Experimental Study on Fire Characteristics of Cable Compartment in Utility Tunnel with Fire Source at Shaft Side

Zhenpeng Bai, Haowei Yao, Huihui Zhang

Abstract—**This paper studies fire characteristics and cable layout of the cable compartment in utility tunnel. In this paper, the fire characteristics are studied by small-scale model method in cable compartment of utility tunnel. The locations of fire source have some effects on temperature distribution below the ceiling in the cable compartment of utility tunnel. During the construction of the cable compartment, and the normal operation in the cable compartment of utility tunnel, the fire source location in the cable compartment could be locates at one end close to the air supply shaft, and away from the other exhaust shaft. In addition, the effects of different fuels on cable ignition conditions are also studied in this paper. Finally, this paper mainly studies the small-scale model tests of fire characteristics in the cable compartment of utility tunnel.**

Index Terms—**Experimental study, Fire characteristics, Cable compartment, One side**

I. INTRODUCTION

When fire occurs in a tunnel, it is great dangerous [1]. In case of fire in cable compartment of utility tunnel, the smoke is difficult to diffuse vertically, and can be discharged from the vents of the shafts at both ends of the utility tunnel [2]. Therefore, the smoke tends to propagate along the longitudinal direction in cable compartment. Usually, a small fire in cable compartment leads to a huge disaster [3]. In case of fire, with the ventilation velocity and heat release rate (HRR) varies, the temperature field in cable compartment changes, and the temperature distribution also changes with the passage of time [4].

Previous studies have used numerical simulation methods to study fire characteristics in tunnels [5]. Zhao et al. [6] proposed a simplified model of jet behavior below the ceiling in tunnel. The model was verified by numerical calculation. For the radial expansion zone, the Alpert equation was simplified, and a simplified solution was obtained. Ji et al. [7] studied the influence of tunnel aspect ratio on smoke temperature distribution below the ceiling of the fire source area. The results showed that the tunnel width have little effect on the smoke mass loss rate and the maximum smoke temperature below the ceiling, but the tunnel width has a significant effect on the smoke temperature distribution. Vaquelin and Van et al. [8][9] found that the critical ventilation velocity related to tunnel width in computational fluid dynamics (CFD) [10]. However, for the simulation of the cable compartment in utility tunnel, a large number of grids are required to be established, and the simulation time is long.

In the past few years, a series of fire experimental tests in cable rooms have increased significantly after fatal tunnel fires in Europe. Different from the small-scale and large-scale experimental tests, the memorial tunnel experiments showed that the experimental measurement results in the far-field of the fire source were consistent with the experimental measurement results [11-13]. Fan [14] conducted an experimental study in a 1:20 model tunnel, studied the flame length integral model considering the influence of tunnel section and ventilation velocity under the conditions of large HRR near the fire source, which proposed the dimensionless ventilation velocity from considering the hydraulic diameter of the tunnel. Through a series of fire experiments, Jiang [15] studied the phenomenon of the central smoke exhaust system of the tunnel through a series of fire experiments, measured the smoke height, analyzed smoke temperature and flow rate of the smoke layer under the smoke exhaust. In addition, Kurioka [16] [17] conducted experiments on three 1/10, 1/2, full-size model tunnels, rectangular and horseshoe sections, and used square fire sources as model fire sources to study the tunnel section aspect ratio, HRR and longitudinal forced ventilation velocity changes. Kurioka pointed out that the smoke diffusion process could be divided into four stages, which were plume rising stage, radial diffusion stage, transition stage and horizontal diffusion stage. The first three stages were located near the fire source area. In summary, in previous studies, CFD simulation method is a very effective tool analyze the laws of fluid movement [18-20].

The ventilation in the utility tunnel has been studied previously. Curiel et al. [21] studied the ventilation in utility tunnel to reduce the harm of air pollution and provided a safe and healthy environment. Legrand et al. [22] proposed a multi standard method to make the utility tunnel safer and more sustainable, and studied the impact of the drainage network location on the total cost of the utility tunnel. However, there are some problems in the study of fire characteristics in cable compartment of utility tunnel. Firstly, the fire source types are linear and square in the cable compartment of utility tunnel. There are some differences in the temperature

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distribution in the cable compartment. Secondly, the location of cable fire in cable compartment of utility tunnel could be located at one end near the shaft. Different longitudinal positions of fire sources have different effects on the development of cable fires. Thirdly, the constant temperature alarm device is adopted in cable compartment of utility tunnel. After reaching the set alarm temperature, the air supply and exhaust ports of the cable compartment are closed to form a closed space. In this case, the fire characteristic of cable compartment are different.

In this paper, the longitudinal fire source location is studied in cable compartment of utility tunnel. Three square oil pools and three linear oil pools are used to study the temperature distribution characteristics at the initial stage of fire in cable compartment of utility tunnel. Secondly, when the fire source is located at one end of the cable compartment shaft, the influence of near-wall fire on the temperature distribution in cable compartment of the utility tunnel is studied. In this paper, 57 ℃ is used as the alarm temperature. When the temperature is at 0.5 m away from the fire source shows that the temperature reaches 57°C, it immediately closes the air supply outlet and exhaust outlet of cable compartment, form a closed space in the cable compartment, and observe the development fire characteristics. This paper can supplement the existing fire protection design scheme in the design code, and has certain guiding significance for the early fire protection of the cable compartment in urban utility tunnel.

II. METHOD

A. *Physical Model and Fire Scenario*

The size of full-scale model utility tunnel is 36 m × 2.4 m × 3.0 m. In this paper, it uses the method of small-scale model experimenal tests to study fire characteristics. The small size of cable compartment platform is 6.0 m × 0.4 m × 0.5 m (Length × Width × High). The experimental platform is 0.5 m above the ground. It is supported by a steel frame. The model scale is 1:6. As shown in Fig 1, it clearly shows the physical model.

Fig 1. Physical model of cable compartment in utility tunnel.

As shown in Table 1, longitudinal ventilation is used in cable compartment of utility tunnel. The exhaust fan, supply fan, exhaust outlet and air supply outlet shall be adjusted according to the actual situation. The exhaust outlet and air supply outlet are half opened. In these cases, the ventilation velocity is measured by the anemometer in cable compartment of utility tunnel.

TABLE 1
CABLE COMPARTMENT FIRE SIMULATION CASE

No.	Exhaust fan	Air inlet fan	Exhaust outlet	Air supply outlet
FS1	√	×	√	√
FS2	√	×	◐	√
FS3	√	×	◐	◐
FS4	×	√	◐	◐
FS5	×	√	√	◐
FS6	×	√	√	√
FS7	√	√	√	√
FS8	√	√	◐	√
FS9	√	√	◐	◐
Remarks	√ : Open; ×: Closed; ◐: Half open and half closed.			

The setting of fire scene can be divided into two situations. In cases 1 ~ 15, the fire source is located at one end of the cable compartment, 0.8 m away from the end wall of the air supply shaft. The oil pool is placed on the electronic balance. The fire source height is 0.13 m. Ventilation are not used in cases 1 ~ 6. And there are 9 ventilation conditions in cases 7 ~ 15. As shown in Table 2, it can be seen that there are different ventilation modes in the tests of cable compartment. In this paper, there are 15 cases of fire experimental tests are carried out in cable compartment of utility tunnel.

TABLE 2
CABLE COMPARTMENT FIRE EXPERIMENTAL STUDY CASES

Case	Fire source height (m)	Fuel quantity (ml)	Oil pool type (cm)	Ventilation
1	0.13	168	9.2×9.2	——
2	0.13	84	13×13	——
3	0.13	42	18.3×18.3	——
4	0.13	42	4×21	——
5	0.13	42	2×42	——
6	0.13	42	4×42	——
7	0.13	42	9.2×9.2	FS1
8	0.13	42	9.2×9.2	FS2
9	0.13	42	9.2×9.2	FS3
10	0.13	42	13×13	FS4
11	0.13	42	13×13	FS5
12	0.13	42	13×13	FS6
13	0.13	42	18.3×18.3	FS7
14	0.13	42	18.3×18.3	FS8
15	0.13	42	18.3×18.3	FS9

The fire source is 0.8 m away from the side of the air supply shaft in the utility tunnel. The fuel is n-heptane. Axial fan is selected. The fan type is eg-2.5a-2. The voltage is 220 V. The flow rate is 1200 ~ 1740 m^3 /h. The rotating speed is 2800 r/min. The total pressure of the fan is 168 ~ 126 Pa. Cable types are flame retardant XLPE sheathed PVC insulated cable ZRYJV and RVVR. The number of cores of flame retardant cable ZRYJV is 2. The area is 10 mm^2. The number of cores of flame retardant cable RVVR is 1, The area is 10 mm^2.

A total of 53 thermocouples are arranged in cable compartment of utility tunnel. Among them, 14 thermocouples are arranged on the longitudinal center line, 21 thermocouples are arranged below the ceiling, and 18 thermocouples are arranged on one side. In addition, there are 13 ventilation speed measurement points. There are 8 ventilation speed measurement points below the ceiling. There are 2 ventilation speed measurement points on both sides. There are 3 ventilation speed measurement points on the other side wall.

B. Theoretical Analysis

In order to predict the HRR of fire source, the HRR measured in the experimental tests should be calculated as follows:

$$\dot{Q}=Q_{burner}+Q_{cable} \tag{1}$$

where, Q_{burner} and Q_{cable} are ignition HRR and cable HRR, respectively.

YASUSHI OKA [23] proposed that the time difference in the process of smoke transportation is not considered. Plumes and ceiling jets have different temperature decay characteristics. The HRR can be calculated according to the following equation (2).

$$\dot{Q}=[\frac{\Delta T_{dp}}{4.73T_{\infty}}(c_p\rho T\sqrt{g})^{2/3}H_{ef}^{5/3}(0.6+\frac{r}{H})^{4/3}]^{3/2} \tag{2}$$

where, ΔT_{dp} is below the ceiling temperature in cable compartment of utility tunnel, T_{∞} is the ambient temperature in cable compartment, c_p is the constant pressure specific heat capacity.

For the experimental test case where fire occurs near the side wall in cable compartment of utility tunnel. Equation (2) can be modified using the mirror model equation (3) proposed by Zukosi [24].

$$\dot{Q}=[\frac{\Delta T_{dp}}{4.73\times\vartheta\times T_{\infty}}(c_p\rho T\sqrt{g})^{2/3}H_{ef}^{5/3}(0.6+\frac{r}{H})^{4/3}]^{3/2} \tag{3}$$

where, ϑ=1.59.

III. Results And Discussions

Under the condition of mechanical ventilation, the critical ventilation velocity upstream of the fire source exacerbates the mixing of the air layer downstream of the cable compartment of utility tunnel. It contributes to the rapid and full development of the downstream flow field. However, without ventilation, the distance to steady state in the cable compartment was long. The fire characteristics of the cable compartment of natural ventilation and longitudinal ventilation were studied respectively.

A. Influence of Natural Ventilation

The fire source was located at the end of the cable compartment in the utility tunnel. It was close to the air inlet shaft and 0.8 m away from the end of the cable compartment in utility tunnel. In cases 1 ~ 6, the mass loss rate of six oil pools were tested using three square oil pools and three linear oil pools. Thermocouples record the corresponding temperature distribution below the ceiling of the cable compartment in utility tunnel.

As shown in Fig 2, in cases 1-6, the temperature at X = 0.2 m in the cable compartment of utility tunnel varies with time. In case 1, the duration time was the longest, and the maximum temperature reached about 200 °C. The reason was that there are multiple fuels in case 1. In case 1, the amount of fuel was 84 ml. In the case of three square oil pools burning, the ceiling temperature of the cable compartment was higher than that of the three linear oil pools. This is because the square oil pool opening has a larger surface area, better contact with air, and a larger HRR.

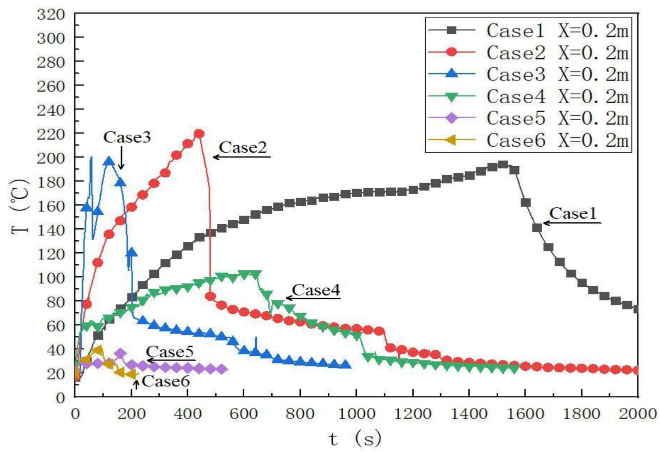

Fig 2. Temperature change with time at X = 0.2 m in case 1 ~ 6 in cable compartment of utility tunnel.

The HRR of the n-heptane pool fire was calculated from the mass loss rate in the quasi-stable combustion stage, as shown in equation (4).

$$\dot{Q}=\chi\dot{m}\Delta H \tag{4}$$

Where, χ is combustion efficiency, $\dot{m}$ is mass loss rate, ΔH is n-heptane combustion calorific value 29.7 MJ/kg. The combustion efficiency of n-heptane combustion is close to 1. In this paper, the HRR of small and medium-sized test ranges from 0.440 kW to 14.044 kW.

As shown in Fig 3, in cases 1 ~ 6, the average HRRs of the three square oil pools were 9.2 × 9.2 cm, 13 × 13 cm, and 18.3 × 18.3 cm, respectively, and the average HRRs of fire source were 2.214 kW, 3.905 kW and 5.779 kW respectively. The three linear oil pools are 4 × 21 cm, 2 × 42 cm, and 4 × 42 cm. Three linear oil pools were selected as the ignition source, and their average HRRs were 1.324 kW, 1.026 kW and 1.816 kW respectively.

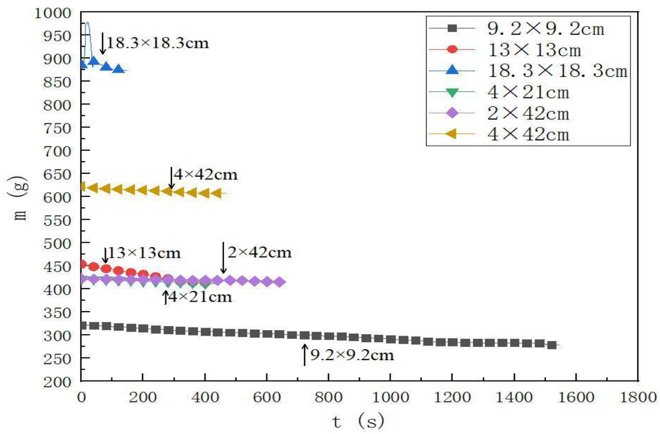

Fig 3. Time dependent combustion quality of six types of oil pool in cable compartment of utility tunnel

The burning time of the six oil pools in the cable compartment of utility tunnel is different. The burning times were 1545 s, 438 s, 148 s, 646 s, 834 s and 471 s, respectively, and the burning times of the six types of oil pools were 9.2 × 9.2 cm、13 × 13cm、18.3 × 18.3cm、4 × 21cm、2 × 42 cm and 4 ×42 cm. The more n-heptane fuel, the longer the burn time. When the amount of n-heptane fuel was the same, the larger the size of the oil pool, the shorter the combustion duration.

The combustion efficiencies of the six types of oil pools were 9.2 × 9.2 cm、13 × 13 cm、18.3 × 18.3 cm、4 × 21 cm 、 2 × 42 cm and 4 × 42 cm, and the combustion efficiencies of the six types of oil pools were 0.000352, 0.001295, 0.000171, 0.000903, 0.000171 and 0.000164 respectively.

When the temperature indicator was 0.5 m away from the fire source, the burning time was set as the alarm time. The alarm temperature of the detector below the ceiling of the cable compartment of the utility tunnel was 57 ℃. The six types of oil pools are 9.2 × 9.2 cm、13 × 13 cm、18.3 × 18.3 cm、4 × 21 cm、2 × 42 cm and 4 ×42 cm, and the alarm times were 86 s, 36 s, 12 s, 188 s, 582 s and 198 s respectively.

According to the temperature at 0.5 m away from the fire source, the predicted HRRs of the fire source were 9.2 × 9.2 cm, 13 × 13 cm and 18.3 ×18.3 cm. The predicted average HRRs for the three square oil pools are 3.870 kW, 5.486 kW and 7.412 kW respectively. The three linear oil pools were 4 × 21 cm, 2 × 42 cm and 4 ×42 cm, and the average HRR of the fire source are 2.211 kW, 1.309 kW and 2.339 kW respectively. The average HRR predicted from the fire source based on the temperature at a distance of 0.5 m from the fire source is higher than the HRR calculated from the actual oil pools. However, the overall HRR differences were small, and the relative errors were within reasonable limits.

B. *Influence of Longitudinal Ventilation*

In the cable compartment of the utility tunnel, the effect of longitudinal ventilation with n-heptane as fuel on nine oil pools was studied. First, the distribution of longitudinal ventilation velocity was measured. The results showed that the longitudinal distribution of ventilation velocity in the cable compartment of utility tunnel was completely different in cases 7 ~ 15. As shown in Fig 4, the ventilation velocity distribution was displayed at different positions in the cable compartment of utility tunnel.

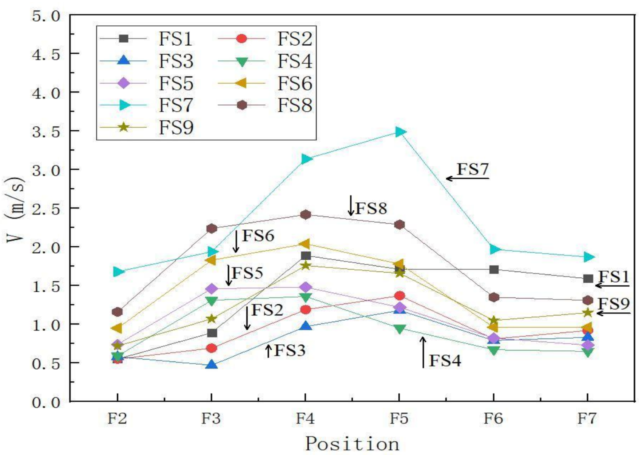

Fig 4. Ventilationspeed changes at different positions in the cable compartment of utility tunnel

In the cable compartment the of utility tunnel, the effect of longitudinal ventilation on the temperature below the ceiling was studied. There are nine different ventilation cases (cases 7 ~ 15), and the temperature below the ceiling is different that in the cable compartment of utility tunnel. As shown in Fig 5, in 9.2 × 9.2 cm, 13 × 13 cm and 18.3 ×18.3 cm, there were three oil pools under different ventilation conditions. The temperature change trend below the ceiling of the cable compartment of utility tunnel was basically the same. The n-heptane fuel in cases 7 ~ 15 was 42 ml. The type of oil pool was 9.2 × 9.2 cm, the corresponding ventilation are shown in cases 7, case 8 and case 9 were FS1, FS2 and FS3 respectively. The oil pool type was 13 × 13 cm, the corresponding ventilation conditions were FS4, FS5 and FS6 in cases 10, 11 and 12 respectively. The type of oil pool was 18.3 × 18.3 cm, corresponding ventilation conditions were FS7, FS8 and FS9 in cases 13, 14 and 15 were respectively.

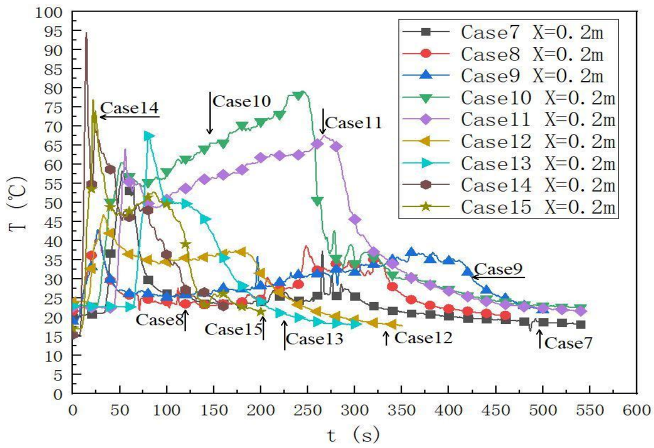

Fig 5. Temperature change with time at X = 0.2m in case 7 ~ 15 in cable compartment of utility tunnel

According to the type of oil pool type and the effect of longitudinal ventilation, the burning time of fire source and the combustion efficiency of the oil pool were summarized, as shown in Table 3. As shown in Table 3, the combustion duration and oil pool combustion efficiency were listed in cases 1 ~ 15.

TABLE 3
CABLE COMPARTMENT FIRE EXPERIMENTAL RESULTS IN CASES 1-15

Case	Mass before combustion (g)	Mass after combustion (g)	Total duration of combustion (s)	oil pool combustion efficiency ($g/(cm^2 \cdot s)$)
1	931.5	885.5	1545	1545
2	1403.5	1355.5	438	438
3	2352	2343.5	148	148
4	1231.5	1182.5	646	646
5	1753.5	1741.5	834	834
6	2122	2109.0	471	471
7	1020	981.0	270	270
8	1033.5	988.0	379	379
9	1029	994.5	415	415
10	1372.5	1334.0	227	227
11	1367	1312.5	238	238
12	1371	1303.5	179	179
13	2360.5	2322.0	105	105
14	2406	2332	110	110
15	2339.5	2337.5	118	118

Fig 6 shows the predicted value of the total HRR of the fire source under the condition of longitudinal ventilation in cable compartment of utility tunnel. According to the actual burning time in the test, the combustion time in cases 7 ~ 15 was calculated. This paper uses the temperature prediction equation (3) to calculate the predicted value of total HRR of fire source. The predicted value of the total HRR of the fire source in cases 7 ~ 15 was calculated based on the temperature 0.5 m away from the fire source. It can be seen from the Fig 6, the ignition source combustion can be divided into three stages, namely, the initial development stage, the complete combustion stage and the decay stage. The HRR of the fire source is different from cases 7 to 15, because the HRR of the fire source is affected by the type and size of the oil pool, the ventilation velocity, and the combustion efficiency of the oil pool. Even in the same mass of n-heptane fuel, the HRR is different.

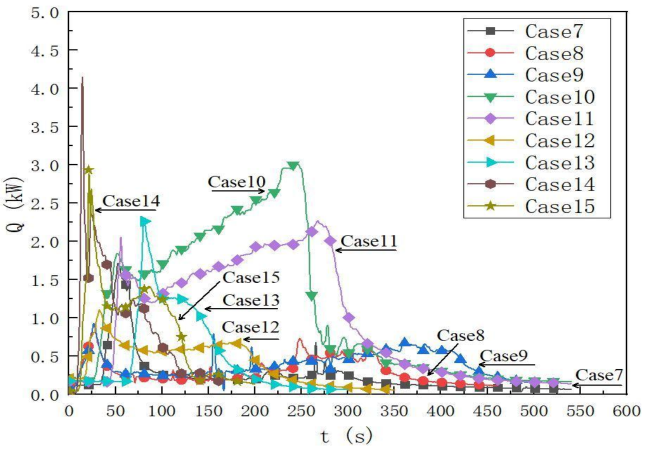

Fig 6. Total HRR in case 7 ~ 15 fire source under longitudinal ventilation in cable compartment of utility tunnel

In this paper, the temperature and HRR of the cable compartment of the utility tunnel are studied. Natural ventilation and longitudinal ventilation are considered. Through experimental tests, the fire characteristics of cable compartment of the utility tunnel are studied when the fire source is arranged on one side of the shaft. It is of great significance to test and study the fire characteristic of the cable compartment the of utility tunnel.

IV. Conclusions

When the temperature below the ceiling is 57 ℃ away from the fire source, the air supply outlet and exhaust outlet are closed. The cable compartment changes the closed state of the interior space so that it is not affected by natural ventilation. This paper mainly studies the fire characteristics of natural ventilation and longitudinal ventilation in the cable compartment of the utility tunnel. The combustion mass loss rates of six types unvented oil pools at a distance of 0.8 m from the end side of the air supply shaft was studied. The main conclusions are as follows:

Under nine different ventilation modes, the effect of ventilation velocity on the temperature distribution below the ceiling of cable compartment of the utility tunnel is different. In a cable compartment of utility tunnel fire, the fire temperature distribution and total HRR varied with the type of oil pool, ventilation velocity and fuel volume.

References

[1] Wu Y, Bakar M Z A. Control of smoke flow in tunnel fires using longitudinal ventilation systems–a study of the critical velocity. *Fire Safety Journal*, 2000, 35(4): 363-390.

[2] Gao R, Li A, Lei W, et al. Study of a proposed tunnel evacuation passageway formed by opposite-double air curtain ventilation. *Safety science*, 2012, 50(7): 1549-1557.

[3] Carvel R O, Beard A N, Jowitt P W. The influence of longitudinal ventilation systems on fires in tunnels. *Tunnelling and Underground Space Technology*, 2001, 16(1): 3-21.

[4] Bari S, Naser J. Simulation of smoke from a burning vehicle and pollution levels caused by traffic jam in a road tunnel. *Tunnelling and Underground Space Technology*, 2005, 20(3): 281-290.

[5] Migoya E, Crespo A, Garcı J, et al. A simplified model of fires in road tunnels. Comparison with three-dimensional models and full-scale measurements. *Tunnelling and Underground Space Technology*, 2009, 24(1): 37-52.

[6] Zhao W, Zong R, Wei T, et al. The physical model and validation study of ceiling-jet flow in near-field of corridor fires[J]. International Journal of Heat and Mass Transfer, 2015, 88: 91-100.

[7] Ji J, Bi Y, Venkatasubbaiah K, et al. Influence of aspect ratio of tunnel on smoke temperature distribution under ceiling in near field of fire source[J]. Applied Thermal Engineering, 2016, 106: 1094-1102.

[8] Vauquelin O, Wu Y. Influence of tunnel width on longitudinal smoke control. *Fire Safety Journal*, 2006, 41(6): 420-426.

[9] Van Maele K, Merci B. Application of RANS and LES field simulations to predict the critical ventilation velocity in longitudinally ventilated horizontal tunnels. *Fire Safety Journal*, 2008, 43(8): 598-609.

[10] Li Y Z, Ingason H. The maximum ceiling gas temperature in a large tunnel fire. *Fire safety journal*, 2012, 48: 38-48.

[11] Steckler K D, Baum H R, Quintiere J G. Fire induced flows through room openings-flow coefficients //*Symposium (International) on Combustion*. Elsevier, 1985, 20(1): 1591-1600.

[12] Migoya E, Crespo A, Garcı J, et al. A simplified model of fires in road tunnels. Comparison with three-dimensional models and full-scale measurements. *Tunnelling and Underground Space Technology*, 2009, 24(1): 37-52.

[13] Colella F, Rein G, Verda V, et al. Multiscale modeling of transient flows from fire and ventilation in long tunnels. *Computers & Fluids*, 2011, 51(1): 16-29.

[14] Fan C G, Yang J, Li M H. A theoretical and experimental study of flame length under a tunnel ceiling[J]. Journal of Thermal Analysis and Calorimetry, 2017, 128(2): 1143-1149.

[15] Jiang X, Liao X, Chen S, et al. An experimental study on plug-holing in tunnel fire with central smoke extraction[J]. Applied Thermal Engineering, 2018, 138: 840-848.

[16] Kurioka H, Oka Y, Satoh H, et al. Properties of plume and near fire source in horizontally long and narrow spaces[J]. Journal of Structural and Construction Engineering, 2001 (546): 151-156.

[17] Kurioka H, Oka Y, Satoh H, et al. Fire properties in near field of square fire source with longitudinal ventilation in tunnels[J]. Fire safety journal, 2003, 38(4): 319-340.

[18] Fan Y, Cheung L K, Chong M M, et al. Computational Fluid Dynamics Analysis on the Upper Airways of Obstructive Sleep Apnea Using Patient- Specific Models. IAENG International Journal of Computer Science, 2011, 38(4): 401-408.

[19] Suebyat K, Pochai N. A numerical simulation of a three-dimensional air quality model in an area under a Bangkok sky train platform using an explicit finite difference scheme. IAENG International Journal of Applied Mathematics, 2017, 47(4): 471-476.

[20] Haelterman R, Bogaers A, Degroote J, et al. Quasi-Newton methods for the acceleration of multi-physics codes. International Journal of Applied Mathematics, 2017, 47(3): 352-360.

[21] CURIEL-ESPARZA J, CANTO-PERELLO J. Indoor atmosphere hazard identification in person entry urban utility tunnels[J]. Tunnelling and Underground Space Technology, 2005, 20(5): 426-434.

[22] LEGRAND L, BLANPAIN O, BUYLE-BODIN F. Promoting the urban utilities tunnel technique using a decision-making approach[J]. Tunnelling and Underground Space Technology, 2004, 19(1): 79-83.

[23] Nitta K , Oka Y , Yamaguchi J , et al. Prediction of heat release rate based on ceiling jet temperature in case of time-dependent fire[J]. Fire Safety Science, 2008, 9(3):813-824.

[24] E.E. Zukoski, Properties of Fire Plumes, in: G. Cox (Ed.), Combustion Fundamentals of Fire, Academic Press, London, 1995, pp. 101-220.