Numerical Simulation Study on Ventilation Effect in Utility Tunnel

Zhenpeng Bai, Xiaohan Zhao, Huaitao Song, Hengjie Qin, Yang Zhang, Haowei Yao

***Abstract*—Urban utility tunnels have developed rapidly in recent years. The effective ventilation system maintains the air quality of the utility tunnel. In order to improve the ventilation performance of utility tunnel, a three-dimensional model of utility tunnel was established according to the design drawings. Based on Fluent 14.0 software, a flow model was established. And numerical simulation methods were used to study the optimization of air ducts and ventilation methods. The utility tunnel used top ventilation and interlayer ventilation. The ventilation methods of different ventilation areas of urban utility tunnels are compared. The results showed that the combination of operational gain and ventilation zone length mainly affected the ventilation effect. Based on the simulation results, a comprehensive ventilation mode consisting of top ventilation, natural ventilation at 400 m long entrance and mechanical outlet exhaust was proposed. Electric valve, fire door, exhaust fan and induction fan could be opened in the urban public utility tunnel at low speed. This new combination method is considered the optimal combination method for the maximum ventilation speed of urban utility tunnels.**

***Index Terms*—Utility tunnel, Ventilation, Numerical simulation, Optimization**

I. INTRODUCTION

The utility tunnels are the underground infrastructure of cities [1]. It contains various pipelines such as communication, electricity, heating, and hydraulic . Compared to traditional pipeline laying, utility tunnels repeatedly excavate the road surface. The maintenance of municipal pipelines in utility tunnels is very convenient. With the development of cities, urban roads are becoming increasingly scarce and pipeline layouts are becoming more complex. The utility tunnel is an important facility to ensure the operation of urban pipelines. In the absence of ventilation conditions, the temperature and humidity of utility tunnels are relatively high [1]. In order to improve air quality in utility tunnels, it is necessary to evaluate and implement ventilation strategies to improve ventilation in urban utility tunnels.

Many studies have focused on the safety of utility tunnels, and previous studies have used software to optimize ventilation systems for modeling [2]. Jin et al. [3] established a 1/36 scale highway tunnel model as a natural ventilation experimental platform system. They measured the distribution of wind speed at the opening, and analyzed the hourly characteristics and ventilation speed. Chasse´ [4] conducted a three-dimensional natural ventilation tunnel. J. Kunsch et al. [5] derived an expression that considers the effect of the aspect ratio of the tunnel cross section on the critical ventilation velocity. Ren et al [6] studied the measurement and progress of dust inhalation control strategies in mine ventilation systems. Torano et al [7] demonstrated the necessity of analyzing dust behavior in assisted ventilation systems by computational fluid dynamics (CFD). The ventilation mode control strategy was very specific. Improper design, the ventilation effect was not very good. Therefore, it might worsen the ventilation effects under harsh conditions.

Generally, the most unfavorable ventilation conditions occur in the utility tunnels. It is necessary to control the underground environment. Therefore, it is important to use a method to address this problem. Therefore, the system needs to consider all ventilation parameters to address efficiency, health, and safety issues simultaneously. However, the association is often overlooked. The ventilation design of the utility tunnel is an important aspect of the tunnel design. It plays a fundamental role in two situations. First, under normal working conditions, ventilation can reduce the concentration of smoke and polluted air in the tunnel. Second, in emergency situations, the role of ventilation is to eliminate smoke and achieve safe evacuation and activities [8]. The ventilation design focuses on the shape and length of the tunnel. Attention should be paid to the local weather conditions and the surrounding environment. The toxic gas discharged from the natural gas pipeline flows into the utility tunnel [9].

Ventilation usually consists of various forms and combinations of natural ventilation and mechanical

Manuscript received May 15, 2023; revised April 6, 2024. This work was supported by the Key R&D and Promotion Special Project (Science and Technology Research) in Henan Province (242102240096, 232102321094, 242102321104, 242102241051), Natural Science Foundation of Henan Province (232300420314), the Key Scientific Research Project Plan of Colleges and Universities in Henan Province (23B560003), Doctor Scientific Research Fund of Zhengzhou University of Light Industry (2021BSJJ048), Henan Province Central Leading Local Science and Technology Development Fund Project (Z20231811020), Zhengzhou University of Light Industry Science and Technology Innovation Team Support Program Project (23XNKJTD0305), Henan Province Key R&D Special Project (231111322200).

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ventilation [10]. According to the ventilation methods of utility tunnels, the ventilation methods are generally divided into horizontal ventilation, semi horizontal ventilation, and vertical ventilation [11]. Most ventilation shaft systems have many drawbacks. The utility tunnel requires a high vertical shaft and separates the main space of the tunnel section into an air duct. Therefore, large-scale projects may incur significant costs during use. In recent years, longitudinal ventilation has been applied in long tunnels in developed countries such as Japan and Germany [12]. In longitudinal ventilation, in order to close the tunnel, circulating air is formed at the entrance of the tunnel. This mixing directly reduces the efficiency of ventilation shafts and increases their operating costs [13]. This is an urgent issue that needs to be addressed in the ventilation design and engineering of utility tunnels. Therefore, it is necessary to study the air mixing problem inside utility tunnels in order to reveal the causes and behaviors of circulating air in utility tunnels. It is necessary to propose effective improvement measures.

In recent decades, with the rapid development of utility tunnel construction, research on ventilation shafts in public engineering tunnels has become unprecedentedly popular [14]. The research technology for ventilation in utility tunnels mainly includes theoretical analysis, numerical simulation, program design, scaled down model experiments, and on-site measurements. The one-dimensional conventional calculation theory of longitudinal ventilation in tunnels has been fundamentally improved. The theoretical basis includes continuity equations, momentum equations, and energy equations. The dynamic calculation of longitudinal ventilation is quite complex. It requires experimental research and simulation analysis. In recent years, ventilation shaft engineers from around the world have been dedicated to the calculation and programming of vertical ventilation. Previous studies have discussed various optimization models [15]. However, further research is needed on the different application performance of CFD in public ventilation shafts. The concept of ventilation rate has been introduced as a ventilation indicator for utility tunnel environments. It is used to characterize air freshness, representing the ratio of tunnel air volume to tunnel space volume.

In previous studies, most studies have overlooked the issue of different schemes for utility tunnels under ventilation methods. However, design methods may affect ventilation effectiveness. To overcome these shortcomings, this paper proposes several cases to simulate the full-scale actual tunnel model of ventilation paper. This paper compares the ventilation effects of hydraulic trench, thermal compartment, and electrical compartment. The numerical simulation used two modes, namely top ventilation and interlayer ventilation. A three-dimensional physical model was established and analyzed through numerical simulation. Compared with the different ventilation modes, the ventilation effect of the electrical compartment is the most unfavorable. Based on the simulation results of the ventilation shaft in the utility tunnel, it is recommended to use mechanical ventilation and induction fans. It calculates the average air velocity at the cross-section. This paper compares the ventilation capacity and the hourly air change capacity under different operating conditions.

II. METHOD

A. *Physical Model*

A series of typical utility tunnels were selected as the research models for China, as shown in Figs. 1~2. It selected the size results of utility tunnels based on typical values applied in actual projects. Ventilation method used top ventilation. The utility tunnel used four ventilation methods. The first model was a 200 m long electrical compartment without mechanical ventilation. The second model was a 200 m long electrical compartment with an induction fan; The third model was a 400 m long electrical compartment without mechanical ventilation. The fourth model was a 400 m long electrical compartment with an induction fan. The utility tunnel was 400 m long, 3 m high, and 2 m wide. The top ventilation consisted of three compartments, which was one of the common ventilation systems in utility tunnels. Floor ventilation was a ventilation system shared by three compartments.

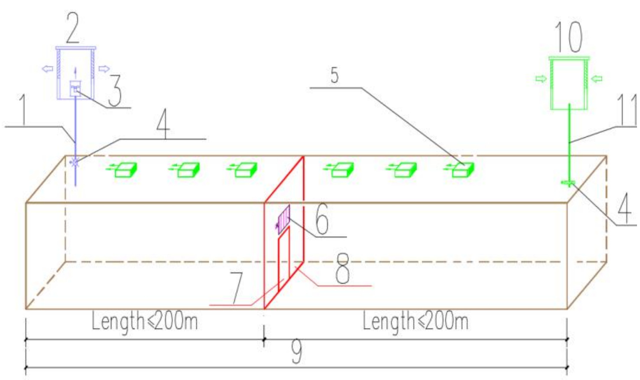

Fig. 1. Ventilation mode of the electrical compartment with 400 m length
1. Air outflow. 2. Exhaust duct 3. Air exhausting fan. 4. Motorized valve 5. Inductive fan 6. Motorized valve . 7. Fire proof door 8. Firewall 9. Ventilation zone10. Air inflow 11. Air inlet duct

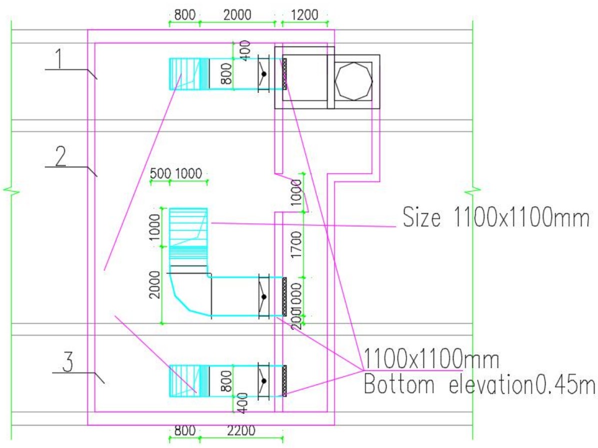

Fig. 2. Ventilation mode with 3 compartments in utility tunnel of 200 m length
1. hydraulic trench. 2. thermal compartment 3. electrical compartment

The hydraulic , hot water room, and electrical room shared a common ventilation system. The fourth mode option was 200 m long, 3 m high, and 9 m wide. Model one included four ventilation options. Option one was a 200 m long ventilation partition without an induction fan in the utility tunnel. Option two was a 400 m long ventilation partition, including an electric valve and a fire door in the middle of the tunnel. Option three was a 200 m long ventilation partition with an induction fan. Option four was a 400 m ventilation zone, which included electric dampers, fire doors, and induction fans. The distance between induction fans was 22 m. As shown in Fig. 2, Model two was a 200 m long ventilation partition without an induction fan. The air flowing into the utility tunnel was the general air flowing into the hydraulic trench, thermal compartment, and electrical compartment.

This numerical simulation method was implemented using the commercial CFD program ANSYS Fluent 14.0, which solved the control equations. The SIMPLE algorithm was used to solve the coupling problem of velocity and pressure [16]. The momentum equation, energy equation, and turbulent momentum dissipation rate equation were all second-order upwind dispersion schemes. The turbulence effect used achievable with standard wall functions $k-\varepsilon$ model in the simulation .

B. Boundary conditions

The ambient air pressure was 101325 Pa. The inlet boundary condition was the velocity inlet. The outlet boundary condition was the pressure outlet. The natural intake speed was 0 m/s. The fan airflow was 2400 m^3/h, 4800 m^3/h and 14400 m^3/h. The wind speeds for mechanical ventilation were set to 2.67 m/s, 5.33 m/s, and 16 m/s. The wind speed of the induction fan was 3.83 m/s. The ventilation velocity did not slide on the tunnel wall. Different ventilation systems were used to create different simulation cases in utility tunnels. In contrast, the main difference was that the induction fan operates at high or low speeds. The detailed boundary conditions were shown in Tables 1 and 2. In cases 1~4, the length of the cable compartment was 200 m, and the outlet flow was mechanically ventilation. In cases 5~12, the length of the cable compartment was 400 m, and the outlet air was mechanically ventilation.

TABLE 1 SIMULATION CONDITIONS OF ELECTRICAL COMPARTMENT VENTILATION PARTITIONS WITH 200M.

Case	Air inflow	Inductive fan	Air changes	Fan capacity (m^3/h)
1	Natural ventilation	No	2	2400
2	Mechanical ventilation	No	2	2400
3	Natural ventilation	Yes	2	2400
4	Mechanical ventilation	Yes	2	2400
5	Natural ventilation	No	2	4800
6	Natural ventilation	No	6	14400
7	Mechanical ventilation	No	2	4800
8	Mechanical ventilation	No	6	14400
9	Natural ventilation	Yes	2	4800
10	Natural ventilation	Yes	6	14400
11	Mechanical ventilation	Yes	2	4800
12	Mechanical ventilation	Yes	6	14400

The enclosure structure of the utility tunnel was a concrete structure. Heat dissipation was mainly studied in summer. The ambient temperature was 20 ℃. In the electrical room, when normal and unexpected ventilation was met, the cables and surrounding soil eliminated heat dissipation. This utility model simplified the heat source. Ventilation rate was required to eliminate total heat dissipation, which was calculated for electrical compartments. It explored a more reasonable ventilation method for electrical compartments by analyzing the ventilation effects under different ventilation methods. Future research may provide ignition sources for utility tunnels. This paper only focused on the selection of ventilation modes [17].

As shown in Table 2, a numerical simulation example of a 200 m long utility tunnel was provided. The main difference in each case lied in the selection of air supply mode and fan capacity. There was no induction fan.

TABLE 2 THE VENTILATION PARTITIONS WITH 200M LONG UTILITY TUNNEL SIMULATED CASES.

Case	Ventilation	Compartment	Width (m)	Fan capacity (m^3/h)
13	Natural ventilation	Electric compartment	2	2400
		Thermal compartment	5	6000
		Hydraulic trench	2	2400
14	Mechanical ventilation	Electric compartment	2	2400
		Thermal compartment	5	6000
		Hydraulic trench	2	2400

The physical model generated a grid using ANSYS software. A 200 m long electrical compartment was used in cases 1 ~ 4. In cases 5 ~ 12, it used a 400 m long electrical compartment. The 400 m long electrical compartment included an induction fan scheme. The grid was generated for a 200 m long utility tunnel, which included hydraulic trench, thermal compartment, and electrical compartment. In order to avoid the influence of grid size on numerical results and verify the independence of the grid, this paper used a calculation grid of 1.36×10^6 for a 200 m long utility tunnel. The grid quantity of a 400 m long utility tunnel was 2.4×10^6.

The unstructured tetrahedral mesh in commercial software ICEM 14.0 was used in the field of decentralized computing. To test grid independence, check the grid quality in ICEM and the grid convergence index of all utility tunnels [18,19]. In all cases, the method of controlling the overall grid quality and grid convergence index is similar. Convergence was achieved with the residuals of the continuity equation less than 1×10^{-6} . The results showed that the numerical model had good accuracy and reliability. Therefore, this numerical model was suitable for predicting air velocity in utility tunnels. By comparing different simulation speeds under different cases, it can be seen that the simulation results under different cases were in good agreement. Thus, the current numerical model was accurate enough to predict the velocity contour lines in the utility tunnels.

According to the fire partition of the tunnel, the electrical compartments of the utility tunnel were equipped with several independent mechanical ventilation systems. In order to eliminate the residual and humid air in the heated electrical compartment, the smoke and dust were discharged into outdoors through the shaft [20-25]. The vertical shaft air supply (natural air) was introduced from outside, and the exhaust fan was installed in a separate dedicated space. The exhaust fan was a two-speed fan, usually running at low speed to meet the requirements of 2 times/h exhaust air. After the accident, it operated at high speed to meet the emergency ventilation requirements of 6 times/h. The ventilation amount required to eliminate waste heat from utility tunnels was less than the design ventilation amount. The ventilation amount was designed based on the actual ventilation amount [15]. The ventilation rate was determined by calculating the section size and ventilation rate. The ventilation volume was calculated according to Eq. (1).

$$Q=V*N*\phi \quad (1)$$

Where, Q is the ventilation quantity, m^3/h. V is the ventilation partition volume, m^3. N is the air changes, times/h. ϕ is the safety factor (> 1) .

III. Results And Discussions

For the intake and exhaust modes at one end, due to the large area, large supply and limited supply speed of the utility tunnel, the vortex appears in the utility tunnel, which affects the heat dissipation effect. Therefore, it is necessary to focus on the wind speed distribution in the middle section to determine the effectiveness of the ventilation scheme.

A. Ventilation partition length

The electrical compartment in the utility tunnel was a 200 m long ventilation partition. The paper compared the ventilation effect of different air supply modes.

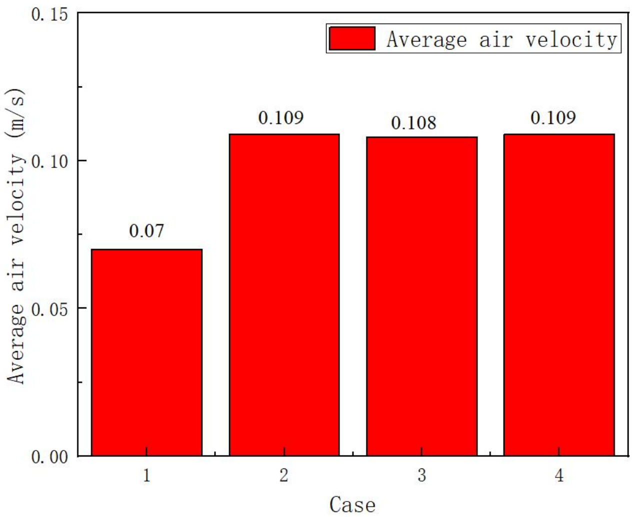

Fig. 3. Average air velocity in the middle cross section of 200m long utility tunnel

As shown in Fig. 3. The average wind speed in the middle section of case 1 was 0.07 m/s. The average wind speed in the middle section of case 2 was 0.109 m/s. The results showed that mechanical ventilation was better ventilated than natural ventilation in 200 m long tunnels. The average wind speed in case 3 was 0.108 m/s. The average flow velocity in the middle of case 4 was 0.109 m/s. The difference between case 3 and case 4 was very small, which was in the middle of the average wind speed. The ventilation effect of mechanical ventilation was better than that of natural ventilation. The simulation results for case 4 were better than case 3, mechanical ventilation and 200 m ventilation (including fan induced ventilation) were better than natural ventilation, mechanical ventilation, and 200 m ventilation including fan.

As shown in Fig. 4, in case 5 natural ventilation the average air velocity was 0.068 m/s at damper, in case 6 emergency ventilation the average air velocity was 13.37m/s at damper in case 6. The average air velocity at fire door was 0.074 m/s in case 5. Fan ventilation effect ran at high speed better than at low speed. Fan ventilation effect when the fire door was opened, which was better than the fire door was closed. It indicated that better fan ventilation effect when fan ran at high speed.

The utility tunnel was 400 m long, which included mechanical entrances, mechanical exhaust outlets, and open electric dampers. In case 7, average wind speed at the damper was 0.594 m/s. While in case 6, the average wind speed at the damper was 1.547 m/s. The average flow velocity at the fire door in case 7 was 0.604 m/s. The results showed that the fan operated better at high speed than at low speed. The results showed that the ventilation effect of high-speed operation of the fan was better than that of low-speed operation.

The utility tunnel was a 400 m long ventilation section equipped with induction fans, pure air supply, mechanical exhaust, and electric air dampers. The average wind speed in case 8 was 1.436 m/s. The average wind speed in case 9 was 1.513 m/s. In case 10, the average wind speed was 0.965 m/s. The average wind speed at the fire door was 1.802 m/s. The effect of opening the fire doors was greater than that of the high-speed fan.

The length of the ventilation area was 400 m, and the induction fan, mechanical air supply, mechanical exhaust, and electric air damper were activated. The average wind speed at the electric air damper of case 11 was 0.724 m/s. The average wind speed at the electric air damper in case 12 was 1.685 m/s. The ventilation effect of the 400 m ventilation area where the fire door was open and the fan ran at low speed was slightly worse than the 400 m ventilation area where the fire door was closed and the fan ran at high speed. The results showed that the ventilation effect of the fan running at high speed was better than that of at low speed.

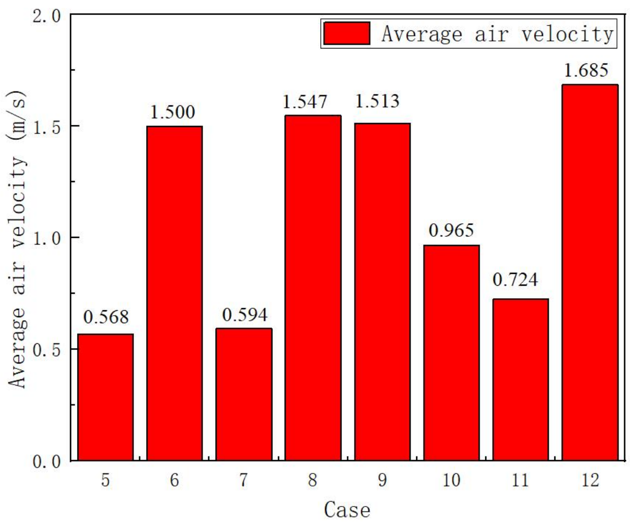

Fig. 4. Average air velocity in the middle cross section of 400 m long utility tunnel

B. Air supply method

As shown in Figs. 5 and 6, the average air velocity in case 13 was 0.479 m/s. In case 14, the average air velocity was 0.756 m/s. In case 13, the total ventilation volume through the cross section of the medium was 10346.4 m^3/h. The number of air changes was 3.83 times/hour. The air change in case 13 was greater than the ventilation design value. In case 14, the total ventilation volume through the middle section was 16329.6 m^3/h. The number of air changes was 6.048 m^3/h. The air change rate in case 14 was greater than the design ventilation rate meeting the requirements.

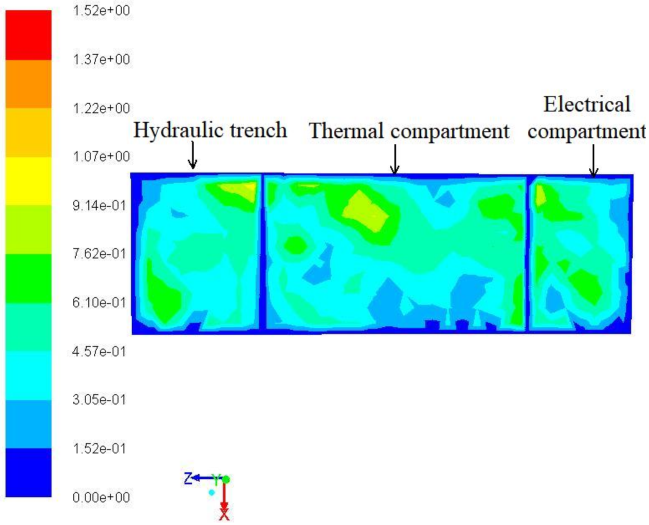

Fig. 5. Air velocity field at the cross-sectional of the case13

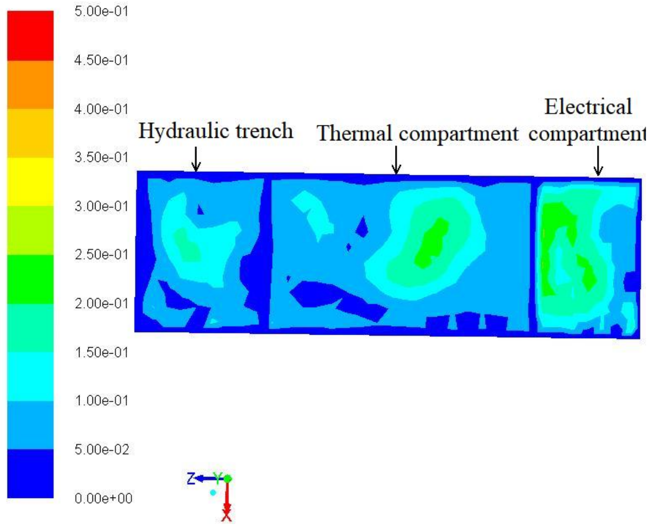

Fig. 6. Air velocity field at the cross-sectional of the case14

C. Ventilation rate

As shown in Fig. 7, in case 1, the total ventilation volume through the middle section was 1512 m^3/h. In case 2, the total air volume through the middle section was 2354.4 m^3/h. In case 3, the total ventilation volume through the middle baffle and fire door was 2332.8 m^3/h. In case 4, the total ventilation volume through the middle baffle and the fire door was 2343.6 m^3/h.

In case 5, the ventilation rate through the middle baffle and fire door was 567.27 m^3/h. In case 7, the total ventilation volume through the middle baffle and fire door was 4634.7 m^3/h. In case 9, the total ventilation volume through the middle baffle and fire door was 13797.42 m^3/h. In case 11, the total ventilation volume through the middle baffle and fire door was 4929.4 m3/h.

In case 6, the ventilation rate through the middle baffle and fire door was 1540.22 m^3/h. In case 8 the ventilation rate through the middle baffle and fire door was 13091.66 m^3/h. In case 10 the ventilation rate through the middle baffle and fire door was 9712.37 m^3/h. In case 12 the ventilation rate through the middle baffle and fire door was 13097.95 m^3/h.

The ventilation volume was calculated from the tunnel section size and ventilation area. Based on the simulation results, the air velocity was obtained between cases 13 and 14. According to the ventilation calculation formula, the ventilation rates of the hydraulic trench, thermal compartment, and electrical compartment were calculated separately.

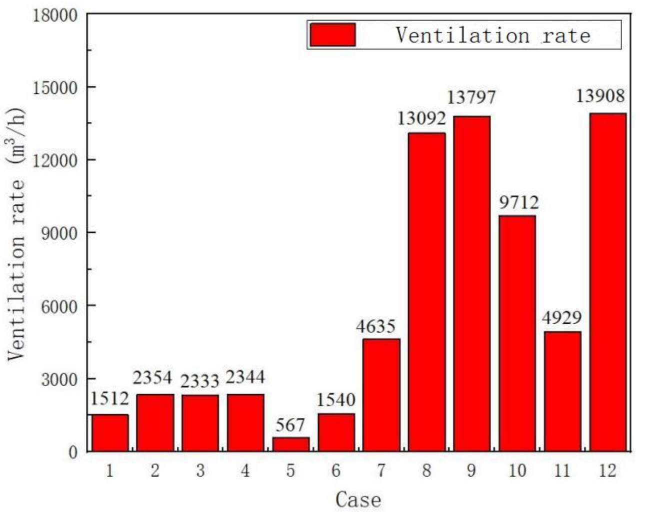

Fig. 7. Ventilation rate in the electrical compartment middle section of various case.

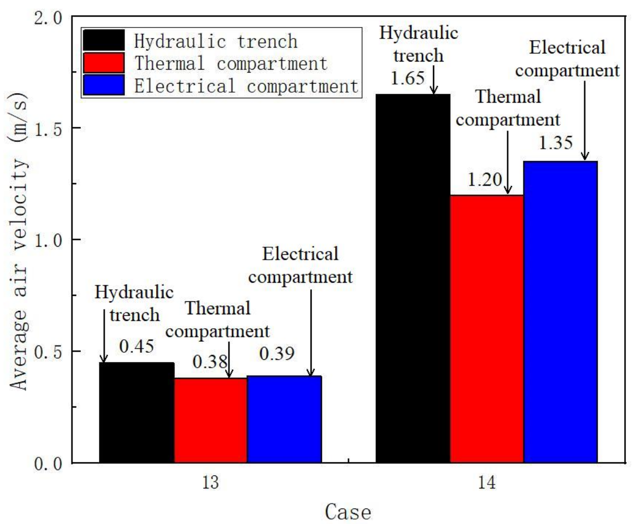

Fig. 8. Average air velocity in the middle section of the utility tunnel

As shown in Fig. 8, the average air velocity in the utility tunnel. In case 13, the air velocity in the hydraulic trench was 0.45 m/s. In case 13, the air velocity in the thermal compartment was 0.38 m/s. The air velocity in the middle of the electrical compartment in case 13 was 0.39 m/s lower than that in case 14. In case 14, the air velocity in the hydraulic trench was 1.65 m/s. In case 14, the air velocity in the thermal compartment was 1.20 m/s. The air velocity in the middle of the electrical compartment in case 14 was 1.35 m/s. In case 13, the air velocity between the hydraulic trench, thermal compartment, and electrical compartment was lower than that in case 14.

The ventilation rates for the utility tunnels were compared. In case 14, the ventilation rates of the hydraulic trench, thermal compartment, and electrical compartment in the utility tunnel were higher than those in case 13, respectively. The ventilation rates of the hydraulic trench, thermal compartment, and electrical compartment in case 14 were 1872 m^3/h, 3384 m^3/h, 1080 m^3/h larger than those in case 13, respectively.

In case 13, the actual number of air changes was 7.35 times/hour, 2.52 times/hour and 6.38 times/hour in hydraulic trench, thermal compartment, and electrical compartment, respectively. In case 14, the actual number of air changes was 26 times/hour, 7.65 times/hour and 21.4 times/hour in hydraulic trench, thermal compartment, and electrical compartment, respectively.

IV. Conclusions

The ventilation design and fire protection design of utility tunnel are inseparable from the fire-fighting design. Considering the risk of utility tunnel fire, it usually meets the needs of normal ventilation. The utility tunnels with electrical partition length of 200 m and 400 m respectively have different ventilation mode effects. In this paper, the optimal ventilation simulation mode was established by analyzing the examples of ventilation control mode. The main conclusions are as follows:

(1) The results showed that under natural ventilation mode, the utility tunnel entrance using mechanical ventilation was more effective than natural ventilation. Meanwhile, during the accident ventilation, the ventilation performance of the fan was good during high-speed operation.

(2) Under certain restrictions, a utility tunnel with a ventilation area of 400 m was constructed. It was equipped with operation mode, electric air door opening, low-speed operation fan and installed induction fan.

(3) It is worth noting that the ventilation performance when the fire door was opened was greater than the ventilation effect when the fan was running at high speed. The ventilation effect of ventilation shafts with induction fans was better than that of ventilation shafts without induction fans.

(4) The results showed that the average cross-sectional wind speed in the middle of utility tunnels such as hydraulic trench, thermal compartment, and electrical compartment was compared. In a 200 m long ventilated area, the changes in average wind speed, natural supply air, and mechanical exhaust air were slightly worse than those of mechanical supply air. The results showed that the ventilation effect of mechanical air supply was better than that of natural air supply. In addition, design of optimized operation was also very useful for utility tunnels.

References

[1] J. Canto-Perello, J. Curiel-Esparza, and V. Calvo. “Criticality and threat analysis on utility tunnels for planning security policies of utilities in urban underground space”. *Expert Systems with Applications*, vol. 40, no. 11, pp. 4707-4714, 2013.

[2] D. Hargreaves, and I. Lowndes. “The computational modeling of the ventilation flows within a rapid development drivage”. *Tunnelling and underground space technology*, vol. 22, no. 3, pp. 150-160, 2007.

[3] S. Jin, J. Jin, and Y. Gong. “Natural ventilation of urban shallowly-buried road tunnels with roof openings”. *Tunnelling and Underground Space Technology*, vol. 63, pp. 217-227, 2017.

[4] P. Chasse P. “Sensitivity study of different modelling techniques for the computer simulation of tunnel fire: Comparison with experimantal measures”. *Proceedings of First CFDS International User Conference*. vol. 14, 1993.

[5] J. Kunsch. “Simple model for control of fire gases in a ventilated tunnel”. *Fire safety journal*, vol. 37, no. 1, pp. 67-81, 2002.

[6] T. Ren, G. Cooper, and S. Yarlagadda. “Development of a water-mist based venturi system for dust control from maingate chocks and BSL”. 2011.

[7] J. Toraño, S. Torno, M. Menéndez, and M. Gent. “Auxiliary ventilation in mining roadways driven with roadheaders: Validated CFD modelling of dust behaviour”. *Tunnelling and Underground Space Technology*, vol. 26, no. 1, pp. 201-210, 2011.

[8] K. Funasaka, T. Miyazaki, T. Kawaraya, K. Tsuruho, and T. Mizuno. “Characteristics of particulates and gaseous pollutants in a highway tunnel”. *Environmental Pollution*, vol. 102, no. 2-3, pp. 171-176, 1998.

[9] F. Colella, G. Rein, R. Borchiellini, J. Torero, and V. Verda. “Calculation and design of tunnel ventilation systems using a two-scale modelling approach”. *Building and environment*, vol. 44, no. 12, pp. 2357-2367,2009.

[10] L. Yi, Q. Xu, Z. Xu, and D. Wu. “An experimental study on critical velocity in sloping tunnel with longitudinal ventilation under fire”. *Tunnelling and Underground Space Technology*, vol. 43, pp. 198-203, 2014.

[11] S. Bari, and J. Naser. “Simulation of smoke from a burning vehicle and pollution levels caused by traffic jam in a road tunnel”. *Tunnelling and Underground Space Technology*, vol. 20, no. 3, pp. 281-290, 2005.

[12] L. Barbato, F. Cascetta, M. Musto, and G. Rotondo. “Fire safety investigation for road tunnel ventilation systems – an overview”. *Tunnelling and Underground Space Technology*, vol. 43, pp. 253-265, 2014.

[13] C. Colberg, B. Tona, G. Catone, C. Sangiorgio, W. Stahel, P. Sturm, and J. Staehelin. “Statistical analysis of the vehicle pollutant emissions derived from several European road tunnel studies”. *Atmospheric Environment*, vol. 39, no. 13, pp. 2499-2511, 2005.

[14] Y. Ke, and S. Mumma. “Optimized supply-air temperature (SAT) in variable-air-volume (VAV) systems”. *Energy*, vol. 22, no. 6, pp. 601-614, 1997.

[15] Y. Chang, and W. Chen. “Optimal chilled water temperature calculation of multiple chiller systems using Hopfield neural network for saving energy”. *Energy*, vol. 34, no. 4, pp. 448-456, 2009.

[16] N. Martins, and G. da Graça. “Effects of airborne fine particle pollution on the usability of natural ventilation in office buildings in three megacities in Asia”. *Renewable energy*, vol. 117, no. 4, pp. 357-373, 2018.

[17] G. da Graça, N. Martins, and C. Horta. “Thermal and airflow simulation of a naturally ventilated shopping mall”. *Energy and Buildings*, vol. 50, pp. 177-188, 2012.

[18] L. Eça, and M. Hoekstra. “A procedure for the estimation of the numerical uncertainty of CFD calculations based on grid refinement studies”. *Journal of computational physics*, vol. 262, pp. 104-130, 2014.

[19] P. Roache. “Perspective: a method for uniform reporting of grid refinement studies”. *Journal of Fluids Engineering*. vol. 116, pp. 405-413, 1994.

[20] B. Chenari, J. Carrilho, and M. da Silva. “Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review”. *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 1426-1447, 2016.

[21] 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.

[22] 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.

[23] Z. Bai, Y. Li, J. Zhang, A. Fewkes, and H. Zhong. “Research on the design and application of capillary heat exchangers for heat pumps in coastal areas”. *Building Services Engineering Research and Technology*, vol. 42, no. 3, pp. 333-348, 2021.

[24] 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.

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