Research on the Smoke Flow Law of New Energy Vehicle Fire in Tunnel

Zhenpeng Bai, Jingjing Li, Hengjie Qin, Haowei Yao, Xiaohan Zhao

***Abstract*—The fire risk of new energy vehicles in tunnels cannot be ignored. This paper uses research methods such as data research and theoretical analysis. It is based on FDS simulation method and combined with PyroSim fire simulation software. A simulation model was developed to investigate various operational conditions for numerical analysis. The study focused on examining the fire propagation speed, smoke dispersion patterns, and temperature distribution characteristics of new energy vehicles within tunnel environments. Finally, the numerical simulation data obtained was processed using Origin software to obtain a case data graph. The development characteristics of highway tunnel fires are systematically discussed based on the data graph. This paper obtained the variation law of fire temperature at different time periods through numerical simulation analysis. The results indicated a rapid increase in temperature over time within the tunnel, followed by a peak, and then a subsequent decline towards stabilization. The temperature of the tunnel ceiling exhibited a decreasing trend from the central point towards both ends during a fire event. Additionally, the rate of fire spread within the tunnel was observed to escalate with an increase in the heat release rate (HRR). However, over time, the rate of change stabilized after reaching a critical threshold. This paper can help predict fire progression early and improve fire control and mitigation measures in tunnel environments.**

***Index Terms*—Tunnel, New energy vehicle, Numerical simulation, Fire**

I. INTRODUCTION

In recent years, the rapid development of new energy vehicle technology has significantly accelerated [1]. The current status of new energy vehicles (NEVs) within the domestic and international automotive industry signifies a gradual shift towards becoming the predominant trend in industry development. However, due to the unique characteristics of their powertrain, electrical systems, and other associated components, NEVs pose distinct risks in accident scenarios compared to traditional fuel vehicles. In recent years, scholars have conducted extensive research on the fire behavior of NEVs, both domestically and internationally. Despite this, there remains a notable dearth of research focused on the smoke flow characteristics of NEV fires within tunnel environments.

Zhang [1] devoted his research to the exploration of new energy vehicles, conducting a comprehensive analysis of their fire mechanisms, propagation dynamics, and associated hazards from multiple perspectives. Ingason et al. [2] executed four fire tests within the Runehmar tunnel, yielding heat release rate (HRR) curves for heavy truck fires loaded with varying cargo volumes. Furthermore, a collaborative effort involving nine European countries conducted fire experiments in Norway, capturing the temporal variation of HRRs for fires originating from different vehicle models. Carvel et al. [3-4] employed Bayesian analysis to quantify the influence of longitudinal ventilation on the HRR of tunnel fires, discovering that forced ventilation significantly amplifies the HRR of large trucks but exerts minimal impact on the HRR of conventional automotive fires. Ingason et al. [5] conducted a statistical analysis of extensive data sourced from numerous large-scale tunnel fire experiments and model tests conducted globally. It revealed the influence of factors such as ventilation system, ventilation speed, heat release rate, tunnel geometry, and fire source on the maximum temperature under the roof of a large tunnel fire.

Based on the results obtained from a 1/10 scale model tunnel, Kurioka et al. [6] derived empirical formulas for flame inclination angle, flame height, and maximum temperature and position of the smoke layer. By comparing these empirical formulas with the results of half scale and full-scale experiments, it was confirmed that these formulas are fully applicable for predicting near-field fire phenomena of square fire sources. Zhong et al. [7] conducted comprehensive fire tests under three different fire HRRs. Lou et al. [8] used fire dynamics simulation software FDS to study the effect of curvature on smoke diffusion in curved tunnel fires. A dimensionless constant, namely the ratio of centrifugal force to radial reaction force component, was defined through force analysis of flue gas. The results indicate that the temperature and velocity of external smoke are higher than those of internal smoke near the fire source, and this difference gradually decreases with the increase of tunnel curvature radius. Caliendo et al. [9] used CFD models

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to simulate the fire effects caused by different types of vehicles in bidirectional highway tunnels, focusing on the effects of tunnel fire location, tunnel geometry, longitudinal ventilation, and traffic flow on tunnel fires. It found that the worst-case scenario was when a tanker truck occurred fire and the tunnel was crowded with vehicles, making the situation even more severe. In the event of a fire in an oil pool, the emergency ventilation system could ensure that the temperature, radiant heat flux, and toxic gas concentration remained at a reasonable level for 5 minutes after the fire.

Wang et al. [10] employed numerical simulation techniques to determine the critical wind speed within a curved tunnel. Their findings revealed that the critical wind speed for fires occurring in proximity to convex tunnel walls is considerably higher compared to fires located at other lateral positions. Furthermore, the results indicated a decrease in the critical wind speed as the curvature radius diminishes. The study also observed that the peak temperature initially manifests at the arch waist and arch shoulder of the protruding wall situated above the fire source, with the high-temperature smoke subsequently migrating towards the apex and arch shoulder of the concave wall. Dorsz et al. [11] utilized Computational Fluid Dynamics (CFD) simulations to compare the fire characteristics of electric vehicles (EVs) with traditional internal combustion engine (ICE) passenger vehicles. They estimated the potential impact of enclosed structures, such as underground garages or highway tunnels, on the safety of personnel and property. Additionally, the study investigated thermal runaway and smoke generation within battery modules or battery systems, thereby inferring certain fire risks associated with EVs [12-13]. The author has conducted extensive research in the field of fire and ventilation, encompassing various studies [14-18].

This article presents the establishment of a physical model, which incorporates the arrangement of thermocouples, velocity sensors, and CO sensors. It used numerical simulation methods, the study elucidated the temporal and spatial variation laws of fire smoke propagation rates in the context of fires involving new energy vehicles. Furthermore, the article analyzed the changes in temperature within tunnels over both time and location during fires that involve new energy vehicles.

II. Method

A. Physical Model

A typical tunnel was selected as the research model, as shown in Fig. 1. It selected the size results of the tunnel based on typical values applied in actual projects. The tunnel was 100 m long, 10 m wide, and 8 m high.

B. Boundary conditions

The numerical simulation results are presented in Table 1. The size and location of the fire source power are crucial parameters that determine the scale of a fire. Consequently, in the simulation process, five distinct sizes of fire source power and four varying positions of the fire source were primarily set up for analysis and comparison. When considering the position of the fire source as a variable, the Y-axis coordinates of the fire source were set to Y=0 m, Y=1 m, Y=2 m, and Y=3 m, respectively. The HRR of the fire source was varied at 1 MW, 5 MW, 10 MW, 15 MW, and 20 MW, respectively.

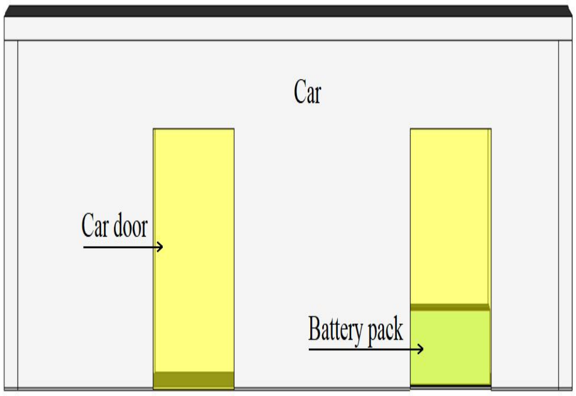

Fig. 1. A physical model new energy vehicle in the tunnel

TABLE 1 SIMULATION CONDITIONS OF CABLE TUNNEL WITH FIRE EXTINGUISH.

Case	Fire source (MW)	Y-axis direction
1	1	0
2	1	1
3	1	2
4	1	3
5	5	0
6	5	1
7	5	2
8	5	3
9	10	0
10	10	1
11	10	2
12	10	3
13	15	0
14	15	1
15	15	2
16	15	3
17	20	0
18	20	1
19	20	2
20	20	3

This article describes the arrangement of thermocouples in a specific configuration relative to a fire source. A thermocouple was positioned 0.4 m above the fire source. Additionally, one thermocouple was placed on the left front door of the driver's car, and another was positioned on the exterior of the roof. Thermocouples were also placed in the Z-axis direction at the tunnel's center point, at distances of 2 m, 2 m, 1 m, and 1.6 m from the car's roof. Furthermore, along the X-axis horizontal line, at a distance of 6.6 m from the car's roof, 25 thermocouples were evenly arranged at intervals of 2 m.

The layout of the speed sensors is detailed as follows. One speed sensor is installed 0.4 m above the fire source, and another is positioned on the left front door of the driver's car. Along the Z-axis direction at the center of the tunnel, speed sensors are installed at distances of 0.5 m, 0.5 m, 0.5 m, 1 meter, 1 m, 1 m, and 1 m from the roof. On the X-axis horizontal line, located 6 m away from the roof, speed sensors are installed every 3 ms, with a total of 13 speed sensors arranged in this configuration.

The distribution of CO concentration sensors in this model is detailed as follows. One CO concentration sensor is positioned above the fire source, another is located on the driver's left front door, and a third is situated 3.8 m away from the roof of the car. Additionally, at this specific point, three CO concentration sensors are placed every 4.5 m along the left X-axis direction.

III. Results And Discussions

A. The variation law of fire temperature with fire location

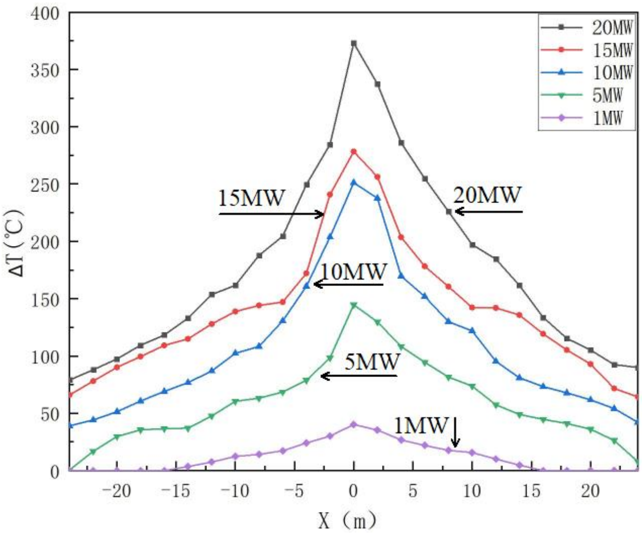

Fig. 2. The temperature change below the ceiling when the car is in the centerline of the tunnel horizontally

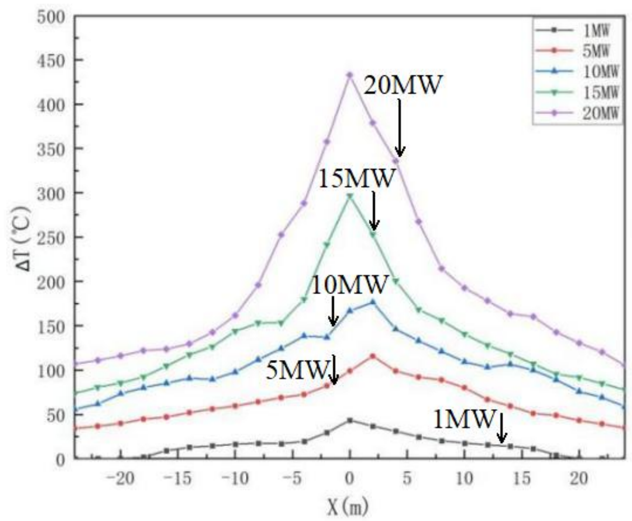

Fig. 3. The temperature change below the ceiling when the car is 1 m away from the centerline of the tunnel horizontally

This tunnel is 100 m long. This article compares the temperature of the tunnel roof with the variation of the transverse fire source in the tunnel. As shown in Fig. 2, when there is no ventilation in the tunnel and the new energy vehicle is located in the center of the tunnel, when a fire occurs in the tunnel and the new energy vehicle is on the straight line above the ignition point Z-axis, the temperature field shows a clear stratification phenomenon when the fire spreads to other positions in the tunnel. When the power of the fire source is constant, as the fire spreads towards both ends of the X-axis of the tunnel, there is a maximum temperature above the car, with a maximum temperature difference of about 450 ℃. However, as the fire spread towards both ends, it gradually weakened, with a maximum temperature difference of about 100 ℃. Therefore, attention should be paid to regional issues when extinguishing fires.

As shown in Fig.s 3 ~ 5, when a car catches fire, similar temperature changes will also occur in other locations in the tunnel.

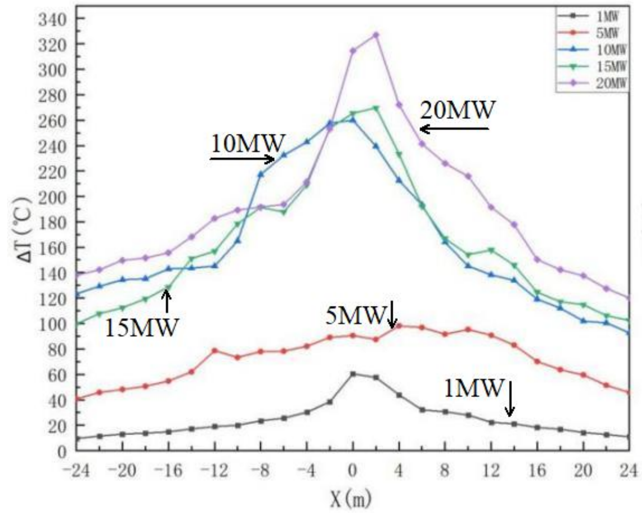

Fig. 4. The temperature change below the ceiling when the car is 2 m away from the centerline of the tunnel horizontally

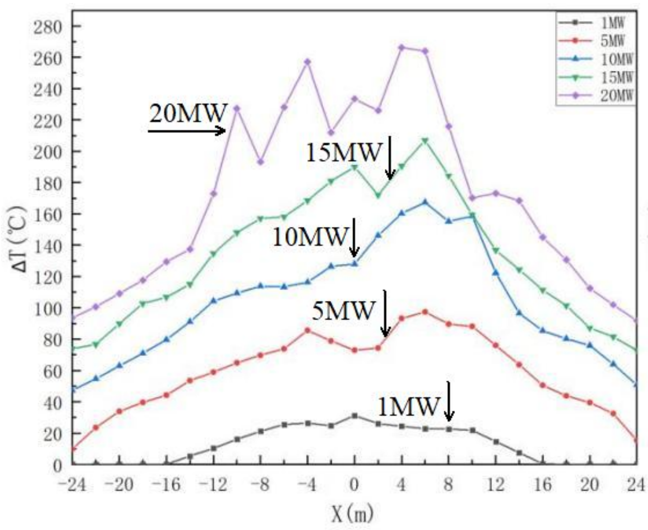

Fig. 5. The temperature change below the ceiling when the car is 3 m away from the centerline of the tunnel horizontally

When the fire source is positioned at the centerline of the tunnel, the HRR is 20 MW. The simulated data has been fitted and presented in Figure 6. A predictive model has been derived for the temperature in the X direction of the ceiling position, which is a function of position. This predictive model is represented in Eq. (1).

$$\Delta T = \Delta T_0 + Ae^{-\frac{(X-X_C)^2}{2W^2}} \tag{1}$$

where, ΔT_0=97.68, A=222.92，X_C=1.30, W=7.10.

Utilizing this predictive model, a clearer comprehension of the temperature variation patterns of fires at various ceiling positions can be obtained. The coefficient of determination (R^2) for the fitting is 0.947, indicating a good fit. This demonstrates that the model is both accurate and consistent, enhancing its reliability.

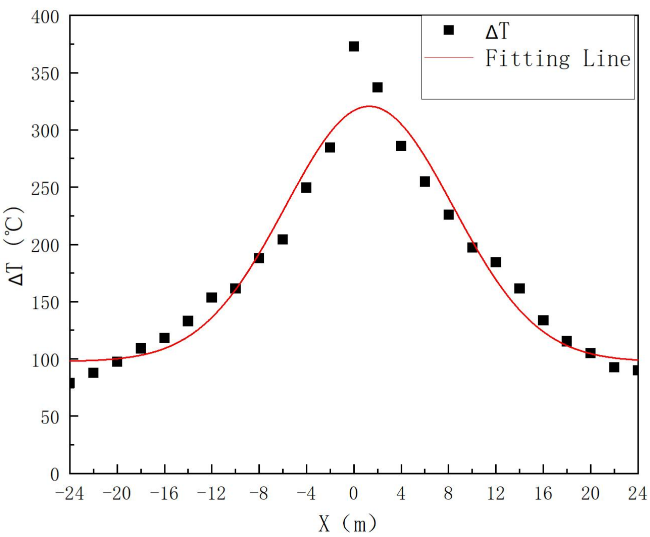

Fig. 6. Fitting curve of temperature change of roof during tunnel new energy vehicle fire

B. The law of smoke spread speed

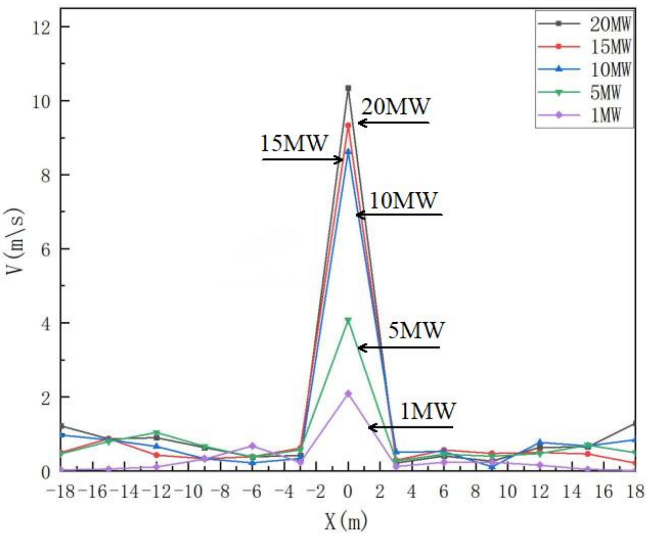

Fig. 7. The velocity change below the ceiling when the car is in the centerline of the tunnel horizontally

As shown in Fig. 7, the fire propagation speed is maximal at the central position of the tunnel. With a constant HRR of the fire source, the fire propagation speed decreases as the distance from the fire source increases. Notably, the fire propagation speed at the fire source location differs significantly from other locations. Specifically, when the HRR of the fire source is 20 MW, the maximum fire propagation speed reaches 11 m/s, which stands out significantly compared to other positions. Additionally, as the HRR of the fire source increases, the fire propagation speed also increases, with a notable difference. However, on both sides of the tunnel, the fire propagation speeds are relatively low, and as the HRR of the fire source increases, there is no substantial difference in the fire propagation speeds on either side of the vehicle. Similar patterns in fire spread speed are observed when a vehicle catches fire at other horizontal positions within the tunnel. The corresponding results are presented in Fig.s 8 to 10, respectively.

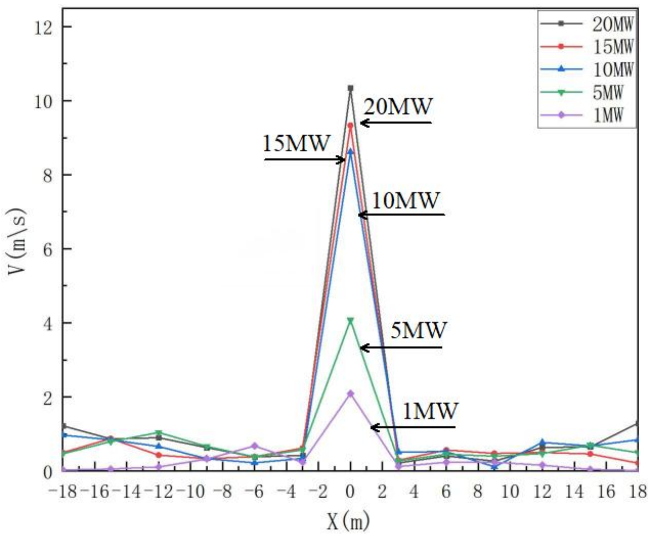

Fig. 8. The temperature change below the ceiling when the car is 1 m away from the centerline of the tunnel horizontally

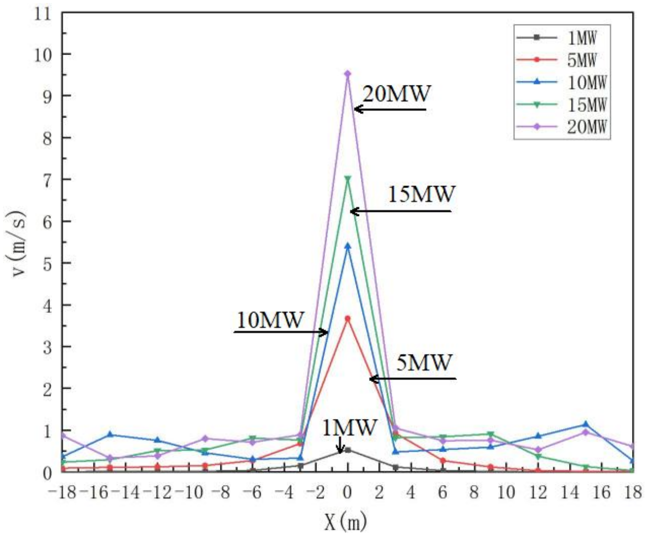

Fig. 9. The temperature change below the ceiling when the car is 2 m away from the centerline of the tunnel horizontally

When the fire source is placed at the centerline of the tunnel, the HRR is 20 MW, the simulated data is fitted as shown in Fig 11. And a predictive model for the velocity variation with position in the X direction of the ceiling position is shown in Eq. (2).

$$V = V_0 + A * \frac{1}{1+e^{-\frac{X-X_C+W_1/2}{W_2}}} * \left(1 - \frac{1}{1+e^{-\frac{X-X_C-W_1/2}{W_3}}}\right) \quad (2)$$

where, V_0=0.70, X_C=0.59, A=9.31, W_1=1.77, W_2=7.63*10-4, W_3=0.05.

From this prediction model, it could get a clearer understanding of the temperature variation patterns of fires at different ceiling positions. The fitting value of R^2 is 0.971.

The fitting effect is well, and the model is more accurate and consistent.

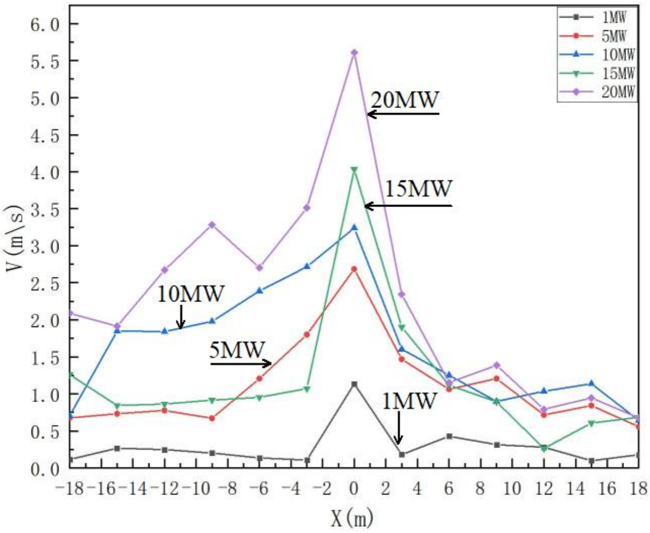

Fig. 10. The temperature change below the ceiling when the car is 3 m away from the centerline of the tunnel horizontally

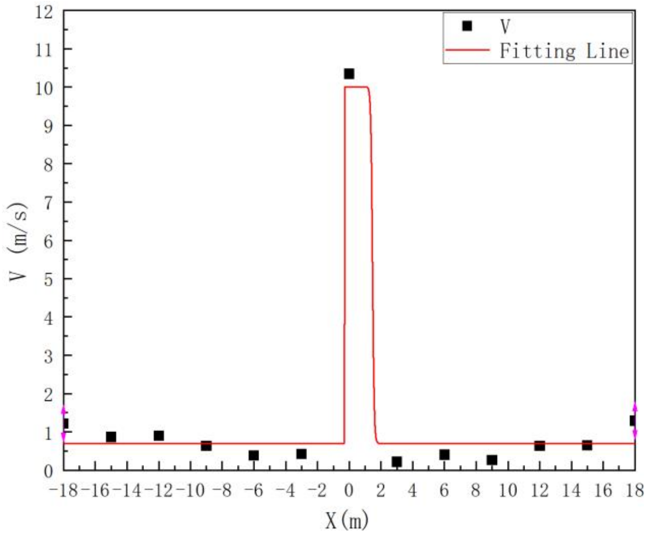

Fig. 11. Fitting curve of velocity change of roof during tunnel new energy vehicle fire

C. The variation law of CO concentration inside new energy vehicle fires

As shown in Figs. 12~13, the changes in CO concentration inside the vehicle. Most casualties in fires are caused by the influence of smoke, leading to suffocation and death. It is also of great significance in exploring the concentration of CO during fire processes. The concentration of CO in the car increases over time, stabilizes within a certain range, and sharply increases within 5 ~ 10 seconds. The increase in CO concentration poses a greater threat to passenger safety. Meanwhile, as the HRR of the ignition source increases, the overall CO concentration inside the vehicle will also increase. If a fire occurs, it should also closely monitor the harm caused by CO to personnel.

When the fire source is located at the centerline of the tunnel, the HRR is 20 MW, and the simulated data is fitted as shown in Fig. 14. A predictive model of CO concentration over time is shown in Eq. (3).

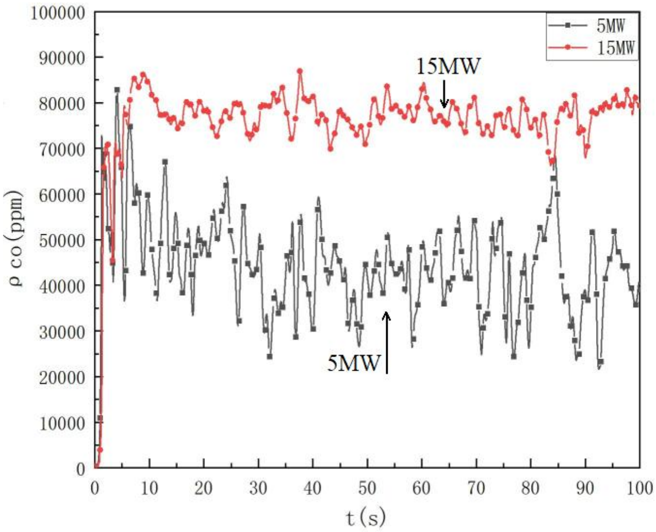

Fig. 12. The variation law of CO concentration in tunnel new energy

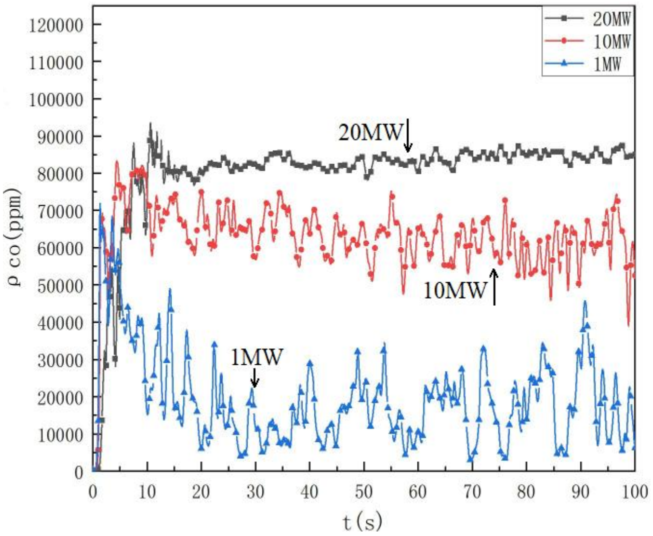

Fig. 13. The variation law of CO concentration in tunnel new energy

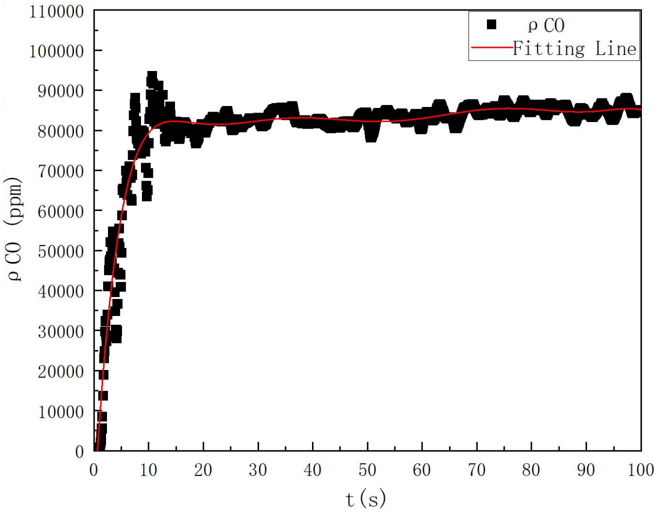

Fig. 14. Data fitting diagram of CO concentration changes inside new energy vehicles in tunnels

$$\Delta T = A_0 + A_1 * t + A_2 * t^2 + A_3 * t^3 + \ldots + A_9 * t^9 \tag{3}$$

where, A_0=-14316.87, A_1=23626.75, A_2=-2339.33, A_3=122.53, A_4=-3.76, A_5=0.07, A_6=-8.21*10^{-4}, A_7=5.68*10^{-6}, A_8=-2.14*10^{-8}, A_9=3.31*10^{-11}.

From this prediction model, it could get a clearer understanding of the CO concentration variation with time. The fitted value of R^2 is 0.945. The fitting effect is well, and the model is more accurate and consistent.

D. The variation law of interior temperature in new energy vehicle fires

When the fire source is located at the centerline of the tunnel, the HRR is 20 MW. The simulated data is fitted as shown in Fig. 15. It obtains a predictive model for the variation of internal temperature over time in a new energy vehicle fire:

$$\Delta T = A_0 + A_1 t + A_2 t^2 + A_3 t^3 + A_4 t^4 + A_5 t^5 \tag{4}$$

where, A_0=-212.45, A_1=116.03, A_2=-5.91, A_3=0.13, A_4=-0.001, A5=4.20*10^{-6}.

From this prediction model, it could get a clearer understanding of the variation pattern of the variation law of interior temperature in new energy vehicle fires with time. The fitted value of R^2 is 0.805. The fitting effect is well, and the model is more accurate and consistent.

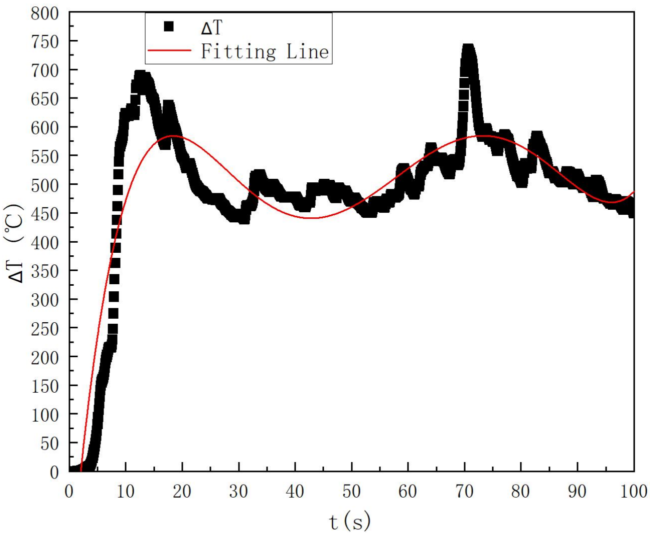

Fig. 15. Fitting of left front door position temperature data for new energy vehicle drivers

IV. CONCLUSIONS

This article employs the PyroSim software to develop a simulation model for analyzing the dynamic fire temperature, fire smoke spread rate, and carbon monoxide (CO) concentration associated with new energy vehicles in highway tunnels. The study integrates literature review, theoretical analysis, and numerical simulation methodologies. The primary findings are summarized as follows:

(1) In the event of a new energy vehicle fire in a highway tunnel, the fire temperature surpasses that of a gasoline vehicle, reaching its peak approximately five seconds later. The overall temperature trend exhibits an initial rise, followed by a decline, and ultimately stabilizes. The influence of the fire spread path results in a lower temperature at the top of the vehicle compared to other locations. When the fire source is positioned on the longitudinal centerline of the tunnel, the vertical temperature is higher than that on both tunnel sides.

(2) When a new energy vehicle catches fire in a highway tunnel, smoke dissemination rapidly intensifies ten seconds prior to the fire, with the surrounding fire also escalating swiftly. The smoke diffusion rate within the tunnel peaks directly above the fire source on the vertical line and decreases towards both tunnel ends.

(3) During the investigation of various characteristic parameter changes on the vehicle body during a new energy vehicle fire, it was observed that in the initial stages of the fire, the temperature above the fire source exceeds that at the vehicle's front end. The temperature above the fire source reaches 400 °C for approximately five seconds, whereas the temperature at the vehicle's front reaches 750 °C for about ten seconds.

REFERENCES

[1] H. Li, W. Peng, X. Yang, H. Chen, J. Sun, and Q. Wang. “Full-scale experimental study on the combustion behavior of lithium ion battery pack used for electric vehicle”. *Fire technology*, vol.56, pp. 2545-2564, 2020.

[2] H. Ingason, and A. Lönnermark. “Runehamar tunnel fire tests”. *Fire Safety Journal*, vol. 71, pp. 134-149, 2015.

[3] R. Carvel, and H. Ingason. “Fires in vehicle tunnels”. *SFPE handbook of fire protection engineering*, pp. 3303-3325, 2016.

[4] R. Carvel, A. Beard, P. Jowitt, and D. Drysdale. “Variation of heat release rate with forced longitudinal ventilation for vehicle fires in tunnels”. *Fire Safety Journal*, vol. 36, no. 6, pp. 569-596, 2001.

[5] Y. Li, and H. Ingason. “The maximum ceiling gas temperature in a large tunnel fire”. *Fire Safety Journal*, vol. 48, pp. 38-48, 2012.

[6] H. Kurioka, Y. Oka, H. Satoh, and O. Sugawa. “Fire properties in near field of square fire source with longitudinal ventilation in tunnels”. *Fire Safety Journal*, vol. 38, no. 4, pp. 319-340, 2003.

[7] M. Zhong, C. Shi, L. He, J. Shi, C. Liu and X. Tian. “Smoke development in full-scale sloped long and large curved tunnel fires under natural ventilation”. *Applied Thermal Engineering*, vol. 108, pp. 857-865, 2016.

[8] B. Lou, R. Qin, H Eric, J. Qin and Z. Huang. “Influence of tunnel curvature on smoke spread in a tunnel fire”. *Journal of the Chinese Institute of Engineers*, vol. 43, no. 4, pp. 386-396, 2020.

[9] C. Caliendo, P. Ciambelli, M. De Guglielmo, M. Meo and P. Russo. “Simulation of fire scenarios due to different vehicle types with and without traffic in a bi-directional road tunnel”. *Tunnelling and Underground Space Technology*, vol. 37, pp. 22-36, 2013.

[10] F. Wang, M. Wang, R. Carvel, and Y. Wang. “Numerical study on fire smoke movement and control in curved road tunnels”. *Tunnelling and Underground Space Technology*, vol. 67, pp. 1-7, 2017.

[11] A. Dorsz, and M. Lewandowski. “Analysis of fire hazards associated with the operation of electric vehicles in enclosed structures”. *Energies*, vol. 15, no. 1, pp. 11, 2021.

[12] S. Zhang, H. Yang, Y. Yao, K. Zhu, Y. Zhou, L. Shi, and X. Cheng. “Numerical investigation of back-layering length and critical velocity in curved subway tunnels with different turning radius”. Fire Technology, vol. 53, pp. 1765-1793, 2017.

[13] L. Yuan, T. Dubaniewicz, I. Zlochower, R. Thomas, and N. Rayyan. “Experimental study on thermal runaway and vented gases of lithium-ion cells”. *Process Safety and Environmental Protection*, vol. 144, pp. 186-192, 2020..

[14] Z. Bai, H. Yao, and H. Zhang. “Experimental study on fire characteristics of cable compartment in utility tunnel with fire source at shaft side”. *Engineering Letters*, vol. 30, no. 2, pp. 806-810, 2022.

[15] Z. Bai, Y. Yu, K. Lv, H. Qin, H. Yao and C. Yang. “Experimental study on influence of natural ventilation on near wall fire in cable Tunnel”. *Engineering Letters*, vol. 31, no. 2, pp. 689-694, 2023.

[16] Z. Bai, Y. Yu, J. Zhang, H. Hu, M. Xing, and H. Yao. “Study on fire characteristics of lithium battery of new energy vehicles in a tunnel”. *Process Safety and Environmental Protection*, vol. 186, pp. 728-737, 2024.

[17] Z. Bai, H. Yao, and H. Zhang. “Experimental study on fire characteristics in cable compartment of utility tunnel with natural ventilation”. *Plos One*, vol. 17, no. 4, pp. e0266773, 2022.

[18] Z. Bai. "Burning characteristics of power cables with cone calorimeter." *Heliyon*, vol. 10, no. 3, pp. e25103, 2024.