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Systematic study of person-to-person contaminant transport in mechanically ventilated spaces (RP-1458)

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Abstract

It is essential to investigate person-to-person contaminant transport in mechanically ventilated spaces to improve air distribution design and reduce the infection risk from airborne infectious diseases. This paper provides a systematic study of the effects of ventilation mode, ventilation rate, and person-to-person distance on person-to-person contaminant transport. This study first collected available cases of person-to-person contaminant transport from the literature to create a database. Then this investigation identified the limitations of the existing data and added a number of cases to complete the database. The additional cases were generated by using a RANS-Eulerian model that was validated by experimental data from an occupied office with under-floor air-distribution (UFAD) systems. The database shows that the overall performance of displacement ventilation and the UFAD systems was better than that of mixing ventilation. A higher ventilation rate was beneficial in reducing person-to-person contaminant transport to some extent. Person-to-person contaminant exposure increased rapidly with a decrease in person-to-person distance when the distance was smaller than 1.1 m. Generally speaking, person-to-person distance is an important parameter when compared with ventilation mode and ventilation rate.

Keywords: Computational Fluid Dynamics (CFD); Mixing; Displacement; Under-Floor Air-Distribution (UFAD) system; Ventilation rate; Person-to-person distance; Office; Tracer gas

Nomenclature

E	the exposure for a particular case
E_{mixing}	the average exposure for mixing ventilation in that study
E^*_{mod}	the relative effect of ventilation mode on exposure
E_{6ACH}	the average exposure at a ventilation rate of 6 ACH in that study
E^*_{ACR}	the relative effect of ventilation rate
$E_{1.1m}$	the average exposure of the cases with a person-to-person distance of 1.1 m in that study
E^*_{dis}	the relative effect of person-to-person distance
θ	the normalized air temperature
T	the local temperature
T_{in}	the temperatures at the inlets
T_{out}	the temperatures at the exhaust
C^*	the normalized SF_6 concentration
C	the local SF_6 concentration
C_{in}	the SF_6 concentration at the inlets
C_{out}	the SF_6 concentration at the exhaust

1. Introduction

There has been strong evidence of an association between airflow patterns and the transmission of airborne infectious diseases in indoor environments (Li et al., 2007). Exhalation activities such as breathing, coughing, talking, and sneezing by an infected person can generate pathogen-carrying particles (Nicas et al., 2005). These particles can be transported to the breathing zone of susceptible individuals and result in infections (Morawska, 2006). Therefore, it is essential to investigate person-to-person contaminant transport in mechanically ventilated spaces in order to improve air distribution design and reduce the risk of infection.

Ventilation mode, ventilation rate, and person-to-person distance are among the factors that may influence person-to-person contaminant transport in enclosed spaces. A number of studies have focused on these influencing factors. The first factor, ventilation mode, was investigated by Qian et al. (2006) and Yin et al. (2011); they compared the effectiveness of mixing and displacement ventilation in controlling person-to-person contaminant transport in hospital wards. Lai and Wong (2010, 2011) and Olmedo et al. (2012) experimentally investigated person-to-person contaminant transport in laboratory chambers with mixing and displacement ventilation. There are more than 30 cases comparing the effect of mixing and displacement ventilation on person-to-person contaminant transport available in these studies. However, fewer studies are available in the literature for another commonly used ventilation mode, the Under-Floor Air-Distribution (UFAD) system (He et al., 2011; Li et al., 2011).

In regard to the second factor, ventilation rate, Qian et al. (2006) experimentally investigated its effect on person-to-person contaminant transport in a hospital ward with a displacement ventilation system. Nielsen et al. (2010) compared the person-to-person contaminant exposure in a hospital ward with ventilation rates of 6, 9, and 10 ACH. In addition, Yin et al. (2011) compared the person-to-person contaminant exposure in an inpatient room with ventilation rates of 4 and 6 ACH. However, in most of these cases, the patients were lying in beds, which may not be representative of normal scenarios such as working in an office.

The third factor, person-to-person distance, was investigated by Qian et al. (2006); they assessed its effect on person-to-person contaminant transport in a hospital ward with a ventilation rate of 4 ACH. Recently, Olmedo et al. (2012) experimentally investigated the effect of person-to-person distance on exhaled contaminant transport in a room with a ventilation rate of 5.6 ACH. However, the effect of person-to-person distance on exhaled contaminant transport under high ventilation rates has not been well understood.

The review of existing studies shows that additional cases of person-to-person contaminant transport are needed to in order to address the limitations discussed above. Thus, this study aims to develop a database and systematically investigate the general effect of ventilation mode, ventilation rate, and person-to-person distance on person-to-person contaminant transport in mechanically ventilated spaces.

2. Methods

2.1 Developing a database from the literature

This study first collected the cases available in the literature to create a database. Note that different studies used different units or normalization methods for the exposure data. Thus, the selected studies must be comparative so that the relative effects of the target factors on person-to-person contaminant transport can be calculated for each individual study. In this investigation, the relative effect of ventilation mode on exposure was calculated for each study by:

$$E^*_{\mathrm{mod}} = \frac{E}{E_{mixing}} \tag{1}$$

where E is the exposure for a particular case, and E_{mixing} is the average exposure for mixing ventilation in that study. Thus, the relative effects of ventilation mode on exposure could be compared among different studies. The database from the literature included 32, 34, and 4 cases for mixing ventilation, displacement ventilation, and UFAD systems, respectively.

Because all the collected studies included at least one case with a ventilation rate of 6 ACH, the relative effect of ventilation rate was calculated by:

$$E^*_{ACR} = \frac{E}{E_{6ACH}} \tag{2}$$

where E_{6ACH} is the average exposure at a ventilation rate of 6 ACH for each study. The database from the literature contained 23, 20, 15, and 15 cases for 4, 6, 9, and 10 ACH, respectively.

Because all the collected studies included at least one case with a person-to-person distance of 1.1 m, the relative effect of person-to-person distance was calculated by:

$$E^*_{dis} = \frac{E}{E_{1.1m}} \tag{3}$$

where $E_{\mathrm{1.1m}}$ is the average exposure of the cases with a person-to-person distance of 1.1 m for each study. There are 40 cases for different person-to-person distances available in the literature.

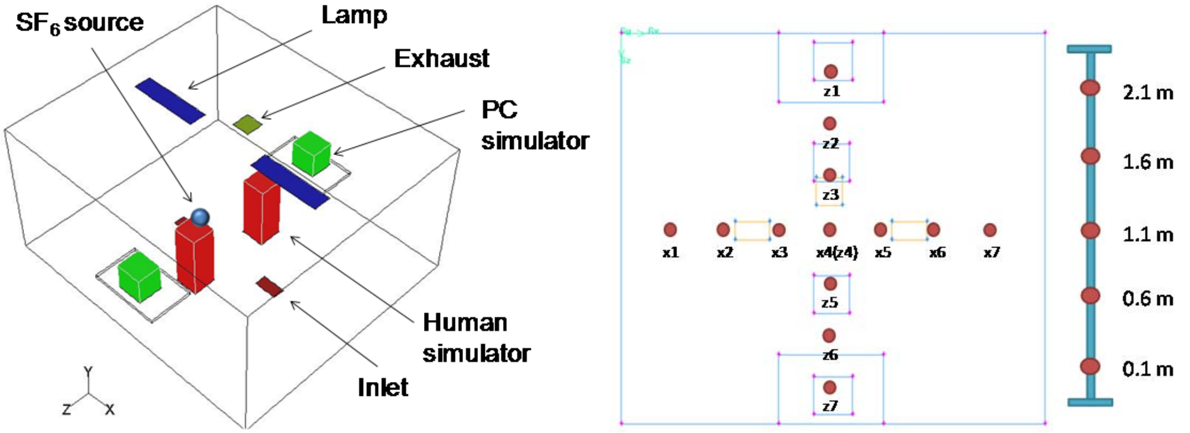
2.2 Adding necessary cases to the database

As discussed in the introduction, the effect of the UFAD system on controlling person-to-person contaminant transport has not been thoroughly studied. Thus, this study added 24 UFAD system cases with different ventilation rates and person-to-person distances to the database. The ventilation rate varied from 3 to 9 ACH, which is a reasonable range for common indoor environments. The person-to-person distance varied from 0.5 to 1.8 m, which corresponds to common scenarios in a two-person office. Because only comparative data could be used for the database, 12 mixing ventilation and 12 displacement ventilation cases were also set up for comparison with the UFAD systems. Table 1 lists detailed information about ventilation mode, ventilation rate, and person-to-person distance for the cases added to the database.

Table 1. Case setup for this study.

Case	Mode	ACR (ACH)	Dis. (m)	Exp.	CFD	Case	Mode	ACR (ACH)	Dis. (m)	Exp.	CFD
1	UFAD	3	0.5	√	√	25	Mixing	3	0.5		√
2	UFAD	3	0.8		√	26	Mixing	3	1.1		√
3	UFAD	3	1.1	√	√	27	Mixing	5	0.5		√
4	UFAD	3	1.8		√	28	Mixing	5	1.1		√
5	UFAD	5	0.5		√	29	Mixing	6	0.5		√
6	UFAD	5	0.8		√	30	Mixing	6	1.1		√
7	UFAD	5	1.1		√	31	Mixing	7	0.5		√
8	UFAD	5	1.8		√	32	Mixing	7	1.1		√
9	UFAD	6	0.5	√	√	33	Mixing	8	0.5		√
10	UFAD	6	0.8		√	34	Mixing	8	1.1		√
11	UFAD	6	1.1	√	√	35	Mixing	9	0.5		√
12	UFAD	6	1.8		√	36	Mixing	9	1.1		√
13	UFAD	7	0.5		√	37	Displace	3	0.5		√
14	UFAD	7	0.8		√	38	Displace	3	1.1		√
15	UFAD	7	1.1		√	39	Displace	5	0.5		√
16	UFAD	7	1.8		√	40	Displace	5	1.1		√
17	UFAD	8	0.5		√	41	Displace	6	0.5		√
18	UFAD	8	0.8		√	42	Displace	6	1.1		√
19	UFAD	8	1.1		√	43	Displace	7	0.5		√
20	UFAD	8	1.8		√	44	Displace	7	1.1		√
21	UFAD	9	0.5	√	√	45	Displace	8	0.5		√
22	UFAD	9	0.8		√	46	Displace	8	1.1		√
23	UFAD	9	1.1	√	√	47	Displace	9	0.5		√
24	UFAD	9	1.8		√	48	Displace	9	1.1		√

In addition, the literature assessed the effect of ventilation rate on the transport of contaminants exhaled only by reclining patients, which may not be representative of normal scenarios such as working in an office. Although the patient room settings are more likely to a concern for infectious disease transmission, numerous studies have focused on the contaminant transport in hospital environments (Chen et al., 2010; Chen et al., 2011; Ching et al., 2008; Nielsen et al., 2010; Qian et al., 2006; Yin et al., 2011; Zhao et al., 2009a). The office settings where people spend considerable time are also important, since the cross infections occurring in the offices are strongly related to working efficiency and productivity. Therefore, this study investigated person-to-person contaminant transport in an office with different ventilation rates to extend the knowledge in this area. The schematic of the office is depicted in Figure 1(a). There were two seated persons with a height of 1.2 m, two personal computers, and two desks in the office. The following section details the strategy for obtaining person-to-person contaminant exposure data.



(a) (b)

Figure 1. (a) Schematic of the office and (b) measuring locations and heights for air velocity, temperature and SF$_6$ concentration.

2.3 Obtaining person-to-person contaminant exposure data

2.3.1 Strategy for obtaining the exposure data

Compared with experimental measurements, Computational Fluid Dynamics (CFD) modeling is more cost-effective for obtaining person-to-person contaminant exposure data. However, the reliability of the CFD modeling should be verified. Thus, this study first conducted experimental measurements in the office to validate the model, and then applied the model to obtain the exposure data for all the cases listed in Table 1.

Because the UFAD system has not been well studied, the experiment was conducted for this system. Furthermore, because ventilation rate and person-to-person distance are the target parameters in this study, different ventilation rates and person-to-person distances were included in the experiment. Ventilation rates of 3, 6, and 9 ACH correspond to low, medium, and high ventilation, respectively, in normal indoor environments. Person-to-person distances of 0.5 and 1.1 m correspond to close and normal distances, respectively, for common scenarios. Table 1 also illustrates the measurement cases identified.

2.3.2 Experimental setup

This investigation built a full-scale office using an environmental chamber with dimensions of

4.8 m in length, 4.3 m in width, and 2.4 m in height, as shown in Figure 1(a). There were two inlets installed at floor level, and the exhaust was located at ceiling level. Figure 2 shows the linear type of diffusers used in the experiment. The environmental chamber could provide a controlled air supply at various airflow rates. The enclosures were well insulated so that the chamber could maintain a stable thermal condition.

Figure 2. Linear diffuser used in the UFAD system.

The ventilation rate was set at 3, 6, and 9 ACH, and the person-to-person distance was set at 0.5, 1.1, and 1.8 m, as shown in Table 1. This study used sulfur hexafluoride, SF_6, as a tracer gas to simulate the exhaled contaminants. The SF_6 source was located in the breathing zone of one of the human simulators, as shown in Figure 1. Before each measurement, this investigation operated the HVAC system for 6 to 8 hours to reach a thermally steady-state condition. The measurement started after a steady-state concentration distribution of SF_6 was reached.

The air velocity, temperature, and SF_6 concentration distributions were measured in the experiment. As depicted in Figure 1(b), the air velocity, temperature, and SF_6 concentration were measured in two sections at 13 locations in the plane. At each location the measurements were conducted at five different heights along a pole. The experiment used 30 hot-sphere anemometers to measure the air velocity and air temperature. The hot-sphere anemometers had an accuracy of 0.02 m/s for velocity and 0.2 K for air temperature. A photo-acoustic multi-gas analyzer (INNOVA model 1312) with a multipoint sampler (INNOVA model 1309) was employed to measure the SF_6 concentration with an accuracy of 0.001 ppm. The measurement duration of air velocity, air temperature, and SF_6 at each point was five minutes. Moreover, the air velocity magnitude and direction at the inlets were measured using ultrasonic anemometers. All the surface temperatures were measured using thermocouples as shown in Table 2.

Table 2. Measured boundary conditions.

Boundary	Temperature (^oC)	Boundary	Temperature (^oC)	Heat Power (W)
North wall (-X)	24.7	Lamps (north)	-	87
South wall (+X)	23.6	Lamps (south)	-	70
East wall (-Z)	24.8	Human simulator (east)	27.7	84
West wall (+Z)	24.3	Human simulator (west)	28	93.3
Ceiling (+Y)	24.8	PC simulator (east)	31.4	105
Floor (-Y)	24.3	PC simulator (west)	30.8	90
Supply air (north)	21.1	Supply air (south)	20.2	

2.3.3 Modeling approach

This study applied CFD modeling to obtain the person-to-person exposure data in the office. A RANS model with the Eulerian method for steady-state was used in this study because of the reasonable accuracy and low computing cost associated with the model (Wang et al., 2012). The renormalization group (RNG) k-ε model (Choudhury, 1993) was applied to calculate the airflow and turbulence because it has the best overall performance among all RANS models for enclosed environments (Wang and Chen, 2009). For contaminant modeling, because the mean diameter of the droplets exhaled through breathing was 0.4 μm (Gupta et al., 2010), the effect of gravitational settling on droplet dispersion was negligible (Zhao et al., 2009b). Furthermore, Chen and Zhao (2010) have indicated that the transient process from a droplet to a droplet nucleus due to evaporation is also negligible for particles with a diameter of 0.4 μm. Thus, modeling the exhaled droplets as gaseous contaminants is reasonable. From the perspective of contaminant transport, the major difference between coughing, sneezing and breathing is the influence of exhaled air velocity on contaminant transport. The experimental measurements and then computer simulation of airflow in an aircraft cabin by Gupta et al. (2011) indicated that even a cough without covering mouth can have limited affect on the local airflow field but not the whole airflow field. Moreover, if a mouth is covered when coughing or sneezing as people would usually do, the influence of coughing and sneezing on the airflow field would be minimal. Therefore, exhalation with zero exhaled velocity was assumed in this study.

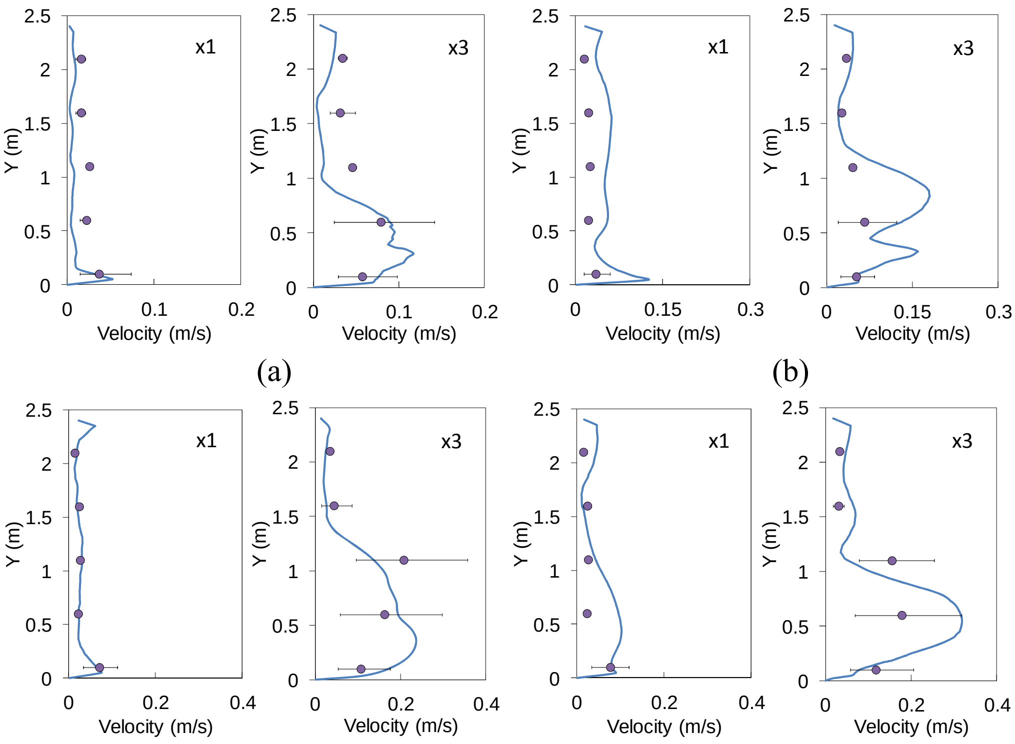
Numerical simulations were conducted using the CFD program, ANSYS Fluent 12.1 (ANSYS 2010). A user-defined function (UDF) was implemented to realize the Eulerian model. Three grid resolutions (101,709, 729,304, and 1,476,360) were tested for CFD grid independence. The 729,304 grid resolution was sufficiently fine to capture such a turbulent flow in the office mockup.

Using the RANS-Eulerian model, this investigation calculated the contaminant concentration at the breathing zone of the receptor for the 48 cases shown in Table 1. The relative effects of ventilation mode, ventilation rate, and person-to-person distance were calculated by Eqs. (1) –

(3). Combining the cases from the literature and this study, we assessed the effect of ventilation mode, ventilation rate, and person-to-person distance on person-to-person contaminant transport.

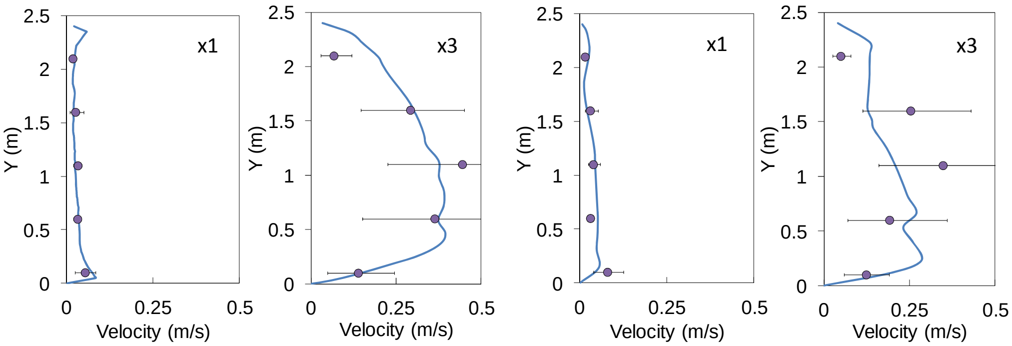
3. Validation of the CFD model

To ensure that the CFD model could produce high-fidelity results for the database, this study first validated the model. Figure 3 compares the measured and calculated air velocity profiles for the six validation cases. The lower and upper bounds of the error bars represent the 10th and 90th percentiles of the measurement data, respectively. There was a large quantity of data; therefore, in order to keep the paper concise, this study shows only representative results at poles x1 and x3. It can be seen in Figure 3 that both the measured and calculated air velocities were higher at the lower region of pole x3, which was near an inlet. At that location, the model predicted higher air velocities when the ventilation rate increased, which agrees well with the measurements. At the locations that were far away from the inlets, such as pole x1, both the measurements and the modeling results show relatively low air velocities. For all the cases, the average relative error of air velocity was 45%.



(a) (b)

(c) (d)



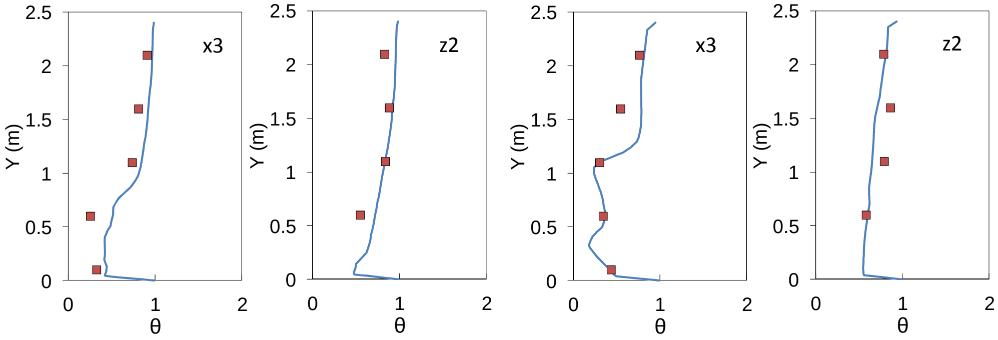
(e) (f)

Figure 3. Comparison of the measured and calculated air velocity profiles for (a) Case 1: 3 ACH and 0.5 m distance; (b) Case 3: 3 ACH and 1.1 m distance; (c) Case 9: 6 ACH and 0.5 m distance; (d) Case 11: 6 ACH and 1.1m distance; (e) Case 21: 9 ACH and 0.5 m distance; and (f) Case 23: 9 ACH and 1.1 m distance.

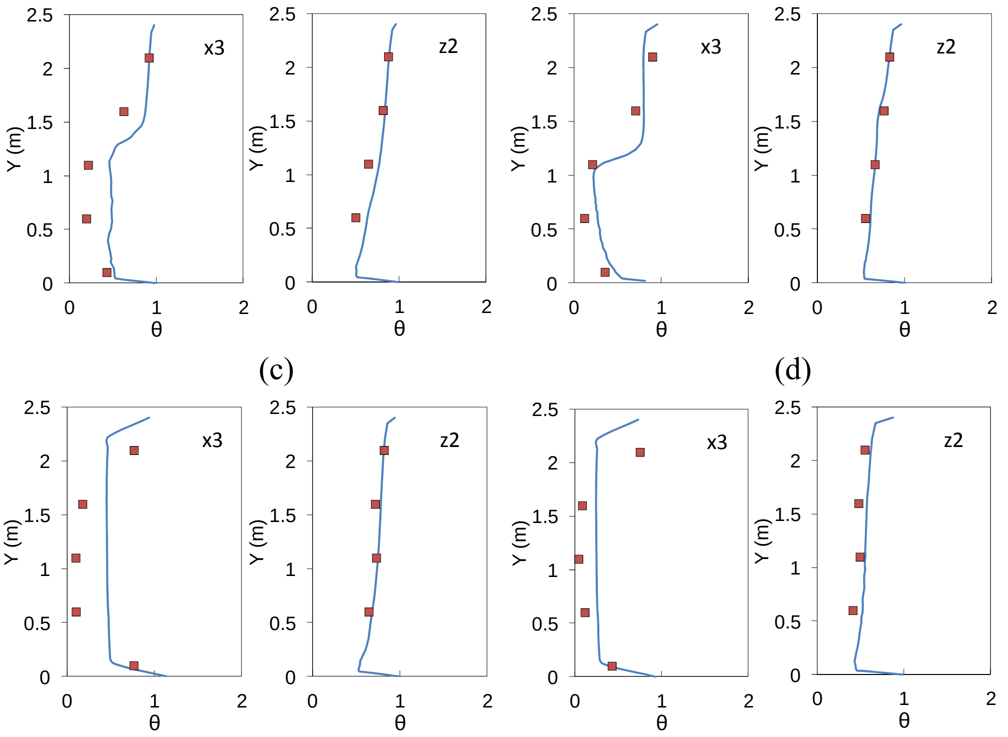
Figure 4 shows a comparison of the measured and calculated air temperature profiles at poles x3 and z2. The air temperature was normalized by

$$\theta = \frac{T - T_{in}}{T_{out} - T_{in}} \tag{4}$$

where T is the local temperature, and T_{in} and T_{out} are the temperatures at the inlets and exhaust, respectively. Both the measured and calculated results show positive vertical temperature gradients for all the cases. At pole x3, which was close to an inlet, the temperature gradients tended to be small when the ventilation rate was increased to 9 ACH. The reason was that such high air velocities near the inlet caused mixing and destroyed the stratification. The model can predict such a phenomenon in good agreement with the measurements. For all the cases, the average relative error of air velocity was 31%.



(a) (b)



(c) (d)

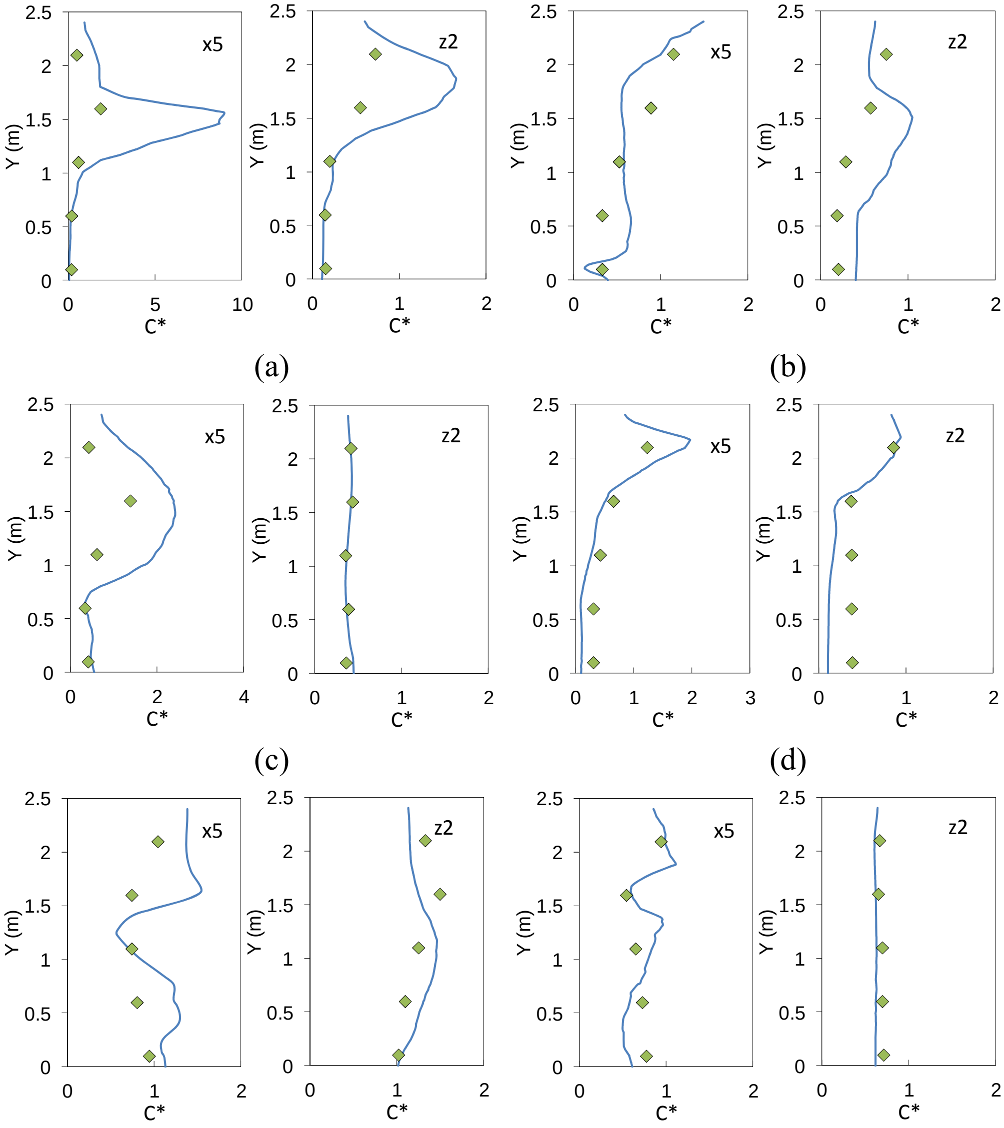
(e) (f)

Figure 4. Comparison of the measured and calculated air temperature profiles for (a) Case 1: 3 ACH and 0.5 m distance; (b) Case 3: 3 ACH and 1.1 m distance; (c) Case 9: 6 ACH and 0.5 m distance; (d) Case 11: 6 ACH and 1.1m distance; (e) Case 21: 9 ACH and 0.5 m distance; and (f) Case 23: 9 ACH and 1.1 m distance.

Figure 5 compares the measured and calculated SF_6 concentration profiles for the six cases. Again, the SF_6 concentration was normalized by

$$C^* = \frac{C - C_{in}}{C_{out} - C_{in}} \tag{5}$$

where C is the local concentration, and C_{in} and C_{out} are the concentrations at the inlets and exhaust, respectively. When the ventilation rate was 3 and 6 ACH, both the measured and calculated results show that the SF_6 concentration had a positive vertical gradient. This confirmed that the UFAD system could create a stratified air distribution. With a high ventilation rate of 9 ACH, the SF_6 concentration was uniform. The high air velocities near the inlets caused the mixing type of air distribution at pole x3. In Figure 4(a), remarkable differences existed between measurement and simulation. For pole x5, the simulation shows that there was a sudden change of concentrations at the height between 1.6 to 1.7 m. A single measurement point here was difficult to capture such a sudden change of concentrations. This might be the major reason for the remarkable difference between measurement and simulation. However, it can be seen that the measured data at 1.6 m matches well with the calculated data at 1.7 m. The measured data did fell in the range of calculated results at the height between 1.6 to 1.7 m. The similar explanation may apply to the remarkable difference at pole z2. For all the cases, the average relative error of air velocity was 44%.



(a)

(b)

(c)

(d)

(e)

(f)

Figure 5. Comparison of the measured and calculated SF_6 concentration profiles for (a) Case 1: 3 ACH and 0.5 m distance; (b) Case 3: 3 ACH and 1.1 m distance; (c) Case 9: 6 ACH and 0.5 m distance; (d) Case 11: 6 ACH and 1.1m distance; (e) Case 21: 9 ACH and 0.5 m distance; and (f) Case 23: 9 ACH and 1.1 m distance.

Generally speaking, the calculated results agree reasonably well with the experimental data in terms of air velocity, temperature, and contaminant concentration distributions. Thus, the RANS - Eulerian model was then used to produce data for the 48 cases shown in Table 1 for establishing the database with confidence. By combining these cases with the cases from the literature, this investigation created a database of 118 cases for studying ventilation mode, 124 cases for ventilation rate, and 88 cases for person-to-person distance.

4. Results

4.1 Effect of ventilation mode

Using the 118 cases in the database that address ventilation mode, it is possible to study the effect of ventilation mode on person-to-person contaminant transport. Figure 6 compares the median value of the relative effect of mixing ventilation, displacement ventilation, and the UFAD system on person-to-person contaminant exposure. The lower and upper bounds of the error bars represent the 10th and 90th percentiles of the data from the database, respectively.

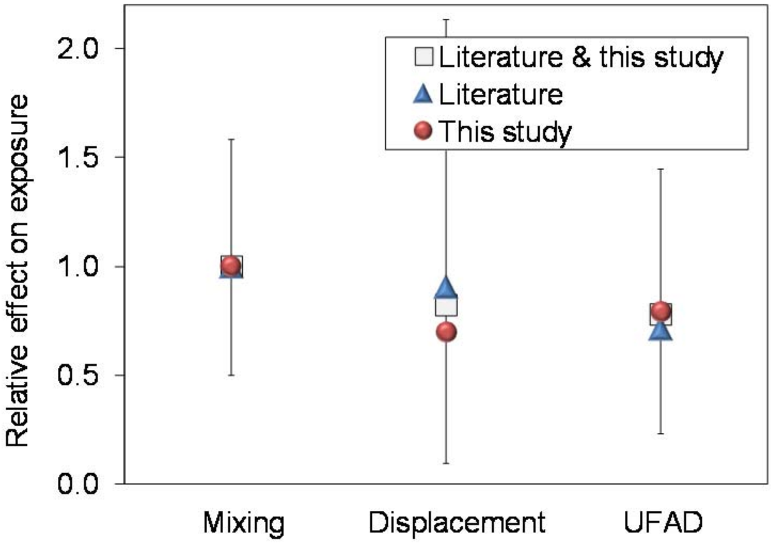


Figure 6. Relationship between ventilation mode and person-to-person contaminant exposure.

The median value of the relative effect from the literature and from this study is also shown separately in the figure. Because the reference for the relative effect was the person-to-person contaminant exposure under mixing ventilation, the median values of the relative effect for mixing ventilation from the literature and from this study were both close to 1.0. The median value of the relative effect for displacement ventilation from the literature was 0.91, while the median value from this study was 0.70. The difference may be attributed to the differences in scenarios. For instance, some cases from the literature were for the scenario of contaminant transport between reclining patients (Qian et al., 2006; Yin et al., 2011). The thermal plumes from the reclining patients tended to be weaker than those from the standing or seated persons in our study. Thermal plumes from the human body play an important role in the distribution of exhaled contaminants (Gao et al., 2012a). Weaker thermal plumes may reduce the chance of removal of exhaled contaminants by fresh air. When the relative effects from the literature and this study were combined, the median value of the relative effect for displacement ventilation was 0.82. The median values of the relative effect for the UFAD system from the literature and from this study were in good agreement. The median value from the combination of the literature and this study for the UFAD system was 0.78. It can be seen that the deviation in the performance of displacement ventilation was larger than in that of mixing ventilation. The high exposure cases of displacement ventilation were the measurement cases by Olmedo et al. (2012) when the person-to-person distance was 0.35 m. Their measurements showed that, when the person-to-person distance was 0.35 m, the exposure under displacement ventilation was much higher than that under mixing ventilation.

Generally speaking, the performances of displacement ventilation and UFAD systems in controlling person-to-person contaminant transport were quite similar. They were about 20% better than mixing ventilation in reducing person-to-person contaminant exposure. Displacement ventilation and UFAD systems can be categorized as stratified air-distribution systems. The cool, fresh air from the inlets remains in the lower region of the room and then moves directly into the occupied zone because of thermal buoyancy. Thus, these systems have the potential to reduce person-to-person contaminant exposure and provide better indoor air quality, as compared with mixing ventilation. This finding is consistent with the results of many previous studies (Chen and Glicksman, 2003; Lau and Chen, 2006). However, Olmedo et al. (2012) pointed out that displacement ventilation may have poorer performance than mixing ventilation in controlling person-to-person exposure under certain circumstances. The large error bars shown in Figure 6 also indicate significant variations in the relative effects for different ventilation modes. The median value of the relative effect was 1.0 for mixing ventilation and around 0.8 for the displacement ventilation and UFAD systems. A factor of 1.25 may represent the general effect of ventilation mode on person-to-person contaminant transport in mechanically ventilated spaces.

4.2 Effect of ventilation rate

Similarly, a total of 124 cases in the database could be used to study the effect of ventilation rate on person-to-person contaminant transport. Figure 7 shows the relationship between person-to-person contaminant exposure and ventilation rate. Each symbol represents the median value of the relative effect for the corresponding ventilation rate. The lower and upper bounds of the error bars represent the 10th and 90th percentiles of the data, respectively. The median values of the relative effect from the literature and from this study are also shown separately in the figure. Because the reference for the relative effect was the person-to-person contaminant exposure under a ventilation rate of 6 ACH, the median values of the relative effect for 6 ACH from the literature and from this study were both close to 1.0. The trends of the relative effects on contaminant exposure versus ventilation rate in Figure 7 show that the results of this study matched well with those from the literature. However, the relative effect for 4 ACH from the literature seems to be lower than the general trend. The reason is unknown, but the difference is not significant. Combining the relative effects from the literature and from this study, a linear regression was performed for the median value of the relative effect with the corresponding ventilation rates. The correlation between ventilation rate and person-to-person contaminant transport is significant, with an R^2 of 0.87.

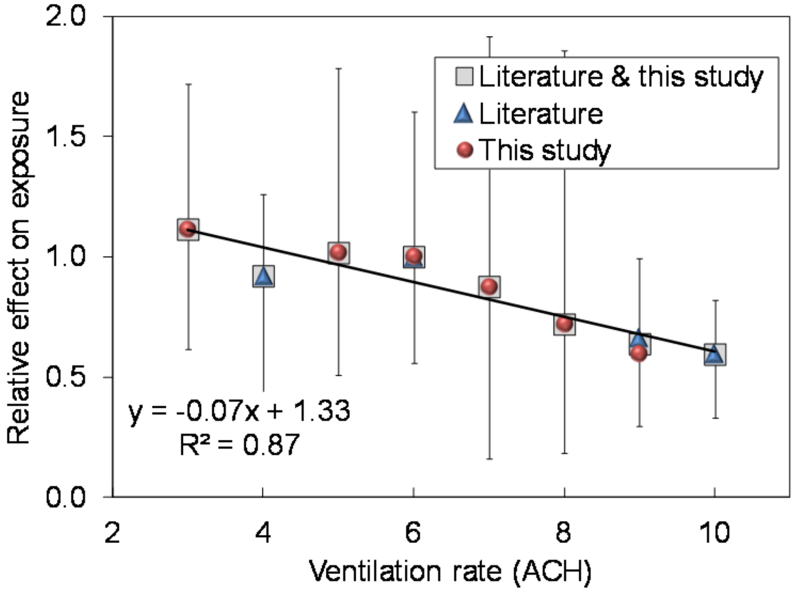


Figure 7. Relationship between ventilation rate and person-to-person contaminant exposure.

The database shows that the exposure was negatively associated with ventilation rate for all the ventilation modes. This finding makes sense because higher ventilation rate corresponds to higher dilution rate, which can reduce contaminant concentration in the breathing zone of the receptor. ASHRAE (2008) and CDC (2005) guidelines recommend a minimum ventilation rate of 12 ACH for hospital isolation rooms. These guidelines are evidence that ventilation rate is important in controlling person-to-person contaminant transport. Gao et al. (2012b) also indicated that increasing ventilation rate together with household isolation could be as effective as school closure for influenza transmission control in schools. However, the large error bars shown in Figure 7 imply significant variations in the relative effects of ventilation rate on person-to-person contaminant transport. Thus, other factors may modify the effect of ventilation rate. In addition, the median values of the relative effect on person-to-person contaminant exposure were 1.1 and 0.6 for ventilation rates of 3 and 10 ACH, respectively. This implies that an increase in ventilation rate by a factor of 3.3 resulted in a decrease of person-to-person contaminant transport by a factor of only 1.8. Memarzadeh and Xu (2012) also indicated that although increasing ventilation rate diluted concentrations more effectively when the contaminant source was constant, it did not necessarily increase the ventilation effectiveness. Thus, controlling person-to-person contaminant transport by increasing ventilation rate may have certain limitations.

4.3 Effect of person-to-person distance

Very similarly to the previous subsections, 88 cases in the database were available for studying the effect of person-to-person distance on person-to-person contaminant transport. Figure 8 shows the relationship between person-to-person contaminant exposure and person-to-person distance. Each symbol represents the median value of the cases at the corresponding person-to-person distance. The lower and upper bounds of the error bars represent the 10th and 90th percentiles of the data, respectively. The median values of the relative effect from the literature and from this study are also shown separately in the figure. Because the reference for the relative effects was the person-to-person contaminant exposure at a distance of 1.1 m, the median values of the relative effect for 1.1 m from the literature and from this study should be close to 1.0, as confirmed in the figure. Most of the median values of the relative effect from the literature were close to those from this study, except at distances of 0.5 and 0.8 m. It is difficult for us to articulate the reason for these differences because there were many unknown factors. The differences are acceptable for our analysis in this investigation. Combining the relative effects from the literature and from this study, a power regression was performed for the median values of the relative effect with the corresponding person-to-person distances. An R^2 of 0.94 implies a strong correlation between person-to-person contaminant transport and person-to-person distance.

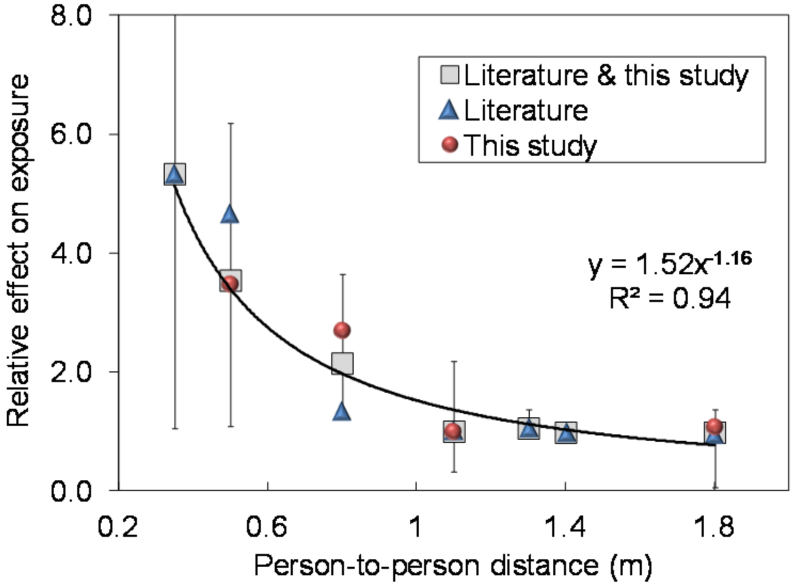


Figure 8. Relationship between person-to-person distance and person-to-person contaminant exposure.

It can be seen that when the person-to-person distance was smaller than 1.1 m, the relative effect on person-to-person contaminant exposure increased rapidly with the decrease in distance. However, when the person-to-person distance was larger than or equal to 1.1 m, the curve tended to be rather flat. This was because the contaminant concentration gradient was larger near the source than in other locations. Thus, when the person-to-person distance increased to some extent, the influence of concentration gradient became insignificant. In this study, 1.1 m can be regarded as a cut-off person-to-person distance in terms of person-to-person contaminant transport. The median value of the relative effect on contaminant exposure was 5.3 for a distance of 0.35 m, and around 1 for a distance of 1.8 m. A factor of 5.3 indicates that person-to-person distance is a rather important parameter in terms of controlling person-to-person contaminant transport, when compared with ventilation mode and ventilation rate.

5. Discussion

This study compared mixing, displacement, and UFAD ventilation systems, which are the most commonly used systems in residential or commercial buildings. However, other ventilation modes may also affect person-to-person contaminant transport. For instance, downward ventilation has been widely used in hospital wards or clean rooms. Qian et al. (2006) reported that downward and mixing ventilation had similar performance in a multi-bed hospital ward. Moreover, personalized ventilation has become a popular ventilation mode. He et al. (2011) concluded that personalized ventilation could increase contaminant concentration in the breathing zone of the receptor as well as provide clean personalized airflow. Whether person-to-person exposure could be reduced depends on the balance of the pros and cons of personalized ventilation.

Although the cases collected from the literature included both breathing and coughing cases, this study did not quantitatively assess the differences between breathing and coughing. The peak exhaled velocity of coughing is much higher than that of breathing. Thus, the contaminant exhaled by a cough tends to travel more quickly than by a breath. The model used in this study was for breathing cases, which can be regarded as a steady-state condition. If the transient particle transport resulting from a cough were investigated, the hybrid model developed and validated in our previous study could be used (Chen et al., 2013).

The key factor in contaminant transport is the “path” of airflow (Memarzadeh and Xu, 2012). The perfect “path” should be that the fresh air firstly goes through the receptor, then reaches to the source, and finally removes the contaminant to the exhaust. However, it is difficult to use a single parameter to describe the “path”. The “path” depends on ventilation mode, ventilation rate, person-to-person distance, and other parameters. At the first stage of design, a designer needs to make a decision on what kind of ventilation mode should be used, how much ventilation is needed, and how far the person-to-person distance (e.g. desk-to-desk distance in an office) should be designed. The statistical results in this study can be a general guideline to support the designers’ decisions at this stage. After that, if possible, the designer can use CFD technique to investigate the “path” in detail.

In addition to ventilation mode, ventilation rate, and person-to-person distance, which are among the ones that mostly related to HVAC design, other factors may influence person-to-person contaminant transport. Previous studies have reported that air cleaners have the potential to reduce person-to-person contaminant transport in hospital wards (Chen et al., 2010). Wearing masks has been identified as an effective method to reduce the risk of exposure to exhaled contaminants (Gupta et al., 2012; Lai et al., 2012). The use of air curtains may also reduce contaminant transport between two zones (Ching et al., 2008; Chen et al., 2011). Moreover, the use of upper-room ultraviolet germicidal irradiation (UVGI) has been proven effective in disinfecting exhaled airborne pathogens and reducing the risk of person-to-person exposure (Yang et al., 2012). Furthermore, the orientations of persons relative to one another (Olmedo et al., 2012) and the gestures of the persons (Zhao et al., 2009a) can also influence person-to-person contaminant exposure.

6. Conclusions

This paper presents a systematic study of the effect of ventilation mode, ventilation rate, and person-to-person distance on person-to-person contaminant transport. This investigation collected a large quantity of data from the literature and used a validated CFD model to generate additional data in order to establish a database. From this database, the following conclusions can be drawn:

- The overall performances of displacement ventilation and a UFAD system were similar in terms of reducing exposure to person-to-person contaminant transport, and the two systems were about 20% better than mixing ventilation.
- The data show that person-to-person contaminant exposure tended to be reduced with an increase in ventilation rate.
- When the person-to-person distance was less than 1.1 m, person-to-person contaminant exposure increased rapidly with distance. At a distance larger than 1.1 m, the effect of distance was insignificant.
- Person-to-person distance is more important than ventilation mode and ventilation rate in controlling person-to-person contaminant transport.

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