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Experimental study on the flow field and economic characteristics of parallel push-pull ventilation system

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ABSTRACT

Push-pull ventilation systems provide excellent control of contaminants and harmful gases. However, since both a push inlet and a pull outlet are used in the push-pull ventilation system, the flow rate required by the system is large. In that case, the energy consumption of the system is large. The purpose of this paper is to study the flow field and economic characteristics of a parallel push-pull ventilation system by reducing the flow rate of the exhaust outlet, which will be achieved by reducing the size of the exhaust hood. The three commonly used push-pull ventilation systems were analyzed: a high velocity push-pull system with high air supply velocity, a low velocity push-pull system with wide airflow and small velocity, and a parallel push-pull system with wide airflow and uniform air supply velocity. Results showed that the parallel push-pull ventilation system was the only one in which the flow rate of the exhaust outlet could be reduced, reducing the overall energy consumption. Under conditions of the parallel air supply jet, the diffusion range of contaminants in the push-pull flow field was the smallest and reducing the exhaust air flow rate did not affect the capture efficiency of pollutants. These results may be useful in guiding the design of push-pull ventilation system and optimize economic constraints.

1. Introduction

During different industrial production processes, contaminants such as dust and steam may be produced. In order to effectively protect the working environment of workers, local ventilation can be used [1–6]. A widely used local ventilation method in industrial applications is the push-pull ventilation system, which has good pollution control [7–9]. The system is composed of two parts: an air supply inlet and an exhaust outlet, which uses an air supply jet as the power to transport contaminants to the exhaust outlet [10–13]. Depending on the type of air supply used, push-pull ventilation systems can be divided into high velocity push-pull ventilation system, low velocity push-pull ventilation system and parallel push-pull ventilation system. A High velocity push-pull ventilation system uses a high velocity supply jet to mix and transport contaminants [14,15]. A low velocity push-pull ventilation system uses low velocity and wide air flow to control workspace contaminants [16]. A parallel push-pull ventilation system uses a low turbulence intensity, uniform, and wide air flow with good directionality to push the contaminants into the exhaust outlet [13,17,18].

Initial research on push-pull ventilation systems was based on the high velocity system [19,20]. Betta et al. explored the capture of pollutants with different particle sizes [21]. Marzal et al. studied the effect of the geometric size of the air supply on capture efficiency and observed flow field characteristics by using airflow visualization [22,23]. Robinson et al. explored the flow field distribution and developed design recommendations for a push-pull ventilation system [24,25]. Rota et al. tested the impact of different factors on contaminant capture and proposed corresponding design suggestions [26]. Enrique Gonzalez et al. studied the effect of different sizes of exhaust hood on capture efficiency [27].

However, excessive air supply velocity at the push inlet can damage the workpiece surface [16,17]. A large number of studies indicate that initial conditions of the air supply jet, such as air supply uniformity, directivity, and turbulence intensity have an important impact on the performance of push-pull ventilation systems [28–30]. Based on these findings, a low momentum system was proposed. There are two types of low momentum system: a low velocity push-pull system that supplies air as slowly as possible but with enough velocity to reach the exhaust outlet and to control the polluted airflow [16], and a parallel push-pull system with uniform air supply velocity, good directivity, and low turbulence density [16].

Low velocity and parallel flow system have developed rapidly in recent years [16,17,31–34]. Hayashi advised that to improve the push-pull system, parallel jets, low velocity, good directionality and a uniform air

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Nomenclature

L	distance between the push and the pull hood (m)
l	distance between the push hood and the source of pollution (m)
h_{in}	height of the push hood (m)
h_{out}	height of the pull hood (m)
b	width of the push hood and pull hood (m)
u_{in}	average velocity at the push hood (m/s)
u_{out}	velocity at the pull hood (m/s)
u_c	centerline velocity along the flow path (m/s)
Q_{in}	volume flow rate at the push hood (m^3/s)
Q_{out}	volume flow rate at the pull hood (m^3/s)
C	concentration of polluted air (PPm)
K	the ratio of the push inlet flow rate to the pull outlet flow rate
SD	standard dispersion
Tu	turbulence intensity
x,y,z	cartesian coordinates
Subscripts	
i	different cross sections

supply should be applied. This was the first time that a parallel flow system was proposed. Hayashi think this kind of system can effectively prevent the spread of contaminants and stop damage to the surface of the workspiece, while simultaneously providing fresh air to workers [17]. Wang et al. compared the diffusion range of contaminants under the low velocity and the parallel push-pull systems and found that the diffusion range of contaminants under the parallel system was smaller [31–34]. Liu et al. studied the performance and optimal flow ratio of a vertical parallel push-pull ventilation system [35,36]. The above studies demonstrate that parallel push-pull systems have a uniform, low-velocity and wide air supply that can control contaminants effectively. However, compared with the three traditional push-pull ventilation systems, there have not yet been sufficient studies of the flow field characteristics and the diffusion range of contaminants. Additionally, there is no consensus on which system is the most economical to use in a specific situation.

The main purpose of this paper is to study the flow field and economic characteristics of parallel push-pull ventilation systems. By using flow visualization techniques and through measuring the velocity field and concentration distribution of contaminants in this paper, the flow fields were analyzed by comparing the three traditional push-pull systems. The corresponding economic characteristics were explored by reducing the flow rate of the pull unit. The research provides relevant data and economic recommendations for optimizing push-pull ventilation systems.

2. Experimental setup

2.1. Experimental facility

The experimental push-pull ventilation system model is shown in Fig. 1(a). The model is composed of the push hood, the pull hood and the pollution source. The pull hood is connected to the exhaust tube, which contains a pressure regulator for determining the exhaust flow rate by adjusting the frequency converter fan.

Both the push hood and the pull hood have a rectangular cross-section with a cross-stream length of $b = 0.3$ m (Fig. 1(b)). The distance between the push inlet and the pull outlet is $L = 1.6$ m. The push hood height, h_{in} could be varied from 0.05 to 0.3 m, and the pull hood height, h_{out} could be varied from 0.15 m to 0.3 m by using a sliding baffle. The coordinate origin of the model was located at the bottom of the push hood, with the x-axis parallel to the direction of flow, the y-axis vertical to the source, and the z-axis was vertical to the ground.

A pollution source with a diameter of 0.08 m and a height of 0.05 m was placed at the center of the flow field. Using SF6 as the gaseous tracer has the advantages of having low background concentration, is non-toxic, and is easy to monitor [37–39]. In order to prevent the deposition of SF6 in the room which would affect the measurements, SF6 and air were mixed at a ratio of 1:16, controlled by the rotor flow rate [11,23]. The release rate was set to 0.05 m/s.

2.2. Layout of measuring points

As shown in Fig. 2(a), 16 velocity monitoring points were arranged on the push hood at distances of 0.075 m between each point to measure the velocity distribution and uniformity. In order to illustrate the flow field characteristics of different push-pull ventilation systems, 15 velocity measuring points were evenly arranged on the central axis (Fig. 2(b)) and nine velocity measuring points were arranged across four cross sections at $x/L = 0.25$, 0.5, 0.75 and 0.875 (Fig. 2(c)). As shown in Fig. 2(c), the concentration distribution of contaminants were measured on the $x/L = 0.5$, 0.75, and 0.875 cross sections in the xoz plane. In addition, a concentration measuring point was placed at the exhaust duct to calculate the capture efficiency of the pollutant. The capture efficiency is equal to the concentration measured when the contaminant is released at the source divided by the concentration when the contaminant is released directly at the exhaust outlet [23]. During the experiment, the contaminants were uniformly released by controlling the flow rate for each measurement, and all measurements were performed at a steady state.

2.3. Measuring cases

Due to the complexity of the push-pull flow field, scholars have proposed a variety of system design methods based on different design concepts. Among these design methods, the flow ratio method is the most widely used [17], and was adopted in this paper to determine the flow rate of the push and pull hoods.

In order to quantitatively describe the uniformity and fluctuation of the air supply of the push-pull ventilation system, the standard dispersion (SD) and turbulence intensity (Tu) indices were used [40–42], with specific formulas as follows.

$$\bar{u} = \frac{1}{N}\sum_{i=1}^{N} u_i \quad (1)$$

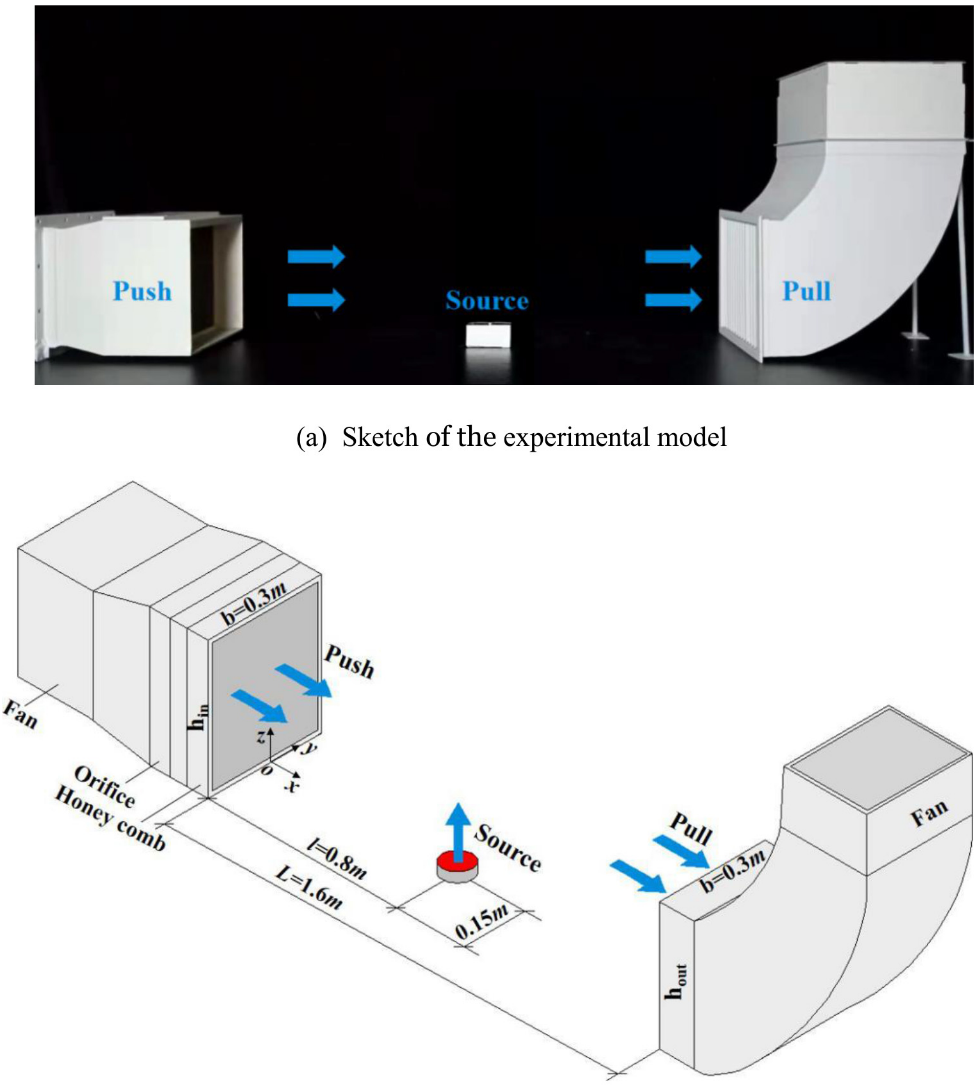
$$SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(u_i - \bar{u})^2} \quad (2)$$

$$Tu = \frac{\sqrt{u_i'^2}}{\bar{u_i}} \quad (3)$$

where u_i is the velocity of the monitoring point i (m/s), u_i' is the turbulence velocity at monitoring point i (m/s), and N is the number of measuring points.

① In order to compare the flow field characteristics between the three push-pull ventilation systems, Cases 1–3 were designed to ensure the same supply and exhaust flow rates. Case 1 was the high velocity push-pull system using a small air supply inlet. As shown in Fig. 3(a), a baffle was used to block the push inlet to achieve high velocity air supply from a small inlet. Case 2 was the low velocity push-pull system using a large air supply inlet in which the airflow was directly sent out from the push inlet. Due to the large air supply area, the air supply velocity was small (Fig. 3(b)).

Case 3 was the parallel push-pull ventilation system (Fig. 3(c)). In order to achieve the parallel jet, a series of flow conditioning devices including two orifice plates and a honeycomb were placed in front of the push hood. The diameter of the holes in the two orifice plates was 1.5 mm, and the distance between adjacent holes was 2.5 mm. The honeycomb was a hexagonal honeycomb body with each six sides of 2 mm



(a) Sketch of the experimental model

(b) Sketch of the experimental setup

Fig. 1. Experimental arrangement.

Table 1
Measurement conditions.

Cases	Push-pull system	Height of push hood h_{in} (m)	Height of pull hood h_{out} (m)	Flow rate of push hood Q_{in} (m^3/s)	Flow rate of pull hood Q_{out} (m^3/s)	Turbulence intensity of push inlet *Tu* (%)	Uniformity of inlet *SD* (%)	Flow ratio K
1	High velocity	0.05	0.3	0.065	0.26	1.91	20.34	1:4
2	Low velocity	0.3	0.3		0.26	17.68	15.24	1:4
3	Parallel	0.3	0.3		0.26	1.41	4.79	1:4
4	Parallel	0.3	0.25		0.217	1.73	6.18	1:3.3
5	Parallel	0.3	0.2		0.172	2.06	5.78	1:2.6
6	Parallel	0.3	0.15		0.13	1.29	4.21	1:2

and a thickness of 75 mm. Studies have shown that the arrangement of the orifice plate can effectively reduce the turbulence of the airflow and improve the uniformity of the airflow velocity, while the honeycomb directed the air supply [17,19,32,37]. Results in Table 1 also show that the air flow supply of the parallel push-pull ventilation system was the most uniform, and the turbulence is the lowest.

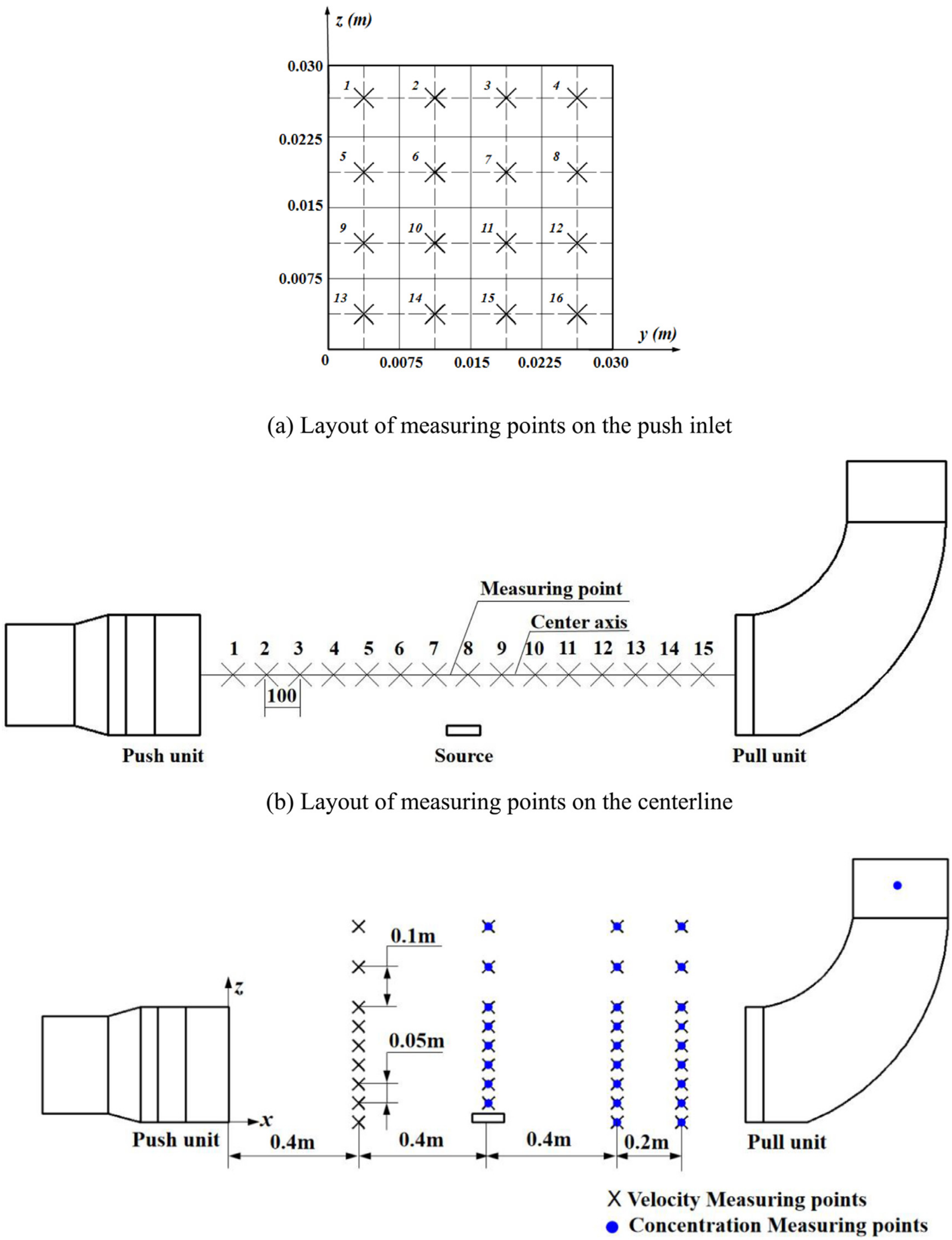
② Four experimental cases were design to further explore the economic characteristics of push-pull ventilation systems. To ensure that the air supply flow rate and the exhaust air velocity were constant, four different flow ratios (Cases 3–6) were designed by changing the height of the pull hood (Table 1). The flow rate ratio (K) is the ratio of the push inlet flow rate to the pull outlet flow rate, as follows:

$$K = \frac{Q_{in}}{Q_{out}} \tag{3}$$

where Q_{in} is the flow rate of the push inlet (m^3/s), Q_{out} is the flow rate of the pull outlet (m^3/s).

2.4. Instrumentation

The Swema 3000 was calibrated prior to the experiment, and was used to measure the velocity field. The measurement range of the Swema



(a) Layout of measuring points on the push inlet

(b) Layout of measuring points on the centerline

(c) Layout of measuring points on the *xoz* plane

Fig. 2. Layout of velocity and concentration measurement points.

3000 is 0.05–3.00 m/s, with measurement accuracy of ±0.03 m/s. Measurements time were taken for 30 s, and each group of data was measured three times to ensure the accuracy of the results [41,42].

In order to observe the control of contaminant flow by the system, smoke from a smoke generator (YWQ-FD300B) was injected into the pollution source to visualize the contaminant flow. The movement of the contaminant was recorded by a CMOS industrial camera (SD-U300) which shot at a rate of 200 frames per second for a duration of 1 s.

In order to measure the distribution of SF6, an infrared spectral gas monitor (INNOVA 1412, Luma Sense Technologies) was used for real-time monitoring, which was connected with a multi-point release and sampling instrument (INNOVA 1303, Luma Sense Technologies). In the experiment, the INNOVA 1314 and INNOVA 1412 sampling integral time (SIT) were set to be every five seconds. The repeatability of the SF6 measurements were ±1% of the measured value, and the lower limit of INNOVA 1412 for SF6 detection was 0.006 ppm [43,44].

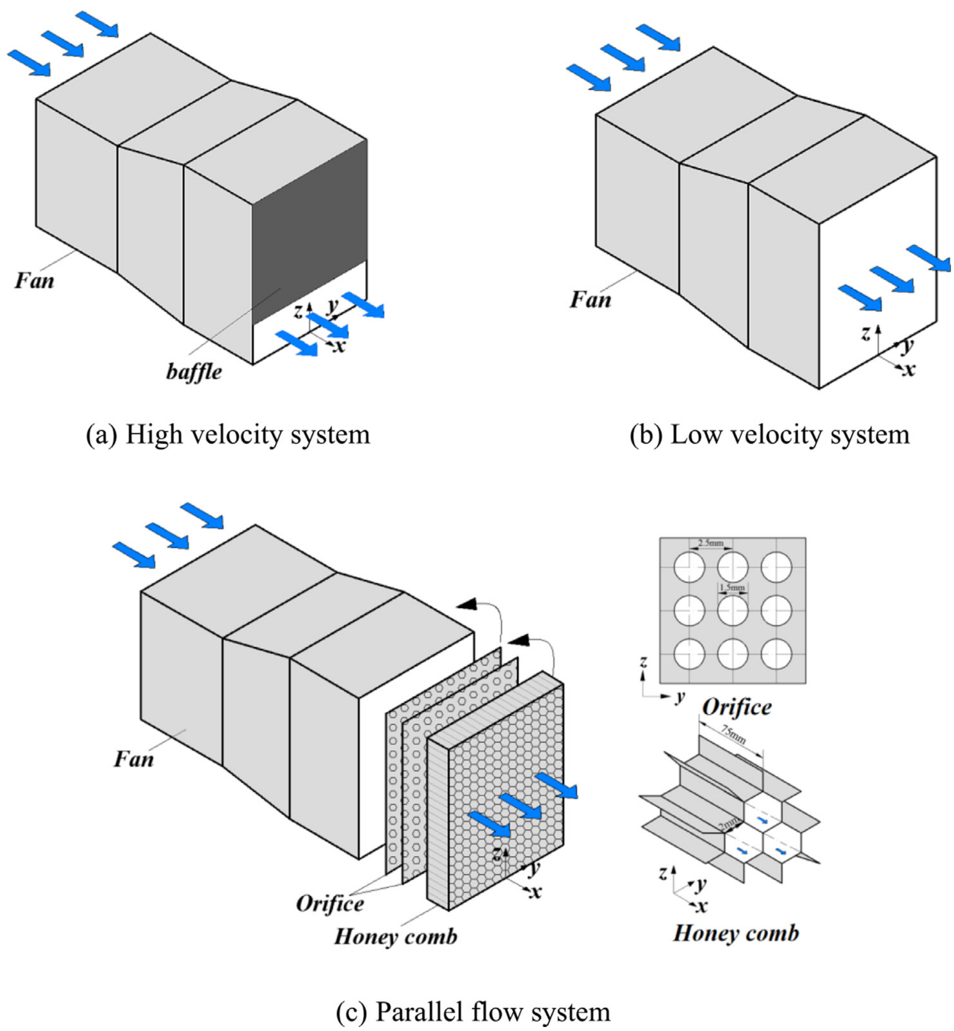


Fig. 3. Air supply devices for different push-pull ventilation systems.

3. Results

3.1. Comparison of the three push-pull ventilation flow fields

3.1.1. Flow visualization under different push-pull systems

Fig. 4 shows the movement of the contaminant under the three traditional push-pull ventilation systems. In the high velocity system and low velocity system, the contaminant diffused throughout whole push-pull flow field. In contrast, under the parallel flow system, the contaminant diffusion range was significantly reduced.

3.1.2. Velocity field

Fig. 5 shows the dimensionless centerline velocity (u_c/u_{in}) under different push-pull ventilation systems, where u_c is the centerline velocity along the flow path, and u_{in} is the average velocity at the push hood. The results showed that the degree of attenuation of the centerline velocity varied under different push-pull ventilation systems. At the same air supply flow rate, the centerline velocity retention was better under the parallel flow system. The attenuation of the centerline velocity was due to the shear effect between the supply air jet and the ambient air, which resulted in a coherent structure at the boundary of the jet [40,45]. The coherent structure caused the ambient fluid to be entrained and mixed with the supply jet. The stronger the degree of mixing, the faster the centerline velocity decayed. Therefore, the high retention of the centerline velocity in the parallel flow system illustrates the low degree of mixing of the supply jet with ambient air in the parallel flow system.

Fig. 6 shows the velocity profiles of the different push-pull ventilation systems. In the section nearest to the push inlet ($x/L = 0.25$), it can be seen that the velocity profiles under the parallel flow system and low velocity system is more uniform than that of the high velocity system. However, the velocity distribution ranges of the parallel flow system and the low velocity system were different. As shown in the Fig. 6(a), the velocity of the parallel flow push-pull ventilation system remained around 0.6 m/s within the range of $z/b \leqslant 1.0$. The low velocity system had a high velocity at the height of $z/b = 1.25$, indicating that the air supply expanded along the z-axis. The larger the expansion range, the higher the mixing degree of the air supply and the ambient air. When $x/L \geqq 0.5$, the velocity of the parallel flow system was greater than the velocity of the low velocity system. This was due to the uneven velocity at the high and low velocity push inlets, which lead to a large amount of mixing with ambient air, decreasing the velocity.

3.1.3. Concentration fields of the contaminant flow

Fig. 7 shows the concentration distribution of contaminant flow under the different push-pull ventilation systems. With the flow of the contaminant from cross sections $x/L = 0.5$ to $x/L = 0.875$, the concentration increased along the z-axis indicating that the supply airflow and the contaminant were continuously mixing during the flow process. In addition, at $x/L = 0.875$, due to the increase in the suction velocity, the diffusion range of the pollutant on the z-axis was smaller than that at $x/L = 0.75$.

At the section $x/L = 0.5$, the contaminant in the three push-pull systems was released at the same velocity and concentration. Fig. 7(a)

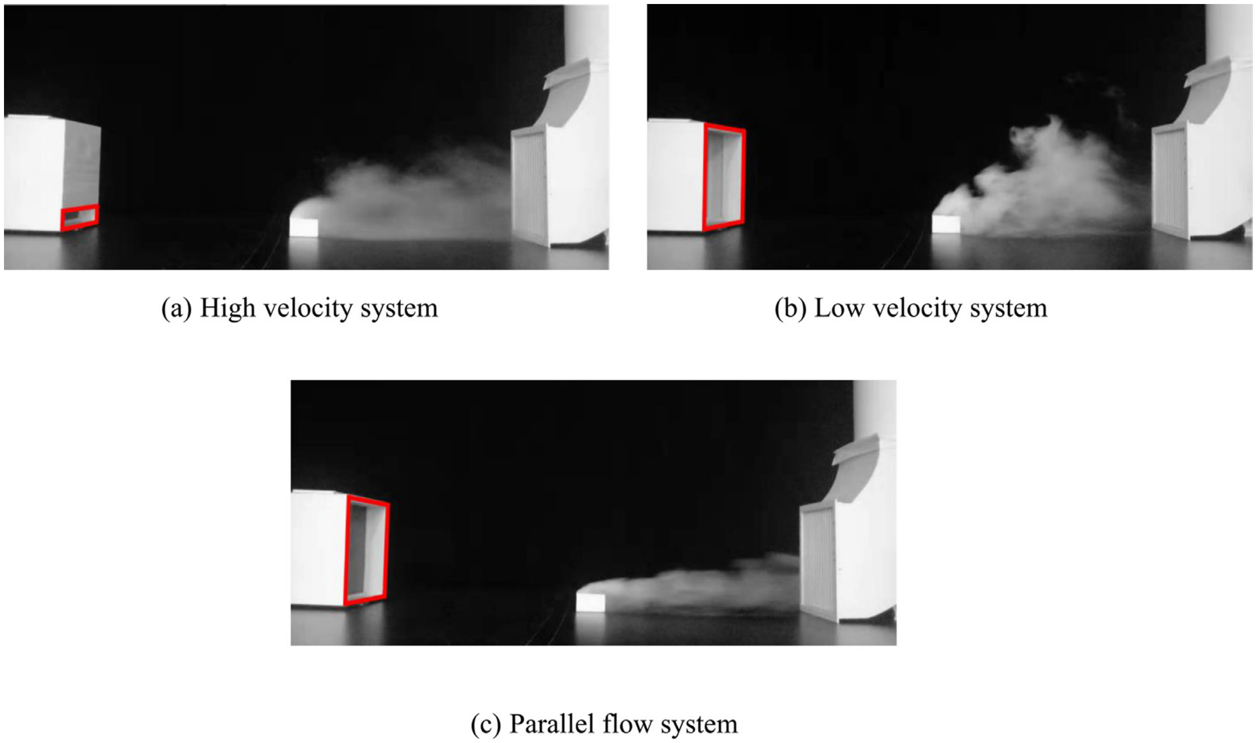


Fig. 4. Visualization of contaminant flow under different push-pull ventilation systems.

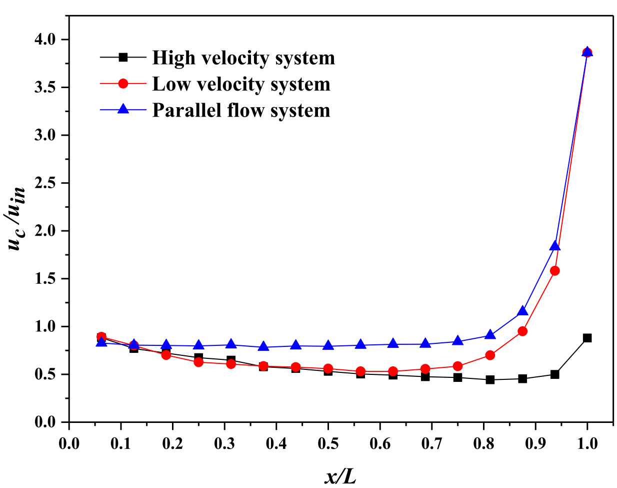


Fig. 5. The dimensionless centerline velocity under different push-pull ventilation systems.

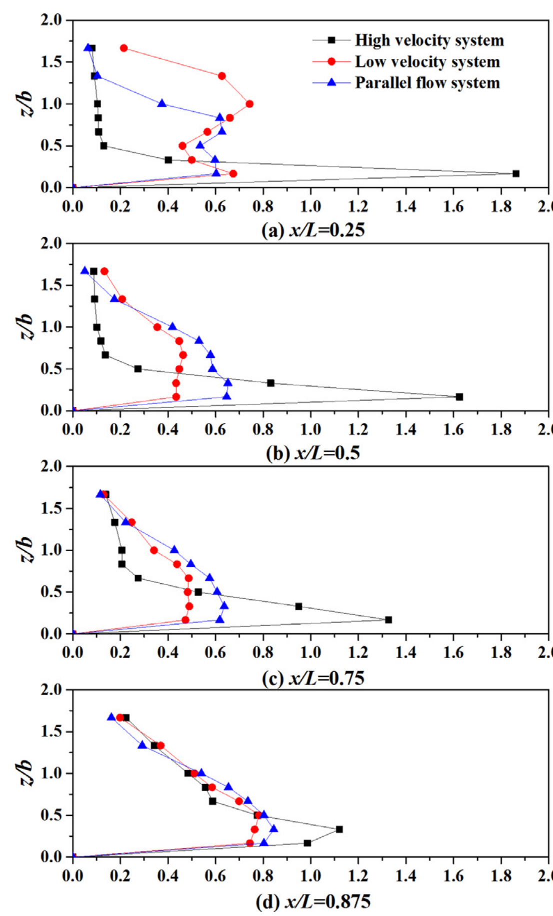


Fig. 6. The velocity profile along the flow path under different push-pull ventilation systems.

shows that the concentration of contaminants was mainly concentrated in the range where z/b < 0.5 under all three systems. This is because the release rate of the pollution source was small and the air supply jet drove the polluted airflow toward the pull hood, preventing it from spreading along the z axis.

On the x/L = 0.75 section (Fig. 7(b)), the contaminant in the high velocity system spread up to z/b = 1.00, the contaminant in the low velocity system spread up to z/b = 1.25, and the contaminant in the parallel flow system was mainly concentrated in the range of z/b < 0.5. On the x/L = 0.875 section (Fig. 7(c)), the contaminant in the high and the low velocity systems was mainly concentrated in the range of z/b < 0.75, while the contaminant in the parallel flow system was mainly concentrated in the range of z/b < 0.5. The range of diffusion of the contaminants in the parallel flow system was significantly lower than the other

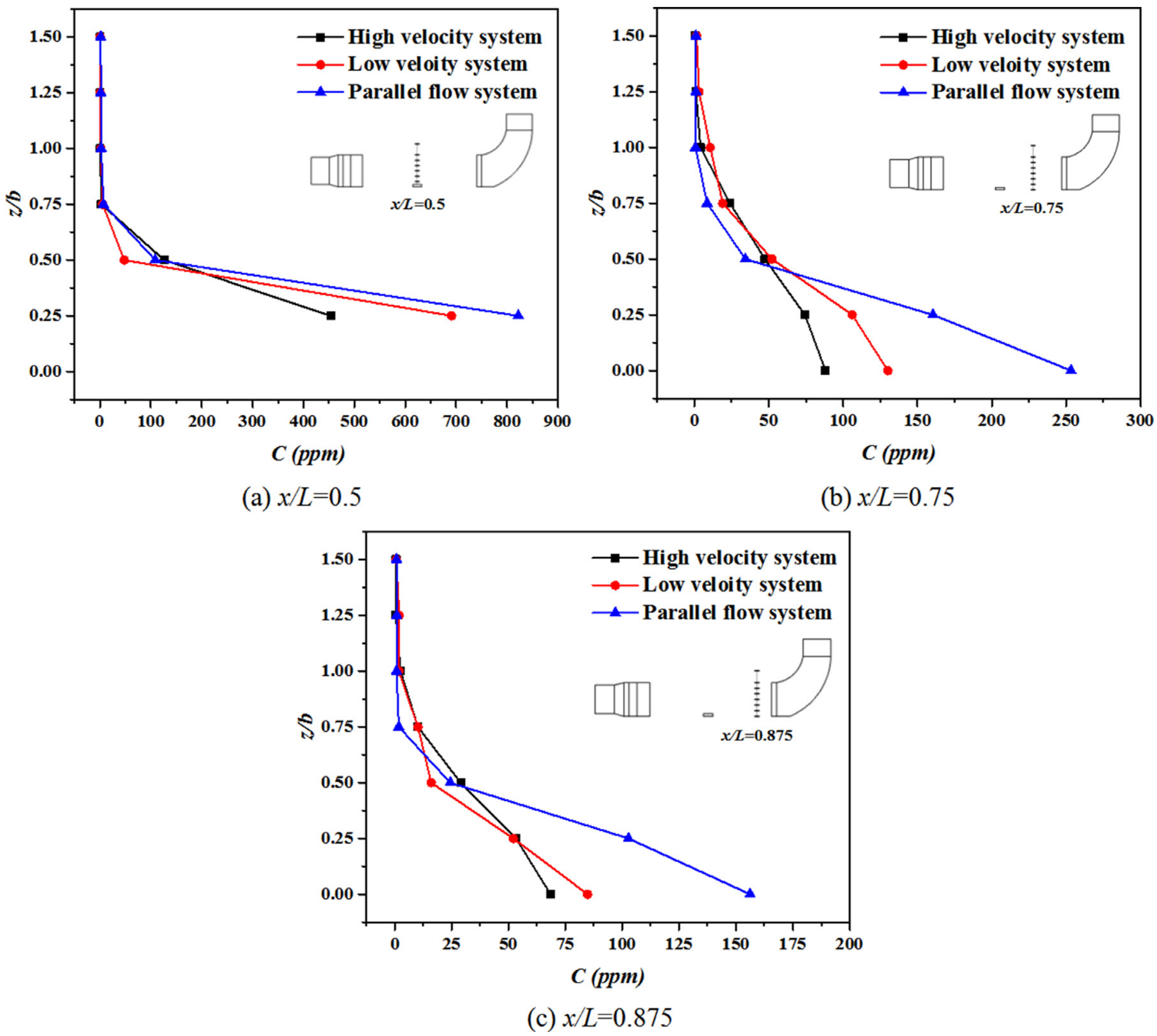


Fig. 7. The concentration distributions of contaminant under different push-pull ventilation systems at different cross sections.

two systems. The smaller the range of diffusion of the contaminants, the lower the degree of mixing of the contaminant airflow and the air supplies, which was consistent with the results in the flow visualization analysis (Fig. 4).

The reason for this phenomenon is that the parallel jets in the parallel flow system have both low velocity, uniformity, and low turbulence intensity (Table 1), which inhibits the mixing of the supply jet, the environmental fluid, and the contaminant flow, thereby reducing the diffusion of the contaminants.

3.2. Economic characteristics of the parallel push-pull ventilation system

In the high velocity system and low velocity system, the contaminated airflow was sufficiently mixed with the supply airflow. In this situation, the pull hood must drain all the air supply and the contaminants to reduce the probability of contaminants entering the ambient air. However, in a parallel flow system, the degree of mixing is small for both the supply airflow and the ambient air, and the supply airflow and the polluted airflow. The diffusion range of the contaminants is small, so it is a question whether the parallel flow system needs the same exhaust flow as the low and high velocity systems to control the contaminants. This question is analyzed in the next section.

3.2.1. Flow visualization under different flow rate ratio

Fig. 8 shows the flow visualization of contaminants under different flow rate ratios. By comparison, as the exhaust air flow rate decreased to 50% based on the flow ratio method, the range of diffusion of the contaminants did not change significantly (Fig. 8(d)). This indicates that for parallel push-pull ventilation systems, the significant reduction of exhaust air flow rate will not affect the dispersion of contaminants.

3.2.2. Velocity field

Fig. 9 shows the dimensionless centerline u_c/u_{in} velocity of the parallel push-pull ventilation system under different flow rate ratios. The trend of the centerline velocity is approximately the same under different flow rate ratios. That is, the decrease in exhaust flow rate did not significantly affect the attenuation of centerline velocity.

Fig. 10 shows the velocity profile along the path of a parallel push-pull ventilation system under different flow ratios. There were no obvious changes in the velocity distribution along the section. Under conditions in which $K \geqq 1{:}2$, the reduction of the exhaust flow rate did not significantly affect the flow field of the parallel push-pull ventilation system.

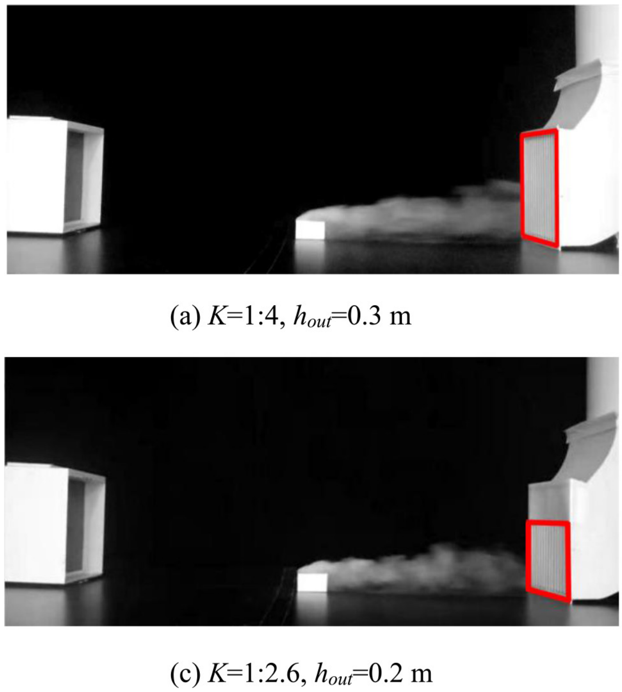


Fig. 8. Visualization of contaminant flow under different flow rate ratios.

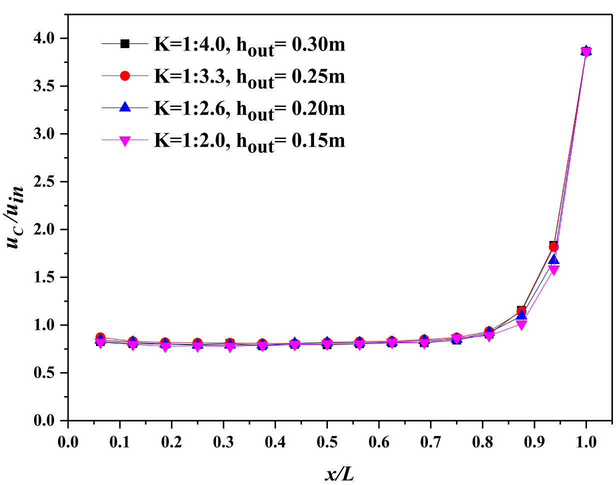


Fig. 9. The dimensionless centerline velocity under different flow rate ratios.

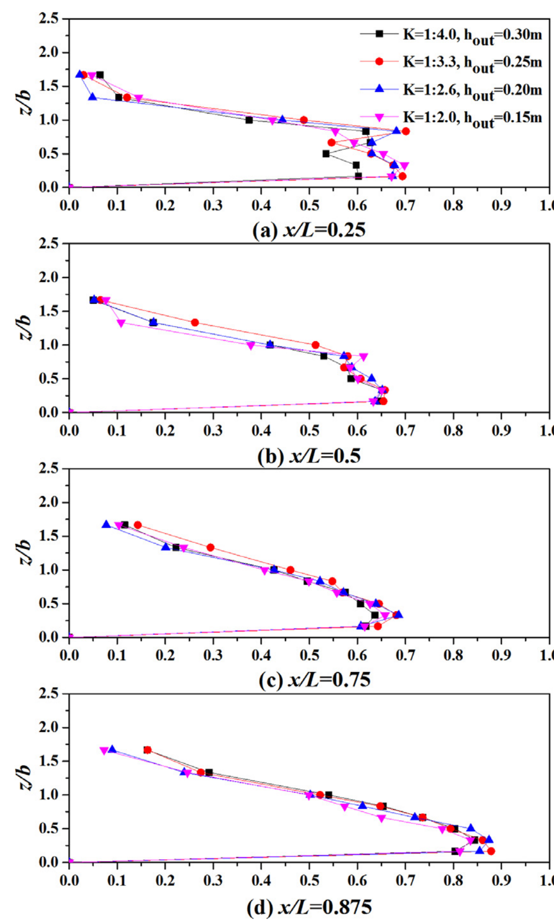


Fig. 10. The velocity profile along the flow path under different flow rate ratios.

3.2.3. Concentration field of the contaminant flow

Fig. 11 shows the concentration distribution of contaminants at different sections under different flow rate ratios. In Fig. 11(a), the $x/L = 0.5$ section shows that the concentration distribution of the pollutants is approximately the same at different flow ratios. As can be seen from the Fig. 11(b) and (c), the concentration distribution of pollutants differed greatly at different flow ratios. However, it is worth noting that although there are some differences in the concentration distribution, the contaminants were still mainly concentrated in the range of $z/b \leq 0.5$. This means that the reduction in flow rate of the pull hood did not change the mixing degree of the contaminants with the supply air.

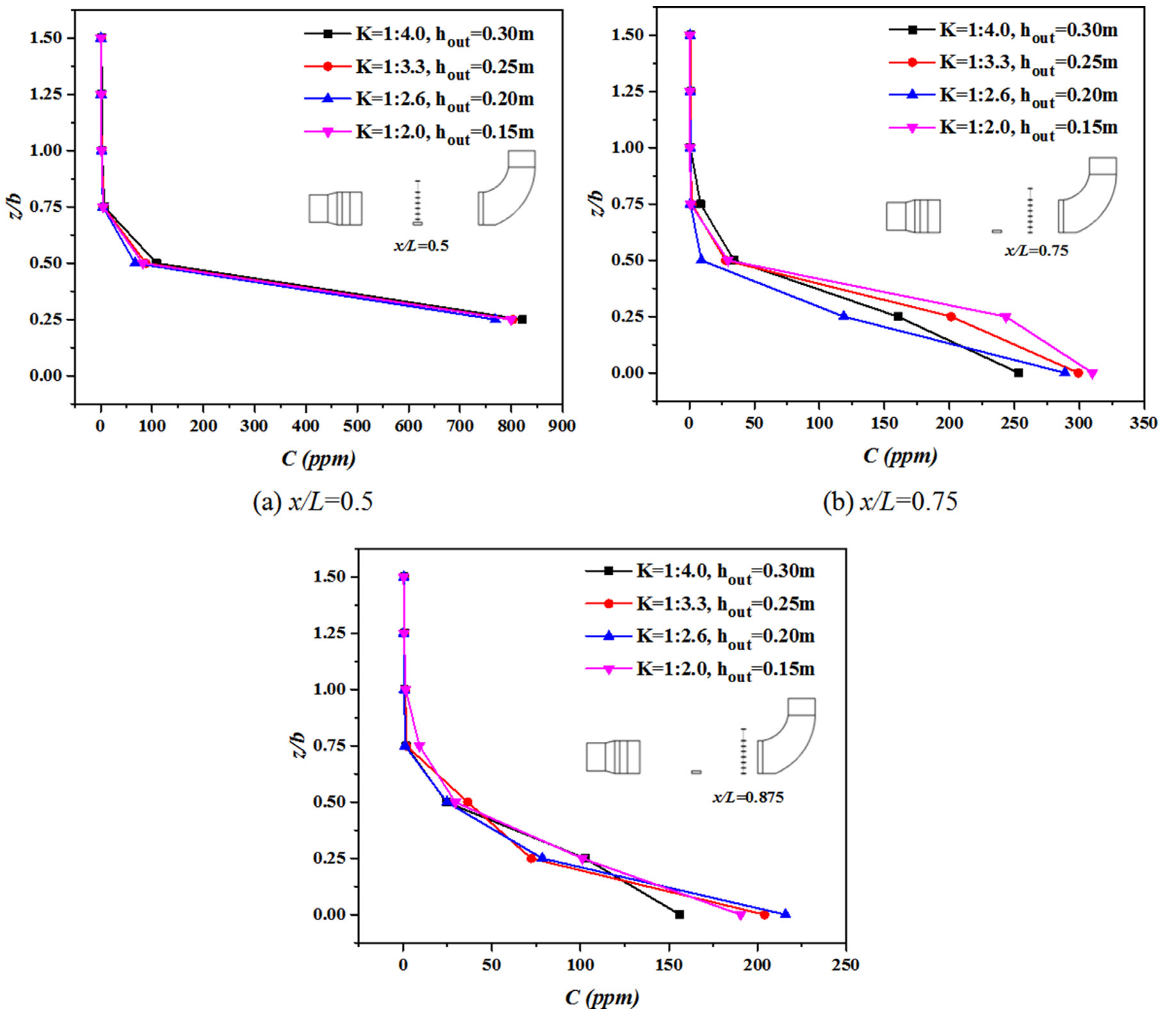


Fig. 11. The concentration distribution of polluted airflow under different flow rate ratios at different cross sections.

4. Discussion

In previous push-pull ventilation design methods, whether it is the capture velocity method proposed by Baturin [46], or the flow ratio method proposed by Hayashi [17], or design methods proposed by ACGIH [16]. The basic principle of these design methods was that when the exhaust hood cannot capture all the supply air, the supply air will carry the contamination into the ambient air. Therefore, the pull hood must absorb all the supply air and contaminants during the design. This design principle is applicable to high or low velocity systems, because experiments have found that in these systems, the contaminated airflow is sufficiently mixed with the supply airflow. When the airflow cannot be completely captured by the exhaust hood, contaminants will enter the ambient air. At this point, the exhaust flow rate must be many times larger than the supply flow rate to reduce the risk of contaminants entering the ambient air.

However, in a parallel flow system, experiments have found that due to the small diffusion range of contaminants, the exhaust flow rate is reduced by 50% on the basis of the flow ratio method, and the contaminants can still be well controlled. This finding can be observed in Fig. 12, in which the capture efficiency of contaminants under different exhaust flow rates is greater than 0.95. That is, for the parallel push-pull ventilation system, the traditional design method of push-pull ventilation system has a large safety margin, because the exhaust hood does not need to drain all the supply airflow, and only needs to remove the polluted airflow from the source and the polluted supply airflow.

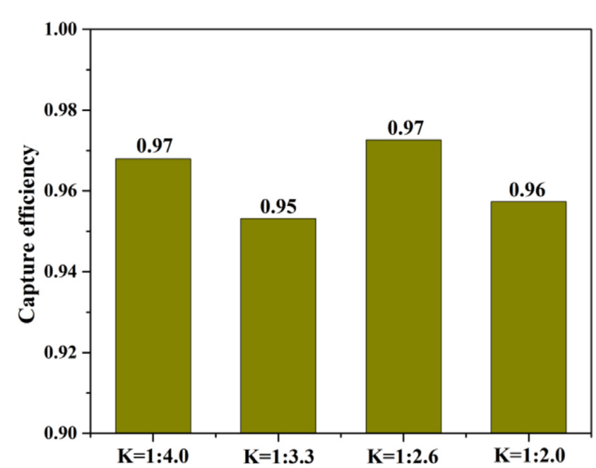


Fig. 12. The capture efficiency of polluted airflow under different flow rate ratios.

4.1. Limitation of the current study and future research

This study shows that the design of parallel flow system with traditional design method has a large safety margin. However, to design an economical and reasonable parallel push-pull ventilation system requires in-depth research on the factors that influence the system performance such as the temperature, size, and location of the pollution source. And according to the similar principle and other methods, a set of detailed design guidelines for different types of pollutants is designed to be applied in practical projects.

5. Conclusions

In this paper, the flow field and concentration field distribution of three commonly used push-pull ventilation systems were experimentally compared: a high velocity system, a low velocity system, and a parallel flow system. On this basis, the economic characteristics of the parallel push-pull ventilation system were explored by reducing the exhaust flow rate. The main conclusions are as follows:

(1) The experimental results showed that in high velocity system and low velocity system, the contaminated airflow was sufficiently mixed with the supply airflow. In this situation, the pull hood must drain all the air supply and the pollution air to reduce the probability of contaminants entering the ambient air. However, compared with the other two systems, under conditions of the parallel air supply jet, the diffusion range of contaminants in the push-pull flow field was the smallest.

(2) Experiments have found that due to the small diffusion range of contaminants when using a parallel flow system, the exhaust flow rate is reduced by 50% on the basis of the flow ratio method, and the contaminants are well-controlled. Therefore, for a parallel push-pull ventilation system, the traditional design method has large safety margin, because the exhaust hood does not need to drain all the supply airflow, and only needs to remove the polluted airflow from the source and the polluted supply airflow.

Conflicts of interest

The authors declare that there is no conflicts of interest..

CRediT authorship contribution statement

Yi Wang: Conceptualization, Methodology, Resources, Writing - review & editing, Supervision. **Mengfan Quan:** Writing - original draft, Software, Validation, Formal analysis, Investigation, Writing - review & editing. **Yu Zhou:** Conceptualization, Methodology, Writing - review & editing, Supervision, Writing - original draft. **Yingxue Cao:** Methodology, Investigation. **Chunbo Xie:** Investigation. **Limei Li:** Investigation.

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