Effect of Opening Size on the Development of Ventilation-limited Fire

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Abstract: There are many factors, that affect the development of indoor fire, such as the size of the fire source, the opening or space of the room, and the nature of the combustible materials. Among them, the space of the room, has a significant impact on the development of a ventilation-limited fire. In this paper, the Fire Dynamics Simulator (FDS) software is used to analyze, the risk of fire initiation in the restricted ventilated compartment, when the size of vertical ventilation space is different. Through, a combination of experimental design, numerical simulation, and theoretical analysis, the changes in the level of carbon monoxide, visibility, temperature, Heat Release Rate (HRR) and, the smoke exhaust efficiency of natural smoke at different opening sizes are observed. It is observed that, when the ratio of inlet and outlet area reaches 2:1, the natural smoke exhaust effect is the best, however, the increasing in the opening size has little significance on the smoke exhaust effect. The research on the influence of smoke outlet size, will helps in the development of the law regarding fire prevention, smoke exhaust design, and fire rescue work of a building.

Keywords: Open size; Vertical ventilation; Exhaust efficiency; Flue gas concentration; FDS

1. Introduction

The smokes that are released from the fire, is the main cause of death. The fire smoke contains hazards that, can categorize into three different types, which are toxic, light-reducing, and high-temperature. The hot temperature of the fire, not only causes physical harm to the human body, but also badly influences people's psychological fear in the dark environment. During the initiation of a fire in a building, the hot smoke begins to rise with the air flow and then descends when, it encounters the ceiling or other partition obstacles until it fills the entire building. In addition, the spreading of the smoke and the decline of the neutral surface usually happens rapidly. The smoke produced from the fire, will affect the deployment of the firefighting and rescue mission, further reduce the efficiency of safe evacuation, and have a great impact on the survival probability of trapped individual. Researchers [1-3] has used FDS software to simulate the fire overflow behavior on different opening sizes in confined spaces. The results show that, when the total rate of the heat release from the fire is higher, compared to the inside of the combustion chamber, a stable fire overflow phenomenon can be obtained similar as in outdoors, and the combustion participation rate of the hot air flowing with the indoor air is positively correlated with the ventilation coefficient, where the fire flow remains stable, until it reaches a certain value. Further, Xu et al., and others [4,5] conducted an experiment by initiating the fire using fuel packs in a hotel room, and studied the changes of the heat release rate, the

temperature, and the smoke concentration in different fire scenarios, by changing the ventilation conditions, and the placement of the fuel packs. Additionally, Kashef A [6], pointed out that, the smoke exhaust is the main source of hazard that has to be dealt, therefore he introduced a hybrid model, an algorithm for smoke filling in fluid dynamics simulation, and smoke modeling of a large multi-compartment building. Through the fluid dynamics algorithm in the fuel gas emission design, the results predicted by Computational Fluid Dynamics (CFD) with different free boundary conditions, are compared with the results of indoor fire tests. Ji J et al., [7], also have introduced a hybrid model that, can simulate the fire smoke and heat movement in a multi-room building, and further understand the mass, and the heat transfer between the compartments. Candido Gutierrez-Montes et al., [8] studied the law of smoke diffusion using natural ventilation and smoke exhaust mode, when a fire occurred in a subway section tunnel, and made a certain analysis on the safety plan during the evacuation of people. Harmathy at al., [9] proposed a simple model of the air and smoke flow, which is caused by the stack effect in high-rise buildings. This model helps architectural designers to understand the smoke movement, and provides guidance and assistance for smoke control strategies. As the main channel for the energy and mass exchange between the building and the external environment, the size of the building opening has an important impact on the initiation and the development of ventilation-limited fires. Therefore, it is important to conduct a study on fire smoke prevention and fire measurement controls, by focusing on the influence of the opening size on the development of ventilation-limited fires.

2. FDS model establishment and conditions setting
2.1. FDS model establishment
Due to the high cost of the full-size combustion test, together with the increasingly complex building structure, and high performance of fire prevention design, therefore, experiment on the fire development process, and flue gas movement law is achieved by simulating the computer models, to study the fire characteristics, and fire safety analysis. This paper will use the FDS model, to simulate the fire experiment by changing the size of the ventilation, followed by a comparative analysis to determine the influence of the size of the opening on the development of ventilation-limited fires. This numerical simulation, can evaluate the combustion performance of the building components and materials in different fire scenarios according to the needs of the designer, with more efficient fire control measurement.

According to the feasibility of the simulation experiment, and the cost of the experiment, a two-story building is built with a reasonable scenario. The building is constructed in a 10m×10m×3m box structure, with the fire floor is located on the second floor of the building. The building has a door at the entrance of the room with the size of 2m^2, and windows facing outside as a smoke drain, and the model is suitable for natural smoke exhaust. When the fire broke out for 90 seconds, the windows were opened for smoke exhaust, and the door was remained open throughout the process. The fire source in the experiment, is designed based on to the wooden table that is used in the daily life, with the density of the wood is around 376 kgm^{-3}. The structure of the room simulated by FDS is shown in **Figure 1**.
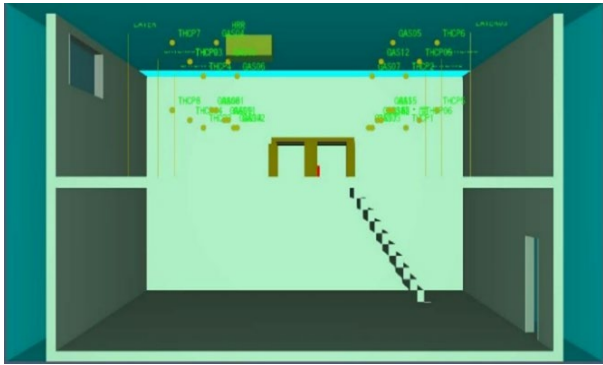
Figure 1. Stimulation diagram of the structure of the burning room

Table 1. Simulated experimental conditions

Conditions	Opening Size/ (m²)	Door Size/ (m²)
1	1.0	2.0
2	1.5	2.0
3	2.0	2.0
4	2.5	2.0
5	3.0	2.0
6	3.5	2.0
7	4.0	2.0
8	4.5	2.0
9	5.0	2.0
10	5.5	2.0
11	6.0	2.0
12	6.5	2.0
13	7.0	2.0

The establishment of the model, is mainly to analyse the influence of ventilation size on the fire smoke characteristics, and fire development by calculating the power, the temperature, the level of carbon monoxide concentration, and the changes in the visibility in the process of fire development.

2.2. Conditions setting

To study the effect of the opening size on the flow of flue gas, a total of 13 simulation conditions has been established by developing rows of fire based on the numerical simulation, as shown in **Table 1**, and the effect of the opening size was compared between the stimulation condition. In this experiment, the size of the entrance door is fixed to 1.0 m × 2.0 m. The changing variable, is mainly the opening size of the exit windows, with ranging from small to large, 1.0 m^2 to 7.0 m^2, and the other parameters remain constant.

3. FDS simulation results analysis

3.1. Effect of opening size on fire source power

Figure 2 and **Figure 3** are the curves of the heat release rate, that is obtained based on the different opening sizes with time. As shown in the figures, the heat release rate is increasing at the initiation stage of the fire before it decreased. The increase in the size of the opening, further delay the peak of the heat release rate, where the heat release rate decreases at the initiation stage of the fire, and then enlarge with the increase of the opening size.
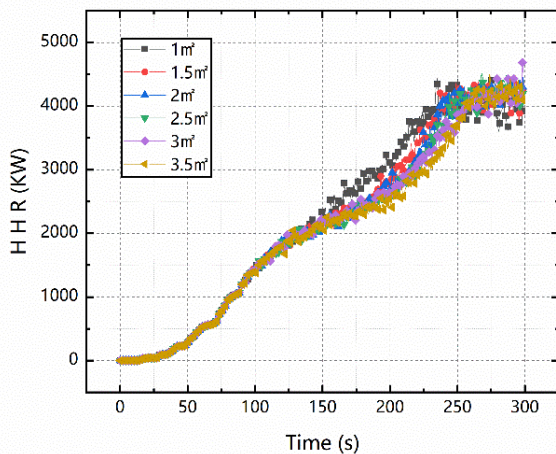

Figure 2. HRR distribution over time, when the opening size is 1m²-3.5m²
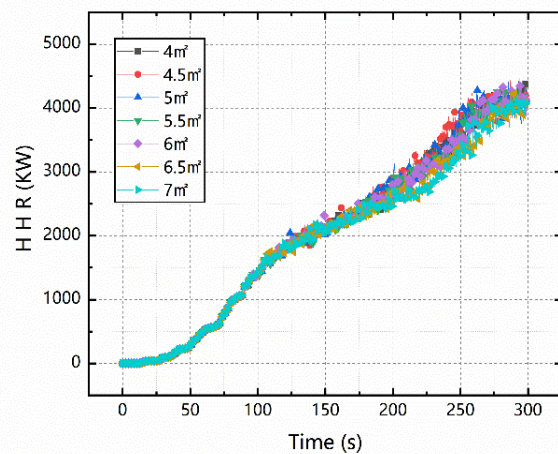
Figure 3. HRR distribution over time when the opening size is 4m²-7m²

To analyse the influence of the opening size on the heat release rate, a steady-state heat release rate distribution diagrams of different opening sizes are prepared, as shown in **Figure 4**. The results show that, if the opening is larger, the heat release rate increased slowly and the steady-state heat release efficiency, initially increases before decreased. When the opening size is 1m²- 3m², the steady-state heat release efficiency increases, in contrast, the steady-state heat release efficiency decreases when the opening size is 3.5m²-7m². The results show that, when the opening size is 1m² -3m², the steady-state heat release efficiency is similar to ventilation control type. When the opening size is greater than 3m² or the larger the opening, more oxygen is flows to the outside, leading to greater combustion efficiency, further reduced the heat release rate of the room. In summary, the steady-state heat release rate decreases as the opening size is enlarged.
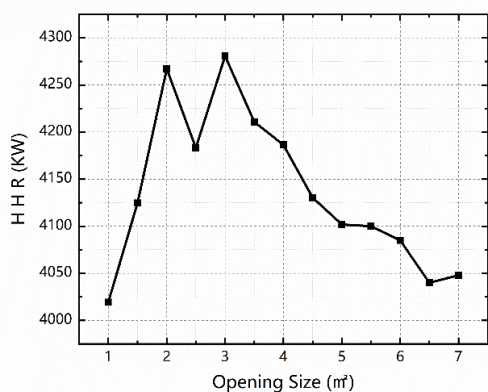
**Figure 4.** HRR distribution of different opening sizes
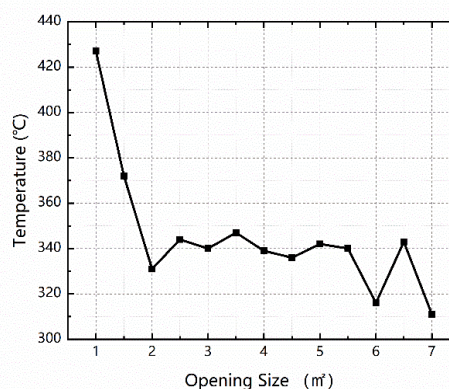
Figure 5. Temperature distribution of different opening sizes at 1m from the fire source

Figure 5 shows the temperature distribution based on the different opening sizes at 1m from the fire source. The figure shown that, when the size of the opening is less than 2m², the temperature decreases rapidly with the enlargement of the size of the opening, because the steady-state heat release rate increases with the enlargement of the size of the opening, and the space temperature become cooler faster. Therefore, the temperature decreases rapidly with the enlargement of the size of the opening. Additionally, the enlargement of the opening will allow the temperature to drop faster, however the combustion efficiency will increase due to the increase in the input amount of the oxygen, suggesting that the enlargement of the opening will not cause a continuous drop in the temperature, in return the temperature will be maintained within a certain range.

3.2. Effect of opening size on smoke toxicity

The opening size may also influence the smoke toxicity. In this paper, the level of carbon monoxide concentration is used, to evaluate the smoke toxicity. **Figure 6** and **Figure 7** show the distribution of the carbon monoxide concentration over time with different opening sizes. The level of carbon monoxide concentration with different opening sizes has an overall upward trend, where the level is increased over the time. Additionally, over the time, the oxygen in the room will be depleted, and the insufficient combustion will lead to the accumulation of carbon monoxide concentration. With the enlargement of the opening size, the fluctuation of the carbon monoxide concentration distribution increases. Bigger opening size, increase the external oxygen input, which can cause the carbon monoxide to be fully burned into carbon dioxide, further the continuous consumption of oxygen will lead to the incomplete combustion of carbon dioxide to produce carbon monoxide. Therefore, the carbon monoxide concentration increases in a fluctuating manner.
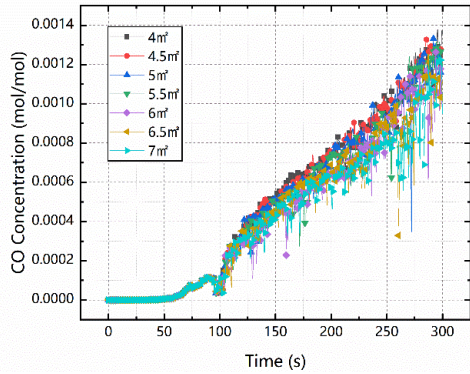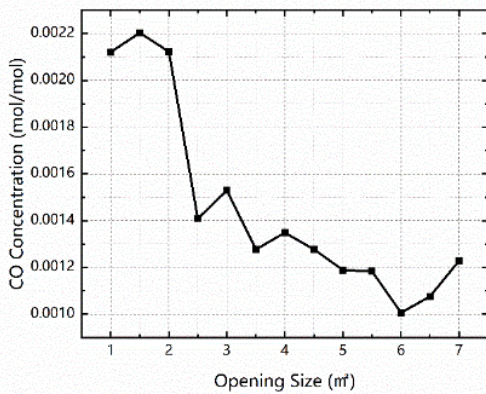
**Figure 6.** Carbon monoxide concentration distribution with opening size of 1m²-3.5m²
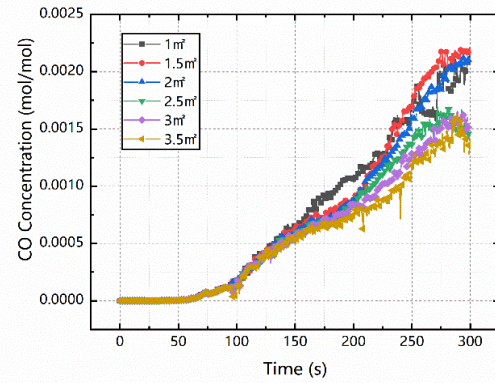
Figure 7. Carbon monoxide concentration distribution with opening size of 4m²-7m²

By calculating the average of carbon monoxide concentration at 270-300s, the carbon monoxide concentration distribution with different opening sizes, is obtained as shown in **Figure 8**, where the carbon monoxide concentration decreases with the enlarging of the opening size. The enlargement of the opening increases the amount of oxygen entering into the room, therefore, the flame can be fully burned, resulting in a reduction of carbon monoxide level, subsequently, leads to incomplete combustion product in the flue gas, leading to decrease in carbon monoxide concentration. In summary, when the inlet area and outlet area of a single smoke vent reach 1:3 ratio, the concentration of carbon dioxide is at the lowest.


Figure 8. Carbon monoxide concentration distribution of different opening sizes
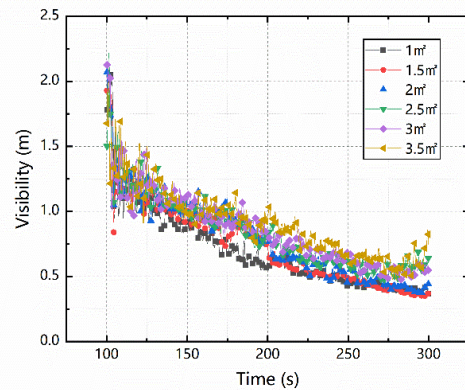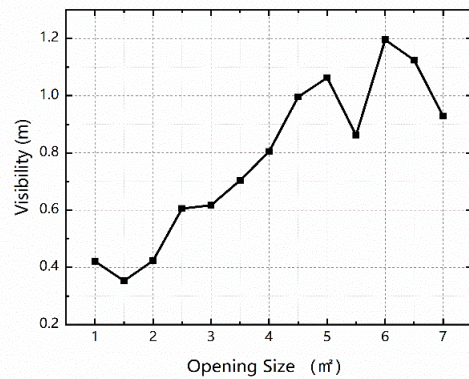

Figure 9. Visibility distribution with opening size of 1m²-3.5m²

3.3. Effect of opening size on visibility

Figure 9 and **Figure 10** show the visibility curve plotted with different opening sizes against the time. The diagram shows that, with the increase in time, the smoke in the space continues to accumulate, further decreased the visibility. When the opening size is smaller, more smoke accumulates in the space, leading to visibility decreases in a faster mode. In conclusion, smaller opening leads to the slower smoke spills out of the room, resulting in the smoke accumulation in the room in a short period of time, leading visibility decreases in faster mode.
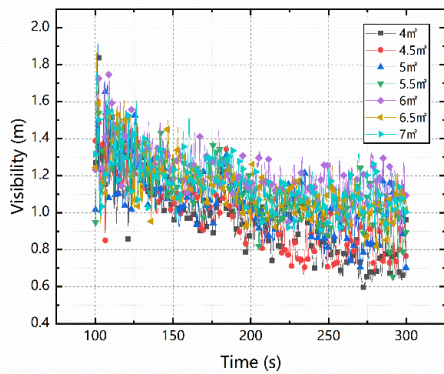
Figure 10. Visibility distribution with opening size of 4m²-

Figure 11. Visibility distribution of different opening sizes7m²

Figure 11 shows, the visibility distribution of different opening sizes. The visibility increases at first before decreases with the enlargement of the opening size. The enlarging of the opening size will be conducive to discharge the smoke, therefore, large size of the opening with leads to increase in the visibility, however, only for limited of time. When the size of the opening is more than 6m², the combustion intensifies due to the entry of oxygen, therefore, the speed of smoke emission become less, compared to the speed of the smoke production, reducing visibility. In summary, the visibility is the highest, when the entrance area and the exit area of a single smoke outlet reach 1: 3 ratios.

4. Conclusion

In natural smoke exhaust, the size of the ventilation opening has an important impact on the development of the fire, further the ventilation control at each stage will also affect the progress of the fire. This paper is expected to provide theoretical reference for the command, for the decision-making and the deployment of the firefighting for a rescue operation.

It can be concluded, that the efficiency of opening size is the highest when the ratio of the inlet and outlet area of a single exhaust port is 2:1. Opening more windows will reduce the efficiency of each window, but will also cause higher total smoke emissions. Additionally, when the ratio of 1:3 is reached, opening of the window is no use any longer. It should be noted that, this conclusion is only valid for vertical ventilation on the condition that the door is completely below the smoke layer, the window is above the neutral plane and completely used for smoke exhaust.

Disclosure statement

The authors declare no conflict of interest.

Author contributions

Y. H. conceived the idea, performed the analytical work, and wrote the paper. J. L. and P. C. performed the investigation.

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