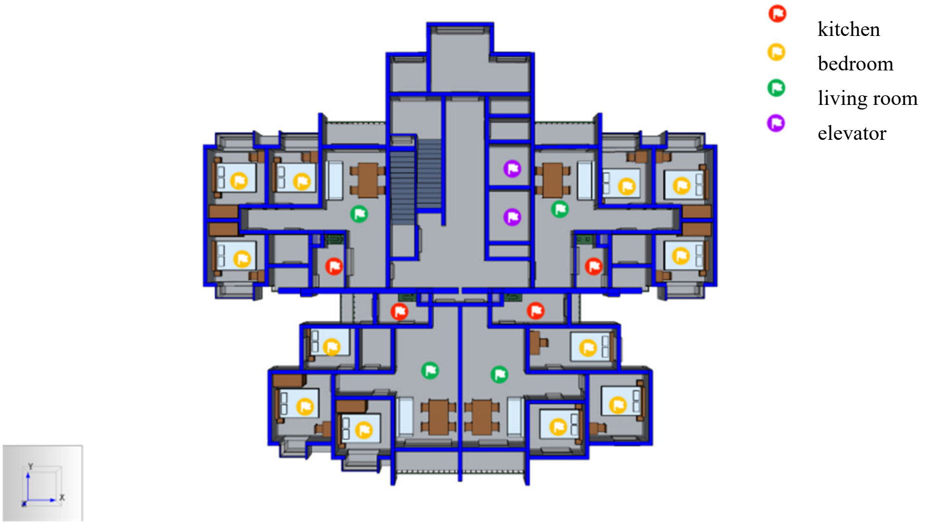


Figure 1. Floor Plans of the Ground Floor and Standard Floor

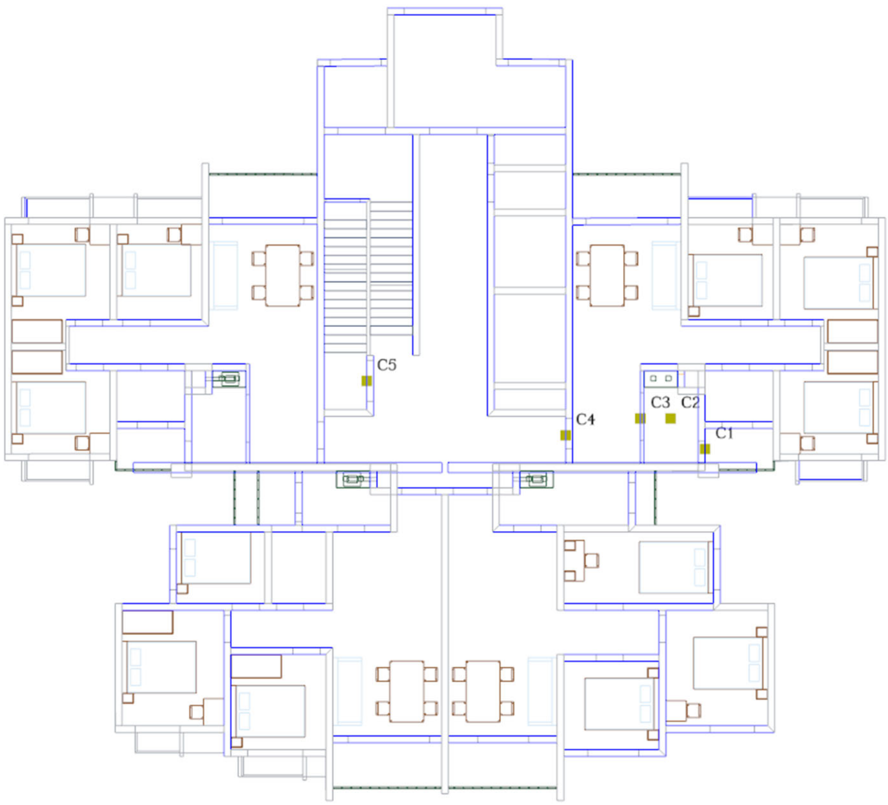


Figure 2. Plan Layout Diagram of Measuring Points

2.3. Mesh Generation and Layout of Measuring Points for Working Conditions

There are four simulations in this paper. Through the comparison of multiple simulation results, the grid size for electrical short - circuit, natural gas leakage and oil pan fire is 0.3m×0.3m×0.3m. The grid size for the fire in the oil fume duct is 0.2m×0.2m×0.2m. Monitoring points with a height of 1.8m are set on the 10th to 18th floors, named C1, C3, C4 and C5 respectively, as shown in Figure 2. There is also a monitoring point C2 in the middle of the kitchen ceiling, which is used to monitor the intuitive feeling of the change of the fire source smoke. When a fire occurs in the kitchen on the 12th floor, it basically has no impact on the 1st to 9th floors of the high - rise residential building, so no measuring points are set. From the 10th to 18th floors of the entire building, the monitoring points set on each floor are the same.

In order to analyze the diffusion path of the smoke more comprehensively, horizontal slices with a height of 2m from the floor are set on the 10th to 18th floors for monitoring, and a vertical slice in the middle of the fire source is also set. As shown in Figure 3.

2.4. Parameter Settings of Working Conditions

The combustion model is a t^2 fire model. The t^2 fire model (also known as the squared growth fire model) is an idealized model used to describe the rate of heat release (HRR) of a fire over time. It assumes that the rate of heat release from a fire is proportional to the square of time, and its mathematical expression:

$$\mathrm{HRR} = \alpha t^2 \tag{5}$$

α is the fire growth coefficient, the unit is kW/s^2, it determines the rate of fire growth; t is the time calculated from the start of the fire and is measured in s.

Through relevant data query, in this paper, the fire sources of electrical short - circuit, natural gas leakage and oil pan fire are set on the stove. The shape is a cube with a total area of 0.2 square meters. For the fire in the oil - fume pipeline, the fire source is set inside the pipeline, attached to the inner wall of the pipeline, with a total area of 36 square meters. The fire source power is shown in Table 1.

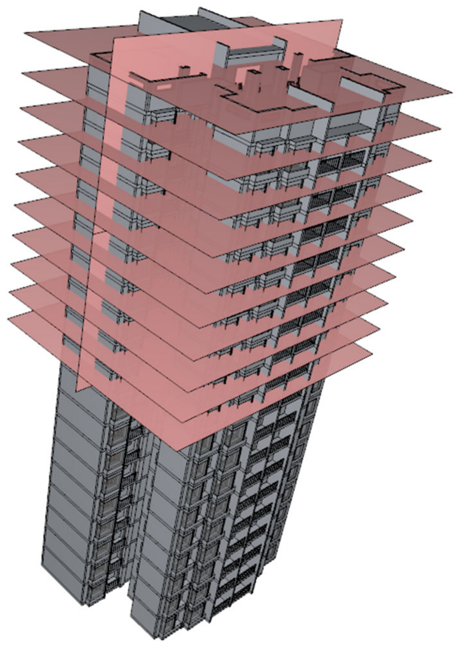


Figure 3. Layout Diagram of Slices

Table 1. Setting Table of Fire Source Power

Fire source type	Maximum heat release rate(kW/㎡)	The time it takes to reach the maximum heat release rate(s)
oil fume duct	1000	146
Electrical short-circuit	2500	210
Gas leaks	10000	103
The oil pan is on fire	5000	584

2.5. Grid Independence Verification

In this paper, three kinds of grid sizes are set, namely rough, medium and fine, as shown in Table 2.

Table 2. Detailed Table of Mesh Generation

Type of fire	Meshing method	Grid size(m*m*m)	Number of meshes(piece)	Calculate the time(sky)
oil fume duct	rough	0.22×0.22×0.22	3737610	7
	medium	0.2×0.2×0.2	4972800	10
	filigree	0.18×0.18×0.18	6826092	30
Electrical short-circuit Gas leaks The oil pan is on fire	rough	0.4×0.4×0.4	621600	1
	medium	0.3×0.3×0.3	1473120	3
	filigree	0.2×0.2×0.2	4972800	6

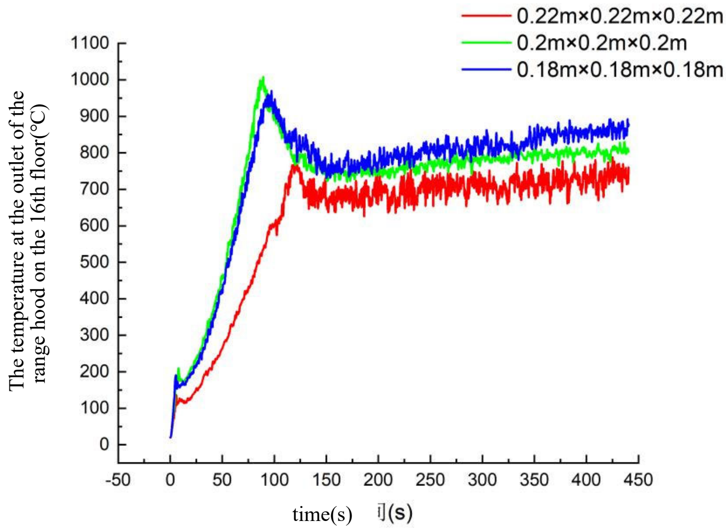


Figure 4. Comparison Diagram of Temperatures with Different Grids for the Fire in the Oil Fume Duct

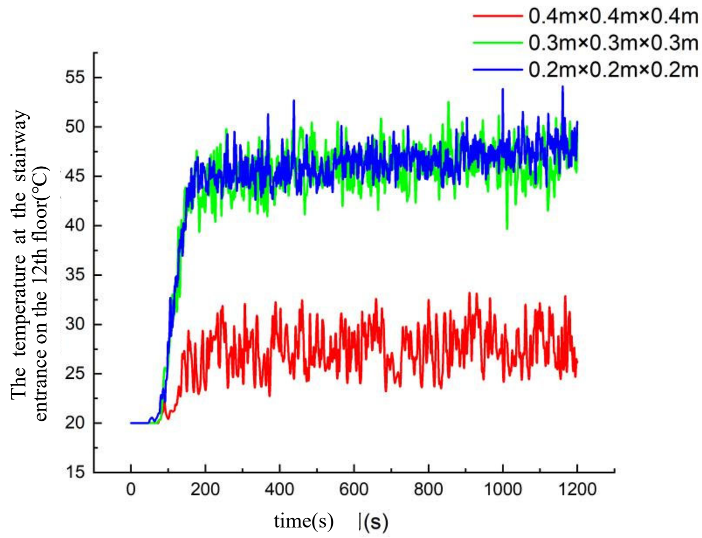


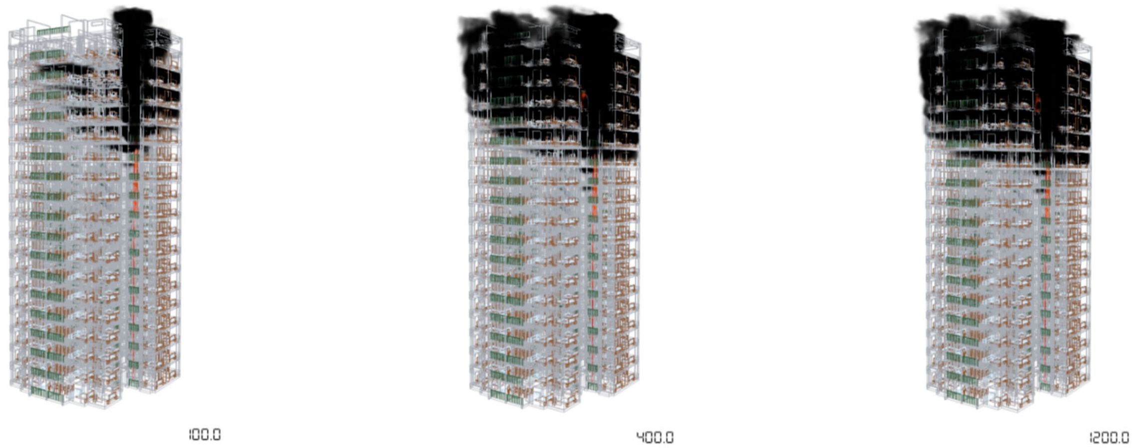
Figure 5. Comparison Diagram of Temperatures with Different Grids for Electrical Short Circuit, Natural Gas Leakage and Oil Pan Fire

As shown in Figures 4 and 5, there is little difference in calculation accuracy between the medium grid and the fine grid. The calculation time of the fine grid is approximately three times that of the medium grid. Considering both the calculation accuracy and the calculation cost, this paper adopts the medium grid division method.

3. Numerical Simulation Analysis of Kitchen Fire Accidents in High-rise Residential Buildings

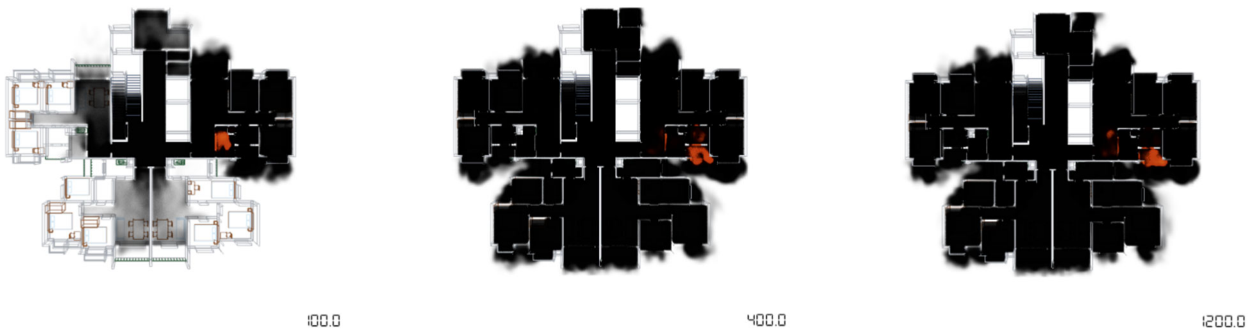
3.1. Simulation Analysis of Kitchen Oil Fume Pipeline Fire

As shown in Figures 6 and 7. According to the fire dynamics simulation, when the fire occurs for 5 seconds, smoke first ejects from the exhaust hood opening of the kitchen on the 17th floor. When the fire occurs for 180 seconds, the entire 17th floor has been covered by smoke, and the smoke spreads to half of the areas on the 10th to 18th floors. Finally, as time goes on, the 13th floor is also basically filled with smoke. During the whole fire process, due to the influence of the chimney effect, the high-temperature smoke mainly diffuses upward. Except for the 18th floor directly affected by the smoke plume, the lower the floor is, the smoke concentration decreases in a gradient, and the floors below the 12th floor are less affected.



(b) T=100s (d) T=400s (f) T=1200s

Figure 6. Elevation Diagram of Smoke Distribution in Residential Buildings



(b) T=100s (d) T=400s (f) T=1200s

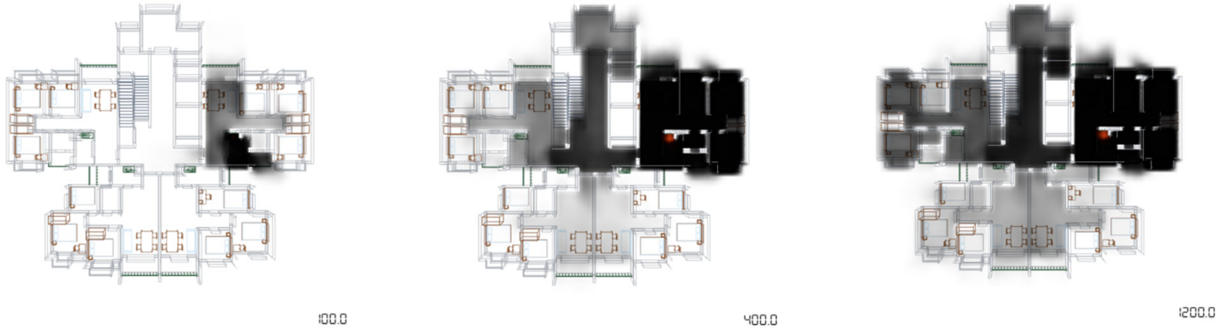
Figure 7. Plan Diagram of Smoke Distribution in Residential Buildings

3.2. Simulation Analysis of Kitchen Electrical Short - circuit Fire

As shown in Figures 8 and 9. According to the fire dynamics simulation, when the fire occurs for 32 seconds, driven by thermal buoyancy, the high-temperature smoke breaks through the kitchen window, forms a plume along the outer facade of the residential building and spreads to the 13th floor. When the fire occurs for 300 seconds, half of the floors above the 12th floor are shrouded in smoke. As time goes on, all the floors above the 12th floor of the entire high-rise residential building are completely filled with smoke, but due to the effect of the thermal pressure barrier, there is only a trace of penetration on the 11th floor and the floors below it.

(b) T=100s (d) T=400s (f) T=1200s

Figure 8. Elevation Diagram of Smoke Distribution in High-rise Residential Buildings

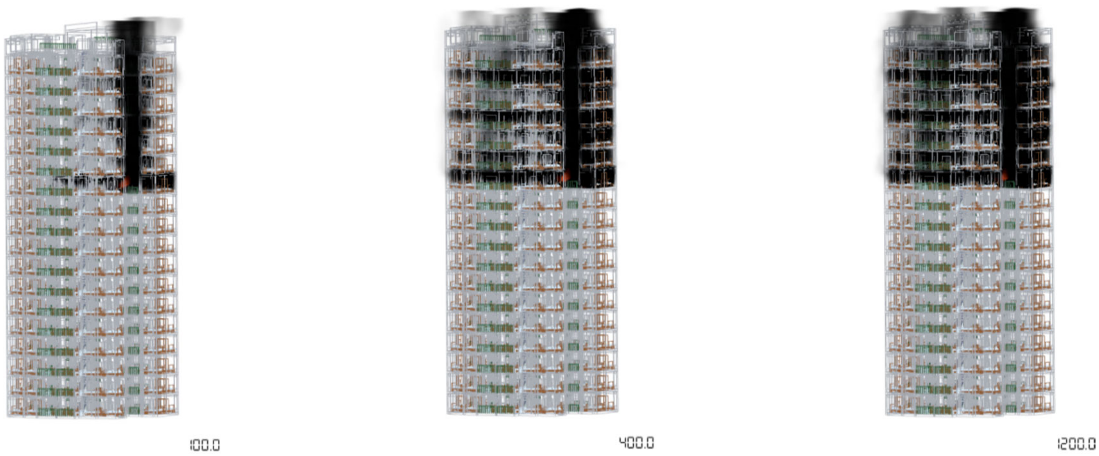


(b) T=100s (d) T=400s (f) T=1200s

Figure 9. Plan Diagram of Smoke Distribution in High-rise Residential Buildings

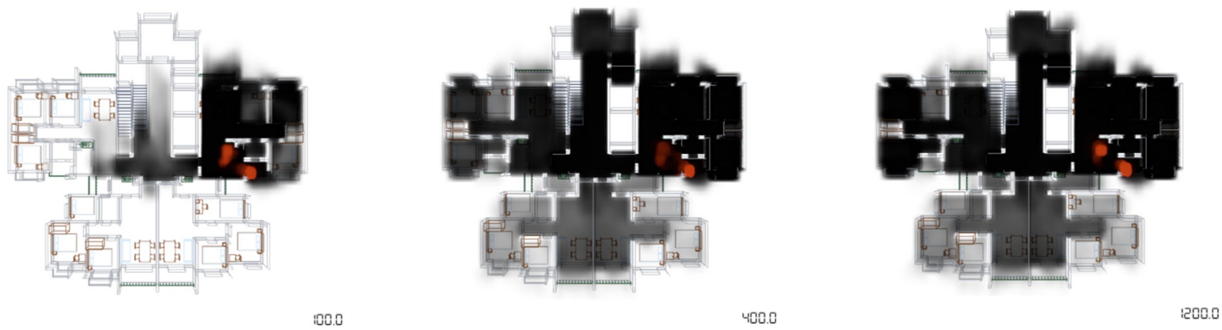
3.3. Simulation Analysis of Fire Caused by Natural Gas Leakage in the Kitchen

As shown in Figures 10 and 11. According to the fire dynamics simulation, when the fire occurs for 20 seconds, driven by thermal buoyancy, the high-temperature smoke breaks through the kitchen window, forms a plume along the outer facade of the residential building and spreads to the 13th floor. When the fire occurs for 300 seconds, the 12th, 13th, 15th and 17th floors are already filled with smoke. As time goes on, all the floors above the 12th floor of the entire high-rise residential building are completely filled with smoke, but due to the effect of the thermal pressure barrier, there is only a trace of penetration on the 11th floor and the floors below it.



(b) T=100s (d) T=400s (f) T=1200s

Figure 10. Elevation Diagram of Smoke Distribution in High-rise Residential Buildings

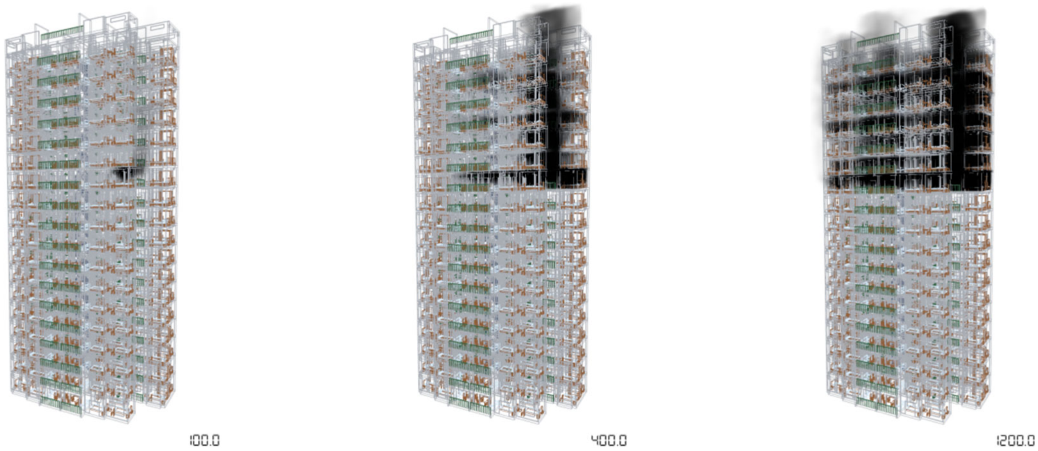


(b) T=100s (d) T=400s (f) T=1200s

Figure 11. Plan Diagram of Smoke Distribution in High-rise Residential Buildings

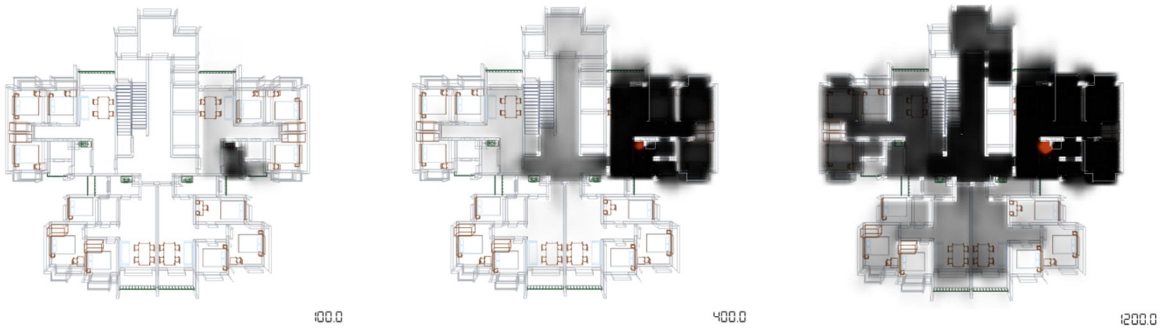
3.4. Simulation Analysis of Fire Caused by an Oil Pan Fire in the Kitchen

As shown in Figures 12 and 13. According to the fire dynamics simulation, when the fire breaks out for 60 seconds, driven by thermal buoyancy, the high-temperature smoke breaks through the kitchen window, forms a plume along the outer facade of the residential building and spreads to the 13th floor. When the fire has been burning for 726 seconds, the entire 12th floor has been engulfed by smoke. When 867 seconds have passed since the fire started, the 12th, 13th, 15th and 17th floors are already filled with smoke. As time goes on, all the floors above the 12th floor of the entire high-rise residential building are completely filled with smoke, but due to the effect of the thermal pressure barrier, there is only a trace of smoke penetration on the 11th floor and the floors below it.



(b) T=100s (d) T=400s (f) T=1200s

Figure 12. Elevation Diagram of Smoke Distribution in High-rise Residential Buildings



(b) T=100s (d) T=400s (f) T=1200s

Figure 13. Plan Diagram of Smoke Distribution in High-rise Residential Buildings

4. Discuss

4.1. Comparative Analysis of Evacuation Results

Due to the chimney effect and thermal buoyancy effect of the smoke, coupled with the fact that the simulation is the most unfavorable state in which the doors and windows are open, the chimney and thermal buoyancy effect will occur on each floor, which leads to the uneven distribution of fire spread. The most dangerous floors for smoke pipe fire are the 15th, 16th, and 17th floors, and the smoke on these three floors spreads quickly, so it is mainly these three floors that affect the safe evacuation time. The 12th floor is the most dangerous floor for electrical short-circuit fires, natural gas leakage fires, and oil pan fires, and the 12th floor is also the first to reach the critical value of dangerous conditions. After the fire simulation of the four situations in the kitchen, it can be seen that the fire of the smoke pipe is the most dangerous and the fastest diffusion, when the smoke pipe is on fire, the flame quickly spreads vertically throughout the smoke pipe, and then when the check valve of the range hood reaches the temperature limit, after the check valve fails, the fire quickly spreads from the mouth of the range hood to the household; The second is the natural gas leakage fire, due to the volatile nature of the natural gas itself, when the natural gas catches fire, the fire quickly spreads horizontally on the 12th floor, and the fire spreads to the entire floor; The oil pan fire and electrical short circuit fire are relatively slow, but the harm to the whole building is also very large, the electrical short circuit fire has a large impact on the evacuation of personnel in the early stage, but the oil pan fire to the fire development period, the hazard surpasses the electrical short circuit fire.

4.2. Tracer gas experiment verification

To further verify the fire simulation results, a tracer gas experiment was carried out in this paper. The experimental site is located in a community in Changsha City, Hunan Province.

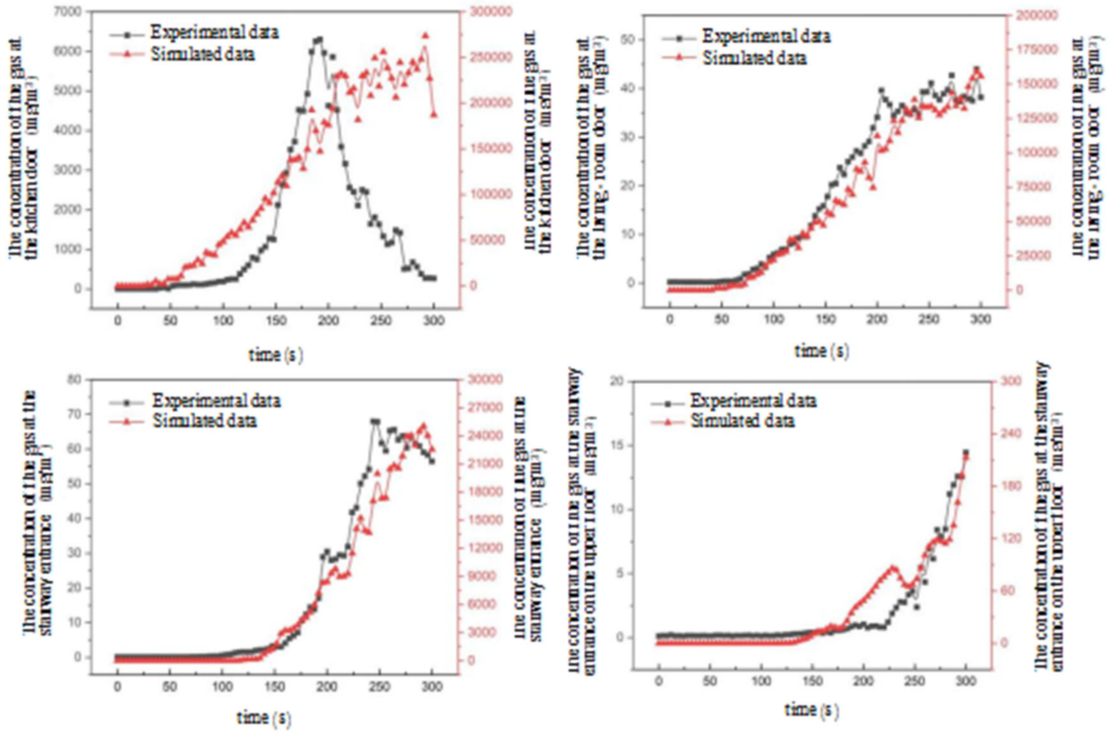


Figure 14. Comparison Diagram of Smoke between the Experiment and the Simulation

As shown in Figure 14. In this experiment, there may be differences in the numerical values of the smoke concentration between the experiment and the simulation. This is because the smoke output of the smoke cakes used in the experiment is much less than that in the real fire situation. However, overall, the changing trends of the smoke concentrations obtained from the experiment and the simulation basically coincide, showing the characteristics of consistent changes within a specific time period.

5. Conclusion

In this paper, the fire simulation software Pyrosim is used to model, draw grids and simulate fire simulations of high-rise residential buildings, and conduct in-depth analysis of the changes of smoke in the fire by setting different fire situations, and the following conclusions are drawn through the analysis:

In addition to the top floor, the higher the floor, the greater the degree of damage, and the short-circuit fire of electrical appliances, natural gas leakage and oil pan fire are closer to the fire source The greater the damage to the residential building on the floor. With the help of the chimney effect, the flue gas spreads rapidly and vertically in the smoke pipe, and then the flue gas enters the room from the mouth of the range hood for horizontal diffusion; Natural gas leakage fire is the second, natural gas leakage fire first spreads horizontally on the floor where the fire source is located, and then rises rapidly vertically through windows, stairs, etc. due to thermal buoyancy, and then spreads horizontally; The initial development of electrical short-circuit fire is rapid, and the spread rate slows down in the later stage. In the middle and late stages of the oil pan fire, the smoke diffusion accelerates, and the harm gradually intensifies. The hazards of the oil pan fire are prominent in the middle and late stages, and the electrical short-circuit fire is relatively controllable. The smoke distribution of each fire type shows an alternating pattern of "chimney effect dominates vertical diffusion, and thermal buoyancy decays and then spreads horizontally", resulting in non-uniform distribution of smoke in the vertical direction of the building.

Based on the research results, the fire prevention and control of high-rise residential kitchens should focus on strengthening the regular cleaning of oil smoke pipes to prevent the accumulation of oil scale and cause fires. At the same time, an effective natural gas leakage early warning device is installed to detect and deal with leakage problems in a timely manner.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (52276094) and the Key Project of Hunan Provincial Education Department (24A0188).

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