Prediction of Back-layering Length and Critical Velocity with Lithium-ion Battery Car Fires in Tunnel

Zhenpeng Bai, Xiaohan Zhao, Huaitao Song, Yang Zhang, Haowei Yao, Jin Zhang

Abstract—**The purpose of this article is is to investigate the critical speed and back-layer length of smoke propagation during fires of lithium-ion battery vehicles in tunnels. The combustion of lithium-ion battery vehicles in tunnels is numerically simulated. This article uses heat release rate (HRR) and ventilation rate to predict the length of smoke counterflow in tunnel fires with new energy vehicles. Temperature is an important parameter for calculating smoke counterflow. The temperature in the tunnel is measured by thermocouples. The results showed that dimensionless critical velocity influences dimensionless HRR. The numerical simulation results indicated that there is a certain correlation between the HRR variable, which corresponds to the dimensionless smoke counterflow length and the critical speed in the tunnel. This article proposed a computational model for predicting the length of smoke counterflow. This paper contributes to the prevention of tunnel fires and reduction of social and economic losses. Therefore, this paper guides the propagation of smoke under the roof of lithium-ion battery vehicle fires in tunnels.**

Index Terms—**Backlayering length; Critical velocity; Tunnel; Ventilation; Lithium-ion battery car.**

I. INTRODUCTION

The tunnel develops rapidly in recent years [1]. Thermal runaway of lithium-ion batteries is difficult to control. It causes irreparable loss of life and property[1]. Domestic and foreign research mainly focused on the problem of electric vehicle power lithium-ion battery fire [2][3]. However, the focus is on the safety performance and thermal effects of batteries.

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Ribière P et al.[4] found that individual lithium battery also emits large amounts of heat and toxic gases. Baird [5] calculated the gas production and explosion pressure of different battery cells, and evaluated the impact of other parameters such as cell chemistry and SOC on the overall explosion risk of the battery. Compared to the 4 × 1 arrangement of lithium-ion batteries, Liu [6] found the 2×2 arrangement lithium-ion batteries had a higher explosion pressure, oxygen consumption, CO and CO_2 generation due to the larger thermal area and higher mass loss. Wang [7] studied the production of CO_2 and CO gases at different heating powers. They found that the higher the heating power, the higher the molar ratio of CO_2 to CO gas, indicating more complete combustion. Yu et al. [8] investigated the burning characteristics of high-capacity lithium phosphate ion power batteries using a laboratory fire heat release test device. The heat dissipation rate of lithium phosphate ion power batteries after thermal runaway was measured.

In order to study the burning state of ordinary automobiles under fire conditions, Song et al. [9] conducted experimental research on the burning state of three ordinary cars and analyzed the impact of fire development on the surrounding environment. To get a deeper understanding of the characteristics of electric vehicle fires, Zhu et al. [10] conducted the thermal runaway caused by heating of lithium-ion batteries in electric vehicles, and conducted full-scale electric vehicle combustion tests to study the combustion characteristics, as well as changed in the external heat flow and temperature properties of fires caused by thermal running of power batteries. Zhang et al. [11] compared the differences in ignition mechanisms, spreading combustion mode, and hazards between electric vehicles and traditional internal combustion engines. Electric vehicles have new characteristics that differ from traditional car fires due to their different fuel supply and driving methods. However, there is relatively little research in cases of fire involving new energy vehicles in tunnels. When the length of the smoke counterflow is zero, the ventilation rate at this time is the critical speed. The back-layering length of smoke in tunnel is the same as smoke counterflow length.

The length of smoke backflow is one of the important parameters that need to be studied for smoke control in tunnel fires. Several previous studies have investigated the smoke counterflow length and critical speed in tunnel. Thomas [12][13] pointed out that the calculation of the critical Froude is shown in Eq. (1).

$$Fr_c = \frac{\Delta\rho g H}{\rho_0 V_c^2} \tag{1}$$

Thomas pointed out that the formula for calculating the critical velocity is shown in Eq. (2).

$$V_c = \left(\frac{gQ_c H}{\rho_0 c_p T_f A}\right)^{1/3} \tag{2}$$

Kennedy [14] pointed out that the formula for calculating the critical velocity is shown in Eq. (3).

$$V_c = K_g\left(\frac{gQ_c H}{\rho_0 c_p T_f A Fr_c}\right)^{1/3} \tag{3}$$

where, $T_f = \frac{Q_c}{\rho_0 c_p A V_c} + T_0$

Li et al. [15] pointed out the backlayering length in Eq. (4).

$$l^* = \begin{cases} 18.5\ln(0.81 Q^{*1/3}/V^*), Q^* \le 0.15 \\ 18.5\ln(0.43/V^*), Q^* > 0.15 \end{cases} \tag{4}$$

$$Q^* = \frac{Q}{\rho_0 c_p T_0 g^{1/2} H^{5/2}} \tag{5}$$

The dimensionless longitudinal ventilation speed:

$$V^* = \frac{V}{\sqrt{gH}} \tag{6}$$

Due to the increasing use of new energy vehicles, highway tunnels are an important transportation hub for new energy vehicles. The daily operation ventilation and fire control smoke exhaust scheme usually adopts a combination of longitudinal ventilation and centralized smoke exhaust. When a new energy vehicle fire occurs, longitudinal ventilation is used to control the upstream smoke in a certain area near the fire source. At the same time, one or several centralized smoke exhaust outlets near the fire source are opened, and high-temperature smoke is transported into the independent smoke exhaust duct installed on the side through the centralized smoke exhaust outlet and discharged from the tunnel. At present, the focus of research is still on centralized smoke exhaust on the ceiling or the combination of vertical ventilation and centralized smoke exhaust on the ceiling. However, the centralized smoke exhaust system after new energy vehicle fires in highway tunnels has gradually been promoted and used with the rise of new energy vehicles. Most existing studies use methods such as tunnel fire simulation to study lateral centralized smoke exhaust systems, including the height to width ratio of smoke exhaust outlets, smoke exhaust outlet positions, and smoke exhaust air volume. However, there are still some discrepancies between existing research and actual situations, and there is still a lack of systematic research on the smoke spread law under longitudinal ventilation mode.

Many studies conducted the smoke counterflow length in tunnels. The ventilation rate in tunnel fires has also received widespread attention. These parameters are also important in the fire prevention of public engineering tunnels. This paper proposes a model for calculating the smoke length when smoke return layer and critical ventilation rate in tunnels. In summary, previous studies have extensively investigated tunnel fires in public works. However, there are differences smoke counterflow in the tunnel where lithium-ion battery car fires occur.

Based on the current research status at home and abroad, it has been found that previous studies mainly focused on the burning states of lithium-ion batteries in open spaces. Currently, there is relatively little research on fires in narrow and confined spaces of lithium-ion batteries. The burning states and mechanisms of fires are not yet clear. With the development of urban underground spaces, lithium-ion batteries will be increasingly used in small and confined spaces. Once a fire occurs, it will cause huge losses.

This article takes the 32650 type lithium- ion phosphate battery as an example, in order to study the burning states of lithium-ion batteries in narrow confined spaces. The main research focuses on the effects of charging state, ventilation wind speed, battery pack size and arrangement on mass loss, flame mode, temperature field, smoke and concentration field. This article uses numerical simulation methods to analyze the diffusion of high-temperature smoke generated by car fires in tunnels. Pyrosim software was used for numerical simulation research, analyzed and compared the fire simulation results of fuel vehicles and new energy vehicles. The changes were analyzed with heat release rate, smoke and temperature during the fire process. It conducted in-depth research on the characteristics and hazards of electric vehicle fires.

II. Method

As shown in Fig. 1, a schematic diagram of a lithium-ion battery vehicle model was constructed in the tunnel. This

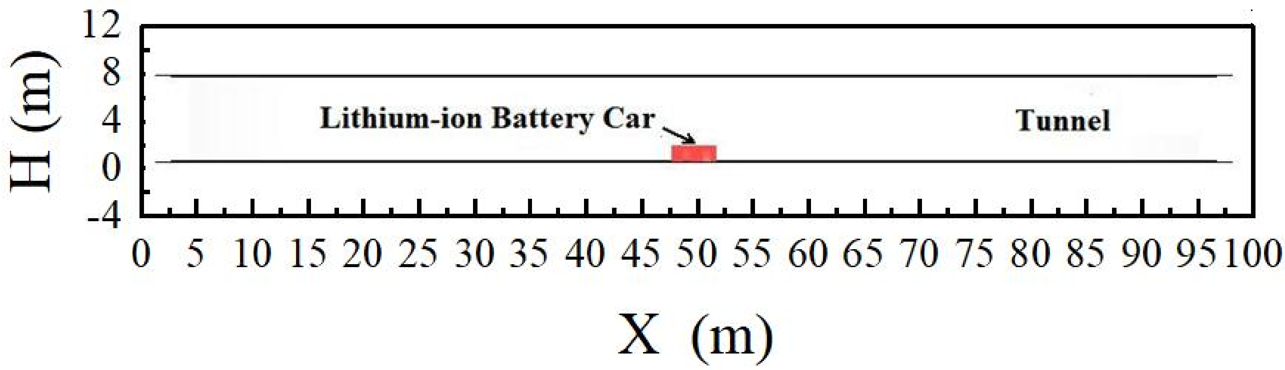

Fig. 1. A model of lithium-ion battery car in tunnel.

figure is to describe the physical model established in fire dynamics simulator (FDS). The tunnel was 100.0 m long, 8.0 m high and 10.0 m wide. The new energy car was 4.2 m long, 1.4 m high and 1.8 m wide. The new energy car had 4 doors and windows. Each window and door was 0.6 m wide and 1.0 m high. This paper used 35650 lithium-ion phosphate battery as the experimental object. There were four lithium-ion battery packs, each of which was 630 mm long, 820 mm wide, 230 mm wide. In addition, CO, CO_2, O_2 and smoke detectors were arranged directly above the new energy vehicle and 0.2 m below the ceiling of the tunnel. In order to measure the temperature above the model, thermocouples were set up at different heights. The distances between the vertical thermocouples and below the ceiling of the tunnel were 0.5 m, 1 m, 1.5 m, 2 m, 2.5 m, 3 m, 3.5 m, 4 m, and 4.5 m, respectively. In the vertical direction, thermocouples were arranged along the centerline below the ceiling of the tunnel with the fire source as the center, and 9 thermocouples were arranged on each side with a spacing of 5 m.

FDS was a good tool for assessing smoke propagation in tunnel fires [16-20]. The material used in the floor, ceiling and wall were concrete [21]. The numerical simulation time was 100 s. The fire source was a t^2 fire. The grid size was 0.25 m×0.2 m×0.2 m in the near fire area. The grid size was 0.5 m×0.4 m×0.4 m in the far fire area.

TABLE 1 32650 TYPE IRON SHELL CYLINDRICAL IRON CARBONATE LITHIUM BATTERY PARAMETERS TABLE

Parameters	Parameter Value
Mass (g)	140
External dimensions (diameter × height, mm)	32×65
Rated capacity (mAh)	6000
Rated voltage (V)	3.2
Charge good cut-off voltage (V)	3.65
Internal resistance (mΩ)	≤40

The vehicle was simplified to a simple model by assuming that the initial temperature at the beginning of the simulation was 20 ℃. The vehicle was parallel to the tunnel direction. It simulated that the vehicle was in the tunnel. The reaction was set up as a simple chemical reaction model, in which carbon atoms were 6.2, hydrogen atoms were 7.1, oxygen atoms were 2.2, and nitrogen atoms were 1.0. As shown in Table 1, the parameters of the 32650 iron-cased cylindrical lithium-iron phosphate battery are presented. As shown in Table 2, the numerical simulation conditions of new energy vehicle fires in tunnels

TABLE 2 SIMULATION CASES OF NEW ENERGY VEHICLE FIRES IN TUNNELS

Case	HRR (MW)	Ventilation speed(m/s)				
1	0.25	1.4	1.6	1.8	2.0	2.2
2	0.50	1.8	2.0	2.2	2.4	2.6
3	1.0	2.4	2.6	2.8	3.0	3.2
4	1.5	2.8	3.0	3.2	3.4	3.6
5	2.0	3.2	3.4	3.6	3.8	4.0
6	2.5	3.2	3.4	3.6	3.8	4.0
7	3.0	3.6	4.0	4.4	4.8	5.2
8	5.0	3.8	4.2	4.6	5.0	5.4

III. RESULTS AND DISCUSSIONS

A. The smoke counterflow length

To calculate the backflow length of smoke in new energy vehicle fires, numerical simulation studies were conducted using Pyrosim software with HRR of 0.25 MW, 0.5 MW, 1 MW, 1.5 MW, 2.0 MW, 2.5 MW, 3.0 MW, and 5.0 MW. Fig.s 2 and 3 showed the effects of longitudinal ventilation speed and heat release rate on the length of smoke counterflow in a tunnel when a new energy vehicle occurs a fire. If the longitudinal ventilation speed of the tunnel decreases, the length of smoke counterflow will increase relatively quickly.

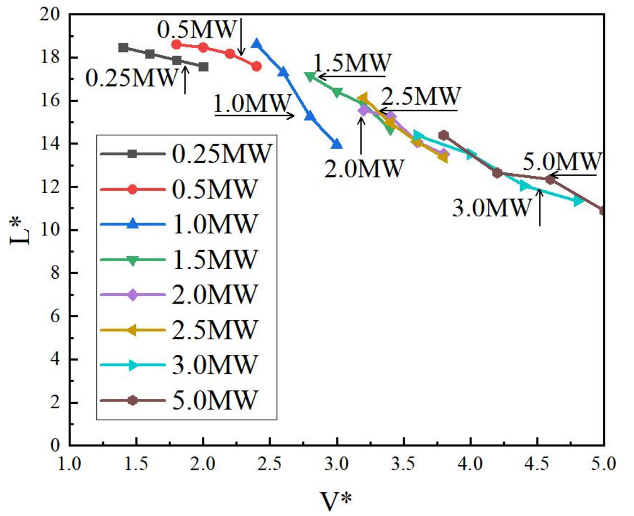

Fig. 2. The smoke counterflow length in the tunnel with ventilation speed.

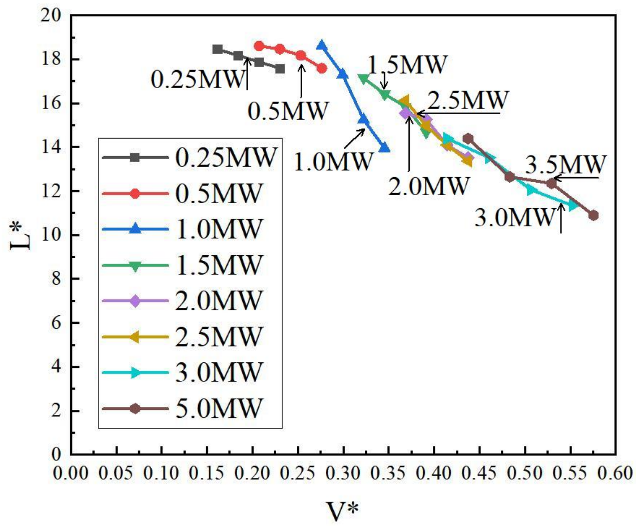

Fig. 3. The dimensionless smoke counterflow length in the tunnel with dimensionless ventilation speed.

B. Dimensionless critical speed

As shown in Fig. 4, the dimensionless critical ventilation speed was related to the dimensionless heat release rate when the lithium-ion battery car in the tunnel occurred fire. The results showed that the dimensionless critical ventilation speed increased with the dimensionless heat release rate, when the lithium-ion battery vehicle in the tunnel occurred fire.

The dimensionless critical ventilation speed at the time of lithium-ion battery car fire in the tunnel is shown in Eq. (7). The correlation coefficient of Eq. (7) is 0.963.

$$V^* = 0.80 \cdot Q^{*(1/3)} + 0.01 \tag{7}$$

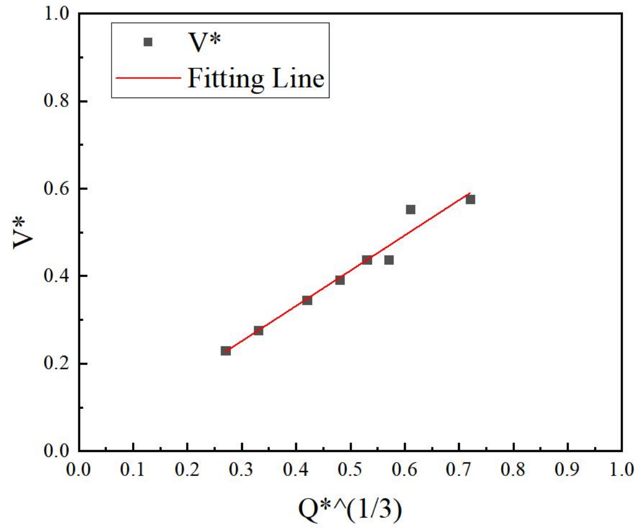

Fig. 4. The dimensionless critical ventilation speed in the tunnel.

C. Dimensionless smoke counterflow length

The numerical simulation data were further analyzed using dimensional analysis. Fig. 5 showed the curves of dimensionless smoke counterflow length versus variable of heat release rate and ventilation speed for tunnel, when heat release rates were 0.25 MW, 0.5MW, 1 MW, 1.5 MW, 2.0 MW. It is clear that the variable of heat release rate and ventilation speed correlates well with the dimensionless smoke counterflow length.

As the variable of heat release rate increased, the back-layering length increased. The numerical simulation data of smoke counterflow length in tunnel when fire source located in tunnel could be correlated into a universal form. The proposed equation as follows:

$$L^* = 2.43 \cdot \ln(Q^{*(1/3)} / V^*) + 17.26 \tag{8}$$

A correlation coefficient was 0.991 for Eq. (8).

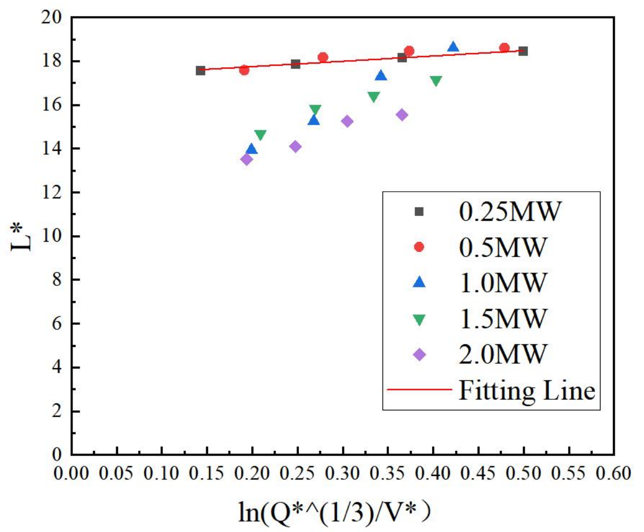

Fig. 5 Correlation of dimensionless smoke counterflow length with variable of $\ln(Q^{*(1/3)} / V^*)$ with small HRR.

As shown in Fig. 6, it was correlation of dimensionless smoke counterflow length with variable of heat release and ventilation speed, when heat release rate was 2.5 MW, 3.0 MW and 5.0 MW. As the variable of heat release rate increased, the smoke counterflow length increased. The dimensionless back-layering length was shown in Eq. (9).

$$L^* = 16.01 \cdot \ln(0.93 / V^*) + 1.22 \tag{9}$$

A correlation coefficient was 0.990 for Eq. (9).

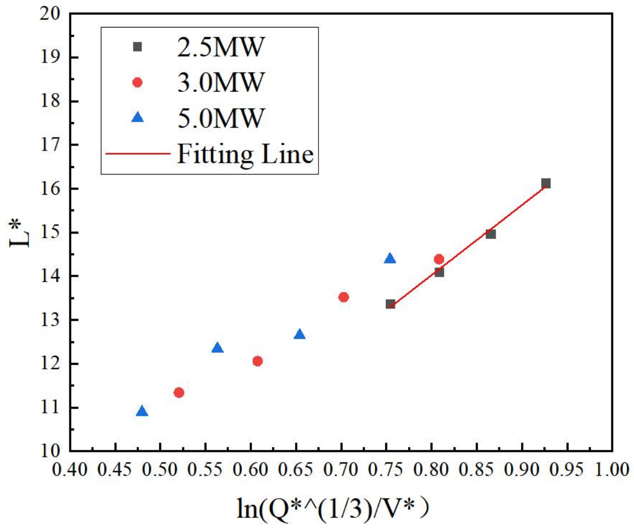

Fig. 6. Correlation of dimensionless smoke counterflow length with variable of $\ln(Q^{*(1/3)} / V^*)$ with high HRR.

D. Comparison between the smoke counterflow length and Li model

Fig. 7 showed a comparison between the numerical simulation experiment and the Li model with lithium-ion battery car fire that occurred in the tunnel. The results showed that the numerical simulation experiments do not fit well with the Li model data. The reason is that lithium-ion battery car fires released more heat and the distance between the smoke back-layering length was greater. Therefore, the model proposed in this article fills the gap in controlling smoke counterflow for new energy vehicles in highway tunnel fires. This has significant guiding significance for the fire safety of new energy vehicles in highway tunnels

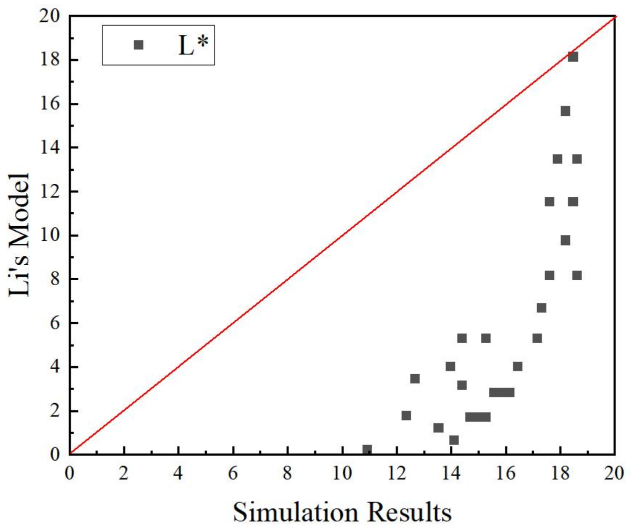

Fig. 7. Comparison between simulation results and Li model prediction of smoke counterflow length

IV. CONCLUSIONS

This paper conducted numerical simulation research on a lithium-ion battery car fire that occurred in a tunnel. It also studied the back-layering length of the smoke layer inside the tunnel under different ventilation speed. Two important factors were considered, which are ventilation rate and heat release rate. These factors affected the length of smoke retention inside the tunnel. The main conclusions drawn from this paper are as follows.

(1) The proposed correlation well reflected the critical velocity at which lithium-ion battery vehicles occurred fire in tunnels.

(2) The smoke counterflow length was related to the heat release rate and critical velocity. The numerical simulation results showed that when a lithium-ion battery car fire occurred in a tunnel. There was an exponential relationship between the dimensionless smoke counterflow length and the heat release rate and ventilation speed.

(3) A correlation method based on numerical simulation data was proposed to predict the smoke counterflow length. In addition, compared the numerical simulation data of the smoke counterflow length during lithium-ion battery vehicle fires in tunnels with the results of the previous studies, it was shown that there was an improved model that could predict the smoke counterflow length during tunnel fires.

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