Smoke movement analysis in an inner corridor building with vents on the stairwell

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Abstract. One inner corridor building was constructed by computational fluid dynamics (CFD) software and a series of CFD simulations were conducted in the building with/without a vent on the stairwell for different negative pressure differences induced by the surrounding wind. The result shows that the area affected by smoke is significantly decreased when the vent is set on the stairwell and the height of neutral plane increases significantly. However, it will increase the spread trend of smoke in low floors. The surrounding wind will produce negative pressure differences at the vent. For the high floors, with the increasing of negative pressure difference, the area affected by smoke is further reduced, but the degree of reduction is not obvious. For the low floors, the trend of smoke spread has not been alleviated with the increasing of negative pressure difference.

1. Introduction
With the rapid development of urbanization, high-rise buildings emerged in large numbers and popularize in big cities. According to the Council on Tall Buildings and Urban Habitat (CTBUH) 1502 buildings over 200 meters have been constructed in the world by 2019 and the number has almost tripled over the past 10 years. Numerous high-rise building could meet the needs of urbanization, while it would increase the difficulty level in fire control 1. In recent years, fire safety of high-rise buildings has drawn public attention due to the occurrence of many catastrophic fires which has brought great casualties and economic losses to society.

In general, modern high-rise buildings have vertical shafts, such as stairwells, elevator shafts, ventilating ducts and atriums 2-3. In the architectural design, in order to promote the air flow exchange, the vent is usually set at the top of the shaft structure 4. Because the design is simple and economic, a large number of shaft structures are often used. Under the action of surrounding wind, negative pressure difference will be formed at the top of a building (showed in Figure 1). Therefore, when a fire occurs, the impact of this negative pressure difference on the smoke spread in the shaft structure has become the focus of building fire protection.
Many studies have been conducted to investigate smoke movement in vertical shafts. Shi et al. [5] studied the mechanisms of smoke movement in emergency staircase through a set of experiments in a scaled building model with 12 floors. Li et al. [6] investigated the characteristics of fire smoke induced buoyant plume movement in a 12-storey stairwell with three vents though a set of experiment which is conducted in a 1/3 scale stairwell. Ji et al. [7] conducted a set of experiments to study the influence of external wind on burning rates of n-heptane pool fires in a long passage connected to a shaft. Chen et al. [8] presents a mathematical model for predicting vertical temperature distributions in ventilation shafts. In this model, the influence of both shaft walls and ventilation is considered. And a series of validation experiments were conducted under various exhaust rates. However, the corridor structure directly connected to shaft were usually ignored or partly considered in previous studies. In this paper, an inner corridor building with multiple openings is constructed by computational fluid dynamics (CFD) software. And a series of CFD simulations would be conducted in the building with/without a vent on the stairwell for different negative pressure differences induced by the surrounding wind to analyze the characteristics of smoke movement in a stairwell.

2. Model configuration

In this study, the analysis of smoke movement in the shaft structure with/without vent is based on a series of CFD simulations by the FDS software which was released by the National Institute of Standards and Technology (NIST). The Navier–Stokes equations for fire-driven fluid flow are solved by large Eddy Simulation (LES), which is second-order accurate with respect to space and time differences. The governing equations for smoke flowing in a fire are the conservation laws of mass, momentum and energy. More details on the LES can be found in the references [9].

The model configuration is shown in Figure 2. The dimension of the modeled building section is 18.2m×3.6m×27.2m (L×W×H). Each floor is 3.0m high. Since the each door of room should be closed in order to prevent the toxic smoke flow into room, the rooms connect with corridor could be ignored. Each floor has a openings connected with the outside and the area is 1.0 m× 1.0 m. The vent is set at the top of the shaft structure, the dimension of the vent 1.0m×1.0m (L×W).

The negative pressure differences at vent is different under various wind speed, which can be reduced to the model in equation (1)

\[ \Delta p_v = \frac{1}{2} \left( C_p \rho_0 v^2 \right) \]  

(1)
Where \( \Delta p_w \) is the additional pressure on the building surface caused by the wind, Pa; \( \rho_0 \) is air density, kg/m\(^3\); \( v \) is wind speed, m/s; \( C_w \) is the wind pressure coefficient, which is related to the wind direction and the shape of the building. Since the vent is set at the top of the building, \( C_w \) could be chosen as \(-0.7\). Wind speed increases exponentially with altitude, which can be reduced to in equation (2)

\[
v = v_0 \left( \frac{Z}{Z_0} \right)^n
\]  

(2)

Where, \( Z_0 \) is the reference height, m, which generally measured at 10m above the ground; \( Z \) is the actual height, m which could be chosen as 27.2m; \( v_0 \) is the wind speed measured at reference height, m/s; \( v \) is wind speed measured at actual height, m/s; \( n \) is the dimensionless wind speed index, which could be chosen as 0.4 in the city.

Combined with the equations above, we can get the equation (3)

\[
\Delta p_w = -0.9227 v_0^n
\]  

(3)

According to statistics, the average wind speed in most areas is about 2m/s~7m/s\(^2\), therefore, the \( v_0 \) is chosen as 0m/s, 2m/s, 5m/s and 7m/s respectively and the negative pressure difference could be calculated by equation (3). The details on the simulation settings are summarized in Table 1.

### Table 1. CFD simulation settings.

|                  | Size                        | Environmental temperature |
|------------------|-----------------------------|---------------------------|
| building         | 18.2m \( \times \) 3.6m \( \times \) 27.2m \((L \times W \times H)\) | 25°C                      |
| Floors           | 9                           |                           |
| door             | Size                        |                           |
|                 | 2.0 m\( \times \) 2.4 m \((W \times H)\) |                           |
| openings         | Size                        |                           |
|                 | 1.0 m\( \times \) 1.0 m \((W \times H)\) |                           |
| CFD              | Grid size                   |                           |
|                 | 0.2m \( \times \) 0.2 m \( \times \) 0.2 m \((L \times W \times H)\) |                           |
| Method of simulation | Large Eddy Simulation (LES) |                           |
| Dimensions of fire source | 1m \( \times \) 1m \((L \times W)\) |                           |
| Fuel of fire source | heptane                    |                           |
| HRR of fire      | 5MW                         |                           |
|                  | 1 Closed                    | -                         |
|                  | 2                           | 0                         |
|                  | 3 Open                      | -3.69 Pa                  |
|                  | 4                           | -23.07 Pa                 |
|                  | 5                           | -45.21 Pa                 |

### 3. Results and Discussions

#### 3.1 Smoke distribution in inner corridors

After the smoke spread is relatively stable, Figure 3 presents the smoke distribution in model building for different vent condition. As shown in Figure 3(a) and (b), the area affected by smoke is significantly reduced in the high floors which indict that the spread region of fire or smoke is significantly decrease when the vent is set at top the stairwell. While in the low floors, the smoke concentration is increases to a certain extent, which indicate that it will increase the spread trend of smoke in low floors when the vent is set on the stairwell. When there is negative pressure difference between the vent, with the increase of negative pressure different, the spread region of smoke is decreases continuously (shown in Figure 3c, 3d and 3e). However, compared with condition 2, the reduction is not significant. At the same time, it can be found that the smoke concentration in low
floors of condition 3~5 is still higher than that in condition 1. It indicates that it will not reduce the spread trend of smoke in low floors when negative pressure applied on vent.

![Image](a)  ![Image](b)  ![Image](c)  ![Image](d)  ![Image](e)  

**Figure 3.** Smoke distribution in model building: (a) condition 1; (b) condition 2; (c) condition 3. (d) condition 4; (e) condition 5.

Neutral plane is a horizontal plane where the pressure inside equals to the one outside [6]. Below the neutral plane, the pressure inside a building is lower which leading air flow into the building. Inversely, above the neutral plane, the smoke will flow out. Therefore, the position of the neutral plane is a significant parameter to area affected by toxic smoke. In order to accurately analyze the range of smoke spreading under different vent condition, the height of the neutral plane will be determined by analyzing the height of zero pressure planes. Figure 4 shows the height of neutral planes development under different vent conditions.

As shown in Figure 4, when the vent is set on the top of stairwell, the height of the neutral plane is raised from 14.2m to 16.8m. The results further indicate that the spread region of smoke is significantly decreased when the vent is set. However, with the negative pressure difference is growing, the increasing of neutral plane height is not remarkable. From condition 2 to condition 5, the height of the neutral plane is increase just 1.0m, which further indicate that the negative pressure of vent can further reduce the range of smoke spread, but the degree of reduction is not significant.

![Image](chart)

**Figure 4.** The height of neutral plane for various vent conditions

3.2 Temperature distribution in inner corridors
To further analyze the influence of smoke under different vent condition, the temperature distribution in inner corridors is discussed. Figure 5 presents the temperature curves measured at middle of corridors under different vent condition.

![Temperature curves]({attachment:image1.png})

**Figure 5. Smoke distribution: (a) condition 1; (b) condition 2; (c) condition 3. (d) condition 4; (e) condition 5.**

It can be seen from Figure 5, the range and degree influence by high temperature in high floors are reduced when the vent is set on stairwell, but in the low floors, the influence degree is increased to some extent. With the increase of negative pressure difference between the vent, the temperature distribution range and influence degree in the high floors are further reduced, but the temperature value in low floors is still increased (shown in Figure 5c, 5d and 5e). Based on the result, it was concluded that the vent set on stairwell can effectively reduce the movement range of smoke in the high floors, but it will increase the spread trend of smoke in the low floor area. The negative pressure difference between vent can further reduce the movement range of smoke in high floors, but the reduction degree is not significant. At same time, with the negative pressure increase, the temperature in low floors even slightly increased compare with condition 1 that the stairwell is without vent. Therefore, it is necessary to strengthen the prevention and control of smoke in the low-level area when setting the vent for gas exchange.

4. Conclusion
In this study, a set of CFD simulations using FDS were carried out to study the smoke movement when setting the vents on the top of stairwell. Results show that when the vent is set on stairwell, the smoke movement range in high floors can be significantly reduce, while in the low floors, the spread trend of smoke slight increase. The negative pressure difference between vent can further reduce the movement range of smoke in high floors, but the reduction degree is not significant. Meanwhile, with the negative pressure increase, the temperature in low floors even slightly increased.

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References
[1] The Skyscraper Centre, The Global Tall Building Database of the CTBUH. [Online], Available: http://skyscrapercenter.com, Last accessed on August 5th,(2019).
[2] A.A. Stec, T.R. Hull, Assessment of the fire toxicity of building insulation materials, Energy and Buildings 43 (2011) 498–506.

[3] R. Priyadarsini, K.W. Cheong, N.H. Wong, Enhancement of natural ventilation in high-rise residential buildings using stack system, Energy and Buildings 36 (2004) 61–71.

[4] J.H. Klote, J.A. Milke, Principles of Smoke Management, ASHRAE/SFPE, Atlanta, GA, USA/Boston, MA, USA, 2002.

[5] Shi W X, Ji J, Sun J H, et al. Influence of fire power and window position on smoke movement mechanisms and temperature distribution in an emergency staircase. Energy and Buildings. (2014), 79: 132-142.

[6] Li L J, Ji J, Fan C G, et al. Experimental investigation on the characteristics of buoyant plume movement in a stairwell with multiple openings Energy and Buildings. (2014), 68: 108-120.

[7] Ji J, Yuan X, Li K, et al. A mathematical model for burning rate of n-heptane pool fires under external wind conditions in long passage connected to a shaft. Applied Thermal Engineering, (2017),116:91-99.

[8] Chen Y, Zhou X, Fu Z, et al. Vertical temperature distributions in ventilation shafts during a fire Experimental Thermal & Fluid Science,(2016),79:118-125.

[9] K. McGrattan, M. Randall, Fire dynamics simulator (version5) user’s guide NIST Special Publication 1019-5, 2010.

[10] Zhang P, Wang Z. Building fire control. Beijing: Mechanical Industry Press, 2008