Study on Air Volume Ratio of New Connecting Flue Structure in Urban Tunnel

Xuepeng Jiang[1,a], Ding Yuan[1,b,*], Yuyuan Chen[2,c]

[1]Wuhan University of Science and Technology, Wuhan 430081 China
[2]China Railway Fourth Survey and Design Institute Group Co., Ltd., Wuhan 430063 China

[a]jiangxuepeng@wust.edu.cn, [b*]1738190529@qq.com,
[c]004050@crfsdi.com

Abstract. Qingdao Second Cross-Harbour Tunnel connects the north-south line flue by arranging connecting flues at longitudinal intervals on the exhaust ducts of the two tunnels. As there is no case of connecting flue in highway tunnel for reference, it is urgent to clarify the optimal air volume ratio of extra-long cross-sea highway tunnel with connecting flue under different air volume ratios of north-south line and shaft of each line. Fluent software is used to simulate the flow field characteristics under different air volume ratios. The results show that the air volume ratios of the two lines have great influence on the wind speed of the connecting flue. The average wind speed of the flue in the middle of the connecting flue is increased from 0.89m/s to 1.18m/s, which is about 32.58%, and the utilization rate of the connecting flue is increased from 41.18% to 54.75%. It is recommended to use the unbalanced air volume ratio mode of two-line shaft, and the air volume ratio of two-line shaft is 2:8, which has the highest utilization rate of connecting flue.

Keywords: Connecting flue, air volume ratio, extra-long cross-sea tunnel, numerical simulation.

1 Introduction

According to the Statistical Bulletin on the Development of Transportation Industry in 2022, by the end of 2022, there were 24,850 highway tunnels with a total area of 26,784,300 meters in China. Among them, there are 1,752 extra-long tunnels with 7,951,100 meters, and 6,715 long tunnels with 11,728,200 meters. The number of extra-long tunnels has increased by 25.68% compared with the previous year, and the resulting ventilation energy consumption problem of long tunnels and extra-long tunnels cannot be ignored.

Some scholars have studied the ventilation mode of highway tunnel, and Wang Yongdong [1] put forward a mixed ventilation mode, which can effectively solve the problem of limited length of complementary ventilation and reduce the energy consumption of operation ventilation. Guo Zhijie [2] through analyzing the functional characteristics and applicable conditions of different longitudinal ventilation modes,

Z. Ahmad et al. (eds.), *Proceedings of the 2024 5th International Conference on Urban Construction and Management Engineering (ICUCME 2024)*, Advances in Engineering Research 242,
https://doi.org/10.2991/978-94-6463-516-4_14

combined with the characteristics of complementary ventilation and delivery ventilation, proposed a single-channel complementary ventilation mixed ventilation mode, which can reduce the tunnel construction cost. In addition, many foreign scholars pay attention to the contribution of traffic wind and natural wind to energy saving. Experiments have proved that the natural exhaust air volume can account for 53% under favorable conditions [3,4], and the calculation of natural exhaust air volume is modified and introduced into the ventilation control calculation [5].

To sum up, the above research mainly focuses on the utilization of natural wind and piston wind in tunnel ventilation system, and then puts forward and optimizes the tunnel ventilation design scheme. At the same time, the research objects are mostly long straight tunnels or short tunnels with a few branches, and there is no research on extra-long cross-sea tunnels with connecting flue. Therefore, it is necessary to study their operation ventilation strategies and discuss the flow field of ventilation and smoke exhaust systems with connecting flue under different air volume ratios of north-south lines and two lines, with a view to providing reference for ventilation design of extra-long cross-sea tunnels and air volume ratio of shafts.

2 Study on Air Volume Configuration Scheme of Extra-Long Cross-Sea Highway Tunnel

2.1 Geometric Model and Grid Division

Based on the four connecting flues of Qingdao Second Cross-Harbour Tunnel with a distance of 2300m, a 1:1 full-scale model of the tunnel is established by FLUENT numerical simulation software. The length of the model is 13.9km, the distance between the north and south lines is 55m, the global size of the grid is set to 0.5, and the local encryption of the smoke outlet and the connecting flue is 0.2. The model diagram of Qingdao Second Cross-Harbour Tunnel with the smoke outlet at the top of the north-south line connected by the connecting flue is shown in Figure 1.

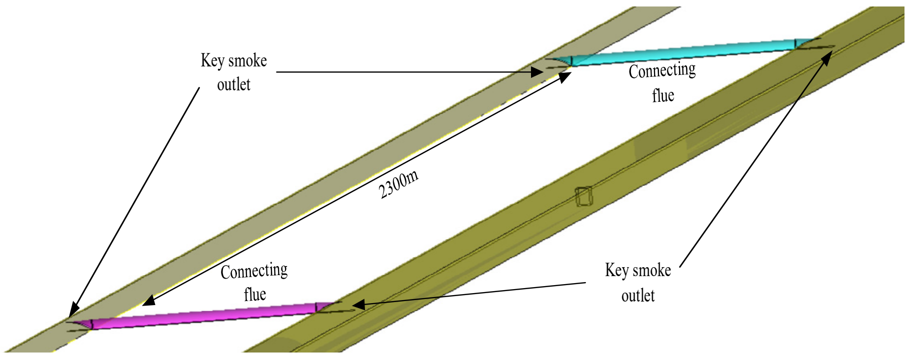

Fig. 1. Model map of Qingdao Second Cross-Harbour Tunnel.

2.2 Simulated Working Condition Setting

The exhaust air volume of the model tunnel is 360m3/s, and under each exhaust air volume, four exhaust ratios of the north-south line are set at 5:5, 4:6, 3:7 and 2:8, and the area of the smoke outlet is 60m2. On this basis, four different exhaust ratios of the shafts on both sides of the same line are set at 5:5, 4:6, 3:7 and 2:8, and their different exhaust ratios are studied.

Table 1. Table of working conditions for different air volume ratios.

Exhaust air volume (m^3/s)	working condition	North-South Line Exhaust Ratio (South: North)	Ventilation ratio of shafts on both sides of each line (left: right)
360	H01~04	2:8	2:8
			3:7
			4:6
			5:5
	H05~08	3:7	2:8
			3:7
			4:6
			5:5
	H09~12	4:6	2:8
			3:7
			4:6
			5:5
	H13~16	5:5	2:8
			3:7
			4:6
			5:5

During ventilation, when the fan is turned on, the air flow will be discharged from the shaft on both sides through the top exhaust port, the connecting flue and the top flue of the North-South line. The control mode of setting exhaust ports at both ends of each connecting flue and uneven exhaust of the shaft fans at both ends of the tunnel is adopted. The layout and position of the connecting flue are shown in Figure 2.

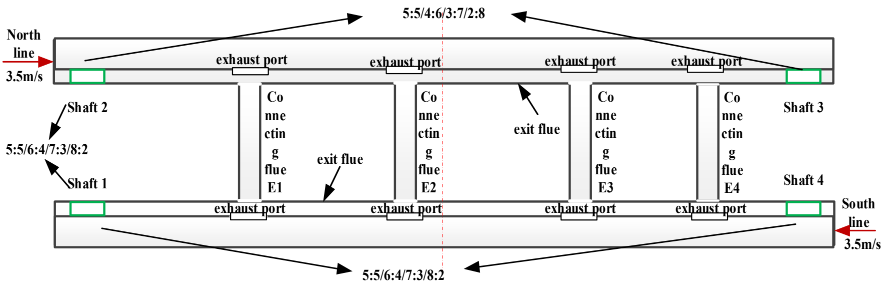

Fig. 2. Schematic diagram of uneven ventilation control model of shaft.

3 Influence of Exhaust Ratio of North-South Line On Connecting Flue

3.1 Analysis of Velocity Field in Flue of Extra-Long Cross-Sea Tunnel

In order to analyze the influence of different air volume ratios between north and south lines on the wind speed of the connecting flue, and keep the air volume ratios of the shafts on both sides of the south line and the north line unchanged at 5:5, 4:6, 3:7 and 2:8, compare the influence of different air volume ratios between north and south lines (5:5, 4:6, 3:7 and 2:8) on the overall smoke exhaust system, and collect the average wind speed of the tunnels on the north and south lines.

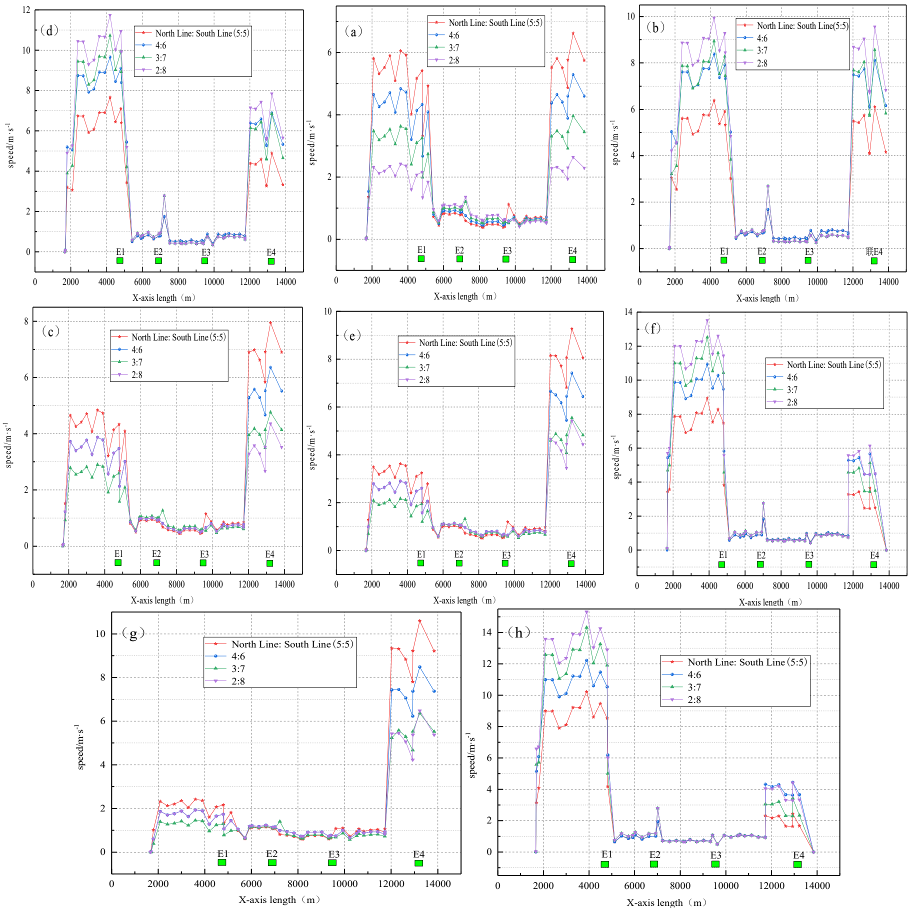

Fig. 3. The average wind speed chart of the north-south line flue under different ratios of north and south lines: (a) North line-left side 5: right side 5, (b) South Line-Left 5: Right 5, (c) Northbound-left side 4: right side 6, (d) South Line-left side 4: right side 6, (e) Northbound-left side 3: right side 7, (f) South Line-Left 3: Right 7, (g) North Line-Left Side 2: Right Side 8, (h) South Line-Left Side 2: Right Side 8.

When the air volume ratio of the North-South line gradually changes from 5:5 to 2:8, the wind speed between the four connecting flues also gradually increases, which can alleviate the situation that the wind speed in the center of the tunnel is too low due to the same air volume on both sides of the North-South line tunnel and mutual suction. The wind speed in the center of the tunnel between the connecting flue E2 and the connecting flue E3 increases from 0.81m/s when the air volume ratio is 5:5 to 1.06 m/s.

To sum up, the difference of air volume ratio between north and south lines can improve the situation of low wind speed area in the center of tunnel to some extent.

3.2 Analysis of Velocity Field in Connecting Flue

In order to further analyze the influence of different air volume ratios between north and south lines on the flow field in the connecting flue, the velocity nephograms of the connecting flue with different air volume ratios between north and south lines are analyzed under the condition that the air volume ratios of shafts on both sides of the north-south line tunnel are both 5:5. The velocity nephograms of the connecting flue with 5:5 and 2:8 are shown in Figure 4 and Figure 5, and figure 6.

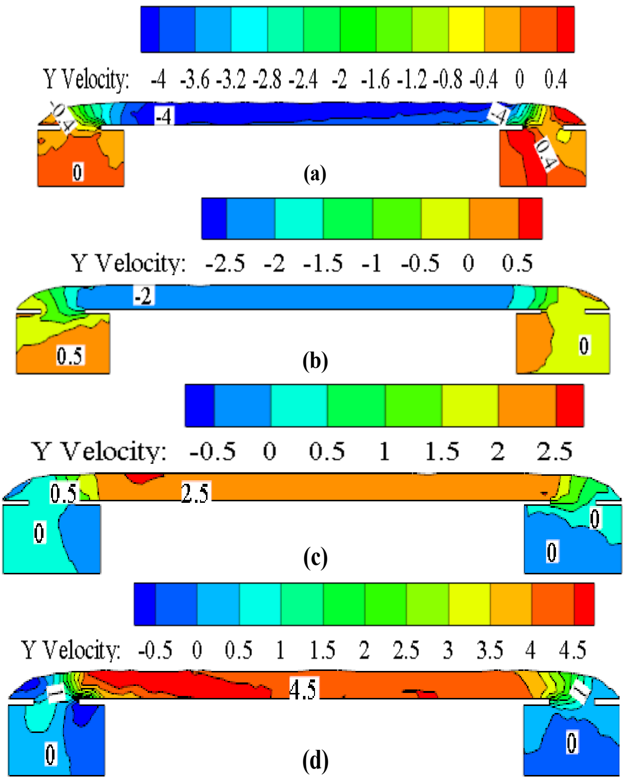

Fig. 4. Velocity nephogram of connecting flue when the ratio of north-south line is 5:5.: (a) connecting flue E1, (b) contact flue E2, (c) contact flue E3, (d) contact flue E4.

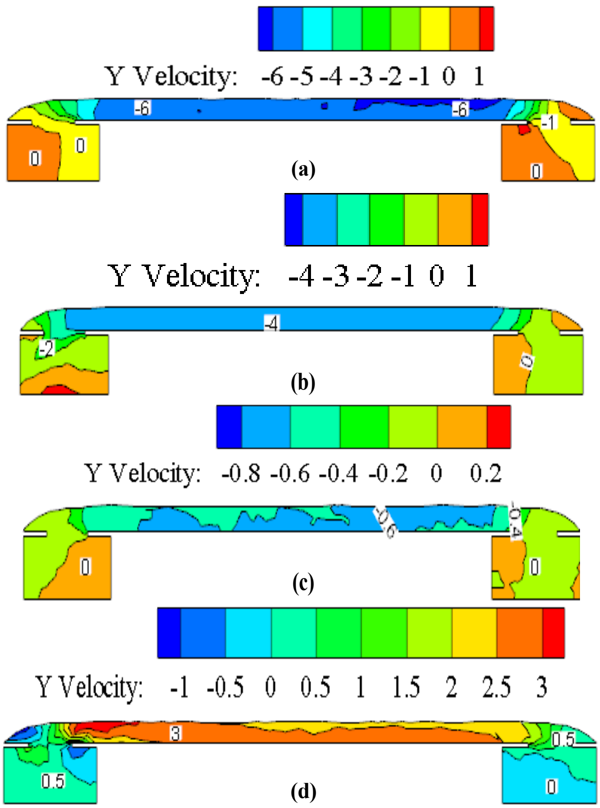

Fig. 5. Velocity nephogram of connecting flue when the ratio of north-south line is 2:8: (a) connecting flue E1, (b) contact flue E2, (c) contact flue E3, (d) contact flue E4.

When the air volume ratio of the north-south line is gradually changed from 5:5 to 2:8, the wind speed of the connecting flue E1 and E2 is obviously improved, from 4.12m/s and 2.45m/s to 6.23m/s and 4.25m/s, but at the same time the wind speed of the connecting flue E3 and E4 is reduced from 2.34m/ s and 4.09m/s to 0.67 m/s.

To sum up, the larger air volume ratio of the north-south line will lead to the disorder of the flow field of the whole smoke exhaust system and the uneven distribution of air volume in the connecting flue, which will lead to the failure of some connecting flue, so it is not recommended that the air volume ratio of the north-south line exceed 3:7.

3.3 Analysis of Utilization Ratio of Connecting Flue

In order to further analyze the influence of different air volume ratios between the north and south lines on the air volume of the connecting flue, when the air volume ratios of the shafts on both sides of the north-south line tunnel are both 5:5, and the air volume ratios between the north and south lines are the wind speeds of the connecting flue when they are changed to 5:5, 4:6, 3:7 and 2:8, the utilization ratio of the connecting flue is calculated as shown in Table 2.

Table 2. Utilization ratio of connecting flue under different air volume ratio of north-south line.

working condition	Contact flue number	Wind speed of connecting flue/m·s^{-1} (positive from north line to south line)	Contact flue air volume/m^3·s^{-1}	Utilization ratio of connecting flue/%
H01	E1	-3.52	193.62	41.18
	E2	-1.70	93.58	
	E3	1.63	89.90	
	E4	3.93	215.88	
H05	E1	-4.11	226.13	41.30
	E2	-2.19	120.51	
	E3	1.13	62.37	
	E4	3.38	185.68	
H09	E1	-4.67	256.96	40.39
	E2	-2.59	142.66	
	E3	0.52	28.41	
	E4	2.79	153.63	
H13	E1	-5.18	284.76	41.03
	E2	-2.87	157.88	
	E3	0.41	22.75	
	E4	2.28	125.46	

When the air volume ratio of the north-south line gradually changes from 5:5 to 2:8, the wind speed between the four connecting flues also changes, but the average air volume of the connecting flue remains at 147.63m3/s, so the utilization rate of the connecting flue also remains at about 40.98%, with no obvious improvement.

To sum up, the air volume ratio of the north-south line has no great influence on the utilization rate of the connecting flue, and the ratio of the north-south line can be adjusted according to the actual situation to increase the wind speed of the connecting flue near the shaft and enhance the ventilation and smoke exhaust effect of the section near the shaft.

4 Influence of Exhaust Ratio of Two-Line Shaft on Connecting Flue

4.1 Analysis of Velocity Field in Flue of Extra-Long Cross-Sea Tunnel

In order to analyze the influence of different air volume ratios of two-line shafts on the wind speed of connecting flue, and keep the air volume ratios of south line and north line unchanged at 5:5, 4:6, 3:7 and 2:8, the influence of different air volume ratios of two-line shafts (5:5, 4:6, 3:7 and 2:8) on the overall smoke exhaust system was compared, and the average wind speed of the smoke exhaust duct of the north-south line tunnel was collected differently.

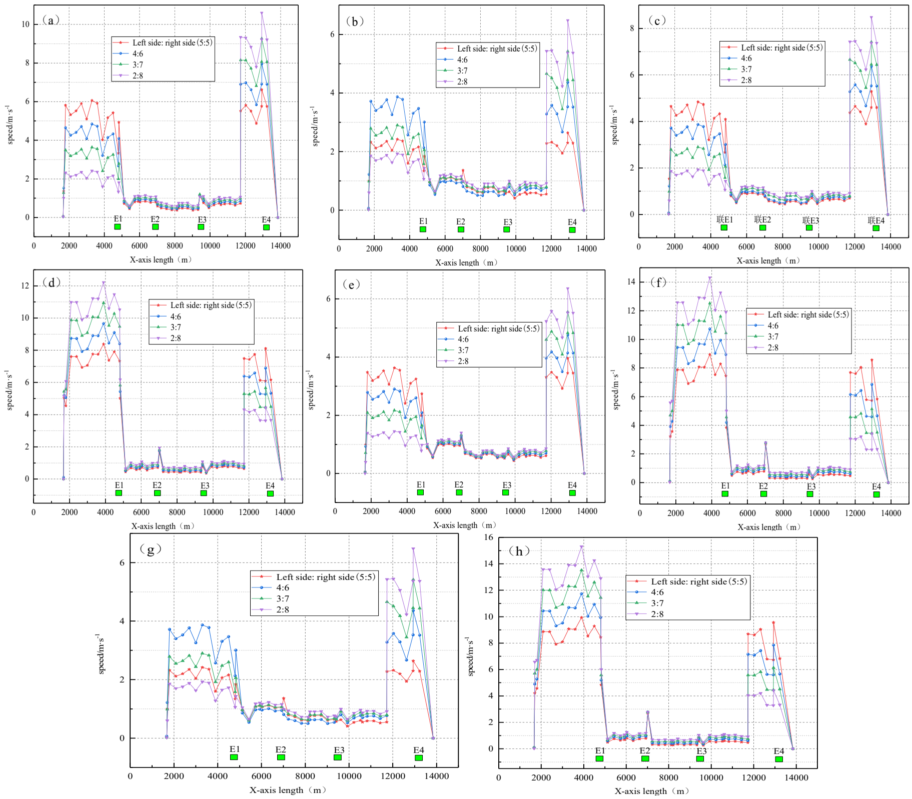

Fig. 6. The average wind speed diagram of the north-south line flue under different air volume ratios of the two-line shaft: (a) the north line-left side 5, right side 5, (b) South Line-Left 5: Right 5, (c) Northbound-left side 4: right side 6, (d) South Line-left side 4: right side 6, (e) Northbound-left side 3: right side 7, (f) South Line-Left 3: Right 7, (g) North Line-Left Side 2: Right Side 8, (h) South Line-Left Side 2: Right Side 8.

When the air volume ratio of the two-line shaft gradually changes from 5:5 to 2:8, the wind speed between the four connecting flues also gradually increases. Taking the average wind speed of the flue in the middle tunnel of the connecting flue as an example, when the air volume ratio of the two-line shaft gradually changes from 5:5 to 2:8, the average wind speed of the flue increases from 0.89m/s to 1.18m/s, with an increase range of about 32.58%.

To sum up, the difference of air volume ratio between the two shafts can effectively improve the wind speed in the low wind speed area in the center of the tunnel, and the greater the difference of air volume ratio between the two shafts, the more obvious the effect.

4.2 Analysis of Velocity Field in Connecting Flue

In order to further analyze the influence of different air volume ratios of two-line tunnel shafts on the flow field in the connecting flue, the velocity nephogram of the connecting flue under different air volume ratios of the two-line tunnel shafts is analyzed under the condition that the air volume ratio of the north-south line is 5:5, and the velocity nephogram of the connecting flue under the condition that the air volume ratio of the two-line tunnel shafts is 5:5 is shown in Figure 7, and that of the two-line tunnel shafts is 2:8 is shown in Figure 8.

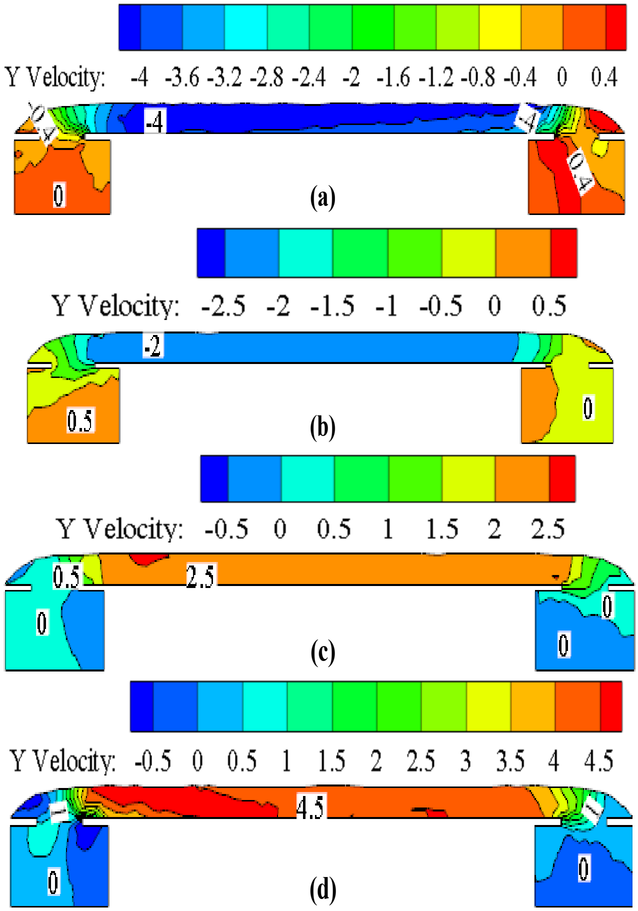

Fig. 7. Velocity nephogram of connecting flue when the ratio of two-line shaft is 5:5: (a) connecting flue E1, (b) contact flue E2, (c) contact flue E3, (d) contact flue E4.

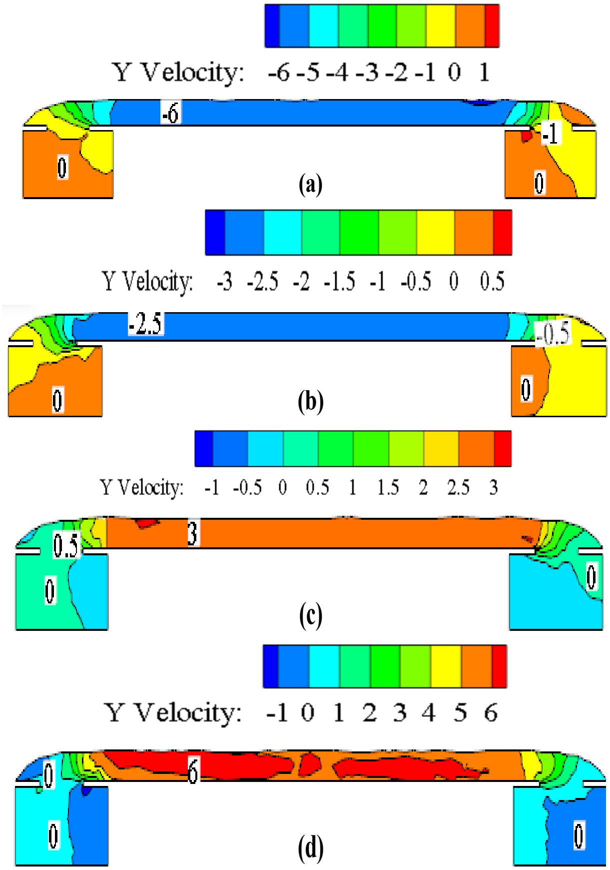

Fig. 8. Velocity nephogram of connecting flue when the ratio of two-line shaft is 2:8: (a) connecting flue E1, (b) contact flue E2, (c) contact flue E3, (d) contact flue E4.

When the air volume ratio of the two-line shaft is gradually changed from 5:5 to 2:8, the wind speed among the four connecting flues is also gradually increased, and the wind speed of the connecting flues E1, E2, E3 and E4 is increased from 4.12m/s, 2.45m/s, 2.34m/s and 4.09m/s to 6.23m/s, 2.67m/s, 2.57m/s, 6.25m/s.

To sum up, the difference of air volume ratio between two-line shafts can improve the wind speed in the connecting flue, and it is recommended to use the unbalanced air volume ratio mode between two-line shafts.

4.3 Analysis of Utilization Ratio of Connecting Flue

In order to further analyze the influence of different air volume ratios of the two-line shaft on the air volume of the connecting flue, when the air volume ratio of the north-south line is 5:5 and the air volume ratio of the two-line shaft of the tunnel is changed to 5:5, 4:6, 3:7 and 2:8, the utilization ratio of the connecting flue is calculated as shown in Table 3.

Table 3. Utilization ratio of connecting flue under different air volume ratio of two-line shaft.

working condition	Contact flue number	Wind speed of connecting flue/m·s^{-1} (positive from north line to south line)	Contact flue air volume/$m^{3}\cdot s^{-1}$	Utilization ratio of connecting flue/%
K01	E1	-3.52	193.62	41.18
	E2	-1.70	93.58	
	E3	1.63	89.90	
	E4	3.93	220.51	
K02	E1	-4.01	220.51	45.66
	E2	-1.83	100.72	
	E3	1.74	95.89	
	E4	4.37	240.36	
K03	E1	-4.52	248.59	50.15
	E2	-1.96	107.70	
	E3	1.85	101.92	
	E4	4.80	263.94	
K04	E1	-4.98	273.74	54.75
	E2	-2.12	116.34	
	E3	1.94	106.97	
	E4	5.30	291.42	

When the air volume ratio of the two-line shaft gradually changed from 5:5 to 2:8, the utilization ratio of the four connecting flues also gradually improved, and the utilization ratio of the connecting flues increased from 41.18% to 54.75%, and the utilization ratios of the four connecting flues E1, E2, E3 and E4 all improved. There was no situation that the wind speed of the connecting flue changed but the overall distribution air volume remained unchanged under different air volume ratios of the north and south lines.

To sum up, the difference of air volume ratio between two-line shafts can effectively improve the utilization rate of connecting flue, so it is recommended to use the unbalanced air volume ratio mode of two-line shafts, and the air volume ratio of two-line shafts is 2:8, which has the highest utilization rate of connecting flue.

5 Conclusions

Comparing the air volume ratio of different north-south lines with that of different two-line shafts, the following conclusions are drawn:

(1) The change of the air volume ratio of the north-south line has little influence on the wind speed of the connecting flue, but it can alleviate the situation that the wind speed in the center of the tunnel is too low due to the same air volume on both sides of the north-south line tunnel and mutual suction. The wind speed in the center of the

tunnel between the connecting flue E2 and the connecting flue E3 rises from 0.81m/s when the air volume ratio is 5:5 to 1.06m/s when the air volume ratio is 2:8. The ratio of the north-south line can be adjusted according to the actual situation to increase the connection near the shaft.

(2) The air volume ratio of the two lines has a great influence on the wind speed of the connecting flue. When the air volume ratio of the two lines is gradually changed from 5:5 to 2:8, the average wind speed of the flue in the middle of the connecting flue is increased from 0.89m/s to 1.18m/s, which is about 32.58%. The flow field in the connecting flue is not disordered, and the utilization rate of the connecting flue is increased from 41.18% to 54.75%. To enhance the ventilation and smoke exhaust effect of the smoke exhaust system, it is recommended to use the unbalanced air volume ratio mode of two-line shaft, and the air volume ratio of two-line shaft is 2:8, which has the highest utilization rate of connecting flue.

References

1. Yongdong, W., Sihao, H., Zhiwei, H. (2020)Hybrid ventilation design system of cross passage combined with single air shaft for extra-long highway tunnel. J. journal of traffic and transportation engineering., 20(6): 160-170. DOI:10.19818/j.cnki.1671-1637.2020.06.014.
2. Zhijie, G., Jijun, H., Cancheng, Z. (2019)Study on ventilation scheme comparison of Jinmen extra-long highway tunnel. J.Tunnel construction (in Chinese and English).,39 (increase 1): 321-326. https://kns.cnki.net/kcms/detail/41.1448.U.20190911.1131.080.html
3. JIN, S., JIN, J., GONG, Y. (2020)A theoretical explanation of natural ventilation at roof openings in urban road tunnels. J.Tunnelling and Underground Spacce Technology., 98: 103345.1-103345.11. DOI:10.1016/j.tust.2020.103345.
4. Krol, M., Krol, A., Koper, P. (2019)The influence of natural draught on the air flow in a tunnel with longitudinal ventilation. J.Tunnelling and Underground Spacce Technology., 85: 140-148. DOI:10.1016/j.tust.2018.12.008.
5. Porras-Amores, C., Mazarrón, F.R., Cañas I. (2019)Natural ventilation analysis in an underground construction: CFD simulation and experimental validation. J.Tunnelling and Underground Space Technology., 90: 162-173. DOI:10.1016/j.tust.2019.04.023.