A study on the characterization of smoke movement in shafts with different fire source positions

Zhu Jie, Yang Tianyou, Wu Jianbo, Du Lulu
(Fire Research Institute of Sichuan Normal University, Chengdu 61010, China)

Abstract: In this study, experimental and numerical simulation methods were combined to simulate the changing course of the temperature and velocity fields in nine different fire scenes. The characteristics of smoke movement in shafts with different fire source position factors (h/H) were quantitatively investigated, and the non-dimensional fitting function between the fire source position factors and the maximum temperature was deduced. The results showed that the location of the neutral plane moved upward as the fire source rose, and all the generated smoke spread to the upper areas; however, there was barely any smoke in the lower areas. The maximum temperature was inversely proportional to the fire source position factor; the higher the source position is, i.e. the higher the ratio factor is, the lower the maximum temperature is in the shaft. The experimental verification of the fire dynamics simulator (FDS) showed good results.

Key words: different fire source position; shaft structure; smoke movement; FDS field simulation; temperature; fitting function

1 Introduction

In high-rise and super high-rise buildings, there are many vertical passages, such as elevator shafts, stairwells, piping shafts and a cable pit. When a fire occurs, under the combined influence of the stack effect, these shaft structures of hot smoke buoyancy and surface wind fields markedly promote the spread of fire and smoke, causing severe damage [1, 2]. Currently there have been studies around the world on the characterization of smoke movement in shaft structures under certain conditions, yet few investigators have explored the mechanisms behind the driving force of smoke movement in the shaft structure. In particular, there has been very little study on the influence of fire source position on smoke movement in shaft structures [3-24].

In this study, prototype experiments, numerical simulations and theoretical analyses were combined to simulate the changing course of the temperature field and the maximum temperature of fire smoke in nine shaft structures, all with different fire source positions. The characteristics of smoke movement in the shaft structures with different fire source position factors (h/H) were quantitatively investigated, and the non-dimensional fitting function between the fire source position factors and the maximum temperature was deduced. Our results provide a theoretical basis as well as practical guidance to smoke control and exhaust design, as well as personnel evacuation in high-rise buildings.

2 Experiment method and implementation

2.1 Experimental device

The shaft model was self-made using fireproof glass and steel plate. The model included two areas: the shaft area and the lobby area. The size of the model was: length × width × height = 780 mm × 300 mm × 2700 mm; the size of the lobby area was length × width × height = 240 mm × 300 mm × 2700 mm, and the size of the shaft area was length × width × height = 540 mm × 300 mm × 2700 mm. Partitions were placed in the lobby area every 270 mm, thus the lobby was divided vertically into 10 independent spaces. The sizes of the vents situated between the lobby and shaft and between the lobby and the outside were width × height = 90 mm × 140 mm. The fire source was placed in the lobby. Throughout the experiment, the vent between the shaft and the lobby was either opened or closed, depending on different simulated working conditions.

Received 1 March 2013

72 ENGINEERING SCIENCES
conditions. The diagram of the model experimental device is shown in Fig.1; the subdivisions of the lobby were numbered A1–A10 from bottom to top. Fig.2 shows the model in the actual experiment scene.

There were 20 test points in the middle of the shaft along the connection between the shaft and the lobby. The temperatures, CO concentrations, visibility and changes in air velocity of these test positions were all measured during the simulations. The positions of the test points are shown in Fig.3, those in the shaft were numbered 1–10 from bottom to top, and those along the connection between the lobby and the shaft were numbered 11–20 from bottom to top. An intersection was set at \( Y=0.15 \), where the temperature field, velocity field, visibility and changes in the CO concentration field were all measured. The location of the intersection is shown in Fig.3. In the study, the pressure was set at the ambient pressure 101.325 kPa; the temperatures inside and outside the shaft, and the fire source areas were set as the corresponding values measured in the prototype experiment; the fuel used was kerosene. Grid division was set as 0.005 m×0.005 m×0.005 m.

2.2 Initial condition and design of the experiment

The spread of fire smoke in the shaft was explored using different ratios of fire position \( h \) to shaft height \( H \) without taking the wind outside into consideration. In the simulated experiment, the vent at lobby subdivision A10 was always open; the vent in the lobby where the fire source was located was also open; the fire source area was \( 1.13 \times 10^{-2} \) m\(^2\); power was 12.4 kW; the temperatures inside and outside the shaft were all set as the ambient temperature measured in the prototype experiment (fluctuating around 30 °C). Parameters of different fire scenes with different fire source positions are shown in Table 1.

Temperature and humidity were set as the measured environmental temperature and humidity; pressure was set at the ambient pressure, approximately 101.325 kPa; the duration of each experiment run was 500 s. Thermocouples were numbered 1–10 from bottom to top; thermocouple No.1 was 0.135 m away from the bottom of the shaft, and the adjacent thermocouples were 0.27 m apart.
Table 1  Fire scene parameters under different fire source position conditions

<table>
<thead>
<tr>
<th>Fire scene No.</th>
<th>h/m</th>
<th>H/m</th>
<th>h/H</th>
<th>Located lobby subdivisions of the open vents</th>
</tr>
</thead>
<tbody>
<tr>
<td>XFSC 1</td>
<td>0.14</td>
<td>2.7</td>
<td>0.05</td>
<td>A1, A10</td>
</tr>
<tr>
<td>XFSC 2</td>
<td>0.41</td>
<td>2.7</td>
<td>0.15</td>
<td>A2, A10</td>
</tr>
<tr>
<td>XFSC 3</td>
<td>0.68</td>
<td>2.7</td>
<td>0.25</td>
<td>A3, A10</td>
</tr>
<tr>
<td>XFSC 4</td>
<td>0.95</td>
<td>2.7</td>
<td>0.35</td>
<td>A4, A10</td>
</tr>
<tr>
<td>XFSC 5</td>
<td>1.22</td>
<td>2.7</td>
<td>0.45</td>
<td>A5, A10</td>
</tr>
<tr>
<td>XFSC 6</td>
<td>1.49</td>
<td>2.7</td>
<td>0.55</td>
<td>A6, A10</td>
</tr>
<tr>
<td>XFSC 7</td>
<td>1.76</td>
<td>2.7</td>
<td>0.65</td>
<td>A7, A10</td>
</tr>
<tr>
<td>XFSC 8</td>
<td>2.03</td>
<td>2.7</td>
<td>0.75</td>
<td>A8, A10</td>
</tr>
<tr>
<td>XFSC 9</td>
<td>2.3</td>
<td>2.7</td>
<td>0.85</td>
<td>A9, A10</td>
</tr>
</tbody>
</table>

3 Results and analysis

We characterized the spread of the fire smoke in the shaft structure when the fire source was in the same area but in different positions. The vent at the fire source was set at different positions, and the changing course of the air temperature in the shaft was monitored. The results are shown in Fig. 4. The subheading of each panel denotes plot category (fire position)_fire source position (A1~A9)_panel number (a~i).

![Fig. 4 The prototype experiments results of temperature change at different test points in the shaft with different fire source positions](image_url)
3.1 Temperature change in the shaft with different fire source positions

3.1.1 Results of prototype experiments

Data were collected from the prototype experiments. Temperature changes within certain time periods were recorded and the speeds of the temperature changes at different test points in the shaft during different time periods were examined. The results are shown in Fig. 4.

As illustrated in Fig. 4, as time progressed, the rates of rising temperatures in areas above the fire source gradually increased; the temperatures in areas below the fire source barely changed, and almost remained at the initial temperature of 30 °C. When the fire source was located at the second layer or below (Fig. 4a & Fig. 4b), i.e. when the fire source was at a low position in the shaft, driven by hot buoyancy and under the influence of the stack effect, the smoke basically spread from the bottom up through the whole shaft. This made the temperature in the whole shaft area rise fairly quickly. Temperatures in the areas closer to the fire source were higher, with the highest reaching 500 °C; temperatures in areas farther away from the fire source were lower; the temperature monotonically decreased as the vertical height increased.

When the fire source was at the third layer and above (Fig. 4c~Fig. 4i), the temperatures in the subdivision where the fire source and the vent were located were high, but the maximum temperature was lower than that when the fire source was located below the third layer. As the fire position rose, the position of the neutral plane also moved up. Most of the hot smoke generated by the fire source spread directly upward and funneled out through the vent at the top layer. In areas below the fire source, there was little smoke or only a small amount of jet smoke descent; with such a small amount of heat radiation from the fire source, the temperature in this area remained mostly unchanged, at the initial value of 30 °C. This was particularly true as the fire source position went higher.

3.1.2 Validation of the fire dynamics simulator (FDS) field simulation

Data were collected from the simulated experiments. Temperature changes within certain time periods were recorded and the speeds of the temperature changes at different test points in the shaft during different time periods were examined. The results are shown in Fig. 5.

As illustrated in Fig. 5, the rate of rising temperature was the fastest at the layer where the fire source was located, as well as at A10 at the top; in these two subdivisions the maximum temperature was the highest, reaching up to 870 °C. The rate of the rising temperature at the layers above the fire source increased with time; whereas in the layers below the fire source, the temperature changed rather slowly and mostly remained at the initial temperature of 30 °C. The curves showed a drop at 300 s. This was because at the early stage, the intense combustion of the fuels at the fire source consumed a large amount of oxygen in the lobby, causing an insufficient oxygen supply in the lobby, which led to a decrease in the heat release rate. Therefore, the heat carried by the smoke decreased correspondingly and the temperature dropped.

The numerical simulation results in Fig. 5c~Fig. 5h show that the temperature at the layer where the fire source and the open vent were located was the highest; the temperature at the topmost layer was the second highest; the temperature at the bottom layer mostly remained unchanged at the initial value of 30 °C. In Fig. 5a and Fig. 5b, aside from the test points close to fire source where the temperature rose quickly, the rates of rising temperatures at all other test points were relatively stable. In Fig. 5c, at 150 s the temperatures at A3, A4, A5, A6 and A7 showed a quick rise, followed by an immediate drop.

These results were mostly consistent with those of the prototype experiment. Yet during the prototype experiments, due to the limitations of the experimental conditions, a zero smoke leak could hardly be achieved. This made the temperature measured at the top layer deviate slightly from the theoretical calculation. However, such minor flaw did not invalidate the results obtained from the prototype experiments.

3.2 Variations in maximum temperatures at different test points with different fire source position factors

In order to better illustrate the influence of fire source positions on the distribution of smoke temperature, and to facilitate formulating the function equations between the fire source position factor and the height at which the temperature reached its maximum level, the maximum temperature at different test points and its corresponding height obtained from both the prototype experiments in the shaft and the FDS field simulations are summarized as shown in Table 2.
Fig. 5  The numerical simulation results of temperature change at different test points in the shaft with different fire source positions

Note: The coincidence of part line

<table>
<thead>
<tr>
<th>Scene No.</th>
<th>$h/H$</th>
<th>Maximum temperature at the test points/°C</th>
<th>Height of the location of maximum temperature/m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Experiment value</td>
<td>FDS simulation result</td>
</tr>
<tr>
<td>FSC 1</td>
<td>0.05</td>
<td>500</td>
<td>724</td>
</tr>
<tr>
<td>FSC 2</td>
<td>0.15</td>
<td>193</td>
<td>343</td>
</tr>
<tr>
<td>FSC 3</td>
<td>0.25</td>
<td>480</td>
<td>499</td>
</tr>
<tr>
<td>FSC 4</td>
<td>0.35</td>
<td>392.8</td>
<td>467</td>
</tr>
<tr>
<td>FSC 5</td>
<td>0.45</td>
<td>420</td>
<td>478</td>
</tr>
<tr>
<td>FSC 6</td>
<td>0.55</td>
<td>446.2</td>
<td>434</td>
</tr>
<tr>
<td>FSC 7</td>
<td>0.65</td>
<td>283</td>
<td>548</td>
</tr>
<tr>
<td>FSC 8</td>
<td>0.75</td>
<td>289</td>
<td>491</td>
</tr>
<tr>
<td>FSC 9</td>
<td>0.85</td>
<td>455</td>
<td>268</td>
</tr>
</tbody>
</table>
As seen from Table 2, the maximum temperature in the shaft was usually at the same layer as the fire source, which fitted the reality perfectly. Meanwhile, aside from a rare number of test points where the temperature fluctuation was relatively large, the maximum temperature in the shaft showed a tendency to decrease as the fire source moved up. This suggests that as the fire source position moved higher, the hot smoke generated by the fire source flew through a smaller portion of the shaft area, meaning that the range in which hot smoke supplied heat to the shaft decreased. This made the heat accumulation in the shaft decrease, thus leading to a similar decrease in the maximum temperature in the shaft.

### 3.3 Fitting function between the fire source position factor and maximum temperature

Fig. 6 and Fig. 7 show the fitting curves of the maximum temperatures in the shaft versus the fire source position factors \((h/H)\) obtained from the prototype experiments and the simulated experiments, respectively. The least square method was used to deduce the fitting functions under the two circumstances. For the results from the prototype experiments, the fitting function between the maximum temperature and the fire source position factor was

\[
y = -307.5x + 537.58
\]

In prototype experiments, the fitting function between the maximum temperature and the height of its location was

\[
y = -0.006 \times x + 3.86
\]

For results from the simulated experiments, the fitting function between the maximum temperature and the fire source position factor was

\[
y = -351.2x + 659.86
\]

The fitting function between the maximum temperature and the height of its location was

\[
y = -0.004 \times 3x + 3.29
\]

![Fig. 6 Fitting curves of the distribution of maximum temperature in the shaft measured in the prototype experiments](image1)

![Fig. 7 Fitting curves of the distribution of maximum temperature in the shaft obtained from the simulated experiments](image2)

Fig. 6a and Fig. 7a show the fitting curves of the maximum temperature versus the fire source position factor obtained from the prototype experiment data and the FDS simulation data, respectively; Fig. 6b and Fig. 7b show the fitting curves of the maximum temperature versus its corresponding position obtained from the prototype experiment data and the FDS simulation data, respectively. As seen from the figures, the fitting curves related to the distribution of the maximum temperature in the shaft obtained from both the prototype experiments and the simulations were all straight lines; the maximum temperature in the shaft was approximately inversely proportional to the fire source position factor \((h/H)\), and the
maximum temperature usually occurred at a place close to the test point in the fire source layer.

In the two fitting functions, the slope of the former was larger and the temperature change occurred faster; the slope of the latter function was smaller and the rate of the temperature drop was slower. Due to the limitations of the experimental conditions, a zero smoke leak could hardly be achieved. This plus the heat transfer from the shaft to the outside environment would inevitably lead to a lower maximum temperature and a faster rate of temperature drop measured in the prototype experiments than obtained in the simulated experiments. The difference between the two slopes was 43.7; within the experimental errors the two were similar to each other.

3.4 Velocity vector diagram of the temperature field in the shaft at 100 s

To better illustrate the distribution of the temperature field in the shaft, the temperature contour map and its vector map obtained from the FDS numerical simulation in different fire scenes are shown in Fig.8.

As seen in Fig.8, the temperature vector lines in the fire source layer and the top layer were the densest, and the temperature gradients were the sharpest. As the fire source position moved up, the temperature gradient lines moved up as well, i.e. the temperature gradient lines in areas above the fire source tended to be denser, suggesting that in these areas the heat in the temperature field was localized and the temperature was relatively high. In contrast, the temperature gradient lines were sparsely distributed in areas below the fire source, showing only sporadic patches, suggesting that in these areas the heat in the temperature field was dispersed and the temperature was relatively low.

4 Conclusions and suggestions

1) Fire position has a significant impact on the spread of fire smoke in shaft structures. As the fire source position moves up, the position of the neutral plane also moves up; the generated smoke all spreads to the upper areas, whereas there is barely any smoke in the lower areas.

2) The maximum temperature in the shaft is inversely proportional to the fire source position factor \((h/H)\); the higher the fire source position is, i.e. the higher the ratio factor is, the lower the maximum temperature is in the shaft.

3) The fitting functions of the relation between the fire source position factor and maximum temperature, and the relation between the maximum temperature and the height of its position obtained from the prototype experiments are: 
   \[
   y = -307.5x + 537.58, 
   y = -0.0066x + 3.86, 
   \]
   respectively; the corresponding fitting functions obtained from the simulated experiments are: 
   \[
   y = -351.2x + 659.86, 
   y = -0.0043x + 3.29, 
   \]
   respectively. This shows that the FDS simulation can be verified well with prototype experiments.

References

[12] Kumar S, Shashi, Kumar R, et al. Simulation of an experimen-