The optimization of personalized ventilation based on a jogger's unsteady breathing cycle

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Abstract. Jogging is increasingly popular as a robust activity. However, the concentration of the exhaled carbon dioxide exposes to human during the outdoor exercise. Thus, the healthy air supply is in growing demand. By changing vertical and horizontal locations and air supply rate, an additional airflow field can alter the performance of local ventilation. This work assumes the addition of an auxiliary personalized ventilation device (PV), under various specific air supply rates, distances and angles to investigate the optimization of concentration dissipation and microclimate promotion. The results show the flow field characteristics and concentration distribution in respiration area under an unsteady breathing process. Based on the orthogonal test, the condition with those determined parameters (the supply velocity: 3m/s, distance from the nostrils: 2cm and the angle: + 20 °) has the optimal performance. Moreover, the velocity of air supply is the primary factor among other factors that influence the performance of pollutant removal, through the sensitive test.

1. Introduction

Most of the early investigations focused on the respiration behavior of seated occupants. Respiratory can be described by a simplified function (Murakami and Zeng 1997). The characteristics of breathing cycles in an air-conditioned chamber were revealed to investigate the flow features of the contaminant dispersion (Zhu 2005).

With the development of computers and software, a computer-simulated person is widely adopted to carry out the elaborate and accurate experiment. The focus of researches deflects from a single occupant situation to multi-occupant conditions based on the spread of indoor pollutant. (Qian et al. 2008). Simulation is carried out extensively in hospital, school chambers and waiting rooms of public transportation. Apart from flow fields, researchers consider exhaustive factors such as metabolic heat,
humidity, occupancy (Gu Jiefan 2017) and thermal effect in the target space (Spengler and Chen 2000). Poussou (2010) began to investigate the relationship of flow feature and concentration distribution of a moving occupant. Recently, the microclimate around the respiration region is brought up to evaluate the contaminant distribution (Ito 2014). Moreover, uncertainty and sensitivity analysis can investigate the behavior of these influential factors (Pang 2018).

However, there is little research on the concentration distribution of the breathing zone while running. Therefore, this paper assumes a personalized ventilation device as an additional flow to alter the existing flow fields via CFD simulation and evaluates the optimization of PV based on three parameters. The designed experiments are listed by the concept of single-factor analysis and orthogonal test. The results are carried out via a rational index named SVE5. Finally, conclude the optimal condition and the sensitive sequence.

2. Outline of methods

2.1. Assumption of breathing cycle

A simplified breathing cycle contains inhalation, exhalation and breathing break. Divide it into eight stages, shown in Fig.1. Regarding the previous work, the volume of inhalation is assumed to be 0.3 L/s. For simplicity, we presuppose that the jogger breathes through the nose, and a single area of the nostrils is 2.0988 cm².

2.2. An index for evaluation

The Scale for Ventilation Efficiency 5(SVE5) is taken to evaluate the performance of the contaminant dilution. The equation of SVE5 is:

\[
SVE5 = \frac{C(x,n)}{C_0(n)}
\]  

Where \( n \) represents the number of exhaust vents, \( C(x,n) \) represents the concentration at a point \( x \) obtained. \( C_0(n) \) is the initial concentration.

2.3. Analysis method

Both single-factor and multi-factor analysis are taken to evaluate the simulation results. It facilitates to quickly grasp the trend of its influence on the performance by altering the value of a single parameter. However, the optimized result is only corresponding to a condition where any other factors keep a constant value. Once over two variables are taken into consideration, the optimization would be inaccurate and unacceptable. Therefore, the multi-factor analysis must be carried out.

3. Outline of simulation

3.1. Physical model

Due to the geometric symmetry, this study builds half of the 3D head model, which emphasizes the outline of nostrils while neglecting any other facial features. The scale of the model is the same as that of reality. For a full development of flow fields, a relatively large computational domain is modelled as shown in Fig.2. Set the installation distance from the nose as 2, 4, 6, 8, 10 cm. The installation angle between the centre of the nose and the device changes from -20°, -10°, 0°, 10°, 20°(shift to an anticlockwise direction is positive).
3.2. Boundary details

The whole study is set up in the summer night with the background air velocity of 2.0 m/s. The natural air contains CO$_2$ concentration of 300ppm (Zhu XiYang 2015). The ratio of CO$_2$ concentration to the exhaled air is 0.02522. The rate of air supply is set as 1.0, 1.5, 2.0, 2.5, 3.0 m/s.

3.3. CFD method selection

The standard k-$\varepsilon$ turbulence model with revised closure coefficient is selected. And the standard wall function is chosen, because it ignores details of the flow in the low-Reynolds-number region below the first-layer grids, and ignore their effects on the entire wall-bounded flow as well (Abe, Kondo, & Nagano, 1994; Abe, Kondo, & Nagano, 1995).

4. Results

To investigate the performance of contaminant removal, analyse the flow fields, and the efficiency of contaminant dilution via simulation.

4.1. Characteristics of human inhalation and exhalation

The sequence of illustration is based on the breathing cycle to describe the feature of flow fields during exhalation and inhalation. There are four phases in the exhalation period, from A to D. The background air flows around cylinder due to the nose, and generates a relatively large eddy. This clash of exhaled air and pure air is regarded as a disturbance on development of the eddy just below nostrils. Four phases from E to H constitute the inhalation process. The head-on wind will be immediately induced into nostrils, as a negative pressure vent, which expects a trifling portion of exhaled CO$_2$. 
4.2. Flow fields

For understanding the effect of each parameter well, the characteristics of flow fields are demonstrated based on the single-factor analysis. As shown in the Fig.4, the higher the velocity is, the weaker the eddy is. At the velocity of 1.0 m/s, the clash of exhaled air and supply air is limited to nostrils for lacking adequate momentum. Consequently, the flow cannot reach the space where the eddy grows or remove the contaminants out of the inhalation region. On one hand, significant flow around the nose happens when the angles are -20° and 0°. This stream blows downwards and skips the eddy zone. Thus, the eddy grows without disturbance and limitation. On the other hand, the air flow blows directly to the eddy zone under the angle of + 20°, generating a windward side below the nostrils and hampering the growth of eddy. The effect of installation distance on the distribution of flow fields is similar to the impact of airflow velocity because of the real entrainment phenomena. However, the flow around a cylinder is more significant than the entrainment phenomena due to a relatively small distance from the air supply.
Based on the features of breathing cycles, the mainly concerned aspect is the residual concentration of the exhaled CO2, which is equal to the amount of CO2 that may be inhaled at the impending inhalation phase. Besides that, only the nostrils are considered as the exhaust openings. According to the previous researches (Zhu 2005), the respiration area of the jogger is limited to the region of the head. Consequently, the targeted region is limited in the region shown in the Fig.7, which is selected by the widest influenced region based on the analysis of flow fields. The SVE5 is adopted to evaluate this phenomenon among various conditions.

Fig.7 The targeted breathing region

Fig.8 Velocity of air supply vs. SVE5

4.3.1 The effects of air-supply speed
Fig.8 shows the relationship of velocity and SVE5. An increasing velocity corresponds with a smaller value of SVE5, reflecting a more significant performance of contaminant removal. So, the flow of low speed lacks an adequate momentum to remove the contaminants out of the respiration region, and this can demonstrate the distribution of contaminant concentration. Moreover, there is no apparent discrepancy on the SVE5 among designed conditions, which means the limited effect of velocity.

Fig.9 Installation distance vs. SVE5
Fig.10 Installation angle vs. SVE5

4.3.2 The effects of installation horizontal distance
From the Fig.9, there is an apparent downward trend in the removal performance along with the distance increment. Because of the entrainment phenomena, the air flow from a relatively long distance loses momentum before reaching the eddy zone, and causes a small even negligible impact on the contaminant concentration. With the distance increases, the SVE5 increases. The reason is the flow around a cylinder is so significant that the stream of pure air directly dashes downwards instead of removing the contaminant of the respiration region.

4.3.3 The effects of installation angle
A small discrepancy exists among the angle of -20°, -10°, 0°, 10°, due to the similar phenomena of flow around the nose shown in Fig.10. Because the air flow directly blows to the eddy zone, the capability of contaminant removal is spurred in the angle of +20° and the air flow severely disturbs the eddy development and dilutes the concentration of the target space.
4.4 Orthogonal analysis

Through the analysis above, we can conclude each optimal result under a single variable while other parameters are fixed. Considering the complication of experiment times and economical cost, an orthogonal test needs carrying out for multi-factor analysis. The orthogonal list is designed as L25(5³). As shown in Table 1, the value k_{ij} represents the average of total SVE5 under level i in the column j. The smallest k_{ij} is regarded as the optimal level by comparison of numbers under a certain factor (Yifei Wu, 2018). And the R_j represents the difference between the maximum and minimum average values among the levels in the same column, which indicates the sequence of sensitiveness of several parameters. R_j can be described by the equation:

\[ R_j = \max(R_{1j}, R_{2j}, ..., R_{kj}) - \min(R_{1j}, R_{2j}, ..., R_{kj}) \]  

As shown in Table 1, the optimal combination is A_5 B_5 C_1 and the sensitive sequence is A (the velocity of air supply) > C (the distance of installation) > B (the angle of installation), which can be regarded as a rational reference while improving the performance.

|   | A  | B  | C  | SVE5  |
|---|----|----|----|-------|
| 1 | 1  | 1  | 1  | 0.1872|
| 2 | 1  | 2  | 2  | 0.1763|
| 3 | 1  | 3  | 3  | 0.1902|
| 4 | 1  | 4  | 4  | 0.1941|
| 5 | 1  | 5  | 5  | 0.1931|
| 6 | 2  | 1  | 2  | 0.1381|
| 7 | 2  | 2  | 3  | 0.2326|
| 8 | 2  | 3  | 4  | 0.2018|
| 9 | 2  | 4  | 5  | 0.1895|
|10 | 2  | 5  | 1  | 0.2228|
|11 | 3  | 1  | 3  | 0.1792|
|12 | 3  | 2  | 4  | 0.1561|
|13 | 3  | 3  | 5  | 0.2202|
|14 | 3  | 4  | 1  | 0.2119|
|15 | 3  | 5  | 2  | 0.1901|
|16 | 4  | 1  | 4  | 0.1853|
|17 | 4  | 2  | 5  | 0.1692|
|18 | 4  | 3  | 1  | 0.1541|
|19 | 4  | 4  | 2  | 0.2462|
|20 | 4  | 5  | 3  | 0.2267|
|21 | 5  | 1  | 5  | 0.1742|
|22 | 5  | 2  | 1  | 0.1578|
|23 | 5  | 3  | 2  | 0.1688|
|24 | 5  | 4  | 3  | 0.1608|
|25 | 5  | 5  | 4  | 0.2351|

\[ k_1 = 0.2243 \quad 0.1882 \quad 0.1728 \]
\[ k_2 = 0.1982 \quad 0.1970 \quad 0.1784 \]
\[ k_3 = 0.1826 \quad 0.1915 \quad 0.1870 \]
### 5. Conclusion

This study carries out a series of simulation based on three variables and adopts SVE5 to evaluate the performance of contaminant removal in respiration region according to single-factor and multi-factor analysis.

1. A personalized ventilation device has a significant impact on flow fields. The additional airflow not only disturbs the development of eddy but also provides pure air to dilute the concentration of contaminants while running.

2. The SVE5 decreases with the augment of the velocity of air supply. In the meanwhile, the performance of contaminant removal tends to be flat, indicating a limitation of adjustment. The distance has a threshold value on the capability of pollutant removal. The impact of the angle on contaminant dilution depends on the positive or negative degree. When the angle of +20 degree, the airflow directly dashes into the respiration region and generates a windward side, which strengthens the ability of contaminant removal.

3. The multi-factor analysis reveals that the optimal combination among various conditions, whose parameters are respectively set as the velocity: 3m/s, angle: +20 degree and the distance: 2cm. Moreover, the speed of the air supply of personalized ventilation device is the most sensitive factor that alters the performance of contaminant removal.

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