Zhao, Weixin; Lestinen, Sami; Guo, Miao; Kilpeläinen, Simo; Jokisalo, Juha; Kosonen, Risto

An experimental study on airborne transmission in a meeting room with different air distribution methods

Published in:
Building and Environment

DOI:
10.1016/j.buildenv.2024.111522

Published: 15/05/2024

Document Version
Publisher's PDF, also known as Version of record

Building and Environment 256 (2024) 111522

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

An experimental study on airborne transmission in a meeting room with different air distribution methods

Weixin Zhao [a,*], Sami Lestinen [b], Miao Guo [c], Simo Kilpeläinen [a], Juha Jokisalo [a], Risto Kosonen [a,d]

[a] Department of Mechanical Engineering, Aalto University, Espoo, Finland
[b] A-Insinöörit Suunnittelu Oy, Espoo, Finland
[c] Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing, 400045, China
[d] College of Urban Construction, Nanjing Tech University, China

ARTICLE INFO

Keywords:
Airborne transmission
Infection probability
air distribution
Heat gain
Meeting room
Tracer gas

ABSTRACT

Aerosols are one of the major sources of cross-infection. The main purpose of this study is to analyze the effects of heat gain, airflow rate, air distribution, and the location of an infector on the airborne transmission and infection probability in a meeting room. In a six-person meeting room the droplet nuclei of an infected person were simulated with tracer gas (SF_6) generated by a thermal breathing manikin. An overhead perforated duct (OPD) and low velocity unit (LVU) were used and their performance was compared. With OPD, the average contaminant removal efficiency in the breathing zone was quite uniformly between 0.9 and 1.1. With LVU, the average contaminant removal efficiency varied greatly between 0.2 and 10.1. The airborne generation was assumed to be 5 quantum/h by an infected person. The infection probability for every exposed person was found to be quite uniform with OPD, 1.4 % with a heat gain and air flow rate of 38 W/m^2 and 61 l/s and 0.9 % with a heat gain and air flow rate of 60 W/m^2 and 116 l/s after 3 hours' exposure. However, variation of the infection probability with LVU was significant and the highest risk reached 4 %. The infection probability was lower if the exposed person was farther from the infector, or in the case of OPD if the infector was near the exhaust. With LVU, the infection probability depended on the airflow rate and the relative distance between the supply unit and the exposed person.

1. Introduction

The main respiratory transmission route for many infectious diseases is the airborne transmission between humans [1]. Particles (e.g., droplets) exhaled by an infected person may contain pathogens and infect nearby persons [2]. Therefore, it is important to understand the mechanism of aerosol particles transmission in the occupied space and methods to reduce the risk of cross infection. By increasing the airflow rate, it is possible to reduce the infection risk in many cases. However, an increase of the airflow could increase the concentration level of aerosol particles locally [3]. From the energy-efficiency point of view, it is not always the most optimal manner to reduce the infection risk. Recently it has been clearly proven that airflow distribution methods have a significant effect on the personal exposure to indoor air pollutants [4–8]. Thus, it is possible to reduce the infection risk with suitable air distribution and without increasing the total airflow rate.

According to the WHO guideline [9], the minimum required ventilation rate for ordinary workplaces or public spaces is 10 l/s per person. A minimum of 15 l/s per person is required for an indoor space where much aerosol is generated through singing, loud speaking, aerobic exercise, or other activities. According to EN 16798–1:2019 [10] results in default Indoor Climate Category I-II to 4.9–7.0 l/s per m^2 (10–14 l/s per person) outdoor airflow rates in meeting rooms for non-low-polluted building.

Two main categories of air distribution are displacement ventilation and mixing ventilation [11]. In mixing ventilation, Fig. 1 a), the outdoor air is supplied at a high velocity outside the occupied zone, such as near or at the ceiling. This promotes good mixing with uniform temperature and pollution distribution in the occupied zone. In displacement ventilation, Fig. 1 b), the principle is to replace but not to mix the room air with supply air, where the clean and cold air is utilizing convection flows of heat gains.

* Corresponding author.
E-mail address: weixin.zhao@aalto.fi (W. Zhao).

https://doi.org/10.1016/j.buildenv.2024.111522
Received 18 January 2024; Received in revised form 15 March 2024; Accepted 8 April 2024
Available online 9 April 2024

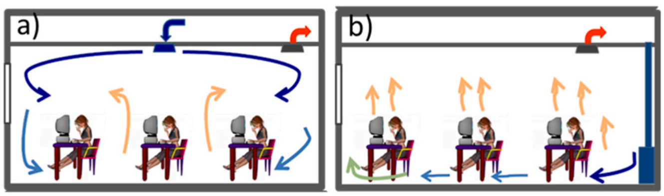


Fig. 1. a) mixing ventilation and b) displacement ventilation.

The free convection flow [12] generated by a human body forms a convective boundary layer around the body, which transforms into a thermal plume that rises above the head. Clean air penetrates the free convection flow in front of occupant's body and is then inhaled by occupant. Qian et al. [13] showed that the exhaled jet penetrates a short distance and is diluted quickly with the ambient room air. This results in the distribution of exhaled droplet nuclei being influenced by the convection flows and jets. With displacement ventilation, a high concentration layer of exhaled droplet nuclei could exist due to thermal stratification locking. The exhalation jet from the infector can penetrate the breathing zone of the exposed person with displacement ventilation, resulting in higher human exposure to viral aerosols than in mixing ventilation case [14]. Increasing the ventilation rate can effectively reduce human exposure due to a dilution effect and a more pronounced air stratification.

To improve the air quality for the occupants, advanced ventilation air distribution methods including personalized ventilation [15], local air diffusers [16], and ventilation fans [17] have been added to the ordinary mixing ventilation configurations.

To prevent the transmission of exhaled air, the ventilation approach should rely on source and air distribution control rather than on dilution, i.e., supplying large volumes of clean conditioned air. This includes extracting the pollutants locally and/or organizing the airflow pattern from clean zone toward less clean zones inside the occupied space followed by efficient polluted air removal. The studied local exhaust units were found to be efficient against airborne transmissions in densely occupied spaces. Bolashikov et al. [18] found that a personal local exhaust unit incorporated in a headset-microphone had a high potential for capturing exhaled air. Yang et al. [19] stated that with the top-personalized exhaust or shoulder-personalized exhaust, the exposure for the healthy person was lower after 30 min than the exposure after 10 min without a personalized exhaust.

Depending on the location of the infected person and the combined airflow around the person, airborne transmission can be different when occupants sit at different locations [20,21]. A quantum is defined as the dose of airborne droplet nuclei required to cause infection in 63 % of susceptible persons [22]. In a previous study [23], the infection risk was numerically investigated for mixing and displacement ventilation systems in an office space. With displacement ventilation, the infection probability was 0.74 % after 4 h with 10.5 quantum/h by an infected person, which is lower than in well-mixed conditions (2.9 %). This indicated the buoyancy-driven air distribution methods may have good performance at preventing cross-infection. However, the infection risk is sensitive to the location of the infector with displacement ventilation [23], depending on whether the infector is near or far from the air supply diffuser. Moreover, other factors such as the heat gain from equipment and solar heat gains were not considered in the study.

In our previous study [24], airborne transmission risks with personalized convective and radiant cooling systems in an office room were studied. The study showed that the lowest infection risk of 0.5 % occurred in the inhaled air with personalized systems with an airflow rate of 42 l/s after 2 h' exposure with 5 quantum/h generation by an infected person. A fully mixed ventilation system requires around a two times higher airflow rate for the same infection risk as the personalized system. Moreover, the convection flow from varied heat gain levels has a limited effect on the airborne transmission with a personalized system.

It has generally been acknowledged that the convection flows caused by thermal heat gains may affect the airflow pattern. In this study, the effect of the strength of the heat gain levels and corresponding increase in the airflow rates on the airborne transmission and infection risk were analyzed in a meeting room. To investigate the effect of the infector's location on the exposure level with different air distribution methods, the location of the infected person was varied.

The novelty of this paper is to quantitatively analyze airborne transmission and infection risk using overhead perforated duct (OPD) and low velocity unit (LVU) under different heat gain conditions and airflow rates. The infection risk is affected by the location of the infector in the room. This helps to understand the behavior of airborne transmissions and the findings provide insights into effective ventilation methods to prevent the occupants' exposure in meeting rooms.

2. Methods

The experiments were conducted in a full-scale test room, where a stable indoor climate can be maintained. The dimensions of the test room were 5.50 m (length), 3.80 m (width), and 3.60 m (height) from the floor to the ceiling.

2.1. Climate chamber

The aim of this experimental layout was to simulate a typical meeting room. A meeting table for six persons was placed in the middle of the room, as shown in Fig. 2. The length and width of the meeting table was 5.2 m × 0.8 m. One breathing thermal manikin, one heated dummy [25], and 4 persons simulated by heated cylinders were placed around the table. The dummy and four cylinders [26–28] were used as exposed persons with similar thermal plumes but without the breathing process. Only the manikin and dummy were equipped with a laptop. Lights were installed in the middle of these workstations on the ceiling. One side of the wall was equipped with heated radiant panels to simulate a warm window. These panels were supplied with hot water to reach the desired surface temperature. The average surface temperature of the warm window was 28 °C and it was quite near the air temperature. To simulate the impact of direct solar radiation, an electric heating mat was placed on the floor 0.8 m from the heated window panel wall. The heat gains used in the test room are summarized in Table 1. The exhaust was located in the ceiling near the warm window to remove the thermal plume of the window directly.

2.2. Air distribution methods

2.2.1. Mixing air distribution with overhead perforated duct (OPD)

The mixing air distribution was implemented with an overhead perforated duct (OPD) [29] in the ceiling zone, (Fig. 3 a). The perforated duct was extended for the entire length of the room and the supplied airflow was downwards toward the direction of the floor. The diameter of the perforated duct was 200 mm and the total length was 5.5 m.

2.2.2. Displacement air distribution with low velocity unit (LVU)

The displacement air distribution was achieved with a low velocity unit (LVU) (Fig. 3 b). A rectangular perforated low velocity unit was installed in the middle of the wall opposite the door on the floor. The width and height of the low velocity unit was 1140 mm × 550 mm.

2.3. Experimental conditions

To investigate the airborne transmission between the sitting persons in the meeting room, two important influential parameters were varied: the heat gain level in the room (38 W/m^2 to simulate mid-season indoor heat gain conditions and 60 W/m^2 for peak heat gain conditions), and the air distribution methods (OPD and LVU).

The operative temperature was controlled at 25 ± 1 °C at a height of

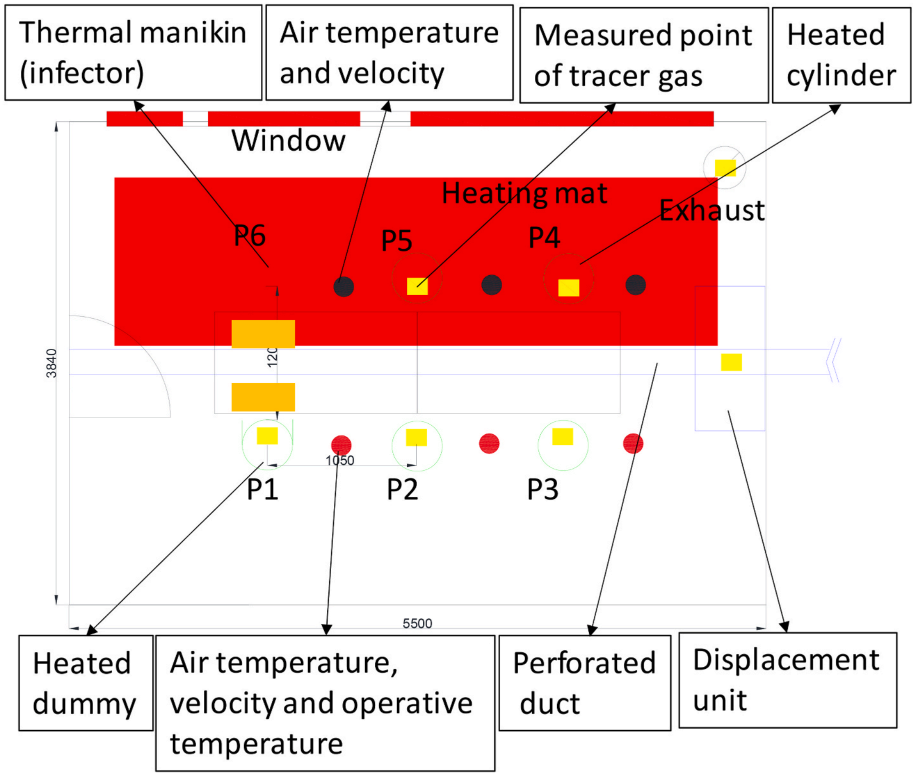


Fig. 2. The setup of the test chamber.

Table 1
Heat gains, airflow rates and design parameters under two heat gain levels.

		Heat gain and cooling load balance	
Total heat flux	W/m^2	60	38
Floor area	m^2	21	21
Total heat gain	W	1, 253	805
Manikin	W	80	80
Dummy	W	85	85
4 Cylinder dummies	W	4*80 = 320	4*80 = 320
2 Laptops	W	2*40 = 80	2*40 = 80
2 Lights	W	2*45 = 90	2*45 = 90
Heated Window panels	W	133	105
Solar load at floor	W	420	0
Equipment of manikin	W	45	45
Supply air flow rate	L/s	116	61
Air change rate	1/h	5.5	2.9
Supply air temperature	°C	16	14
Design room air temperature	°C	25	25
Cooling load	W	−1, 253	−805

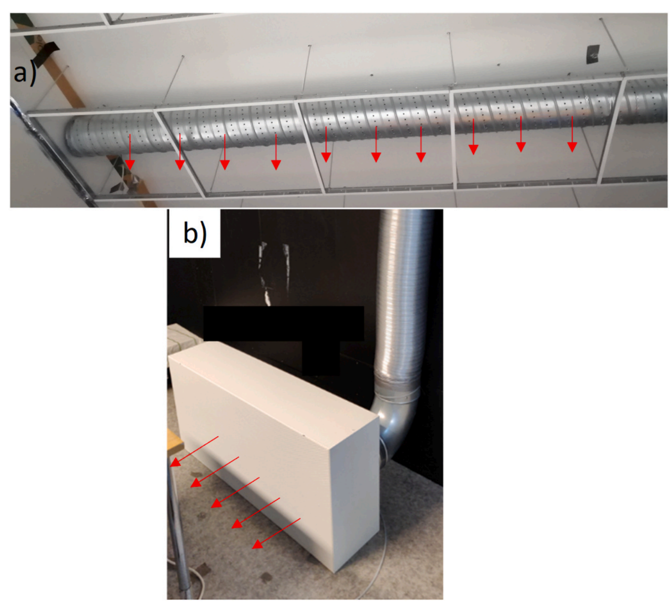


Fig. 3. a) Mixing air distribution with overhead perforated duct in the ceiling and b) displacement air distribution with low velocity unit on the floor.

1.1 m. The supply air temperature was kept at 14 °C with 38 W/m^2 and 16 °C with 60 W/m^2. The exhaust air temperature was around 25 °C. The supplied airflow rates were 116 l/s and 61 l/s with the 60 W/m^2 and 38 W/m^2 to be balanced with the total heat gain used, as shown in Table 1. The airflow rates correspond to an air change efficiency of 5.5 1/h and 2.9 1/h, respectively. The control of the supply and exhaust airflow was achieved by measuring the differential pressure with a balancing damper installed in the corresponding ducts. The test chamber was located inside a laboratory hall to ensure the environment outside the chamber was stable.

In this study, a thermal breathing manikin was used to simulate an infected sitting person in the room space, and one heated dummy and four heated cylinders represented the exposed persons. The breathing cycle of the manikin consisted of 2.5 s inhalation, 1 s break, 2.5 s exhalation and 1 s break.

To investigate the behavior of gaseous indoor-emitted pollutants, a tracer gas can be used to simulate droplet nuclei from the exhaled air and to study the effect of the air distribution on the local concentration levels. Ai et al. [30] demonstrated that the tracer gas technique is applicable to analyzing airborne transmissions in air distribution studies. Bivolarova et al. [31] also confirmed that a tracer gas can be used as a reliable predictor to assess the exposure level to different sizes of particles. SF_6 as a tracer gas, is not naturally present in the room air. Measurements of tracer gas SF_6 concentrations in the exhalation of an infected manikin and in the inhalation of an exposed manikin can quantitatively evaluate the infection risk [24,32,33]. The tracer gas concentration in the inhaled air of exposed persons and exhaled air infector was measured by Multi-gas Sampler and Monitor. This equipment took air samples via plastic tubes in the breathing zone and analyzed the components in the air. In this study, tracer SF_6 was released by exhaling through the nose of the thermal manikin with a pulmonary ventilation rate of 6 l/min. This was dosed directly into the artificial lung of the infector. The dosing rate was 2 ml/s, resulting in a contaminant concentration of the exhaled flow around 20,000 ppm. The breathing air of the manikin was heated to a setpoint of 35 °C and humidified to a level of 85 %. During the experiment, continuous tracer gas measurements using a multi-gas sampler and monitor were taken at 7 locations, including the breathing zone of the 5 exposed persons, and at the exhaust and supply duct. The distance between two face-to-face persons' noses was 1.2 m and between two side-by-side persons it was 1.05 m.

To investigate the effect of the infector's location on the exposure level, the manikin was placed at 4 different locations in each case as shown in Fig. 4 and the exhaust point was near P4.

The tracer gas dosing started when the indoor air temperature and airflow distribution reached steady-state conditions. In this study, the tracer gas concentration at seven locations was measured as the tracer gas from the breathing manikin began releasing into the room. There were two stages during the tracer gas measurements in the breathing zone and exhaust: firstly, the concentration increased after the tracer gas dosing, and secondly, the concentration reached a steady state at every location. In addition to the tracer gas concentration measurements, the air velocity and air temperature were measured at different workstations at heights of 0.6 m, 1.1 m, 1.4 m and 1.7 m with Dantec ComfortSense anemometers. The operative temperature was measured by a Dantec sensor at a height of 1.25 m. In addition, the room's wall surfaces were photographed with a thermal camera to guarantee the set conditions in the tests. All the measurement devices used during the experiments are summarized in Table 2.

2.4. Evaluation indices

A Wells–Riley model [22] was used that assumed that the whole room volume was fully-mixed and in steady-state conditions as follows:

Table 2
The measuring instruments.

Variable	Model	Accuracy
Temperature Air velocity Turbulence intensity Draught rate Radiant temperature	Omnidirectional probe 54T33 Draught Probe	Air speed (v): range 0–1.0 m/s Uncertainty: ±2 % or ±0.0 2 m/s on reference velocity Temperature (t): range 0–45 °C ± 0.2 °C on reference temperature 2 Hz
Operative temperature	ComfortSense temperature 54T38	Uncertainty: ±0.3 °C on reference temperature 2 Hz
Pressure difference	IRIS-200 damper	±5 %
Tracer gas concentration	Gasera ONE Multi-gas Sampler and Monitor	Detection limit: 0.37 ppm Repeatability: 0.08 %
Temperature Relative humidity	Tinytag plus 2 TGP- 4500	Air temperature ±0.5 °C, RH ±3 % at 25 °C
Surface temperature	ThermaCAMTM P60 infrared camera	±0.02·Tmeas

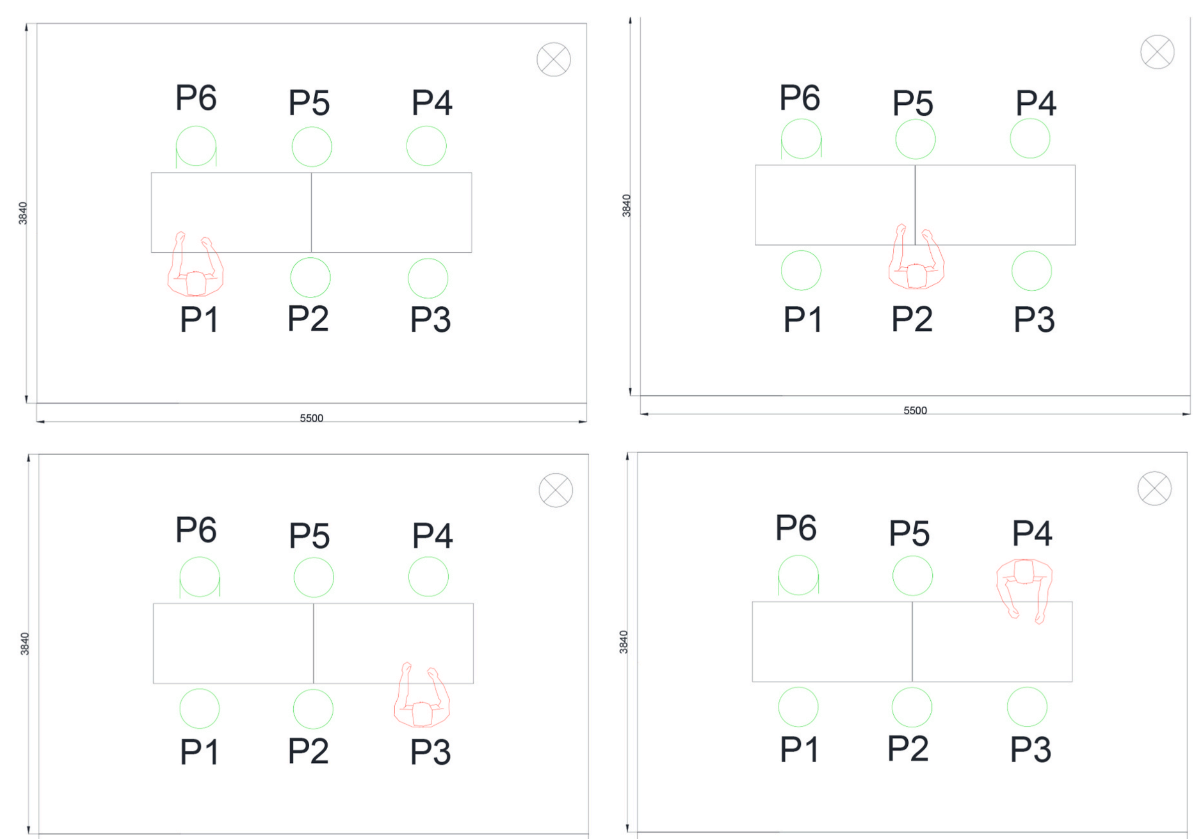


Fig. 4. The locations of the infector (red breathing thermal manikin) in the test room. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$P = \frac{C}{S} = 1 - e^{-\left(\frac{Iqpt}{Q}\right)} \tag{1}$$

where P is the infection probability, C is the number of new infections, S is the number of susceptible people, I is the number of infectors, q is the quantum generation rate by an infected person (quanta/h), p is the pulmonary ventilation rate (m^3/h), t is the total exposure time (h), and Q is the room ventilation rate (m^3/h).

In practice, the room space was not fully mixed due to the air distribution and thermal plumes. Therefore, the concentration of the aerosol was varied spatially and temporally. Zhang and Lin [32] proposed a dilution-based evaluation method for airborne infection risk for not well-mixed conditions. The method proposed is a thorough expansion of the Wells-Riley model for evaluation of airborne infection risk with both spatial and temporal resolutions.

The model is as follows:

$$D = \frac{C_{infector}}{C_{exposed}} \tag{2}$$

$$C_{quantum} = \frac{q}{D * p_{infector}} \tag{3}$$

$$N_{quantum} = \int_0^T p_{exposed}\, C_{quantum}(t)dt \tag{4}$$

$$P_D = 1 - e^{-N_{quantum}} \tag{5}$$

$$P_D = 1 - e^{-\int_0^T \frac{q * p_{exposed}}{D(t) * p_{infector}} dt} \tag{6}$$

where $C_{infector}$ and $C_{exposed}$ are the airborne contaminant concentrations at the infectious point and exposed position respectively (ppm); $C_{quantum}$ is the airborne quantum concentration at the exposed position (quanta/m^3); D is the dilution ratio at the exposed position; $p_{infector}$ is the breathing rate of the infector (m^3/s); $N_{quantum}$ are the inhaled quanta by the exposed person during the given exposure period; T is the total exposure time (h) P_D is the airborne infection risk with the exposed person during the given exposure period estimated by the dilution-based estimation method proposed; $p_{exposed}$ is the breathing rate of the exposed person (m^3/s).

3. Results

3.1. The infection probability in fully mixed conditions

Based on the assumptions for fully mixed conditions [22], Fig. 5 shows the infection probability over time with two airflow rates calculated using the Wells–Riley model. The human quanta yield varies based on pathogens and human activity. The quanta income can be in the tens or hundreds when speaking. In these infection risk calculations, the yield of infected quanta has been assumed to be 5 quanta per hour [34], which is a moderate level. According to Equation (1), the infection probability is only concerned with the airflow rate and does not consider the concentration distribution in non-uniform conditions. Therefore, the infection probability is the same in the whole volume no matter where the infector or exposed person were located. The infection probability decreased with an increased airflow rate. The infection probability was 2.4 % with a heat gain and air flow rate level of 38 W/m^2 and 61 l/s and 1.3 % with a heat gain and air flow rate level of 60 W/m^2 and 116 l/sat and a time of 178 min for the occupancy period, respectively.

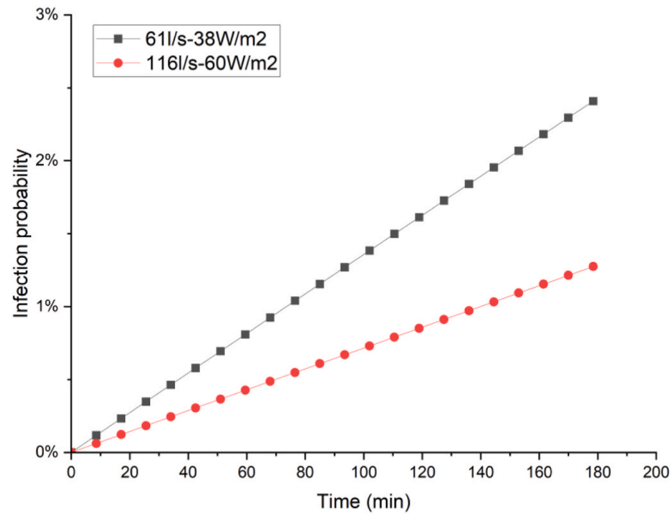


Fig. 5. The airborne infection risks with two heat gains and airflow rates calculated by Wells–Riley model.

3.2. The airborne transmission with OPD and LVU

Fig. 6 shows the tracer gas distribution at different measured locations when the manikin was at P1 and the dummy at P6 (Fig. 3). The tracer gas concentration was increased with time and reached a steady state after 60 min and 34 min at the exhaust with an airflow rate of 61 l/s and 116 l/s, respectively. After the tracer gas concentration at the exhaust reached a stable level, the average concentration in the room with OPD was 21.3 ppm and 11.3 ppm with a heat gain of 38 W/m^2 and 60 W/m^2, respectively. The average contaminant removal efficiency [35] was 0.9 and 1.1 with an airflow rate of 61 l/s and 116 l/s, respectively. Therefore, the air distribution was mixed well in the whole space. With OPD, the concentration distribution was quite uniform at each location, and the average standard deviation was only 0.3–0.6 ppm. This means the air distribution with OPD was quite uniform.

However, the tracer gas distribution varied spatially and temporally with LVU. After the concentration reached steady state conditions at the exhaust point, the minimum concentration was 2.0 ppm, but a maximum value of 52.3 ppm occurred in the breathing zone. The highest standard deviation was 11.2 ppm. Therefore, the horizontally supplied airflow from LVU created a varied air movement, especially close to the opposite wall. Additionally, fluctuations of the concentration at P6 increased with a higher airflow rate. The contaminant removal efficiency varied over time. The highest contaminant removal efficiency reached 10.1 and the lowest was 0.2. The mean value was 4.0 with an airflow rate of 61 l/s and 0.6 with airflow rate of 116 l/s. This indicates that an increasing airflow rate may not lead to a higher ventilation effectiveness.

3.3. The effect of the infector's location on the infection probability

Compared with the standard Wells–Riley model (Fig. 3), the infection probability for the dilution-based model (Figs. 7–10) at different locations varied significantly, especially with the LVU case. Therefore, the infection probability was significantly affected by the location of the infector.

When the infector moved from P1 to P4, the infection probability for different exposed persons was less than 1.7 % with OPD with a heat gain of 38 W/m^2 after 3 hours' exposure (see Fig. 6). As mentioned above, the infection probability was 2.4 % in fully mixed conditions.

There were some variations of infection for the five exposed persons if the infector changed position. When the infector sat at P1, which was far from the exhaust point, the infection probability was the highest (1.7

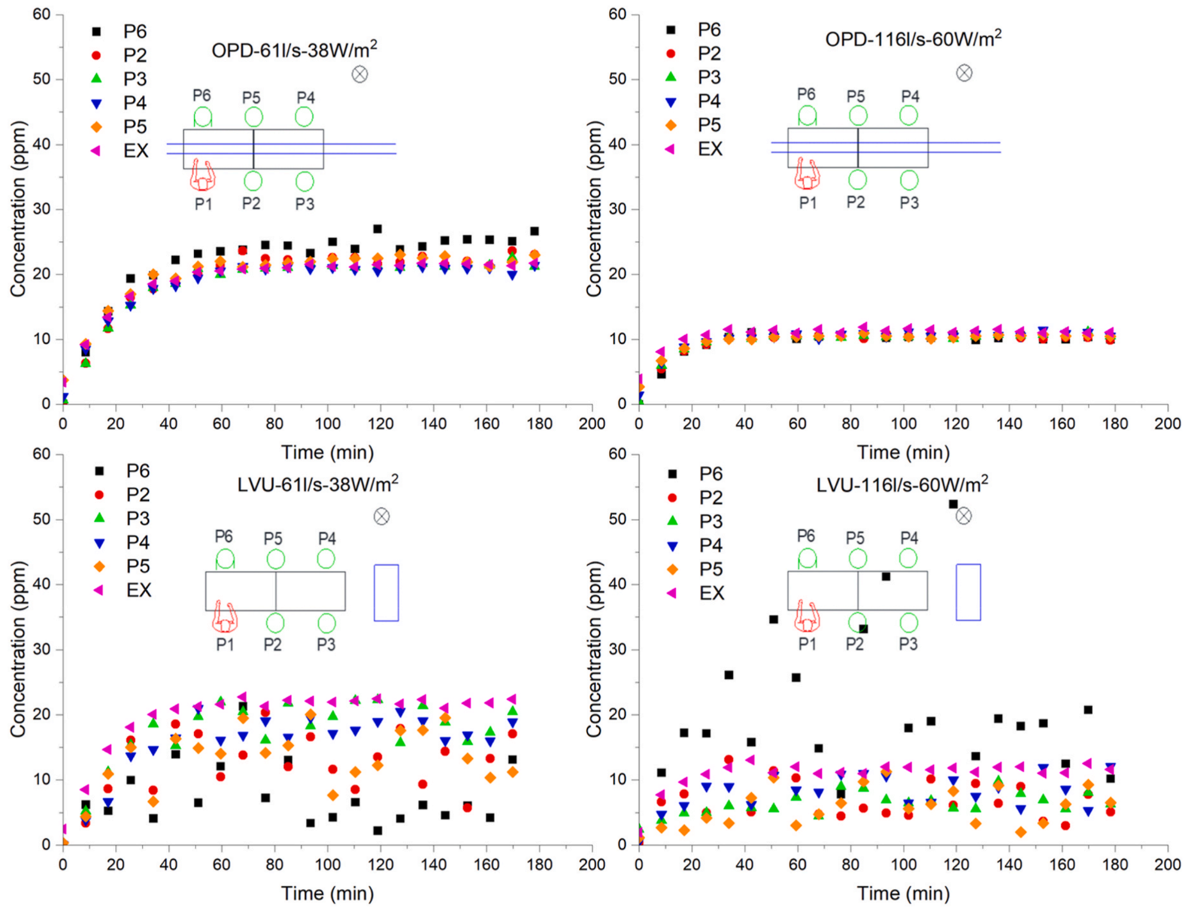


Fig. 6. The concentration distribution of tracer gas at different locations when the manikin was at P1 with OPD and LVU with two heat gains of 38 W/m^2 and 60 W/m^2 and two airflow rates of 61 l/s and 116 l/s.

%) for the exposed persons who sat face to face (P6) and near the infector (P2). The lowest risk (1.1 %) was when the exposed person sat at P6, and the infector was at P4. This means that the safest condition measured can be achieved when the infector was near the exhaust and the exposed person was far from the infector. When the infector sat at P2 (in the middle of the table), the probability was higher for the exposed persons who sat near the infector (P1 and P3) and face to face with the infector (P5), but the others' exposure level was similar.

When the infector sat near the exhaust (P3 and P4), the infection probability at the exhaust point as a reference value was 1.5 % and a little higher than for the other exposed persons. The reason for this is that the exhaled droplets from the infector were removed more effectively if the infector was near the exhaust. Therefore, there were more airborne dispersions between the workstations when the infector was at P1 and P2. Furthermore, the exposure level for all the exposed persons was the lowest at P4. This means the location and effectiveness of the general exhaust were critical for the airborne transmission with OPD.

When the heat gain rose to 60 W/m^2, the supplied airflow rate was 116 l/s. The infection probability was 1.3 % when the fully mixed condition was achieved. Fig. 8 shows that the infection probability for different exposed persons varied from 0.9 % to 1.1 % using OPD with a heat gain of 60 W/m^2 after 3 hours' exposure. Therefore, the infection probability measured with OPD with a heat gain of 60 W/m^2 was lower than that under the theoretical fully mixed condition. Due to the increasing airflow rate, the exposure level was similar regardless of the location of the infector (SD = 0.1 %). This means the location of the infection source may not affect the infection probability if the airflow rate is high enough (5.5 1/h). Similar to the case of 38 W/m^2, the risk of the exposed person was slightly lower when the exposed person was far from the infector. However, the importance of the exhaust point location was minor with a higher airflow rate.

With horizontally supplied air from LVU, the airflow pattern was not uniform in the occupied zone. Therefore, the increase of infection probability was fluctuating over time. At a heat gain of 38 W/m^2 (Fig. 9), when the infector changed location, the infection risk of exposed persons was low (0.3 % - 0.7 %) for those who were far from the low velocity unit (P1 and P6) after 3 hours' exposure. This is because the cold air released from LVU created a full mixing zone far from the terminal unit. When the air jet arrived at the opposite side of the room from the terminal unit, the supply air mixed with thermal plumes and rose upwards. When the infector sat at P1 and P2, the infection risk was higher near the supply air unit than at the other locations except the exhaust. The exposure level near the door side was the smallest in the space. When the infector sat at P4 (near the supply unit), the riskiest workplace was at P5 (up to 4.0 %, which was higher than the theoretical fully mixed condition). This was the worst location for the exposed person with LVU. A possible reason for this was that the airflow from LVU enhanced the airborne transmission to the next workplaces. This indicates that the occupants (exposed or infected) are suggested not to sit near the supply unit when using a displacement ventilation system. Therefore, in not fully occupied room, it is better that all occupants sit in area far from the supply unit. It is interesting that the best (P1 with 0.3 %) and worst (P5 with 4 %) conditions both occurred when the infector was at P4, closest to the exhaust point.

For the case of 60 W/m^2 with LVU, the supply airflow was 116 l/s. Therefore, the momentum flux of the air jet was much stronger than with a lower heat gain level. The distribution of the infection probability with a heat gain level of 60 W/m^2 was different from the conditions with

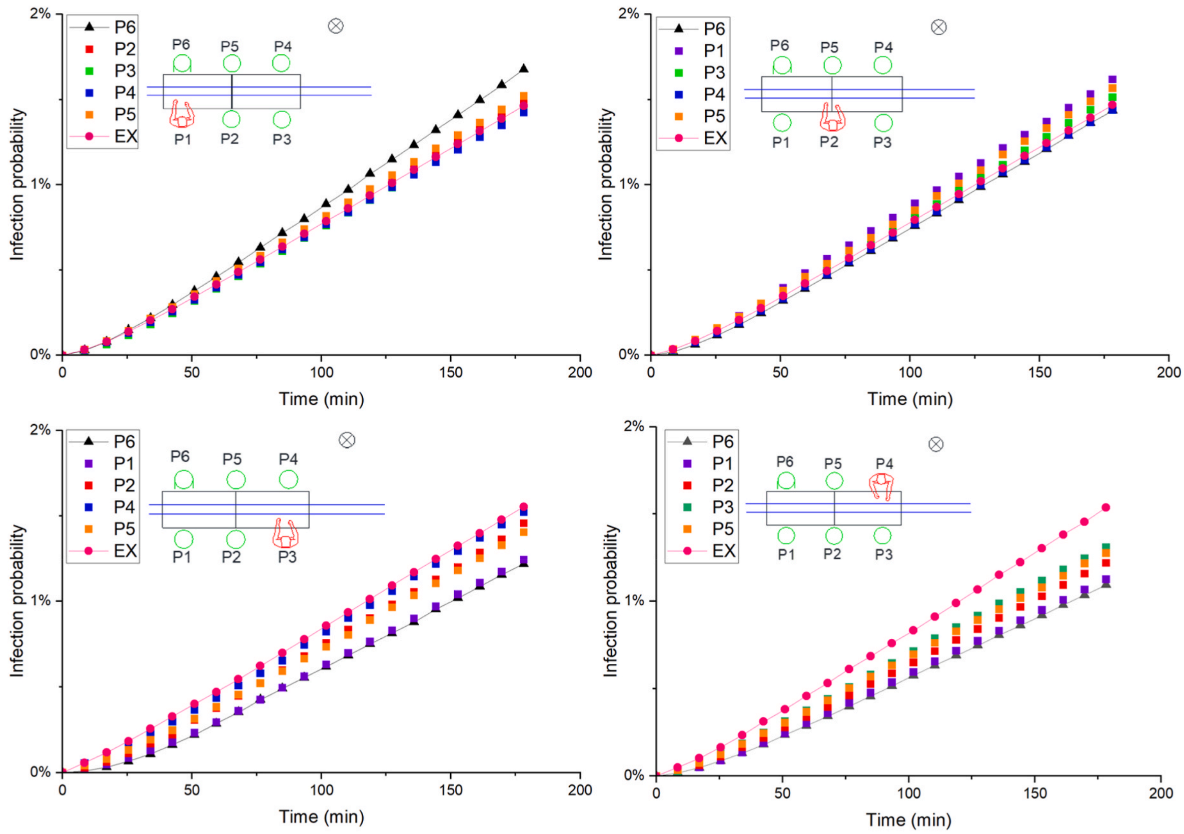


Fig. 7. The infection probability for five exposed persons when the location of the infector was moved with OPD and a heat gain level of 38 W/m^2.

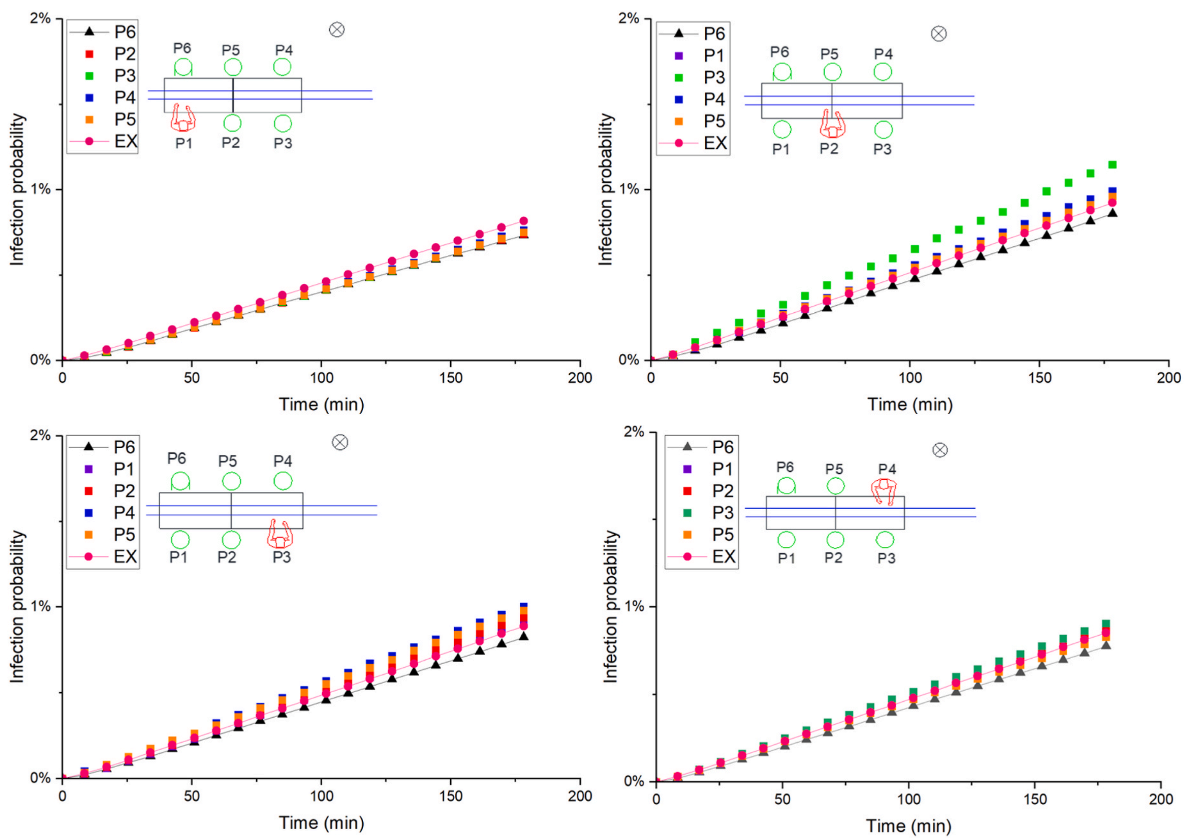


Fig. 8. The infection probability for five exposed persons when the location of the infector was moved with OPD and a heat gain level of 60 W/m^2.

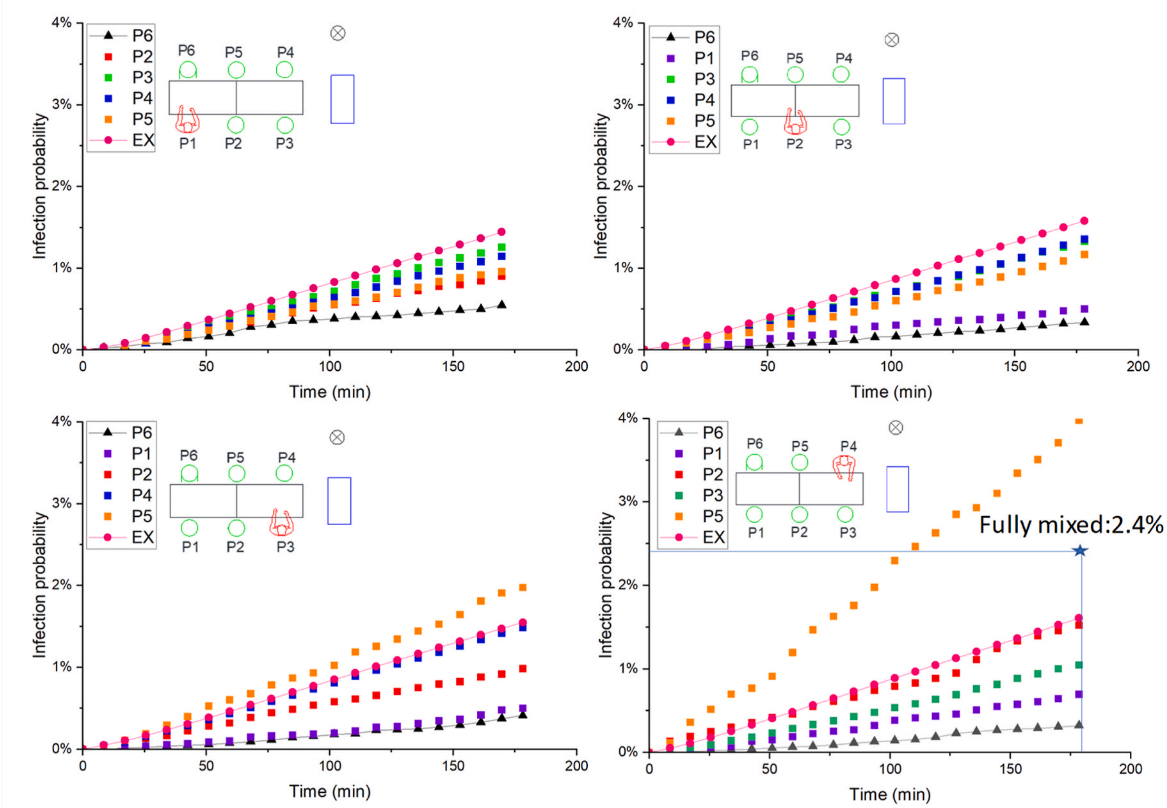


Fig. 9. The infection probability for five exposed persons when the location of the infector was moved with LVU and a heat gain level of 38 W/m^2.

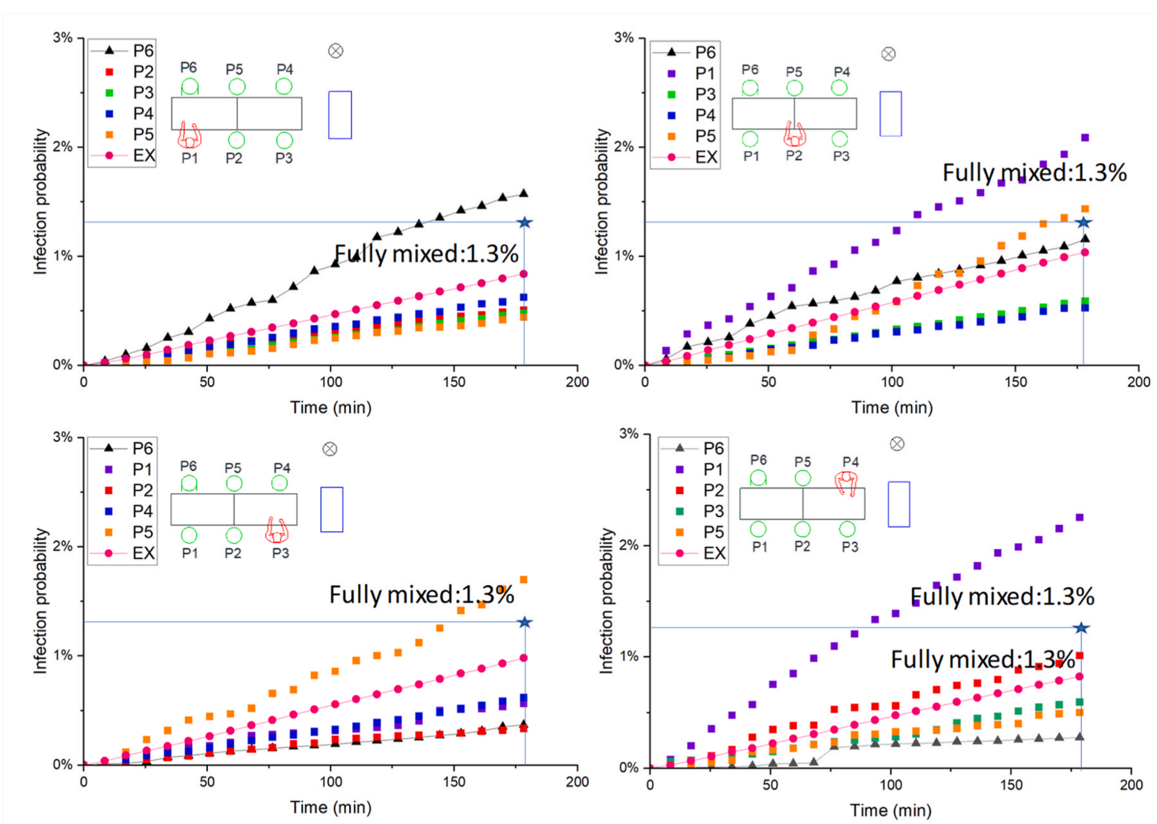


Fig. 10. The infection probability for five exposed persons when the location of the infector was moved with LVU and a heat gain level of 60 W/m^2.

a level of 38 W/m^2. Wherever the infector was seated, there were some persons exposed to a higher risk than in the theoretical fully mixed conditions. In Fig. 10, the infection probability in the zone far from the supply unit (P1 and P6) was much higher than other workplaces or in fully mixed conditions when the infector was at P1 and P2. This phenomenon was totally different with a heat gain of 38 W/m^2. This is because the stronger flow of the air jet from LVU may enhance the airborne transmission following the direction of the air jet to the opposite side of the terminal unit. Moreover, the solar load on the floor with 60 W/m^2 may help the mixing effect between the supply flow and room air, which leads to a lower risk near the supply unit (P3 and P4).

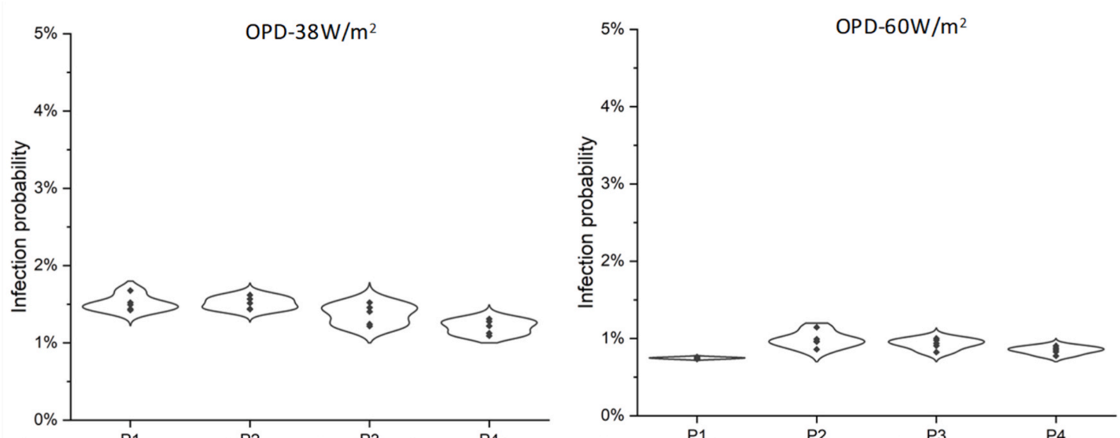
3.4. *The effect of the heat gains and air distribution methods on the infection probability*

Fig. 11 shows the infection probability variations for different exposed persons when the infector changed its location. When the airflow rate was increased from 61 l/s to 116 l/s with OPD, the average infection probability was reduced by 35 % after 3 hours (from 1.4 % to 0.9 %). Therefore, the airflow rate level had a significant effect on the infection probability with OPD. The average infection probability in the room was decreased from 1.1 % to 0.9 % when the airflow rate was increased from 61 l/s to 116 l/s with LVU. Therefore, the increasing airflow rate with LVU reduced the exposure risk by 16 %.

With a heat gain of 38 W/m^2, the average infection risk was 1.4 % and 1.2 % with OPD and LVU, respectively. The average performance of LVU is superior to OPD. With a heat gain of 60 W/m^2, the average infection risk was quite similar (0.9 %) with OPD and LVU. However, with LVU, there were large differences and fluctuations. The highest standard deviation reached 1.4 %. The average standard deviation with LVU was 0.7 % and 0.6 % with heat gains of 38 W/m^2 to 60 W/m^2, respectively. The corresponding value was only 0.1 % with OPD.

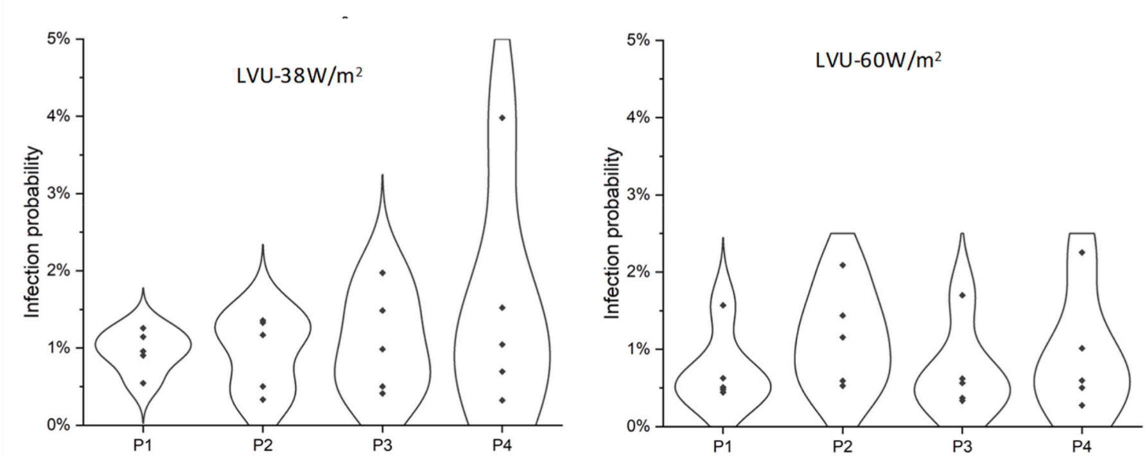
4. Discussion

In general, increasing the ventilation airflow rate dilutes concentrations better and reduces the average concentration level. However, by increasing the airflow rate, local concentration levels could increase more than with a lower airflow rate [3]. In this study, the results confirmed that an increasing airflow rate may not lead to a higher ventilation effectiveness. A higher airflow rate means also higher energy consumption and higher investment costs. Therefore, it is more



	P1	P2	P3	P4	Mean
Mean	1.5%	1.5%	1.4%	1.2%	1.4%
Standard Deviation	0.1%	0.1%	0.1%	0.1%	0.1%

	P1	P2	P3	P4	Mean
Mean	0.7%	1.0%	0.9%	0.8%	0.9%
Standard Deviation	0.0%	0.1%	0.1%	0.0%	0.1%



	P1	P2	P3	P4	Mean
Mean	1.0%	0.9%	1.1%	1.5%	1.1%
Standard Deviation	0.3%	0.5%	0.7%	1.4%	0.7%

	P1	P2	P3	P4	Mean
Mean	0.7%	1.2%	0.7%	0.9%	0.9%
Standard Deviation	0.5%	0.6%	0.6%	0.8%	0.6%

Fig. 11. The infection probability with OPD and LVU in the test room.

important to focus on ventilation efficiency and air distribution.

Besides the indoor air quality, thermal comfort is a critical factor for the occupants' health and work productivity. A higher airflow may cause thermal discomfort. Therefore, it is important to provide a good balance between thermal comfort and air quality.

Moreover, in terms of inhaled air quality, it is difficult for the total volume air distribution to bring supply air into the breathing zone. A personalized ventilation system focuses on the occupied zone and delivers supply air directly to the breathing zone. This leads to a lower infection risk of the exposed person than with a fully mixed system. Some of the latest studies show the benefits of combining conventional air distribution methods with advanced ventilation technologies, such as personalized ventilation or occupied targeted ventilation concepts [24,36,37].

In this study, the tracer gas concentration rise was dynamic over time and took 60 min and 34 min in tests to reach a steady state condition with airflow rates of 61 l/s and 116 l/s, respectively. From the calculation of infection risk point of view, it makes sense that the meeting should last shorter than 60 min before the concentration reach steady state condition. This study also indicates clearly that the location of the infected person has an impact on the local pollutant concentration and further infection risk. Still, the location where a person should sit with the lowest risk is not easy to estimate because of the effect of thermal plumes and air distribution. Therefore, the effectiveness of air distribution is important to analyze under different operation conditions when room is partly and fully occupied.

Depending on the location of the exhaust, the airborne pathogens released from the patient's face can get entrained back into the supply air stream and can eventually spread into the entire room [38]. In this study, the location of the exhaust affected the infection probability with OPD. When the exposed person or infector were near the exhaust point, the infection risk was reduced. It has been proved that the location of return grilles relative to occupants significantly affect cross-infection [39]. This effect did not happen with LVU in the studied small meeting room. In the test room, the supply unit and exhaust point were installed on the same side of the room. Therefore, if the exhaust is installed on the opposite side of the room, the distribution of the concentration could be different, which should be further studied.

In practice, a mixing ventilation system aims to dilute the volume and create a uniform indoor environment for every occupant. Usually, it is closer to fully mixed conditions in a small space. In a large open layout office, however, this does not happen for the infected person case. Larger variations of the concentration distribution could be expected in a large open-layout office than in a small meeting room, which should be further studied.

When the supply airflow was increased from 61 l/s to 116 l/s, the infection risk decreased from 1.4 % to 0.9 % with OPD and from 1.1 % to 0.9 % with LVU. Therefore, OPD was much more sensitive to the increasing airflow rate than LVU regarding preventing airborne transmission. Additionally, the infection risk was more similar for every exposed person with OPD when the infector changed location. However, the distribution of the infection risk varied a lot with LVU. The main research implication is that although the average infection risk with the LVU was slightly lower than with the OPD, the exposure risk at certain locations was much higher. Both the best and worst situations occurred under LVU. This means that LVU can achieve (in this specific case) better performance than mixing ventilation if properly designed. The exposure with LVU may be rather sensitive to the location of the infected occupant. In this study, the exposure risk can be found to correlate to the distance to the supply unit. With a lower airflow rate, the risk at workstations situated far away from the supply unit was small. With a higher airflow rate, the results were the opposite. The higher airflow rate may help the airborne transmission following the direction of the air jet to the opposite side of the terminal unit. One good solution for these issues would be to use several supply units in different places in the room. With the similar distance between the occupants, the results of this study can be applied to other types of rooms, such as classrooms and waiting area of hospital.

Mustakallio et al. [28] experimentally studied the effect of occupant's distribution with heated cylinders on the air distribution. Also, they [27] used computational fluid dynamic (CFD) simulation to analyze indoor climate conditions and validate it, where occupants were simulated with heated cylinders. Zukowska et al. [25] have showed the dummy can successfully be used as a simulator of a sitting person. However, the convective boundary layer of cylinder is slightly different from the dummy. In this study, there were not much difference on the measured concentration of tracer gas with dummy and cylinder with the analyzed systems. Therefore, difference of convective boundary layers with dummy and cylinder did not affect the airborne transmission in this study.

This study focuses on airborne transmission with tracer gas under steady state condition (no person walking). Therefore, this study cannot represent the transient airborne transmission under dynamic conditions. Moreover, the tracer gas SF_6 used in this study cannot contain the complicated dynamic processes of exhaled aerosols, such as evaporation, condensation, coagulation, resuspension, and phase change. Also, the breathing process of the exposed person was not considered in this study. Finally, the parameters of breathing are varied due to age, gender, and metabolic rate, etc., which may also have some effect on the infection risk.

5. Conclusions

The infection probability in the meeting room was investigated by full-scale tests. Air distribution methods with an overhead perforated duct (OPD) and low velocity unit (LVU) were analyzed under two heat gain levels (38 W/m^2 and 60 W/m^2) and two airflow rates (61 l/s and 116 l/s). The following findings can be concluded.

- With OPD, the average contaminant removal efficiency was between 0.9 and 1.1. However, with LVU, the tracer gas distribution varied much (from 2.0 ppm to 52.3 ppm) spatially and temporally, and the average contaminant removal efficiency varied between 0.2 and 10.1.
- The infection probability was different for the OPD and LVU systems. When the heat gain was increased from 38 W/m^2 to 60 W/m^2, the average occupants' exposure after 3 hours with OPD decreased from 1.4 % to 0.9 %. The corresponding values for LVU were 1.1 % and 0.9 %. The infection probability for every exposed person was lower than the fully mixed condition with OPD. However, with an airflow rate of 61 l/s and LVU, one person was exposed to a higher risk only when the infector was seated near the exhaust. When the airflow rate increased to 116 l/s, no matter where the infector was seated, there were one or two persons exposed to a higher risk than in the fully mixed conditions.
- The infection probability was quite uniform (SD = 0.1 %) with the OPD, especially at a higher heat gain level. The variation of infection probability with LVU was significant. The highest standard deviation reached 1.4 %.
- The highest risk was reached at 4 % with LVU when the infector was located near the supply unit. The lowest risk was only 0.3 %. Therefore, both best and worst situations were achieved with LVU, indicating that it can offer (in this specific case) superior performance to OPD if properly designed.
- The effect of the infector's locations on the infection probability varied with air distribution methods and heat gains. With OPD, the infection risk was low if the exposed person sat far from the infector. Further, when the infector sat near the exhaust (P4), the infection probability was the smallest with 38 W/m^2. Therefore, the proper air distribution combined with local exhaust is most effective for source removal. However, this effect was not observed with LVU. With displacement ventilation, the exposed person who was farthest from

the supply unit (P1 and P6) was safer at a lower airflow rate (61 l/s). However, with a high airflow rate of 116 l/s, there were higher risks at workstations situated far away from LVU.

CRediT authorship contribution statement

Weixin Zhao: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Sami Lestinen:** Writing – review & editing, Methodology, Funding acquisition. **Miao Guo:** Methodology. **Simo Kilpeläinen:** Writing – review & editing, Methodology, Conceptualization. **Juha Jokisalo:** Writing – review & editing. **Risto Kosonen:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

The study was supported by SUOJAILMA project funded by the Finnish Work Environment Fund (Grant No. 210099). The comments of Prof. Arsen K Melikov on the manuscript is highly appreciated.

References

[1] Y. Li, J. Tang, C. Noakes, M.J. Hodgson, Engineering control of respiratory infection and low-energy design of healthcare facilities, Science and Technology for the Built Environment 21 (2015) 25–34.
[2] Z.D. Bolashikov, A.K. Melikov, Methods for air cleaning and protection of building occupants from airborne pathogens, Build. Environ. 44 (2009) 1378–1385.
[3] F. Memarzadeh, W. Xu, Role of air changes per hour (ACH) in possible transmission of airborne infections, Build. Simulat. 5 (2012) 15–28, https://doi.org/10.1007/s12273-011-0053-4.
[4] Y. Li, G.M. Leung, J.W. Tang, X. Yang, C.Y. Chao, J.Z. Lin, J.W. Lu, P.V. Nielsen, J. Niu, H. Qian, Role of ventilation in airborne transmission of infectious agents in the built environment-a multidisciplinary systematic review, Indoor Air 17 (2007) 2–18.
[5] E. Bjørn, P.V. Nielsen, Dispersal of exhaled air and personal exposure in displacement ventilated rooms, Indoor Air 12 (2002) 147–164.
[6] Z.D. Bolashikov, A.K. Melikov, W. Kierat, Z. Popio\lek, M. Brand, Exposure of health care workers and occupants to coughed airborne pathogens in a double-bed hospital patient room with overhead mixing ventilation, HVAC R Res. 18 (2012) 602–615.
[7] I. Olmedo, P.V. Nielsen, M. Ruiz de Adana, R.L. Jensen, P. Grzelecki, Distribution of exhaled contaminants and personal exposure in a room using three different air distribution strategies, Indoor Air 22 (2012) 64–76.
[8] D. Rim, A. Novoselac, Transport of particulate and gaseous pollutants in the vicinity of a human body, Build. Environ. 44 (2009) 1840–1849.
[9] W.H. Organization, Roadmap to improve and ensure good indoor ventilation in the context of COVID-19. https://apps.who.int/iris/bitstream/handle/10665/339857/9789240021280-eng.pdf, 2021. (Accessed 27 February 2024).
[10] EN 16798-1: 2019, Energy performance of Buildings—ventilation for buildings—Part 1: indoor environmental Input parameters for design and assessment of energy performance of buildings Addressing indoor air quality, Thermal Environment, Lighting and Acoustics, 2019. Bruxelles, Belgium.
[11] P.V. Nielsen, The "Family Tree" of Air Distribution Systems, Roomvent, 2011, 2001.
[12] A.K. Melikov, Human body micro-environment: the benefits of controlling airflow interaction, Build. Environ. 91 (2015) 70–77.
[13] H. Qian, Y. Li, P.V. Nielsen, C.-E. Hyldgaard, T.W. Wong, A.T. Chwang, Dispersion of exhaled droplet nuclei in a two-bed hospital ward with three different ventilation systems, Indoor Air 16 (2006) 111–128.
[14] G. Pei, M.I. Taylor, Effects of indoor airflow and ventilation strategy on the airborne virus transmission, Build. Eng. 127 (2021) 206–215.
[15] W. Zhao, S. Kilpeläinen, R. Kosonen, J. Jokisalo, S. Lestinen, P. Mustakallio, Thermal environment and ventilation efficiency in a simulated office room with personalized micro-environment and fully mixed ventilation systems, Build. Environ. (2020), https://doi.org/10.1016/j.buildenv.2020.107445.
[16] W. Zhao, S. Kilpeläinen, R. Kosonen, J. Jokisalo, Experimental comparison of local low velocity unit combined with radiant panel and diffuse ceiling ventilation systems, Indoor Built Environ. 29 (2020) 895–914, https://doi.org/10.1177/1420326X20918398.
[17] W. Li, A. Chong, T. Hasama, L. Xu, B. Lasternas, K.W. Tham, K.P. Lam, Effects of ceiling fans on airborne transmission in an air-conditioned space, Build. Environ. 198 (2021) 107887.
[18] Z.D. Bolashikov, M. Barova, A.K. Melikov, Wearable personal exhaust ventilation: Improved indoor air quality and reduced exposure to air exhaled from a sick doctor, Science and Technology for the Built Environment 21 (2015) 1117–1125.
[19] J. Yang, C. Sekhar, D.K. Cheong, B. Raphael, A time-based analysis of the personalized exhaust system for airborne infection control in healthcare settings, Science and Technology for the Built Environment 21 (2015) 172–178.
[20] D. Rim, A. Novoselac, Ventilation effectiveness as an indicator of occupant exposure to particles from indoor sources, Build. Environ. 45 (2010) 1214–1224.
[21] A. Wang, Y. Zhang, J.L. Topmiller, J.S. Bennett, K.H. Dunn, Tracer study of airborne disease transmission in an aircraft cabin mock-up, Build. Eng. 112 (2006) 697.
[22] E.C. Riley, G. Murphy, R.L. Riley, Airborne spread of measles in a suburban elementary school, Am. J. Epidemiol. 107 (5) (1978) 421–432.
[23] W. Su, B. Yang, A. Melikov, C. Liang, Y. Lu, F. Wang, A. Li, Z. Lin, X. Li, G. Cao, Infection probability under different air distribution patterns, Build. Environ. (2021) 108555.
[24] W. Zhao, S. Lestinen, S. Kilpeläinen, X. Yuan, J. Jokisalo, R. Kosonen, M. Guo, Exploring the potential to mitigate airborne transmission risks with convective and radiant cooling systems in an office, Build. Environ. 245 (2023) 110936, https://doi.org/10.1016/j.buildenv.2023.110936.
[25] D. Zukowska, A. Melikov, Z. Popiolek, Impact of geometry of a sedentary occupant simulator on the generated thermal plume: experimental investigation, in: HVAC and R Research, 2012, pp. 795–811, https://doi.org/10.1080/10789669.2012.672925.
[26] S. Lestinen, S. Kilpeläinen, R. Kosonen, J. Jokisalo, H. Koskela, A. Melikov, Flow characteristics in occupied zone – an experimental study with symmetrically located thermal plumes and low-momentum diffuse ceiling air distribution, Build. Environ. (2018), https://doi.org/10.1016/j.buildenv.2017.11.020.
[27] P. Mustakallio, R. Kosonen, A. Korinkova, Full-scale test and CFD-simulation of radiant panel integrated with exposed chilled beam in heating mode, Build. Simulat. 10 (2017) 75–85, https://doi.org/10.1007/s12273-016-0309-0.
[28] P. Mustakallio, R. Kosonen, A. Melikov, The effects of mixing air distribution and heat load arrangement on the performance of ceiling radiant panels under cooling mode of operation, Science and Technology for the Built Environment (2017), https://doi.org/10.1080/23744731.2016.1262662.
[29] P. Raphe, H. Fellouah, S. Poncet, M. Ameur, Ventilation effectiveness of uniform and non-uniform perforated duct diffusers at office room, Build. Environ. 204 (2021) 108118.
[30] Z. Ai, C.M. Mak, N. Gao, J. Niu, Tracer gas is a suitable surrogate of exhaled droplet nuclei for studying airborne transmission in the built environment, in: Building Simulation, Springer, 2020, pp. 489–496.
[31] M. Bivolarova, J. Ondráček, A. Melikov, V. Ždímal, A comparison between tracer gas and aerosol particles distribution indoors: the impact of ventilation rate, interaction of airflows, and presence of objects, Indoor Air 27 (2017) 1201–1212.
[32] S. Zhang, Z. Lin, Dilution-based evaluation of airborne infection risk-Thorough expansion of Wells-Riley model, Build. Environ. 194 (2021) 107674.
[33] Z. Zhang, X. Chen, S. Mazumdar, T. Zhang, Q. Chen, Experimental and numerical investigation of airflow and contaminant transport in an airliner cabin mockup, Build. Environ. 44 (2009) 85–94.
[34] Covid, Rehva, "Guidance Document." How to operate and Use building Services in order to prevent the spread of the Coronavirus disease (COVID-19) virus (SARS-Cov-2) in workplaces: Tech, rep, rep (April 15 2021). https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_V4_23112020.pdf.
[35] M. Mundt, H.M. Mathisen, M. Moser, P.V. Nielsen, Ventilation effectiveness: Rehva guidebooks. https://vbn.aau.dk/en/publications/ventilation-effectiveness-rehva-guidebooks, 2004. (Accessed 10 November 2023).
[36] W. Liu, L. Liu, C. Xu, L. Fu, Y. Wang, P.V. Nielsen, C. Zhang, Exploring the potentials of personalized ventilation in mitigating airborne infection risk for two closely ranged occupants with different risk assessment models, Energy Build. 253 (2021) 111531.
[37] C. Xu, W. Liu, X. Luo, X. Huang, P.V. Nielsen, Prediction and control of aerosol transmission of SARS-CoV-2 in ventilated context: from source to receptor, Sustain. Cities Soc. 76 (2022) 103416.
[38] K. Khankari, Role of HVAC system configuration on probable flow Path of airborne pathogens in a patient room, Build. Eng. 119 (2013).
[39] S. Aghniaey, J.G. Williams, S.D. Chaitow, L. Rivera, Investigating air distribution designs for DOAS systems to reduce cross-Contamination in open offices, Build. Eng. 127 (2021).