Parametric optimization of a novel air supply device used in tunnel fire

Yuanqing Ma1, Tianqi Wang1, Zhiewl Wang1, Hechang Yang2 and Angui Li*

1 School of Building Services Science and Engineering, Xi’an University of Architecture and Technology, 710055 Xi’an, China.
2 Yellow River Engineering Consulting Company Limited, 450003 Zhengzhou, China.

Abstract. Tunnel widely exists in highway, subway and other underground buildings. Due to the structural limitations, the direction of evacuation is consistent with the main flow direction of smoke in the tunnel. For the design of smoke exhaust system, traditional methods aim at reducing the overall smoke concentration in the whole tunnel. However, when fire hazard occurs, rapid personnel escape requires higher visibility. In this paper, a novel air supply device designed for smoke-insulation passageway establishment and ventilation in tunnel fire is introduced. Wall-attached jet and orifice plate jet are combined in this device, which enables passageway to isolate smoke intrusion. In this study, an approach has been devised combining Response Surface Method (RSM) with numerical simulations as well as visualization experiment to get better performance of the device. Parametric optimization was conducted for the three influencing variables, i.e., the air supply volume, opening rate of orifice plate, and width of wall-attached jet. Analysis of variance (ANOVA) indicates that all the three factors are significant. Moreover, the optimal combination can be obtained within the admissible range of the three factors through response optimization. A regression equation is developed to predict the effect of the novel air supply device for any input values of the three influencing variables.

1 Introduction

As an irreplaceable transportation facility, tunnel widely exists in highway, subway and hydropower station, as connections of various buildings[1]. The number of tunnels is growing rapidly in many countries. Tunnel fire which occurred in tunnels show that safety issues are extremely important[2, 3]. Due to the length of the tunnel is much larger than the height or width, and usually outlets are only set at both ends. Once fire hazards occurred, it is difficult to discharge the high-temperature smoke in a short time, and it mainly flows one-dimensional horizontally along the longitudinal direction of the tunnel under the obstruction of the walls on both sides[4, 5]. As a result, the direction of evacuation is consistent with the main flow direction of smoke in the tunnel, while the smoke concentration in local areas in the space is still high, which greatly increases the difficulty of personnel escape and firefighting [6].

The fire development and smoke transportation in the tunnel are different from conventional buildings, and the fire prevention and control are more complex. The danger of fire in the tunnel is mainly reflected in the life threat of smoke to the escape personnel. Because of the combination of the examined random factors and every adopted value of these parameters is likely and may happen in the reality, it is impossible to accurately simulate the evacuation of people even for the given tunnel[7]. According to real tests, in a tunnel the fire develops very quickly[8], on the other hand, the evacuation speed in smoke is influenced by many uncertain factors, such as the evacuees’ age difference, visibility level and familiarity with environment[9].

There are various conditions to influence or control tunnel fire. The main task of smoke exhaust system is to help people evacuate faster and support rescue operations[10]. Therefore, the ventilation and smoke exhaust systems play a very important role to ensure the safe and rapid evacuation of personnel in any tunnel fire. The traditional tunnel ventilation and smoke exhaust systems[11] (natural ventilation, longitudinal ventilation, transverse ventilation) aims at reducing the overall smoke concentration in the whole tunnel, while the smoke concentration in local areas in the space is still high, which reduces the visibility, prolongs the time of personnel evacuation, increases the difficulty of evacuation, and is not conducive to personnel evacuation [12]. In fact, evacuation only uses the lower area of the tunnel, not the whole space. It is only necessary to ensure that the pollutant concentration at the lower part of the channel is acceptable. Controlling the smoke concentration in certain area can create a more favourable escape environment for personnel [13].

In this study, a novel air supply device is proposed, which can reduce the pollutant concentration in the breathing area, improve the visibility, and use the supply air flow to establish a smoke-insulation passageway (as...
shown in Fig 1) for rapid evacuation and both the function of ventilation. And the performance of the device has been further improved.

Fig. 1. View of smoke-insulation passageway.

2 Device model and methodology

2.1 Device structure

This novel air supply device in this paper consists of orifice plate jet and wall-attached jet. The orifice plate has an arc-shaped surface with an included angle of 30°, and four rows of circular air outlets are evenly arranged on the surface, which are marked as D1, D2, D3 and D4 from top to bottom, as shown in Figure 2. The included angles between the center direction and the horizontal direction of D1, D2, D3 and D4 are 0°, 7.5°, 15° and 22.5° respectively. The wall-attached jet is vertical and 2m high from the ground.

Fig. 2. The structure of novel air supply device.

In the initial scheme, the diameter of D1, D2, D3 and D4 are 6mm, 8mm, 10mm, 12mm, while the width of wall-attached jet is 15mm, air supply volume is 250m³/h. The opening rate of orifice plate:

\[ k = \frac{A_k}{A_0} \]  

where \( A_k \) denotes area of orifice plate, \( A_0 \) denotes sum of area of D1, D2, D3 and D4.

Within the allowable value limits, the opening rate of orifice plate studied in this paper is 0.144, 0.176, 0.208, the air supply volume is 250m³/h, 300m³/h, 350m³/h, and the width of wall-attached jet is 15mm, 20mm, 25mm.

2.2 Visualization experimentation

A visualization experiment using smoke tracing method was carried out to obtain direct and reliable source of flow data. In the meantime, the accuracy of simulation can be verified by the deviation from the experimental data. As shown in Figure 3, the experiment was designed to be conducted in a room with a size of 5.0m (L) × 3.0 m (W) × 2.6m (H). The device (l=1m) was placed right in the middle of the back wall, and the wall-attached jet is 2m high from the ground. A black curtain was used to covering the wall of test area, provides a black background to visualize white smoke.

Fig. 3. Layout of visualization experiment: (a) plate of layout, and (b) geometrical configuration.

In this experiment, the air was supplied by an axial flow fan, through plenum chamber and duct. A smoke generator was placed on the inlet of the plenum chamber, the smoke tracer particles (ethylene glycol particles) were generated by the machine and injected into the chamber to mixing, while the supply air was sent into the chamber from the axial flow fan. The measuring points were evenly arranged in the room for velocity as shown in Figure 3(b). According to ASHRAE 55 standard, the test time of each measuring point is 3 minutes or less. Smewa3000 was used to test the velocity changes of each measuring point, and the height of the measuring points was 0.1m, 0.6m, 1.1m and 1.7m [14]. As shown in Figure 4, the supply air from the device creates a smoke-insulation passageway.

Fig. 4. Experimental visualizations with smoke.

2.3 Computational fluid dynamics (CFD) simulation

CFD not only simulates the initial scheme, but also further simulates to compare schemes the schemes with different combinations of opening rate of orifice plate, air supply volume and width of wall-attached jet.

In this paper, FLUENT was used to analyze the air distribution of the novel air supply device. The standard k-ω model and semi-implicit method for pressure linked equations consistent (SIMPLEC) were employed
to solve the flow field. The second-order upwind scheme was applied to discretize the transport equation. A full-scale model of the device and test room was established, the geometric grids of simulation model is shown in Figure 5. Due to the complex structure of the device, the discretization of the computational domain was achieved by means of hybrid mesh, and the Boussinesq assumption was adopted to obtain the control equation.

Fig. 5. Geometric grids of simulation.

The boundary conditions of computational domain were velocity inlet, pressure outlet and the classical no-slip boundary conditions to the walls. A duct with a diameter of 0.1m is set at the inlet of the device as in the experiment to ensure the full development of air. Concerning the turbulence quantities, turbulence intensity I and hydraulic diameter were chosen in the turbulence specification method.

2.4 Response Surface Method (RSM)

The Response Surface Method (RSM) employs various approximate optimization techniques based on mathematical and statistical models [15]. The RSM is performed by following steps [16]:

- Identify the influencing factors and measure their response at various levels.
- Through Analysis of Variance (ANOVA) the significant factors, individual effect, and interaction effect is determined.
- The regression equation is used to predict the response of any unknown value of significant factors.

The response surface is given as a function of independent and continuous variables by the following equation:

$$ Y(x) = f(x_1, x_2, x_3, \ldots, x_n) \quad (2) $$

where n is the number of variables influencing the response function Y.

Many research outcomes have been reported in which RSM is used to identify the significant contribution of influencing factor, optimize these significant parameters. Based on previous literatures, RSM was used to predict the performance of the device on the basis of the contribution of these significant parameters. After the selection of the quadratic order for the data analysis, an Analysis of Variance (ANOVA) was conducted for the parameters with the response function (mean velocity deviation). Mean velocity deviation was estimated using the following equation:

$$ D = \frac{\sum_{i=1}^{m} v_i - \nu}{m} \quad (3) $$

where m is the number of measuring points, $v_i$ is the velocity of measuring point, $\nu$ is the ideal velocity.

3 Results and discussions

Due to the limitation of this paper, only the experiment and simulation results of the measurement point at $x=0.5m$ in the initial scheme are shown here for comparison, as shown in Figure 6. The results in the figure show that the simulation fit well with the experimental test.

Fig. 6. Flow rate variation at measurement points.

After verifying the feasibility of the simulation model, the next step was to perform further simulate by changing the combinations of opening rate of orifice plate, air supply volume and width of wall-attached jet, all simulation schemes are shown in Table 1. ANOVA was performed on the simulation results, and the mean velocity deviation was selected as the response function. The RSM design matrix was given 20 runs for the three levels of each parameter, which is shown in Table 1.

Table 1. Response design matrix.

| Air supply volume (m³/h) | k     | Width of wall-attached jet (mm) | D    |
|-------------------------|-------|---------------------------------|------|
| 250                     | 0.144 | 15                              | 0.131|
| 350                     | 0.144 | 15                              | 0.388|
| 250                     | 0.208 | 15                              | 0.205|
| 350                     | 0.208 | 15                              | 0.480|
| 250                     | 0.144 | 25                              | 0.198|
| 350                     | 0.144 | 25                              | 0.519|
| 250                     | 0.208 | 25                              | 0.316|
| 350                     | 0.208 | 25                              | 0.661|
| 250                     | 0.176 | 20                              | 0.230|
| 350                     | 0.176 | 20                              | 0.544|
| 300                     | 0.144 | 20                              | 0.357|
| 300                     | 0.208 | 20                              | 0.382|
| 300                     | 0.176 | 15                              | 0.295|
| 300                     | 0.176 | 25                              | 0.465|
| 300                     | 0.176 | 20                              | 0.380|
| 300                     | 0.176 | 20                              | 0.393|
| 300                     | 0.176 | 20                              | 0.386|
| 300                     | 0.176 | 20                              | 0.390|
| 300                     | 0.176 | 20                              | 0.389|

The model summary of the ANOVA in Table 2 shows that S, R-Square(adj) and R-Square(pred) are 0.02, 97.65% and 95.35% respectively, which validates the model.

Table 2. Model summary.
Since the model was proven adequate, the response function may be estimated with the regression equation as follows:

\[
D = 0.002Q + 9.15k - 0.007W - 22.00k^2 - 1.314 \quad (4)
\]

where \(Q\) is air supply volume, \(W\) is width of wall-attached jet. Figure 7 shows contour plots for the three parameters' interaction while keeping the third parameter constant. The hold values for the three contour are (a) width of wall-attached jet is 15mm (b) air supply volume is 300m\(^3\)/h (c) \(k\) is 0.144.

**Fig. 7.** Contour related to the influencing parameters.

The ANOVA results obtained are only the optimal values for this condition due to the practical limitations of the device structure. Take Figure 7 (a) as an example, in the case of the contour plot between opening rate of orifice plate and air supply volume while keeping the width of wall-attached jet at 15mm, the blue and green regions represent the mean velocity deviation. To get a better performance of this device with the width of wall-attached jet at 15mm, the combination of opening rate of orifice plate and air supply volume needs to be controlled within the dark blue region. On the other hand, the regression equation estimates the mean velocity deviation for any specific configuration of the influencing variables.

### 4 Conclusions

In this paper, an approach has been devised combining RSM with numerical simulations and visualization experiment to study the parametric optimization of the novel air supply device, and the effect of forming a smoke-insulation passageway was expressed in terms of mean velocity deviation. Also, the significance of the effect of three influencing factors on mean velocity deviation was analyzed. The main conclusions drawn are as follows.

1. All the three factors are significant, and the optimal combination can be obtained within the admissible range of the three factors through response optimization.
2. The methodology proposed in this paper can give guidance on the design of the novel air supply device. When one of the three factors is kept constant, the other two tend to be reversed to optimize the effectiveness of the device in reducing the concentration of pollutants in the breathing zone as well as improving visibility.

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