

Human re-inhalation ratio under typical conditions

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Abstract. Inhaled air quality is directly related to occupants' health and quality of life. In this study, a numerical breathing thermal manikin was employed, who breathed following a sinusoidal function, with 10 breathing cycles per minute. Each cycle was composed of three phases: 2.5 s inhalation, 2.5 s exhalation, and 1 s pause. The influence of pulmonary ventilation rate, breathing mode and breathing cycle period on the re-inhalation ratio were studied by computational fluid dynamics (CFD) technology in combination with the species transport model. It was found that increasing the pulmonary ventilation rate led to a lower re-inhalation ratio. The re-inhalation ratio is the largest with the value of 0.91%, when exhaled through the mouth and inhaled through the nose. The re-inhalation ratio was up to 23.9 % lower with a pause of 1 s in the breathing cycle than without pause. When the pulmonary ventilation rate increased from 6 L/min to 8 L/min, the re-inhalation ratio decreased from 0.91% to 0.71%. This information would be an important basis for the development of the human microenvironment control and technologies, including intelligent, personalized air supply devices, local air supply and exhaust methods, and other advanced ventilation and airflow technologies.

1 Introduction

Inhaled air quality is directly related to occupants' health and quality of life. Before being inhaled by occupants, outdoor (clean) air is mixed with indoor air pollutants, such as Volatile Organic Compound, particulate matters, ozone, microorganism, and exhaled air. Freely exhaled air is typically made up of 74.3% nitrogen, 15.3% oxygen, 6.2% water vapor and 4.2% carbon dioxide.[1] Although most of the exhaled air is diluted into the surrounding air, but there is still a small portion being re-inhaled by the occupants. Re-inhaled air would change the fraction of the components of the inhaled air and thus deteriorate inhaled air quality. Therefore, it's necessary to determine the re-inhalation ratio.

The parameter settings of the human breathing function such as breathing frequency, pulmonary ventilation rate and breathing mode, are crucial to accurately determine the re-inhalation ratio. Some human subject tests have been conducted to measure the characteristics of the natural breathing flow. Gupta et al.[2] indicated that although the time of inhalation was shorter than that of exhalation, the normal breathing flow rate could be best represented by a sine wave for the human subjects. A study by Ai et al.[3] reported that the average breathing cycle period for mouth exhalation from five human subjects ranged from 2.1 to 3.5 s when standing, which was quite different from the most widely used sinusoidal cycle of "2.5 s inhalation + 2.5 s exhalation + 1 s pause". Many studies used a cycle without pause, such as "2 s inhalation + 2 s exhalation."

Melikov and Kaczmarczyk[4] pointed that the re-inhaled air was up to 19% lower with a pause in the breathing cycle than without pause when exhaled through the mouth and inhaled through the nose. The reason was that the exhaled air was removed from the breathing zone during a short pause between exhalation and the following inhalation. Therefore, it's important to simulate the realistic breathing cycle when study the re-inhaled air.

Four breathing modes were usually used in past studies, including mouth inhalation/mouth exhalation, nose inhalation/nose exhalation, mouth inhalation/nose exhalation and nose inhalation/mouth exhalation. The most widely used breathing mode was nose inhalation and nose exhalation. Murakami[5] pointed out that the percentage of exhaled air in the next inhalation is 16.2% when respiring only through the nose, which is higher than the value of 10% in the simulation by Gao and Niu.[6] In addition, Gao and Niu[6] showed that the re-inhalation ratio is almost zero when breathing only through the mouth, because the exhaled air can be brought away by the horizontal buoyant jet from the mouth. In this study, the computational fluid dynamics (CFD) technology in combination with the species transport model was used to investigate the dynamic changes of the human breathing process under typical conditions. The re-inhalation fraction index (RF) was introduced to study the effects of breathing mode, breathing cycle period and pulmonary ventilation rate on human re-inhalation ratio.

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2 Methodology

2.1 Computational geometry

As shown in Figure 1, a full-scale test room with dimensions of 5 m-length \times 4 m-width \times 2.8 m-height was used to investigate the human re-inhalation ratio under typical conditions. The ventilation mode of the room was displacement ventilation, in which the air inlet with dimensions of 0.4 m-length \times 0.2 m-height was located at the bottom of the side wall and the air outlet with the same dimensions was located at the top of the opposite side wall. A numerical breathing thermal manikin with the height of 1.68 m, was located in the middle of the room facing the air inlet.

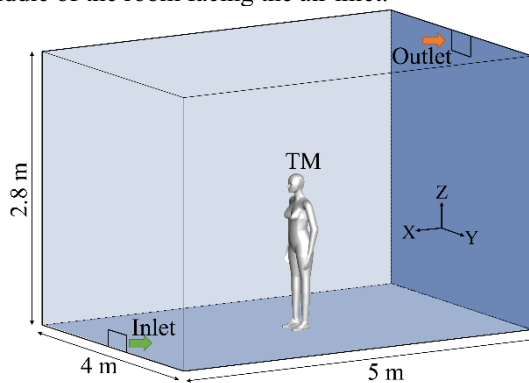


Fig. 1. A schematic layout of the full-scale test room and the location of the thermal manikin.

2.2 Boundary conditions

The air inlet of the room was set as the velocity inlet with the speed of 0.1 m/s and the temperature of 22 °C. The air outlet of the room was set as the pressure outlet, and the backflow total air temperature was set to 30 °C. The floor, ceiling and walls around the room were set to be no-slip, stationary and adiabatic. The mouth open area was 234.7 mm² and nostrils open area was 78.4 mm². The skin temperature of different body parts was different, as shown in Table 1. The thermal manikin breathed following a sinusoidal function, as shown in Figure 2. One breathing cycle was consisted of 2.5 s inhalation, 2.5 s exhalation and 1 s break. Three breathing modes were used in this study, including nose inhalation/nose exhalation, mouth inhalation/nose exhalation and nose inhalation/mouth exhalation. The human pulmonary ventilation rate is related to the working intensity and can be define as 6-9 L/min. The main cases of simulation in this study are listed in Table 2

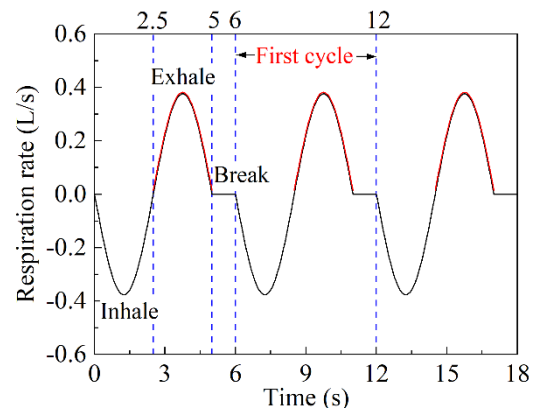


Fig. 2. The assumption of the breathing flow.

Table 1. The skin temperature of different body parts

Body segments	Temperature (°C)
Head	32.7
Mouth	32.7
Nose	32.7
Upper body	32.7
Arm	32.8
Leg	32.8
Foot	30.5

Table 2. A list of the main simulation cases.

Cases	Breathing mode	Pulmonary ventilation rate (L/min)	Breathing cycle period (s)
1	nose inhalation/mouth exhalation	6	2.5 + 2.5 + 1
2	nose inhalation/nose exhalation	6	2.5 + 2.5 + 1
3	mouth inhalation/nose exhalation	6	2.5 + 2.5 + 1
4	nose inhalation/mouth exhalation	7	2.5 + 2.5 + 1
5	nose inhalation/mouth exhalation	8	2.5 + 2.5 + 1
6	nose inhalation/mouth exhalation	6	2.5 + 2.5 + 0.5
7	nose inhalation/mouth exhalation	6	2.5 + 2.5

2.3 Data analysis

The natural tracer gas Carbon Dioxide (CO₂) generated from the human was selected to represent the exhaled air, with a fraction of 4%. The sampling surface was respectively located at the mouth and nostrils, when inhaled through the mouth and nose. To investigate the human re-inhalation ratio under typical conditions, the re-inhalation fraction index (RF) was introduced to evaluate. The re-inhalation fraction index (RF) is defined in Eq. (1).

$$RF = \frac{\int_0^t Q_{in}(t)C_{in}(t)dt}{\int_0^t Q_{ex}(t)C_{ex}(t)dt} \quad (1)$$

where C_{in} is the CO₂ concentration measured during the inhalation process, %; C_{ex} is the CO₂ concentration of 4 % in the exhaled air; Q_{in} is the inhaled flow rate during the inhalation process, m³/h; Q_{ex} is the exhaled flow rate during the exhalation process, m³/h.

3 Results

3.1 Influence of the breathing mode

Figure 3 shows the re-inhalation fraction index (RF) and dimensionless re-inhalation concentration during five breathing cycles (6~36 s) under the four breathing modes. As explained in the Section 2, considering the influence of the background concentration, the RF during the first breathing cycle was selected to indicated the human re-inhalation ratio.

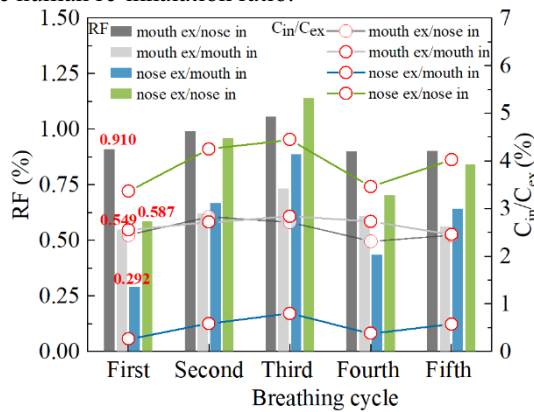


Fig. 3. The re-inhalation fraction index (RF) and dimensionless re-inhalation concentration under different breathing modes: ‘ex’ means exhalation and ‘in’ means inhalation.

Firstly, the RF under the four breathing modes were mostly in a range of 0.3%~1.0% during the five breathing cycles. The re-inhalation ratio is the largest at the value of 0.91% with the breathing mode of mouth exhalation and nose inhalation, while the lowest at 0.3% with the breathing mode of nose exhalation and mouth inhalation. As seen in Figure 3, during the first breathing cycle, the breathing mode with the largest concentration was different from that with the largest RF, but the breathing modes with the lowest concentration and RF were the same. This observation may be explained by that the RF was dominated by the inhaled flow rate (higher inhaled flow rate) under the breathing mode of mouth exhalation and nose inhalation, but by the inhalation concentration (lower inhalation concentration) under the mode of nose exhalation and mouth inhalation, as implied by the definition of the re-inhalation fraction index (see Eq. (1)). These findings indicated that the assessment of human re-inhalation ratio using dimensionless re-inhalation concentration would lead to a misunderstanding of how the exhaled air influenced the inhaled air quality.

Secondly, the variations of both RF and dimensionless re-inhalation concentration over the five breathing cycles were mostly small. Relatively large differences occurred with the two breathing modes of nose

exhalation and mouth/nose inhalation. Particularly, the exhaled air from the nose with a downward direction was more easily accumulated in the breathing zone over time, which was then blown away by the exhaled air of the next breathing cycle. Overall, the re-inhalation ratio was determined by the combined effect of the fluctuating concentration of the exhaled air and the gradual increase of the background concentration. Although the re-inhalation ratio was relatively small in magnitude, the re-inhalation of the exhaled air would potentially deteriorate inhaled air quality.

3.2 Influence of the pulmonary ventilation rate

Figure 4 shows the influence of pulmonary ventilation rate on the re-inhalation fraction index (RF) and dimensionless re-inhalation concentration. It can be seen that increasing the pulmonary ventilation rate would decrease both the RF and dimensionless re-inhalation concentration with the breathing mode of mouth exhalation and nose inhalation. Among breathing cycles, the influence of pulmonary ventilation rate on RF and dimensionless re-inhalation concentration was identical. Compared to the Case of 6 L/min, increasing the pulmonary ventilation rate to 8 L/min greatly decreased the RF from 0.91% to 0.71%. The reason was that, although the pulmonary ventilation rate increased, the re-inhalation ratio was mainly influenced by the concentration effect (lower re-inhalation concentration). The dimensionless re-inhalation concentration was 1.99% with the pulmonary ventilation rate of 8 L/min, which was 18.8% lower than that of 6 L/min. Such a large decrease was probably due to a stronger momentum of the exhaled air when the pulmonary ventilation rate increased, which penetrated the envelope of the body thermal plume and was diluted into the room air.

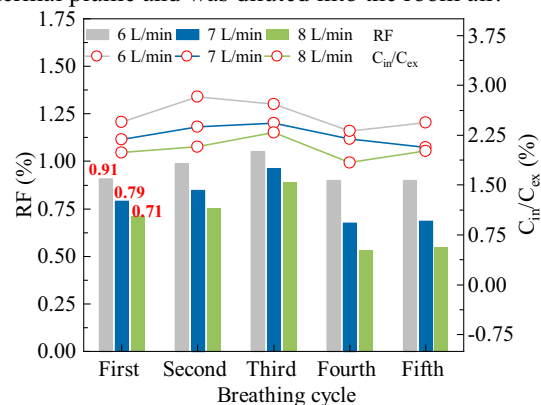


Fig. 4. The re-inhalation fraction index (RF) and dimensionless re-inhalation concentration under different pulmonary ventilation rates with the breathing mode of mouth exhalation and nose inhalation.

3.3 Influence of the breathing cycle period

The influence of breathing cycle period on the re-inhalation fraction index (RF) and dimensionless re-inhalation concentration is shown in Figure 5. The breathing cycle period of 2.5-2.5-1.0 seconds was widely used in past studies, and the break time would be shortened from 1.0 s to 0.5 s and 0 s to investigate the

re-inhalation ratio in present study. It can be found that the reduction of the break time led to the increase of the re-inhalation ratio for the breathing mode of mouth exhalation and nose inhalation. When the breathing break time decreased from 1.0 s to 0 s, the re-inhalation ratio and dimensionless re-inhalation concentration increased respectively from 0.91% and 2.45% to 1.20% and 3.09% for the first breathing cycle. This should be ascribed to that, when increasing the break time, the exhaled air from the mouth with a relatively low momentum moved upward and away by the human thermal plume and the re-inhalation ratio was therefore reduced. However, due to the complex interaction between exhaled air and body thermal plume in the breathing zone, decreasing the breathing break time did not always lead to an increase of the dimensionless re-inhalation concentration.

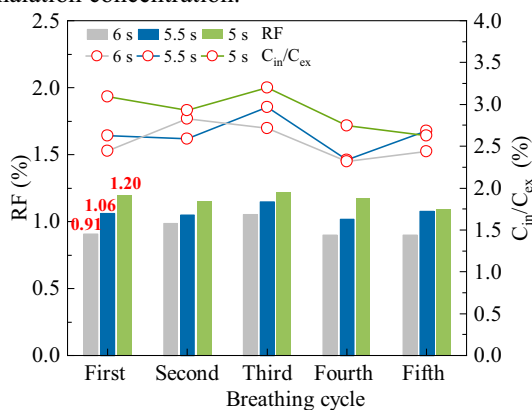


Fig. 5. The re-inhalation fraction index (RF) and dimensionless re-inhalation concentration under different breathing cycle periods.

Discussion

According to the past studies, the ratio of regained air was up to the percentage of ten, which was much higher than the value in this study. When breathing only through the nose, the human re-inhalation ratio (evaluated by inhaled concentration) measured by Gao and Niu[6] is 10%, and 16.2% by Murakami[5], which were respectively 16 and 26.5 times than the value of 0.292% in this study. The discrepancy may be due to the different of the breathing parameter settings, such as breathing cycle period, pulmonary ventilation rate. It was particularly important for a reliable simulation of the breathing cycle period when studying the re-inhalation ratio. A database should be established including human breathing parameters of different ages, genders, working intensity, living regions and so on. Furthermore, the evaluation method, nose open area, sampling location and method, body posture may be considered to influence the re-inhalation ratio. Re-inhalation fraction index (RF) was selected to evaluate the percentage of re-inhalation of one's own exhaled air in this study, which was determined by the breathing flow rate and inhaled concentration together. Compared with the dimensionless re-inhalation concentration, the re-inhalation fraction index (RF) is more reliable. In addition, for the experiments, the re-inhalation concentration obtained only by a single point from the

centre of the mouth and nose, was higher than the realistic results due to the inhomogeneity and instability of respiratory airflow.

Conclusion

In this study, a numerical breathing thermal manikin was employed to investigate the influence of the breathing mode, breathing cycle period and pulmonary ventilation rate on the human re-inhalation ratio. The main findings arising from this study are as follows:

(1) Increasing the pulmonary ventilation rate led to a lower re-inhalation ratio. When the pulmonary ventilation rate increased from 6 L/min to 8 L/min, the re-inhalation ratio decreased from 0.91% to 0.71%. Compared to the dimensionless re-inhalation concentration, The re-inhalation fraction index (RF) is a more reliable and accurate evaluation index.

(2) The re-inhalation ratio is the largest with the value of 0.91%, when exhaled through the mouth and inhaled through the nose. The results agreed with the conventional wisdom that human mainly inhaled through the nose and exhaled through the mouth.

(3) The reduction of the break time led to the increase of the re-inhalation ratio from 0.91% to 1.20%. It is particularly important to have a reliable simulation of the breathing cycle period when studying the re-inhalation ratio.

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