A Numerical Simulation of Smoke Extraction in the Tunnel Sidewall

Yu Li and Shijie Cai

School of Civil and Safety Engineering, Dalian Jiaotong University, Dalian, Liaoning, China, 116028
467797823@qq.com

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Abstract: The rectangular tunnel (450 m × 10 m × 5 m) and smoke vent (4.5 m × 4.5 m) located on the sidewall, with its bottom flush with the ground, were simulated to analyze the law of smoke extraction in the tunnel sidewall. Numerical simulations were conducted to analyze the law of smoke extraction in the tunnel sidewall at different rates of smoke extraction. Based on the results, the output of the smoke extraction system decreases with the increase in extraction rate. By contrast, the efficiency of the smoke extraction system increases with the increase in smoke extraction rate.

1 INTRODUCTION

Timely and efficient extraction of smoke from the tunnel is one of the crucial technologies in emergency rescue during a fire (Jiang Xuepeng, 2014; Hu Longhua, 2005; Jiang Yaqiang,2010; Han Jianyun, 2013; Jiang Yaqiang, 2009). Therefore, analyzing the law of smoke extraction in tunnels is significant.

In this regard, Li et al. (2013), Hu et al. (2008), and Oka et al. (1995) investigated the relationship between the distance of backlayering and the longitudinal velocity of the wind, which is the critical velocity of the wind for restraining the countercurrent flow of smoke. Wu and Bakar (2000), Vauquelin and Telle (2005), and Tanaka et al. (2015) conducted macroscopic studies on the efficiency of horizontal extraction, including the rate of extraction at the smoke vent, the shape and location of the smoke vent, the power of the fire source, and the influence of the relative position of the smoke vent and air inlet on the efficiency of smoke extraction.

During the construction of an extra-long tunnel, a level gallery would be dug for every 400-500m in the tunnel sidewall in order to facilitate transportation, which leads to the outside of the tunnel. When the tunnel is built, the gallerys' openings are naturally used as smoke vents. So in this study, we assume one smoke vent should be set for every 450m in the tunnel sidewall.

2 NUMBERICAL SIMULATION

2.1 Design of The Model of The Tunnel

In this study, FDS 5.5.3 is employed (version, published in 2012). A model of the fire can be established, and movement of smoke, temperature, and toxic concentration during the fire can be predicted (Liang Ping, 2010).

In this study, the size of tunnel in the numerical simulation is set as 450 m × 10 m × 5 m. Propane is used as the fuel. The size of the fire source is 10 m × 2.6 m × 1 m and located at the center 220 m from the left side of the tunnel. The tunnel for mechanical smoke extraction is 130 m from the right side of the fire source, and is set at the internal sidewall of the tunnel. After the fire started, the smoke vent was closed and mechanical smoke extraction began after 60 s. A specific model is shown in Figure. 1.
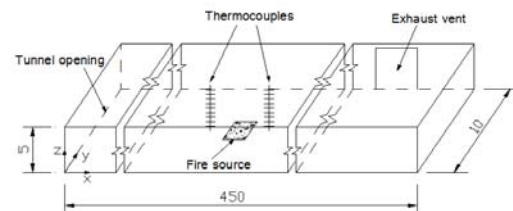

Figure. 1 Simulation model of the tunnel (unit:m)

2.2 Monitoring Equipment

Four thermocouples and two sites for thickness monitoring are set at the left and right sides of the fire source, with the distance of 50 m. Thermocouples are set at locations 50 m from the left and right sides of the fire source, with y equal to 6 m, and are equidistantly distributed along the vertical direction, with the interval of 0.9 m. The highest point is 1.4 m from the ceiling. Thickness monitoring sites are set at locations where the values of y are equal to 6 and 8 m, respectively. At the smoke vent, a total of 60 thickness monitoring sites are set, with the interval along the horizontal direction being 1 m and the interval along the vertical direction being 0.9 m. Forty thermocouples and 40 monitoring equipment of gas flow rate are set with equal distances in the vertical direction. The interval is set as 0.9 m and the distance of the highest point is 1.4 m from the ceiling to ensure that the temperature and velocity of the upper smoke layer and lower air layer can be perfectly detected. A device for monitoring mass flow rate is placed at the right side of the fire source to cover the entire smoke vent. The cross-section at the leftmost side of the tunnel is set to be fully open as the air inlet during smoke extraction.The specific layout is shown in the following figures.
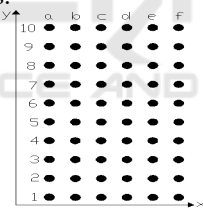

Figure. 2 Schematic diagram of the layout of the monitoring sites for the thickness of the smoke layer
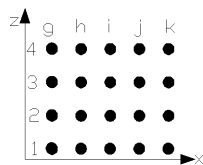

Figure. 3 Schematic diagram of the layout of the monitoring sites for air velocity

2.3 Conditions for Numerical Simulation

The conditions for numerical simulation are listed as follows：The numbers of each condition are 1-10；the power of each fire source is 15MW；each ambient temperature is 20°C；each size of smoke vent is 4.5 m × 4.5 m；each computation time is set as 600s；and the rates of smoke extraction are 0m3/s（NO.1）、20m3/s（NO.2）、40m3/s（NO.3）、60m3/s（NO.4）、80m3/s（NO.5）、100m3/s（NO.6）、120m3/s（NO.7）、140m3/s（NO.8）、160m3/s（NO.9） and 180m3/s（NO.10）.The smoke extraction rate in the tunnel is regarded as a variable. Under different rates of mechanical smoke extraction, the variations of the shape, temperature, and thickness of the smoke layer and the Froude number (Fr) are investigated.

3 RESULTS AND DISCUSSION

3.1 Calculation of The Output and Efficiency of The Smoke Extraction System

Vauquelin (2002, 2008) defined two global parameters used to describe the performance of the horizontal smoke extraction system quantitatively. One parameter is the ventilation system efficiency (*VSE*). The other parameter is the ventilation system output (*VSO*). The expressions of these two parameters are as follows:

$$VSO = q_{se}/q_e \quad (1)$$
$$VSE = q_{se}/qs \quad (2)$$

where q_{se} denotes the mass flow rate of discharged smoke, q_s denotes the mass flow rate of generated smoke, and q_e denotes the mass flow rate of rated smoke extraction. As reported in the literature (Jiang Yaqiang, 2009), under the condition of no plugholing of the smoke layer, the content of discharged gas at the smoke vent is all smoke. As such, q_{se} is equal to q_e. Under this condition, *VSO* is 100% and the system exhibits the best performance. When plugholing of the smoke layer occurs, q_{se} becomes less than q_e. Under this condition, *VSO* represents the proportion of smoke in discharged gas. The remaining proportion $(1 - VSO)$ is air. Evidently, the higher the *VSO*, the better the performance of the smoke extraction system.

In this study, the smoke extraction rate is expressed as V_e and the corresponding mass flow rate is expressed as q_e, i.e., the mass flow rate of gas discharged through the smoke vent. The velocity of smoke (*U*) passing through the monitoring section is assumed to be distributed evenly in the horizontal direction of the tunnel. The thickness of the smoke layer is S_h. Given the distance of 0.5 m from the top of the smoke vent on the sidewall to the ceiling, the

true $S_h'=S_h$-0.5 is obtained. The density of the upper smoke layer is . The width of the tunnel is denoted as d. Then, the mass flow rate of discharged smoke is calculated as follows:

$$q_{se}=\rho_s \times U \times S_h' \times d \qquad (3)$$

Eq. (3) is substituted in Eqs. (1) and (2) to obtain the calculation formulas of VSE and VSO, as follows:

$$VSO = \frac{q_{se}}{q_e} = \frac{\rho_s \times U \times S_h' \times d}{q_e} \qquad (4)$$

$$VSE = \frac{q_{se}}{q_s} = \frac{\rho_s \times U \times S_h' \times d}{q_s} \qquad (5)$$

Figure. 4 shows that *VSO* decreases with the increase in smoke extraction rate by using Eqs. (3), (4), and (5). When the extraction rate is low, the total amount of gas discharged is small, with smoke accounting for a large proportion, i.e., *VSO* is large. With the continuous increase in the smoke extraction rate, turbulence occurs. Although the total amount of extracted smoke also increases, *VSO* gradually reduces and finally stabilizes at 11%. In contrast to *VSO*, *VSE* increases with the increase in the smoke extraction rate. Based on the "Code for Metro Design"(GB, 2003), the amount of discharged smoke in the platform and hall of the station should be calculated as 1 m³/min/m² of the construction area. Based on this criterion, the designed volume of smoke extraction for the model is calculated to be 75 m³/s. Considering Figures.4, the optimum smoke extraction rate for this model is 60 m³/s. Under this condition, *VSO* is 21.14% and *VSE* is 41.59%.
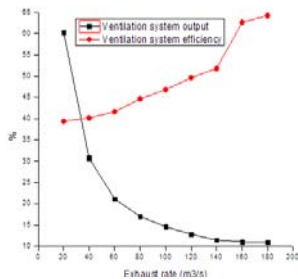

Figure. 4 Change of performance of the smoke extraction system with the variation of the smoke extraction rate

3.2 Analysis of The Fr for The Layering of Smoke

In fluid mechanics, the *Fr* is usually employed to describe the proportion of inertial and buoyant forces. A larger value of the *Fr* indicates a stronger dominance of inertial force (GB, 2003; Vandeleur P H E, 1989). In this study, inertial force, being the

horizontal shear force between smoke and air, is the dominant factor of the occurrence of mixing, whereas buoyant force is the dominant factor in maintaining the layering of smoke. The *Fr* is expressed as follows:

$$Fr = [\frac{\rho_s \Delta V^2}{g \Delta \rho H_{int}}]^{1/2} \qquad (6)$$

where g is the acceleration of gravity；ΔV is the shear velocity；and Hint is the height of the interface of the smoke layer. Smoke is regarded as ideal gas. As such, the average density can be obtained through the conversion of the average temperature in the equation of the state of ideal gas, expressed as follows: PV = nRT (n = m/M). The average temperature is obtained based on the function T(z), which reflects the vertical distribution of temperature. The average temperature of the upper smoke layer is calculated as follows:

$$T_u = \frac{1}{H - H_{int}} \int_{H_{int}}^{H} T(z)dz \qquad (7)$$

The average temperature of the lower air layer is calculated as follows:

$$T_l = \frac{1}{H_{int}} \int_{0}^{H_{int}} T(z)dz \qquad (8)$$

The function reflecting the vertical distribution of temperature obtained by fitting is substituted in Eqs. (6), (7), and (8). Figures. 5 and 6 are obtained by calculating the aforementioned equations，that show the variation of the Fr of the smoke vent with the change of the smoke extraction rate when the power of the fire source is 15 MW and the linear function fitted by using Excel. Figures. 5 and 6 show that the Fr at the smoke vent increases with the increase in smoke extraction rate, i.e., the shearing motion of the smoke and air layers in the tunnel strengthens in general. As a result, mixing of the smoke and air layers at the smoke vent is intensified and the volume of discharged smoke decreases because of turbulence.
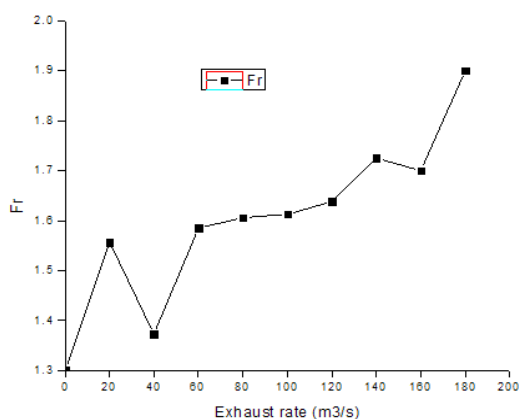
Figure. 5 Variation of the Fr with the change of the smoke extraction rate (15 MW)
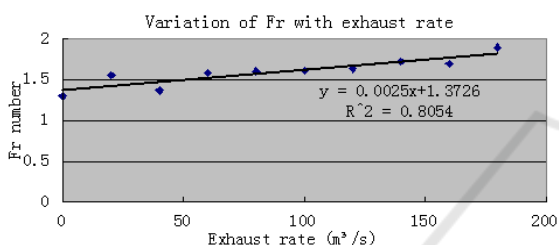

Figure. 6 Fitting of the Fr with the change of the extraction rate (15 MW)

4 CONCLUSIONS

In this study, numerical analyses are conducted under different smoke extraction rates to analyze the law of smoke extraction. We obtained the following conclusions:

(1) *VSO* decreases with the increase in the smoke extraction rate, whereas *VSE* increases with the increase in the smoke extraction rate.

(2) The *Fr* at the smoke vent increases with the increase in the smoke extraction rate.

ACKNOWLEDGEMENTS

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