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Research Article

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A simple method for differentiating direct and indirect exposure to exhaled contaminants in mechanically ventilated rooms

Chun Chen[1,2] (✉), Bin Zhao[3,4], Dayi Lai[5], Wei Liu[6]

1. Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, N.T. 999077, Hong Kong, China
2. Shenzhen Research Institute, The Chinese University of Hong Kong, Shenzhen 518057, China
3. Department of Building Science, School of Architecture, Tsinghua University, Beijing 100084, China
4. Beijing Key Laboratory of Indoor Air Quality Evaluation and Control, Tsinghua University, Beijing 100084, China
5. Tianjin Key Lab of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
6. School of Civil Engineering, ZJU-UIUC, Zhejiang University, Haining 314400, China

Abstract

Many airborne infectious diseases can be transmitted via exhaled contaminants transported in the air. Direct exposure occurs when the exhaled jet from the infected person directly enters the breathing zone of the target person. Indirect exposure occurs when the contaminants disperse in the room and are inhaled by the target person. This paper presents a simple method for differentiating the direct and indirect exposure to exhaled contaminants in mechanically ventilated rooms. Experimental data for 191 cases were collected from the literature. After analyzing the data, a simple method was developed to differentiate direct and indirect exposure in mixing and displacement ventilated rooms. The proposed method correctly differentiated direct and indirect exposure for 120 out of the 133 mixing ventilation cases and 47 out of the 58 displacement ventilation cases. Therefore, the proposed method is suitable for use at the early design stage to quickly assess whether there will be direct exposure to exhaled contaminants in a mechanically ventilated room.

Keywords

ventilation,
non-isothermal jet,
particles,
droplets,
indoor environment

Article History

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1 Introduction

The airborne transmission of infectious diseases in indoor environments has been become a major public health concern worldwide (Wei and Li 2016). An infected person can exhale particles carrying infectious viruses when breathing, coughing, or sneezing (Nicas et al. 2005). These airborne contaminants can be transported to the breathing zone of other persons via the air in a room. If the infectious contaminants are inhaled by susceptible individuals, cross infection of the disease may occur (Morawska 2006). Many outbreaks of airborne infectious diseases have occurred indoors through this transmission route, including influenza (Moser et al. 1979), measles (Bloch et al. 1985), tuberculosis (Menzies et al. 2000), and severe acute respiratory syndrome (SARS) (Olsen et al. 2003). Furthermore, a strong association has been found between the indoor airflow pattern and transmission of airborne infectious diseases (Li et al. 2007). Therefore, it is crucial to investigate the indoor exposure to exhaled contaminants in mechanically ventilated rooms to improve air distribution design and reduce the risk of infection.

Numerous experimental studies have been carried out to measure person-to-person contaminant transport in mechanically ventilated rooms. Bjørn and Nielsen (2002), Olmedo et al. (2012, 2013), Nielsen et al. (2014), and Liu et al. (2017) studied the impact of inter-person distance on personal exposure to exhaled contaminants in displacement, mixing, and downward ventilated rooms. Qian et al. (2006, 2008), and Yin et al. (2011) investigated the effectiveness of

E-mail: chunchen@mae.cuhk.edu.hk

mixing, downward, and displacement ventilation in removing exhaled contaminants in simulated hospital wards. Nielsen et al. (2007) investigated the impact of personalized ventilation on personal exposure in a room ventilated by textile terminals. Lai and Wong (2010, 2011) measured transient exposure to exhaled particles in small-scale laboratory chambers with different ventilation modes. Nielsen et al. (2010) investigated the influence of ventilation rates on person-to-person contaminant exposure in a hospital ward. Cao et al. (2015) proposed protected zone ventilation for reducing personal exposure to exhaled contaminants indoors. These studies have provided great insights and rich experimental data on personal exposure to exhaled contaminants in mechanically ventilated rooms.

In general, there are two modes of personal exposure to exhaled contaminants: direct exposure and indirect exposure (Li et al. 2012; Olmedo et al. 2013; Chen et al. 2014a). Direct exposure occurs when the exhaled jet carrying contaminants from the source person directly enters the breathing zone of the target person. Thus, direct exposure is determined primarily by the impact scope of the exhaled air (Zhang et al. 2011). In contrast, indirect exposure occurs when contaminants disperse in the room and are inhaled by the target person. Therefore, indirect exposure is determined primarily by the ventilation in the room. At the early stage of ventilation design, it may be desirable to have a simple method to quickly assess personal exposure to exhaled contaminants. If the assessment shows that direct exposure may occur, we should consider separating individuals by altering the design for the interior layout, for example by increasing the distance between seats. If the assessment shows that only indirect exposure will occur, we should focus on how to achieve a healthier indoor environment by improving the design of the air distribution system. Therefore, to better support decision making at an early design stage, it is worthwhile to develop a method for differentiating direct and indirect exposure to exhaled contaminants.

Direct and indirect exposure can be differentiated by either experimental measurements (e.g., Olmedo et al. 2012; Liu et al. 2017) or numerical simulations (e.g., Li et al. 2012; Chen et al. 2014a,b). However, these methods are time consuming and therefore may not be appropriate for the early stage of design. Therefore, this study aimed to develop a simple method for differentiating direct and indirect exposure to exhaled contaminants in mechanically ventilated rooms. We first collected experimental data of normalized personal exposure to exhaled contaminants from the literature to form a database. The data were then analyzed to capture the major influencing factors. Based on this analysis, a simple method consisting of the calculation of the impact scope of exhaled air and a simple decision-tree model was developed to differentiate direct and indirect exposure. Finally, the accuracy of the proposed method was assessed by comparing the results with the collected experimental data.

2 Review of experimental data from the literature

2.1 Collection of experimental data

We first collected the experimental data of personal exposure to exhaled contaminants from 10 scientific papers (Bjørn and Nielsen 2002; Qian et al. 2006, 2008; Nielsen et al. 2007, 2010, 2014; Olmedo et al. 2012, 2013; Cao et al. 2015; Liu et al. 2017) to create a database. Data for 191 cases of personal exposure to exhaled contaminants were extracted from the figures or tables in the literature. Table 1 summarizes the ventilation mode, ventilation rate, inter-person distance, and normalized exposure to exhaled contaminants reported in these studies. When collecting the data, we

Table 1 Summary of the ventilation mode, ventilation rate, inter-person distance, and normalized exposure to exhaled contaminants for the 10 scientific papers analyzed

Reference	Ventilation mode	Number of cases	Ventilation rate (ACH)	Inter-person distance (m)	Normalized exposure C_{exp}/C_R
Bjørn and Nielsen 2002	Displacement	11	0.71	0.4 – 1.2	0.58 – 6.93
Qian et al. 2006	Mixing/displacement	14/10	4.0 – 8.0	0.3 – 1.0	0.01 – 2.00
Nielsen et al. 2007	Mixing	6	4.8 – 7.4	0.4 – 2.2	0.31 – 1.05
Qian et al. 2008	Mixing	22	4.0	1.0	0.57 – 1.06
Nielsen et al. 2010	Mixing	45	6.0 – 10	1.8	0.42 – 1.53
Olmedo et al. 2012	Mixing/displacement	4/12	5.6	0.35 – 1.1	0.39 – 12.0
Olmedo et al. 2013	Mixing	25	5.6	0.35 – 1.1	0.96 – 13.0
Nielsen et al. 2014	Mixing	14	N/A	0.35 – 1.1	0.94 – 5.42
Cao et al. 2015	Mixing	3	12	0.35 – 1.1	0.74 – 4.16
Liu et al. 2017	Displacement	25	5.6	0.5 – 3.0	0.05 – 7.25

focused on two major types of ventilation mode: mixing ventilation and displacement ventilation. Downward ventilation was categorized as mixing ventilation based on the findings of Qian et al. (2006). Other ventilation modes, such as protective ventilation and personalized ventilation were not included. There were 133 mixing ventilation cases and 58 displacement ventilation cases. The tested ventilation rate ranged from 0.71 to 12 ACH (air change per hour). The studied person-to-person distance ranged from 0.35 to 3.0 m. Personal exposure to exhaled contaminants was normalized by the concentration at the exhaust of the room as follows:

$$\overline{C} = \frac{C_{\mathrm{exp}}}{C_{\mathrm{R}}} \tag{1}$$

where C_{exp} (#/m^3) is the exhaled contaminant concentration measured in the breathing zone of the target person, and C_{R} (#/m^3) is the exhaled contaminant concentration measured at the exhaust. In a well-mixed condition, the normalized exposure is equal to 1.0. Among the 191 cases, the normalized exposure varied significantly from 0.01 to 13.0, deviations from the well-mixed condition of more than one order of magnitude.

Figure 1 shows the distribution of normalized personal exposures for the 133 mixing ventilation cases and 58 displacement ventilation cases. The vertical axis is the fraction of cases falling within the range of normalized exposures. For example, 36 out of 133 (27%) mixing ventilation cases had a normalized exposure to exhaled contaminants of between 0.95 and 1.05. For mixing ventilation, the majority of cases occurred around the well-mixed condition with a normalized exposure of 1.0. That means a considerable proportion of the cases could be regarded as well-mixed cases. However, there are also many cases with a normalized exposure significantly larger than 1.0, which indicates unacceptably high exposure to exhaled contaminants. It is suspected that direct penetration of the exhaled air jet into the breathing zone of the target person was the main reason for the high exposures. For displacement ventilation, the peak fraction of cases did not occur around the well-mixed condition. There were many cases with a normalized exposure significantly lower than 1.0.

To differentiate the direct-exposure cases and indirect-exposure-only cases, a cutoff value of normalized exposure should be defined. If the room air is well-mixed in all of the cases, the cutoff value of normalized exposure can be set at 1.0. However, it is difficult to achieve the well-mixed condition in actual engineering applications. There must be a certain degree of non-uniform distribution in the room. Therefore, this study set the cutoff normalized exposure at 1.2 for mixing ventilation, i.e. 20% higher than the theoretical value. That is to say, if the normalized exposure is lower than or equal to 1.2, this indicates no direct exposure, only indirect exposure to the background concentration in the room. A number of indirect-exposure-only cases with a normalized exposure ranging from 1.0 to 1.2 were found in Nielsen et al. (2010), Olmedo et al. (2013), and Nielsen et al. (2014). In contrast, a normalized exposure value higher than 1.2 thus indicates serious direct exposure. Using this definition, there were 28 direct-exposure cases and 105 indirect-exposure-only cases for mixing ventilation in the database. Using the same definition, there were 30 direct-exposure cases and 28 indirect-exposure-only cases for displacement ventilation in the database.

2.2 Analysis of influencing factors

To develop an effective method, we first analyzed the factors influencing person-to-person contaminant transport in mechanically ventilated rooms. Person-to-person distance, ventilation mode, and ventilation rate are among the most important influencing factors (Chen et al. 2014b). Figure 2 plots the normalized exposures to exhaled contaminants

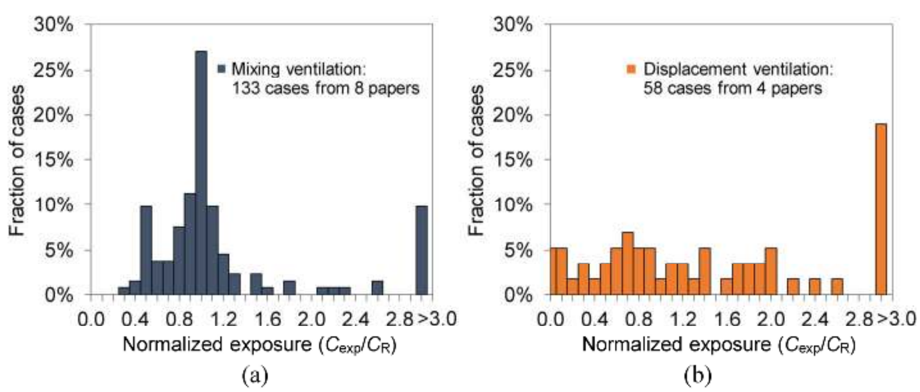

Fig. 1 The distribution of normalized personal exposure to exhaled contaminants for the 191 cases collected from the literature: (a) mixing ventilation and (b) displacement ventilation

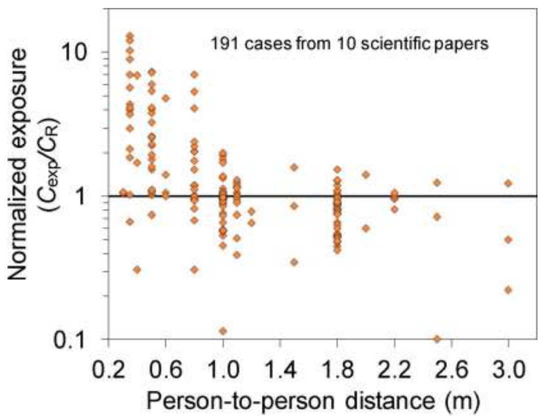

Fig. 2 Relationship between normalized exposure to exhaled contaminants and person-to-person distance for 191 cases extracted from the literature

against the person-to-person distance for the 191 cases. It can be seen that when the inter-person distance was greater than or equal to 1.0 m, the normalized exposure for most of the cases was lower than 1.1. Note that these cases included both mixing ventilation and displacement ventilation. In theory, the normalized exposure for mixing ventilation is 1.0. Assuming a certain degree of non-uniformly distributed airflow, some cases might have a normalized exposure slightly higher than 1.0, e.g. 10% higher or 1.1. When displacement ventilation is designed appropriately, the normalized exposure can be considerably lower than 1.0. Clearly, the collected data included such desirable scenarios. In general, when the inter-person distance was greater than 1.0 m, direct exposure was avoided. However, when the inter-person distance was less than 1.0 m, there were many cases with a normalized exposure significantly larger than 1.0 (as high as 13.0). In these cases, direct exposure significantly increased the risk of cross infection. Even so, it was also observed that a considerable number of cases had a normalized exposure of around 1.0 or lower when the distance was less than 1.0 m. Thus, the inter-person distance may not be an appropriate indicator by which to differentiate the direct and indirect exposures to exhaled contaminants.

In addition to inter-person distance, ventilation rate is an important factor influencing personal exposure to exhaled contaminants. In general, a higher ventilation rate results in lower exposure because of the principle of dilution. The normalized exposure takes into account the influence of ventilation rate. The contaminant concentration at the exhaust can be determined by

$$C_R = \frac{\dot{S}}{\dot{Q}} = 3600\frac{\dot{S}}{\alpha V} \tag{2}$$

where $\dot{S}$ (#/s) is the generation rate of exhaled contaminants, $\dot{Q}$ (m^3/s) is the airflow rate of the ventilation, α (h^{-1} or ACH) is the ventilation rate, and V (m^3) is the volume of the room. Therefore, in theory, the ventilation rate should have almost no influence on the normalized exposure to exhaled contaminants. Figure 3 plots the normalized exposures to exhaled contaminants against the ventilation rate for the 177 cases collected from the literature. Note that the data from Nielsen et al. (2014) are not included in this figure because information about ventilation rates was not provided in that paper. The plotted data indicate that low ventilation rates occurred mainly in displacement ventilation cases, while high ventilation rates occurred mainly in mixing ventilation cases. In general, the data do not show any correlation between normalized exposure and ventilation rate, which is consistent with the theory. Therefore, as long as normalized exposure is used as the index, there is no need to include the ventilation rate when developing a method for differentiating direct and indirect exposure to exhaled contaminants.

Another important influencing factor is the ventilation mode. Figure 4 compares normalized exposures to exhaled contaminants under mixing ventilation and displacement ventilation and shows the minimum, 25th percentile, median, 75th percentile, and maximum values. The median value for mixing ventilation was 0.99, which is very close to 1.0, i.e. the well-mixed condition. However, the median value for displacement ventilation was 1.23, 23% higher than that of a well-mixed condition. This contrasts with the classical theory that displacement ventilation exhibits a higher ventilation efficiency or contaminant removal efficiency than mixing ventilation. This is because the data included many cases with a short inter-person distance. When the influence of inter-person distance overwhelms that of ventilation mode, the advantage of displacement ventilation in removing contaminants may not be observed. Furthermore, exhaled air can be locked in a thermally stratified layer at the height of the breathing zone created by displacement ventilation (Bjørn and Nielsen 2002; Qian et al. 2006; Olmedo et al. 2012). In such cases, the target person, especially if

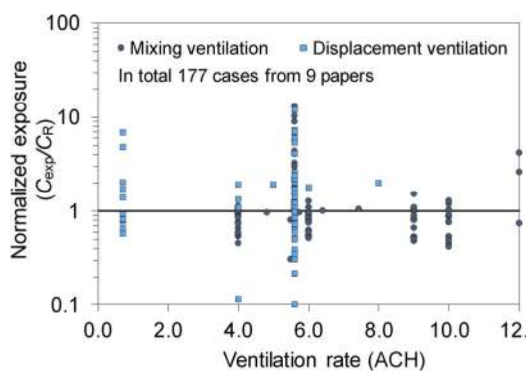

Fig. 3 Relationship between normalized exposure to exhaled contaminants and ventilation rate for 177 cases from the literature

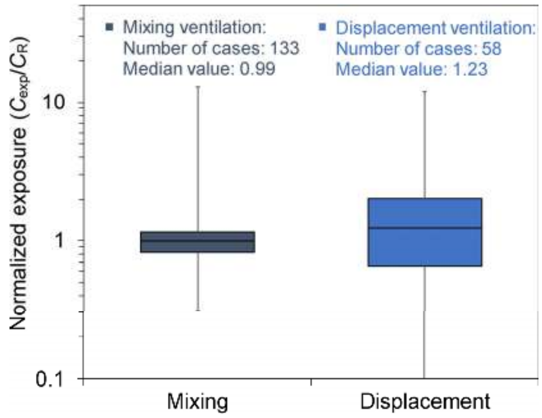

Fig. 4 Comparison of the normalized exposures of cases with mixing and displacement ventilation, showing the minimum, 25th percentile, median, 75th percentile, and maximum values

close to the source person, may be exposed to a very high level of exhaled contaminants in the stratified layer. When the breathing zone of the target person is below the stratified layer, exposure can be very low because the air in the lower zone of the room is much clearer. Such additional influencing factors increase the uncertainties of the normalized exposure under displacement ventilation, as shown in Fig. 4. Therefore, it is necessary to develop separate models for differentiating direct and indirect exposure in mixing ventilation and displacement ventilation scenarios.

3 Development of the methods

Based on the analysis above on the experimental data collected from the literature, we developed separate models for differentiating direct and indirect exposures in mixing ventilation and displacement ventilation conditions.

3.1 Mixing ventilation

Figure 5 shows the typical scenarios of person-to-person contaminant transport in a mixing ventilated room. The source person exhales air with contaminants through breathing, coughing, or sneezing. The breathing zone of the target person is defined as a cube with a volume of 0.027 m^3 in front of his/her mouth (OSHA 2014; Chen et al. 2015a). As illustrated in Fig. 5(a), when the breathing zone of the target person is within the impact scope of the exhaled air, serious direct exposure to the exhaled contaminants may occur. In contrast, when the breathing zone of the target person is far away from the impact scope of the exhaled air, only indirect exposure will occur, as shown in Fig. 5(b). Another common scenario, as shown in Fig. 5(c), is the source and target facing in the same direction, such as people in a concert audience or students seated in a classroom. In such cases, even though the target person is close to the exhaled air, direct exposure may be avoided because the pathway to the breathing zone is blocked by the head. Fig. 5(d) shows another scenario related to the thermal plume generated by the target person, which has been proven to be important in the near-body airflow field and contaminant transport (Liu et al. 2016; Yan et al. 2017). When the exhaled air penetrates the lower zone of the thermal plume boundary layer, the contaminants may move upward with the vertical airflow driven by the thermal plume and enter the breathing zone. In this case, direct exposure may occur. We included these four scenarios in the developed method for differentiating direct and indirect exposure to exhaled contaminants.

To determine the impact scope, it is crucial to understand the nature of the exhaled air. Exhaled air is usually at a relatively high temperature, approximately 32 °C, compared with the room air temperature. Therefore, the exhaled jet is non-isothermal with a curved trajectory as shown in Fig. 6.

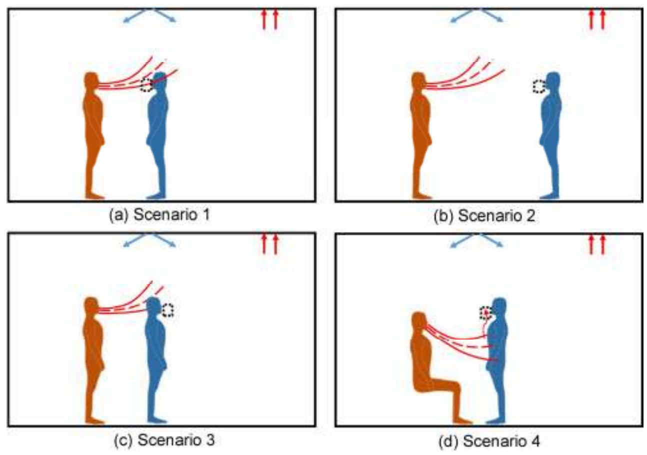

Fig. 5 Person-to-person contaminant transport in a mixing ventilated room: (a) direct exposure: the breathing zone of the target person is within the impact scope of exhaled air; (b) indirect exposure: the breathing zone of the target person is far away from the impact scope of exhaled air; (c) indirect exposure: the pathway of exhaled air to the breathing zone is blocked by the head of the target person; and (d) direct exposure: exhaled air penetrates the thermal plume boundary layer generated by the target person

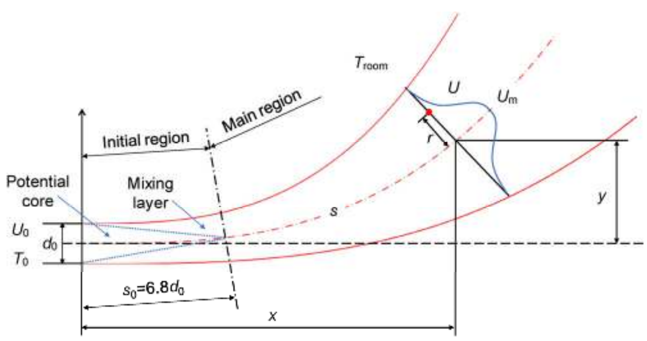

Fig. 6 Illustration of a non-isothermal round jet (modified from Fig. 2 of Xie et al. (2007))

After leaving the mouth or nose, the exhaled jet mixes with the room air and grows thicker. A free round jet consists of an initial section and a main section. In the potential core of the initial section, the centerline velocity of the jet is equal to the initial velocity at the mouth/nose and the radial velocity component is zero. The air velocity distribution in the mixing layer of the initial region is similar to that in the main section, but the maximum velocity is from the centerline to the edge of the potential core. In the main section, the centerline velocity decreases with the increase in the distance from the mouth/nose.

For a non-isothermal round jet, the trajectory equation of the curved centerline can be determined by the following equation (Baturin 1972):

$$y = 0.0354\frac{Ar_0}{A_0}\sqrt{\frac{T_0}{T_r}}\cdot x^3 \equiv \xi\cdot x^3 \tag{3}$$

where A_0 (m^2) is the area of the mouth/nose opening, T_0 (K) is the temperature of the exhaled air, T_r (K) is the room air temperature, and Ar_0 is the Archimedes number, which can be calculated by

$$Ar_0 = \frac{g\sqrt{A_0}\alpha(T_0 - T_r)}{{U_0}^2} \tag{4}$$

where g (m/s^2) is the gravitational acceleration, α (K^{-1}) is the thermal expansion coefficient of air, and U_0 (m/s) is the initial velocity at the mouth/nose. Note that, when the exhaled air direction is not horizontal, the coordinate system shown in Fig. 6 should be altered accordingly. With the curved centerline trajectory of the exhaled air, the relative coordinates of the breathing zone center point, s and r, can be determined as illustrated in Fig. 7. Line_1 is a tangent line to the curved trajectory of exhaled air centerline at the cross point (x_c, y_c). Line_2 is perpendicular to Line_1 and passes through both the cross point (x_c, y_c) and the breathing zone center point (x_b, y_b). Therefore, the relationship between the slopes of the two lines, β_1 and β_2, is

$$\beta_1\cdot\beta_2 = -1 \tag{5}$$

where the slope of Line_1 can be determined by the derivative of the curved trajectory function, Eq. (3), at the cross point

$$\beta_1 = 3\xi\cdot {x_c}^2 \tag{6}$$

and the slope of Line_2 can be calculated by

$$\beta_2 = \frac{y_c - y_b}{x_c - x_b} \tag{7}$$

Furthermore, the cross point is on the curved trajectory, so

$$y_c = \xi\cdot {x_c}^3 \tag{8}$$

The cross point coordinates (x_c, y_c) can then be calculated by solving Eqs. (5) to (8) together. Therefore, the relative coordinates of the breathing zone center point to the exhaled jet centerline, s and r, can be calculated by

$$s = \int_0^{x_c}\sqrt{(\mathrm{d}x)^2 + [\xi(x+\mathrm{d}x)^3 - \xi x^3]^2}\,\mathrm{d}x \tag{9}$$

$$r = \sqrt{(y_c - y_b)^2 + (x_c - x_b)^2} \tag{10}$$

With the relative coordinates of the breathing zone center point, s and r, the local air velocity at this point can be calculated using jet theory. In this case, we used the jet expressions from Bocksell (1998), which were also used by Xie et al. (2007). The centerline velocity can be calculated by

$$U_m = \frac{6.8U_0}{\bar{s}} \tag{11}$$

where U_m (m/s) is the centerline velocity, and U_0 (m/s) is the initial velocity at the mouth/nose, and $\bar{s}$ (unitless) is the dimensionless centerline distance, which is defined as

$$\bar{s} = \frac{s}{d_0} \tag{12}$$

where d_0 is the diameter of the mouth/nose opening. The mean axial velocity component, u_s (m/s), and mean radial velocity component, u_r (m/s), can be calculated by

$$u_s = U_m\,\mathrm{sech}^2(\sigma\eta) \tag{13}$$

$$u_r = U_m\frac{a\eta(1+\eta^2-(1+b)\sqrt{1+\eta^2})}{(1+\eta^2)(1-(1+b)\sqrt{1+\eta^2})^2} \tag{14}$$

where σ is equal to 10.4, a is equal to 0.0046, b is equal to 0.0075, and η is defined as

$$\eta = \frac{r}{s} \tag{15}$$

where r (m) is the distance from the target location to the centerline. Therefore, the velocity magnitude at a location

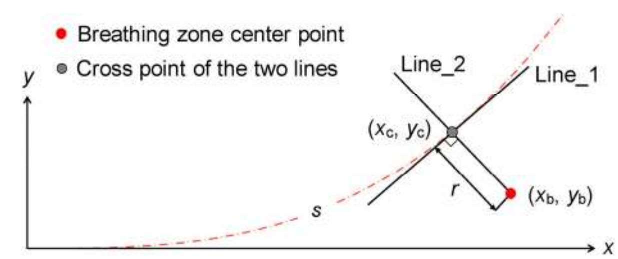

Fig. 7 Determining the relative coordinates of the breathing zone center point to the exhaled jet centerline, (s and r)

in the jet with the coordinates of s and r, U (m/s), is equal to

$$U=\sqrt{u_s^{\ 2}+u_r^{\ 2}} \tag{16}$$

Based on similarity theory, the contaminant concentration at a given location in the jet is correlated to the local air velocity (Berlanga et al. 2017). Therefore, we used the local air velocity (U) at the center of the target person's breathing zone calculated by the model above as an indicator to differentiate the direct and indirect exposure to exhaled contaminants. When the local air velocity is significantly higher than a certain threshold, U^*, (to be determined later), the local contaminant concentration in the breathing zone also tends to be significantly higher than the background concentration in the room. In such cases, the breathing zone of the target person is within the impact scope of the exhaled air, so that direct exposure may occur (Scenario 1). In contrast, if the local air velocity is lower than the threshold, the local contaminant concentration in the breathing zone should be similar to the background concentration in the room. In such cases, it is considered that there is no direct exposure but only indirect exposure to the background concentration in the room (Scenario 2).

Two special scenarios, Scenarios 3 and 4 (shown in Fig. 5) should be further considered. When the pathway from the exhaled air to the breathing zone is blocked by the head of the target person, (e.g. two persons facing in the same direction, one behind the other), the exposure is considered to be indirect only (Scenario 3). To determine whether the thermal plume generated by the target person will result in direct exposure, more calculations are needed, as illustrated in Fig. 8. In the coordinate system shown in Fig. 8, the function of the exhaled air centerline trajectory can still be described by Eq. (3). Line_3 is a line along the body of the target person across the breathing zone center point. This line can be roughly regarded as the pathway of the upward thermal plume. Line_3 is perpendicular to Line_4; thus, the slop of Line_3 can be calculated by

$$\beta_3=-\frac{1}{\beta_4}=-\frac{1}{\tan\theta} \tag{17}$$

where θ is the angle between the x-axis and Line_4 shown in Fig. 8. Therefore, the function of Line_3 is

$$y=-\frac{1}{\tan\theta}x+c \tag{18}$$

where c is a constant which can be determined by

$$c=y_b+\frac{1}{\tan\theta}x_b \tag{19}$$

Because the breathing zone center point (x_b, y_b) is also on

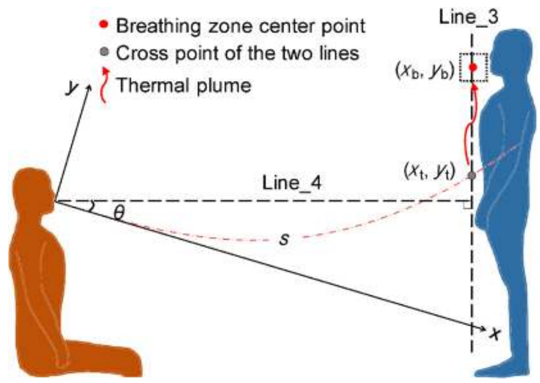

Fig. 8 Determining the coordinates of the cross point (x_t, y_t) and its relative position to the center point of the breathing zone

Line_3. By solving Eqs. (3) and (18) together, the coordinates of the cross point (x_t, y_t) can be obtained. If the cross point is below the breathing zone center point (i.e., $y_t \le y_b$), the cross point is considered to be within the boundary layer of the thermal plume generated by the target person. The next step is to calculate the local air velocity at the cross point, U_t, by Eq. (11). If this local air velocity is greater than the threshold local air velocity, the exhaled contaminant concentration at the cross point is significantly higher than the background concentration. That means a considerable amount of exhaled contaminants enter the boundary layer of the thermal plume. Here, we assume that these contaminants will move upward with the thermal plume to the breathing zone of the target person (Scenario 4).

Figure 9 shows a simple decision tree model used in the proposed differentiation method. First, Eqs. (3) to (16) are used to determine whether the breathing zone of the target person is within the impact scope of the exhaled air. If yes, the face-to-face orientation is examined to see if the pathway of exhaled air to the breathing zone is blocked by the head of target person. If it is not blocked, direct exposure will occur; if it is blocked, only indirect exposure will occur. If the breathing zone is not within the impact scope of exhaled air, Eqs. (17) to (19) will be used to examine if the exhaled air can enter the lower zone of the thermal plume boundary layer of the target person. If yes, it is considered that the contaminants will move upward with the thermal plume and cause direct exposure. Otherwise, only indirect exposure will occur. With this differentiation strategy, the remaining problem is how to define the threshold local air velocity, U^*, to determine the impact scope of the exhaled air.

The next step is to determine the threshold of the local air velocity, U^*, to differentiate the direct and indirect exposures. We used the experimental data from the literature to determine the threshold local air velocity. Note that this study set the cutoff normalized exposure at 1.2 to differentiate the direct-exposure cases and indirect-exposure-only cases

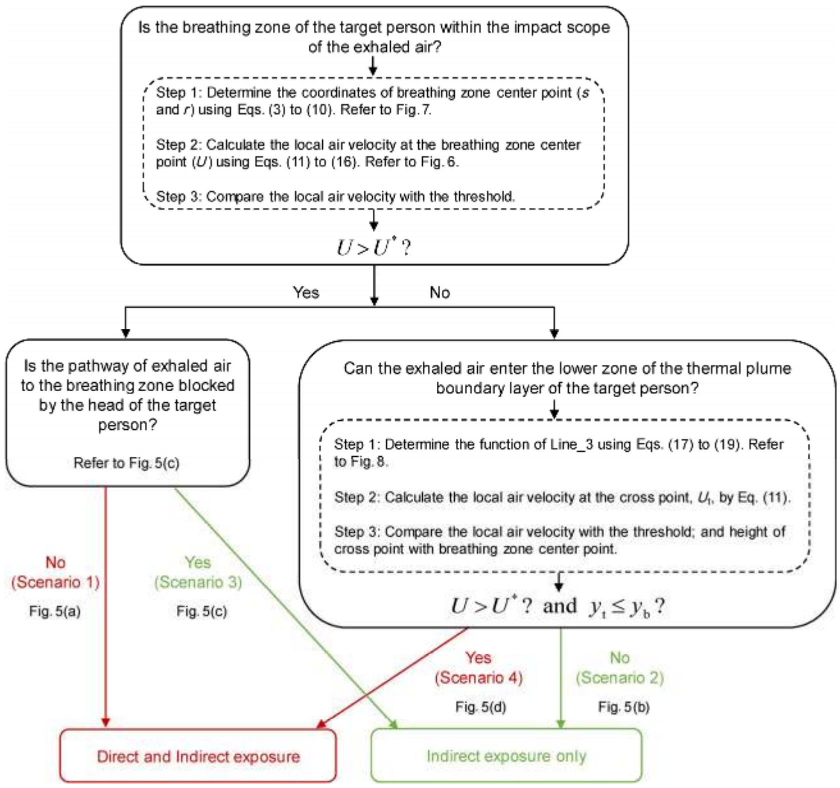

Fig. 9 The simple decision tree model used in the method for differentiating direct and indirect exposure to exhaled contaminants

for mixing ventilation as defined in the last paragraph of Section 2.1. Figure 10 shows the error of the proposed method under different threshold local air velocities. When the threshold local air velocity was 0.05 m/s, the error of the proposed method was the lowest, at 9.8%. Thus, the proposed method could correctly differentiate the direct (C_{exp}/C_R > 1.2) and indirect ($C_{exp}/C_R \le 1.2$) exposure for 120 out of the 133 mixing ventilation cases. Therefore, the threshold local air velocity was set at 0.05 m/s in the method for differentiating the direct and indirect exposure to exhaled contaminants in mixing ventilated rooms.

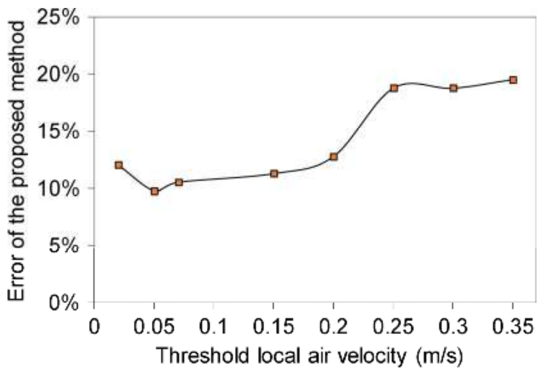

Fig. 10 The error of the proposed method under different threshold local air velocities for mixing ventilation

The proposed method was used to differentiate the direct and indirect exposure to exhaled contaminants for the 133 mixing ventilation cases. Figure 11 shows the distribution of the measured normalized exposure for the predicted direct-exposure cases and indirect-exposure-only cases. From the experimental data, there were 28 direct-exposure cases and 105 indirect-exposure-only cases for mixing ventilation. The proposed method correctly identified 22 direct-exposure cases and 98 indirect-exposure-only cases.

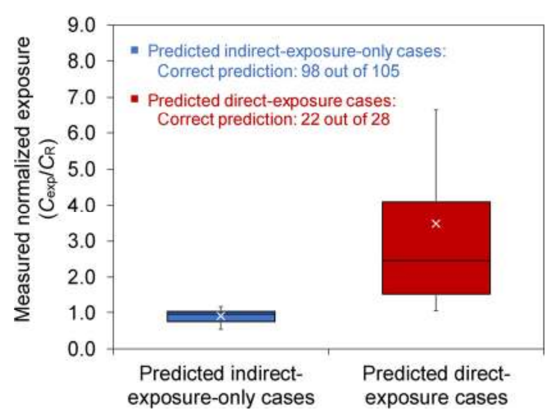

Fig. 11 Measured normalized exposure for the predicted indirect-exposure-only and direct-exposure cases in mixing ventilation (the 10th, 25th, median, mean, 75th, and 90th percentile values are shown)

In general, with a threshold local air velocity of 0.05 m/s the proposed method can reasonably differentiate direct and indirect exposure to exhaled air in mixing ventilation conditions. The median value for the predicted indirect-exposure-only cases was 0.96, which is close to the theoretical value of 1.0. In contrast, the median value for the predicted direct-exposure cases was 2.45, which is significantly higher than 1.0, owing to the direct exposure to exhaled contaminants.

3.2 Displacement ventilation

Figure 12 shows the typical scenarios of person-to-person contaminant transport in a displacement ventilated room. The four scenarios are similar to that shown in Fig. 5, but there are two major differences. First, if the target person is far away from the impact scope of exhaled air, the clean air supplied from the displacement ventilation diffuser may directly enter the breathing zone so that exposure can be reduced. Therefore, in general, the indirect exposure under displacement ventilation is lower than that under mixing ventilation (Chen et al. 2014b). Second, the exhaled air may be locked in the thermal stratification layer created by the displacement ventilation (Bjørn and Nielsen 2002; Qian et al. 2006; Olmedo et al. 2012). In such cases, the exhaled air tends to move more horizontally and have an impact over a greater distance. Zhou et al. (2017) developed a very decent model to predict the exhaled jet centerline trajectory in thermally stratified environments. They found that the lock-up height was lower with a smaller Archimedes number

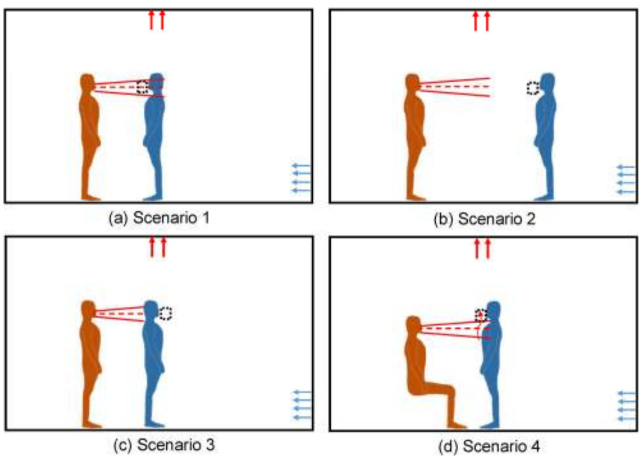

Fig. 12 Schematic of person-to-person contaminant transport in a displacement ventilated room: (a) direct exposure: the breathing zone of the target person is within the impact scope of exhaled air; (b) indirect exposure: the target person is far away from the impact scope of exhaled air; (c) indirect exposure: the pathway of exhaled air to the breathing zone is blocked by the head of the target person; and (d) direct exposure: exhaled air penetrates the thermal plume boundary layer generated by the target person

and a greater temperature gradient. To consider the lock-up phenomenon in the thermal stratification layer but still keep the method as simple as possible, we assumed that the exhaled air moves horizontally even though the Archimedes number is not zero. Note that this assumption tends to result in an over-estimation of direct exposure, because the actual trajectory of the exhaled air is still curved to some extent at the beginning and the lock-up height can be higher than the starting point of the exhaled air (Zhou et al. 2017). Therefore, to compensate for this effect, the threshold local air velocity was determined separately for displacement ventilation. In theory, the threshold local air velocity for displacement ventilation should be greater than that for mixing ventilation.

We used the collected experimental data from the literature to determine the threshold local air velocity for displacement ventilation. Note that this study set the cutoff normalized exposure at 1.2 to differentiate the direct-exposure cases and indirect-exposure-only cases for displacement ventilation as defined in the last paragraph of Section 2.1. Figure 13 shows the error of the proposed method for different threshold local air velocities for displacement ventilation. When the threshold local air velocity was 0.07 m/s, the error of the proposed method was 19.0%, the lowest among all of the tested local air velocities. This means that the proposed method could correctly differentiate direct ($C_{exp}/C_R > 1.2$) and indirect ($C_{exp}/C_R \leq 1.2$) exposure for 47 out of the 58 displacement ventilation cases. Therefore, the threshold local air velocity was set at 0.07 m/s in the method for differentiating the direct and indirect exposure to exhaled contaminants in displacement ventilated rooms. As predicted, the threshold local air velocity for displacement ventilation is lower than that for mixing ventilation, so that the over-estimation of direct exposure due to the assumption of non-curved exhaled air trajectory can be compensated.

The proposed method was applied to differentiate direct and indirect exposure to exhaled contaminants for the 58 displacement ventilation cases. Figure 14 shows the

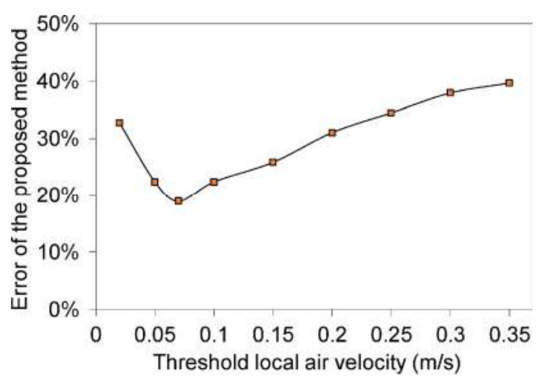

Fig. 13 The error of the proposed method with different threshold local air velocities for displacement ventilation

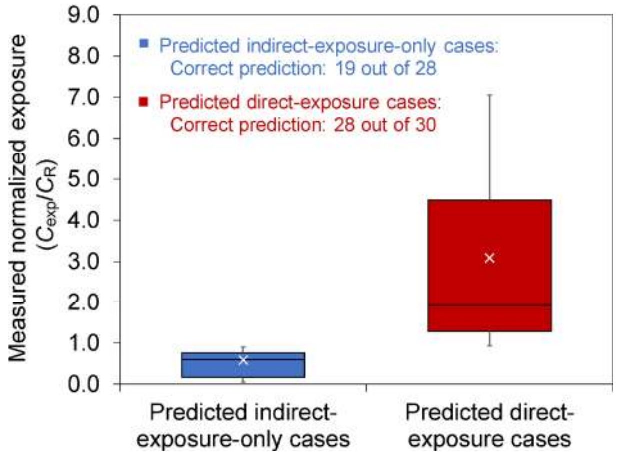

Fig. 14 The distribution of measured normalized exposure for the predicted indirect-exposure-only cases and direct-exposure cases for displacement ventilation (the 10^{th}, 25^{th}, median, mean, 75^{th}, and 90^{th} percentile values are shown)

distribution of the measured normalized exposure for the predicted direct-exposure cases and indirect-exposure-only cases. The experimental database contained 30 direct-exposure cases and 28 indirect-exposure-only cases for displacement ventilation. The proposed method correctly identified 37 direct-exposure cases and 21 indirect-exposure-only cases. In general, with a threshold local air velocity of 0.07 m/s the proposed method can reasonably differentiate direct and indirect exposure to exhaled air for displacement ventilation. The median value for the predicted direct-exposure cases was 1.92, which is significantly higher than 1.0, owing to the direct exposure to exhaled contaminants. In contrast, the median value for the predicted indirect-exposure-only cases was 0.60, which is lower than that for mixing ventilation. That is because when the target person is not impacted directly by the exhaled air, the exposure is reduced by the clean air supplied from the lower zone of the room directly entering the breathing zone. Furthermore, the variation of the normalized exposure for displacement ventilation was greater than that for mixing ventilation. For example, the range between the 25^{th} and 75^{th} percentile values for displacement ventilation was from 0.17 to 0.76. This indicates that, with an appropriate design, displacement ventilation has a better chance of achieving excellent performance in reducing indirect exposure to exhaled contaminants.

4 Discussion

A simple method for differentiating direct and indirect exposure to exhaled contaminants was developed based on experimental data collected from the literature. To keep the proposed method as simple as possible for the early stage of design, the lock-up phenomenon in the displacement ventilation cases was largely simplified in this study. The exhaled air was assumed to move horizontally even though the jet might be locked up at a greater height in reality. To compensate the potential over-estimation of direct exposure due to this assumption, the threshold local air velocity was set greater than that for mixing ventilation based on the experimental database. However, when detailed design is required, the proposed method may not be sufficiently accurate. In that case, computational fluid dynamics (CFD) simulation can be used, although the computing cost is much higher. Recently, Zhou et al. (2017) developed a numerical model to accurately predict the exhaled airflow trajectory in thermally stratified environments by solving six ordinary equations of the exhaled jet. These equations include the continuity, momentum, density difference flux, and centerline trajectory equations. Importantly, this model takes both the Archimedes number of the exhaled jet and the vertical temperature gradient in the room into account. A smaller Archimedes number and a greater temperature gradient can lead to a lower lock-up height (Zhou et al. 2017). Therefore, this model is very suitable to adopt when detailed design is required, because it is more accurate than the proposed method but less computationally costly than CFD.

Furthermore, the proposed method is for quickly differentiating the direct and indirect exposure to exhaled contaminants in mechanically ventilated spaces. However, it is not for predicting the exposure levels. In general, it is difficult to accurately predict the direct exposures at the stage of design, because the information of many individual parameters is unavailable. These individual influencing factors include the exhaled air velocity and direction as well as the height and metabolic rate of the persons. In principle, direct exposures should be avoided through separating individuals by altering the design for the interior layout, if possible. Therefore, from the perspective of design, identifying the possible existence of direct exposure may be more practical than accurately predicting the exposure level. On the other hand, the indirect exposure can be predicted more accurately because it is mainly determined by the ventilation system. At the early stage of design, empirical models can be used to estimate the indirect exposures. For mixing ventilation, the indirect exposure may be roughly estimated by assuming the normalized exposure equal to 1.0 as demonstrated in Fig. 11. For displacement ventilation, the prediction is more challenging because the uncertainty is greater as shown in Fig. 14. If the breathing zone of the target person is in the lower zone of the room, the normalized indirect exposure can be significantly lower than 1.0, because the exhaled contaminants move upward and are directly removed from the exhaust at the ceiling level. However, if the exposure height is above the stratification height, the indirect exposure would occur in the upper mixing layer with a normalized exposure at around 1.0. Several empirical models for estimating indirect exposure under displacement ventilation can be used for quick estimation (e.g. Habchi et al. 2014). At the stage of detailed design, CFD simulation again can be utilized.

The study has some other limitations such as the universality of the method. As the proposed method is very simple, it may not be sufficiently accurate when applied to certain complex air distribution systems, such as personalized ventilation (Nielsen et al. 2007; Zhao and Guan 2007), protected zone ventilation (Cao et al. 2015), or a space with air cleaners (Chen et al. 2010, 2017) or ultraviolet germicidal irradiation devices (Kanaan et al. 2016). The localized air distribution may significantly influence the trajectory of exhaled air, which cannot be predicted by the simple jet equations used in this study. Furthermore, the collected data focused on normal rooms or hospital wards. Therefore, the proposed method may not be applicable to other enclosed environments, such as aircraft cabins (You et al. 2017) and high-speed trains (Zhang and Li 2012).

Note that the size of exhaled droplets ranges from the sub-micrometer to super-micrometer scale (Morawska et al. 2009; Chao et al. 2009), and the trajectory of exhaled droplets greatly depends on the particle size (Xie et al. 2007; Chen and Zhao 2010; Yang et al. 2016). However, this study did not consider the influence of the size of exhaled droplets because most of the studies in the literature used a tracer gas to represent the exhaled contaminants. Therefore, the proposed method is only applicable to fine particles which behave similarly to gaseous contaminants. Large droplets whose trajectories do not follow the exhaled air tend to deposit onto the floor by gravitational settling instead of being inhaled by the target person (Xie et al. 2007; Chen and Zhao 2010). In addition, this study did not consider the transient features of person-to-person contaminant transport because the method was developed for quick differentiation of direct and indirect exposure at the early stage of design. It should be acceptable to start from the steady-state analysis at the early stage of design, especially given that the proposed method is simple with low computing cost. In the stage of detailed design, both experimental measurements (e.g., Chen et al. 2013; Liu and Novoselac 2014) and numerical simulations (e.g., Hang et al. 2014; Chen et al. 2015b,c; Yan et al. 2017) can be used to consider in detail the transient features of personal exposure to exhaled contaminants. In addition, the thermal plume generated by the infected person with relatively large metabolic rate may significantly affect the weak exhaled jet (Rim and Novoselac 2009; Ge et al. 2013). However, at the stage of design, it is difficult to have the information of the metabolic rate and exhaled air velocity. Therefore, it would be safer to assume that the exhaled jet could penetrate the thermal plume in order to avoid any under-estimation of the risks. When more information is available at the stage of detailed design, CFD simulation (Rim and Novoselac 2009; Ge et al. 2013) can be used to further consider this influencing factor.

5 Conclusions

This investigation developed a simple method for differentiating direct and indirect exposure to exhaled contaminants in mechanically ventilated rooms. First, a database was formed by collecting experimental data from the literature. Then, the data were analyzed to capture the main influencing factors. Finally, a method for differentiating direct and indirect exposure was developed for both mixing and displacement ventilation. Within the scope of this research, the following conclusions can be drawn:

(1) Direct exposure to exhaled contaminants is determined primarily by the impact scope of the exhaled air.

(2) Indirect exposure to exhaled contaminants is determined primarily by the ventilation mode and ventilation rate.

(3) The proposed method can reasonably differentiate direct and indirect exposure to exhaled contaminants in both mixing and displacement ventilated rooms.

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