Numerical Modelling and Prediction of the Train-induced Smoke Control in Tunnel Fire

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Abstract: For overall consideration the fire safety in subway system, the risk of train fire in the metro tunnel should be analysed and evaluated. Through theoretical numerical simulation technology in CFD, the smoke propagation characteristics of train fire with metro tunnel are investigated. The suggestion of emergency velocity would be given by considering the fire risk assessment. The result can provide technical support and a scientific basis for designing, making emergency ventilation strategies and setting personnel evacuation plans by design offices or operation managements.

1. Introduction
With the flourishing improvement of infrastructure constructions in Chinese urban rail transit, more and more metro lines have been planned and built in recent decade. Metro has many advantages, such as large capacity, high speed, low energy consumption, safety and comfort, which is an effective way to relieve the road traffic jam. It is particularly applicable for Chinese cities. (Hou, X.F et al. 2017) [1].Nowadays, there are over 34 cities that have been operating railway systems in China. In December 31, 2017, the total length of rail transit lines amounting to 5021.7 km were operated in Mainland China, which is shown in Fig.1.

Fig.1. the Operation Mileage of Metro Line in Mainland China
In addition, many metro systems are under construction in Chinese cities such as Shanghai, Beijing, Guangzhou, Shenzhen, Wuhan, Nanjing, Chengdu, and Hangzhou. The operation length of metro is 3881.8 km. In Guangzhou metro, the passenger volume intensity has reached 10 million person-times. On December 31, 2017, a new year eve, the Guangzhou metro systems transported 10.026 million person-times, which is the Canton highest record of daily passenger flow volume since 1997. Due to the special structure of subway tunnel, long and confined, fire is always a great threaten to the passengers’ safety (K. Fridolf et al. 2013[2]; X.Q. Zhou et al. 2008 [3]). In this condition, the designed capacity of smoke prevention for some stations based on the existing train speed cannot meet the needs of actual smoke control in tunnel fire, and the exhaust ventilation in tunnel fire generates a windy airflow that can increase the burning to a harmful extent (Xi et al. 2015) [4].

2. Methodology

2.1. Theoretical model

The mass equation, energy equation, and species transport equation can be described by

\[
\frac{\partial \rho}{\partial t} + \text{div}(\rho \mathbf{u}) = 0
\]

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \text{div}(\rho \mathbf{u} \mathbf{u}) = \text{div}(k \cdot \text{grad}T) - p\text{div}(\mathbf{u}) + \Phi + S_i
\]

\[
\frac{\partial (\rho Y_i)}{\partial t} + \frac{\partial (\rho u Y_i)}{\partial x} + \frac{\partial (\rho v Y_i)}{\partial y} + \frac{\partial (\rho w Y_i)}{\partial z} = \text{div}(\Gamma_i \text{grad}Y_i) + R_i
\]

In order to confirm the validation of the theoretical model, numerical simulation for the airflow field were conducted of the CFD software, which has widely been used to research on the, heat exchange(Rizzo et al., 2011) [5], and fuel-oil combustion(Goldsworthy, 2006) [6]. The continuity equation and Reynolds equations(RANS) (L. Chen, 2016[7]), and the RNG k-ε turbulence model (Stavrakakis, et al. 2009[8]; Yang.Z, et al. 2009 [9])were employed in this simulation.

The RANS equations can be described by

\[
\frac{\partial (\rho \Phi)}{\partial t} + \text{div}(\rho \mathbf{u} \Phi - \Gamma_{\Phi,\text{eff}} \text{grad}(\Phi)) = S_{\Phi}
\]

The RNG k-ε equation can be described by

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \text{div}(\rho \mathbf{u} \varepsilon) = \text{div}[(\mu + \frac{\mu_t}{\sigma_{\varepsilon}}) \text{grad}\varepsilon] + \mu_t C_{1_s} \varepsilon \frac{P_g}{k} - \rho C_{2_s} \frac{\varepsilon^2}{k} - R_{\varepsilon}
\]

\[
\frac{\partial (\rho k)}{\partial t} + \text{div}(\rho \mathbf{u} k) = \text{div}[(\mu + \frac{\mu_t}{\sigma_k}) \text{grad}k] + \mu_t P_g - \rho \varepsilon
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \text{div}(\rho \mathbf{u} \varepsilon) = \text{div}[(\mu + \frac{\mu_t}{\sigma_{\varepsilon}}) \text{grad}\varepsilon] + \mu_t C_{1_s} \varepsilon \frac{P_g}{k} - \rho C_{2_s} \frac{\varepsilon^2}{k} - R_{\varepsilon}
\]

While the blockage ratio was 0.32, the critical velocity was reduced about 40%~50% than non-blocking condition (Oka.Y, et al., 1995) [10]. Besides, the critical velocity was reduced about 15% when the blocking ratio was 0.12. While the blockage ratio was 0, the model estimates were about 18% higher. With the blockage condition of train, the critical velocity study of tunnel fire is carried out further by Kang K 2006[11]. The local hydraulic diameter is proposed to replace the tunnel height.
The Kang’s equations can be described by

\[ V_c = k \left( \frac{g\bar{H}Q_c}{4.5\rho_f^4 C_p A T_f} \right)^{1/3} \]  

(8)

The non-dimensional number of Froude is analysed by Li, 2012 [12], then, the concept of blockage ratio has been considered. The Li’s critical velocity equations can be described by

\[ V_c = 1.05 \left( 1 - \phi \right)^2 \left( \frac{g\bar{H_f}Q}{\rho_f C_p A T_f} \right)^{1/3} \]  

(9)

In conclusion, the key of calculation about critical velocity is to confirm the temperature of fire smoke, what is influenced by the complexity of the construction model, the obstruction of the train, the combustion model and the boundary conditions. So, it is difficult to consider overall the factors in a general experiment. Obviously, as an efficient methodology, numerical simulation based on accurate calculation model that is reflecting real fire scenario.

2.2. Numerical model
The combustion was set in the middle of the train, and a full-sized numerical simulation was conducted in tunnel that is 1200m long, 4.0m wide, and 5.2m high. The compartment size is 20m long, 2.8m wide and 3.8m high. There are 6 cars in a train, and the total length is 120m. The distance between the bottom of train and tunnel ground was 0.9m. The simulation points are setted between the train and tunnel, as drawn in Fig.2.

| Case   | \( \alpha \) | 0.464 | 0.327 | 0.235 |
|--------|---------------|-------|-------|-------|
| Heat Release Ratio (HRR) | 2.5MW | 5.0MW | 7.5MW | 10.0MW | 12.5MW | 15.0MW |
| Blockage ratio(\( \alpha \)) | Longitudinal Ventilation Velocities (V_c, m/s) |
| | 0.8 | 0.9 | 1.05 | 1.15 | 1.10 | 1.25 | 1.15 | 1.25 | 1.20 | 1.30 | 1.25 | 1.35 |
| Case 1 | 1.0 | 1.1 | 1.25 | 1.40 | 1.35 | 1.50 | 1.35 | 1.50 | 1.40 | 1.55 | 1.45 | 1.60 |
| | 1.0 | 1.1 | 1.25 | 1.35 | 1.50 | 1.60 | 1.65 | 1.75 | 1.70 | 1.80 | 1.80 | 1.90 |
| | 1.2 | 1.3 | 1.45 | 1.55 | 1.70 | 1.80 | 1.80 | 1.90 | 1.90 | 2.00 | 2.00 | 2.10 |
| | 1.05 | 1.15 | 1.40 | 1.50 | 1.60 | 1.70 | 1.75 | 1.85 | 1.90 | 2.00 | 2.15 | 2.25 |
| | 1.25 | 1.35 | 1.60 | 1.70 | 1.80 | 1.90 | 1.95 | 2.05 | 2.10 | 2.20 | 2.35 | 2.45 |
According to the research of tunnel fire around the world, the heat release ratio is between 5MW and 30MW in tunnel fire. In order to obtain the reliable results, the critical velocity was calculated based on different section sizes in longitudinal ventilation. The schematic diagram was shown in Table.1.

3. Results

3.1. Analysis of critical velocities

Condition A: \(HRR = 5\text{MW}, \quad \alpha = 0.464, \quad V_c = 0.00\text{m/s}\)

Condition B: \(HRR = 5\text{MW}, \quad \alpha = 0.464, \quad V_c = 1.05\text{m/s}\)

Condition C: \(HRR = 5\text{MW}, \quad \alpha = 0.464, \quad V_c = 1.40\text{m/s}\)

The distribution of soot density was shown in Fig.3 at different conditions. Affected by the train blocking and the doors opening, the fluctuations of soot density are volatile along the longitudinal distribution in different critical velocities. Besides, the fluctuations of smoke layers are still unstable far from the combustion sources, due to the blockage ratio of existing tunnel is relatively large. On the contrary, when longitudinal ventilation velocity was reached the critical value (1.40m/s), the smoke layer was destroyed seriously, the soot density was increased.

Above all, adopting longitudinal ventilation for smoke control can ensure the safety of upstream personnel who are completely smoke-free situation. However, the downstream personnel will be swallowed up by the smoke in a short time. While the improvement of longitudinal wind velocity can accelerate the smoke emission and reduce the temperature in the tunnel, but the damage to the smoke layer is more serious.
The results were compared between numerical simulation and theoretical model in Fig.4. The figure shows that the critical velocity increases with the improvement of heat release rate, and the increasing trend gradually slows down. The calculation values of critical velocity are less than the numerical simulation results in different fire’s scale.

4. Conclusions
Through the comparison of two theoretical models between Kang K 2006[11] and Li, 2012 [12], the more precise simulation model was found. The following conclusions can be stated:
(1) The numerical model was established in tunnel fire, and the simulation of polyhedron mesh was conducted.
(2) The correlation coefficients between the simulation results and theoretical data are greater than 0.90.
(3) The improvement of HRR makes the critical velocity increased. When HRR has improved to a certain value, the corresponding velocity hold steady.

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References
[1] Hou, X.F., Zuo, C, & Li. N. 2017. Statistics and Analysis of Urban Rail Transit in 2016. Urban Rapid Rail Transit, vol.30(3), pp. 1-7. (In Chinese)
[2] Fridolf, K., Nilsson, D., & Frantzich, H. 2013. Fire evacuation in underground transportation systems: a review of accidents and empirical research. Fire Technology, vol.49(2), pp.451-475.
[3] Zhou, X.Q. Zhao, C.J. & Zhao, X. X. 2008. Numerical simulation and analysis of smoke flow controlling in metro tunnel. Journal of Guangzhou University (Natural Science Edition), vol.7(5), pp.66-70. (In Chinese)
[4] Xi, Y. H., Chow, W. K., & Mao, J. 2015. Aerodynamics simulation on density jump in a long corridor fire. Tunnelling & Underground Space Technology Incorporating Trenchless Technology Research, vol.50, pp 23-31.
[5] Rizzo, E., Heller, R., Richard, L. S., & Zanino, R. 2011. Heat exchanger CFD analysis for the w7-x high temperature superconductor current lead prototype. Fusion Engineering & Design, vol.86(6–8), pp 1571-1574.
[6] Goldsworthy, L. (2006). Computational fluid dynamics modelling of residual fuel oil combustion in the context of marine diesel engines. International Journal of Engine Research, vol.7(2), pp 181-199.
[7] L. Chen. 2016. Study on subway tunnel smoke characteristic of the burning train in running condition. (Doctoral dissertation, Southwest Jiaotong University).
[8] Stavarakakis, G. M., & Markatos, N. C. 2009. Simulation of airflow in one- and two-room enclosures containing a fire source. International Journal of Heat & Mass Transfer, vol.52(11-12), pp. 2690-2703.
[9] Yang, Z., Su, X., Ma, F., Yu, L., & Wang, H. 2015. An innovative environmental control system of subway. Journal of Wind Engineering & Industrial Aerodynamics, vol.147, pp.120-131.
[10] Oka, Y., & Atkinson, G. T. 1995. Control of smoke flow in tunnel fires. Fire Safety Journal, 25(4), 305-322.
[11] Kang, K. 2006. Computational study of longitudinal ventilation control during an enclosure fire within a tunnel. Journal of Fire Protection Engineering, 16(3), 159-181.
[12] Li, L.M. 2012. Temperature Characteristic and Longitudinal Ventilation Control of Fire Smoke in Tunnels. (Doctoral dissertation, University of Science and Technology of China). (In Chinese).