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Exploring the potential to mitigate airborne transmission risks with convective and radiant cooling systems in an office

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ABSTRACT

Based on the recognized airborne infection risk, there is a raised demand to develop innovative ventilation systems to mitigate the airborne transmission risk indoors. This paper focused on two micro-environment ventilation systems, namely personalized ventilation combined with radiant panel system (PVRP) and a local low velocity unit combined with radiant panel system (LVRP) and studied the potential to minimize the airborne infection risk. The performance was compared with a typical mixing ventilation system, where supply air is released from a perforated duct. The droplet nuclei of an infected person were simulated with tracer gas (SF6) released by a thermal breathing manikin. The effect of the heat gain (38 W/m² and 73 W/m²), breathing pattern of the infector (exhaled via the nose or mouth), desk partition wall, and air distribution methods on the infection risk were studied. The results show the infection risk of the exposed person is around 0.5% with micro-environment systems (42 l/s) and 0.7% (61 l/s) with the perforated duct system when the occupants remain for 102 min in the space. The higher heat gain slightly increased the infection risk (from 0.71% to 0.81%) with the LVRP system, but it did not have an effect with the PVRP system. The desk partition wall could reduce the infection risk only to an extent. The breathing patterns of the infector do not have any influence on the infection risk for the three studied air distribution methods.

1. Introduction

Due to people spending more than 90% of their time indoors [1], enclosed indoor environments, offices and meeting rooms are among the most high-risk spaces for airborne transmission under circumstances in which indoor spaces are densely occupied and poorly ventilated. Indoor conditions even more significantly affect occupants in the Nordic countries, where it is cold most of the year [2]. Recent research has pointed out that the importance of aerosol infection is underestimated for some common diseases (e.g., influenza during cold and dry seasons) [3].

The COVID-19 pandemic was an extremely urgent threat to human life, and similar outbreaks may occur in the future. Based on WHO recommendations, ventilation systems are critical for reducing the infection risk for COVID-19 [4]. Effective ventilation is crucial to reducing the risk of airborne transmission [5–7]. Without an adequate airflow supply, a higher risk of infection may occur [8,9]. Understanding the characteristics and mechanism of aerosol transmission is important when applying effective practices for epidemic control.

The COVID-19 virus can survive for several hours in aerosols [10]. Moreover, virus-infected droplet nuclei can be transmitted over long distances indoors [5]. Airborne transmission comes from the inhalation of aerosol droplets which are exhaled by an infected person. This is now considered as the primary transmission route of COVID-19 [6]. The exhaled aerosol droplets from an infected person transmitting to an exposed person is a combined interaction of various airflows, including the breathing flow, human body boundary layer flow [11], and the ventilation flow. The airflow pattern can have a significant effect on the distribution of infectious aerosol spatial and temporal concentrations in an occupied zone beyond the simple effect of an increased ventilation rate in the assumed fully mixed conditions. Therefore, air distribution is a critical factor in reducing the infection risk by providing clean air close to the breathing zone [12].

Since air distribution is one of the primary mechanisms for
transmitting infections and pollution, it is important to examine the function of different air distribution methods. Airborne transmission with seven different air distribution methods was analyzed by computational fluid dynamics (CFD) for 4 h with the Wells-Riley model revised [12]. The numerical results show that in a classroom the performance of non-uniform air distribution, e.g., infection risk of personalized ventilation (0.19 %) and displacement ventilation (0.39 %–0.74 %) are much better than with mixing ventilation (2.94 %). This study indicated that mixing ventilation and diffuse ceiling ventilation has a much higher infection risk. With mixing ventilation, the infection risk may increase for susceptible people who are close to the infector. With personalized ventilation, the concentration level was the lowest in the breathing zone and the risk of infection was the smallest. With stratum ventilation, where the flow is deflected to an occupied area, the position of the infector had a clear impact on the infection risk. The infection risk near the air supply inlets was lower than far away from the air supply inlets.

To minimize airborne cross-infection in a simulated aircraft cabin, personalized ventilation combined with local exhaust has been found to have the potentials to prevent airborne cross-infection [13]. This is because personalized ventilation delivers clean air for inhalation without direct entrainment from infectious exhalation air [14]. Singer et al. estimated the hazards resulting from stratification and poor mixing in rooms heated with overhead supply diffusers. Eliminating stratification is particularly important to ensure that the benefits of outdoor air ventilation are achieved in the room [15].

Lin et al. investigated the droplets coughed by occupants at different locations in a typical classroom. Compared with displacement ventilation, stratum ventilation can significantly reduce the particle concentrations in the breathing zone, implying a lower risk of pathogen inhalation under stratum ventilation than that under displacement ventilation [16]. As for the effect of the breathing flow, the larger the pulmonary ventilation rate of the exposed person, the much greater the risk of cross-infection [17].

As a consequence, more novel air distribution should be introduce to reduce the individual’s exposure to air pollutants and infection risks [18]. The target should be only to control the air quality close to the breathing zone. There could also be a need to introduce more advanced systems where users can influence their local micro-environment. Therefore, more attention should be paid to micro-environment systems that individuals can use to reduce their exposure to air pollutants, and simultaneously we cannot sacrifice indoor conditions to just save energy [19].

A recent study shows that personalized ventilation was effective in reducing the infection risk compared with mixing ventilation alone [20]. However, if only an infected person uses a personalized ventilation unit, the impacting airflow from the personalized ventilation unit will accelerate the mixing of exhaled air from the infector with the room air, and may increase the infection risk of susceptible people [21,22]. The direct exposure risk from the infectious exhaled flow is therefore increased by using personalized ventilation [14]. For this reason, desk partition walls have been recommended as a practical approach to reducing airborne transmission [23].

In general, airborne transmission can be assessed from the concentration distribution of tracer gas using either experimental measurements or computational fluid dynamic (CFD) methods. The tracer gas can be CO₂, SF₆, R134a, and N₂O or particles (representing aerosols and viruses) [24,25]. Tracer gas techniques have been widely used to investigate the airborne transmission between occupants. The cross-infection risk can be estimated quantitatively based on the measured tracer gas concentrations in the inhalation of an exposed manikin [26–30].

We [31–33] focused on the indoor climate in our previous studies, where two advanced micro-environment systems were studied, namely personalized ventilation combined with a radiant panel (PVRP) and a low velocity unit combined with a radiant panel (LRVP). The performance of the two systems was analyzed by taking physical measurements and by conducting short-term human subject tests. Based on the results, the indoor climate of micro-environment systems with less energy use was better than a traditional mixed system. By offering the possibility to control their micro-environment during subject tests, the number of satisfied respondents significantly increased. However, the airborne transmission risk with two micro-environment ventilation systems has not been investigated. More attention should be paid to micro-environment ventilation systems for controlling the airborne cross-infection between people in office spaces.

The objective of this study was to investigate airborne transmission between two sitting persons in a closed office space. Four important influential parameters were varied systematically: the effect of convective flows under two heat gain levels (38 W/m² and 73 W/m²), the breathing pattern of the infector (exhaled via the nose or mouth), a desk partition wall between two workstations, and the air distribution method. The novelty of this study is to explore the potential to mitigate the airborne transmission risk using micro-environment ventilation compared to fully mixed ventilation in the office. The findings of this study are expected to contribute to improved control measures to help prevent the airborne transmission of infection indoors. This paper aims to offer a better understanding and insights into effective ventilation design to maximize its ability to control airborne infection risks in the office.

2. Methods

The experiments were carried out in a full-scale test room. In the test room, the indoor conditions can be controlled. The size of the test room was 5.50 m (L), 3.84 m (W), and 3.60 m (H), and the floor area was 21 m². The test chamber was located inside a laboratory hall to ensure the environment outside the chamber was stable.

2.1. Experimental set-up

2.1.1. Test room

Fig. 1 shows the test room used to simulate an office with two workstations. The setup consisted of one thermal breathing manikin and one heated dummy [34] seated at two workstations. There was a laptop at each workstation and lights were installed in the middle of the test room below the ceiling. A simulated window was mimicked by heated panels where the surface temperature can be controlled. Hot water is circulated inside the window panel. An electric heating foil (5.0 m × 1.0 m) was located under the workstations to simulate the direct solar radiation on the floor (see Fig. 1). The heat gains of each piece of equipment were summarized in Table 1. Exhaust air terminal 1 (EX1) was located at the corner with a perforated duct system. Exhaust air terminal 2 (EX2) was in the middle of the room on the heated window side with the PVRP and LVRP systems.

2.1.2. Air distribution methods

Three air distribution methods are adopted in this study, which is described in Fig. 2 [31–33]. Three air distribution methods were installed in the same chamber. A personalized ventilation air terminal device (ATD) is set in the PVRP system (Fig. 2 a) [35], which was installed on each desk at a distance of 40 cm from the manikin or dummy, and was used for direct fresh air supply to the breathing zone. There were three radiant panels installed over the workstation at a height of 2.1 m to provide the cooling load (Table 2). In the LVRP system (Fig. 2 b), there was a low velocity unit (LV) installed over the head of the occupant above the radiant panels. Below the low velocity unit, the radiant panels were installed over the workstation and fresh air went through perforated panels. With the PVRP and LVRP systems, background ventilation outside the occupied zone was provided by diffuse ceiling ventilation (DCV) [36].

The perforated duct was located above the ceiling panels, as shown in (Fig. 1 b), after removing the ceiling panels which were located at...
3.25 m height and the radiant panel over the workstations (2.1 m high), the duct was located in the middle of the upper room space (Fig. 2 c). The length of perforated duct was 5.5 m, and the diameter of the perforated duct was 200 mm.

2.1.3. Thermal breathing manikin

The thermal breathing manikin consisted of 27 separately heated body segments and was used for the infected sitting person simulation (referred to below as the infector). The size of the manikin was shaped as a 1.75 m male. The heat power and temperature of the body segments were separately controlled by a computer program. During this experiment, the manikin’s surface temperature was controlled as closely as possible to the person skin temperature in the control mode of thermal comfort. In addition, the manikins were dressed in a short-haired wig,

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Fig. 1. The test room set-up a) from top view and b) from side view.
vest and shirt, trousers, light socks, and light shoes. The thermal insulation was 0.5 Clo to simulate the clothes in an office during summer.

The nostrils were shaped as round openings with an area of 44.2 mm² each, and the mouth had the form of an ellipsoidal opening with an area of 113.4 mm². Two jets from the nostrils were deflected 45° downwards from the horizontal axes [37].

In addition, to simulate real human breathing, the manikin was connected to an artificial lung [38], which enables the adjustment of the breathing pattern. In this study, the manikin was controlled in two different breathing patterns: 1. inhalation by nose and exhalation by mouth, and 2. inhalation by mouth and exhalation by nose. The designed pulmonary ventilation rate was 6.0 l/min [39]. Each breathing cycle consisted of 2.5 s of inhalation, 1.0 s break, 2.5 s of exhalation and 1.0 s break. The exhaled air was mixed with tracer gas from the manikin and was heated to 35°C and humidified at 85%.

2.1.4. Measured parameters and instrumentation

In this experiment, tracer gas SF₆ was utilized to simulate the virus-containing droplet nuclei in the exhaled air from the infector manikin [29,40]. Tracer gas was dosed directly into the exhaled flow of the infector through an artificial lung. The flow rate of the tracer gas was 2 ml/s and the pulmonary ventilation rate of the manikin infector was 6 l/min. Therefore, the tracer gas concentration in the exhaled air of the infector was about 20,000 ppm.

During the experiment, tracer gas concentration at 6 locations (CH1–CH6) was measured using a multi-gas analyzer platform (accuracy of 0.37 ppm), as shown in Fig. 1. CH1 was located at the height of the mouth of the exposed person (1.2 m) and measured the tracer gas concentration of the inhaled air of exposed person. CH2 was measured at the exhalation of the manikin. CH3 and CH4 were measured at the unoccupied zone, one located at the corridor side, and one located at the simulated window side at 1.1 m CH5 and CH6 were measured at the exhaust valve and perforated duct.

Tracer gas dosing started after 1 h when the indoor airflow distribution had reached steady-state conditions. There were two stages during the tracer gas measurement in the test room. Firstly, the concentration increased after tracer gas dosing, and secondly, the concentration reached a stable value at every location.

2.2. Experimental conditions and test cases

In this study, the reference air temperature (accuracy of ±0.2°C) was set to 25 ± 1°C at the height of 1.1 m (marked as the reference point in Fig. 1). The operative temperature and mean radiant temperature (accuracy of ±0.3°C) were measured at the same location. The relative humidity of the indoor air was not actively controlled, and it varied slightly from 30% to 40% during the experiments.

The supply air temperature was 17°C with two micro-environment

### Table 1

| Manikin (W) | Dummy (W) | 80 | 80 | 85 | 85 |
| 2 laptops (W) | 80 | 80 | 45 | 45 |
| Light (W) | 90 | 90 |
| 7 Window panels (W) | 734 | 422 |
| Solar load at floor (W) | 420 | 0 |
| Equipment (W) | 45 | 45 |
| Total heat load (W) | 1534 | 802 |
| Floor area (m²) | 21 | 21 |
| Total heat flux (W/m²) | 73 | 38 |

### Table 2

| Total heat flux per floor area (W/m²) | PVRP & LVRP | Perforated duct |
| Floor area (m²) | 21 | 21 | 21 |
| Total heat gain (W) | 1534 | 802 | 1534 | 802 |
| Supply air flow rate (l/s) | 42 | 42 | 116 | 64 |
| Air change rate 1/h | 2.2 | 2.2 | 5.5 | 2.9 |
| Supply air temperature to the space °C | 17.0 | 17.0 | 14.0 | 14.0 |
| Supply air cooling capacity (W) | 454 | 449 | 1534 | 802 |
| Inlet water temperature of radiant panel °C | 15.0 | 22.3 | NA | NA |
| Outlet water temperature of radiant panel °C | 16.2 | 22.6 | NA | NA |
| Water mass flow rate (kg/s) | 0.1 | 0.1 | NA | NA |
| Radiant panel cooling capacity (W) | 1080 | 353 | NA | NA |
| Total cooling load (W) | 1534 | 802 | 1534 | 802 |

* The supply air to the space at 17°C and warmed up to 20°C into the room before ATD.
systems and 14 °C with the perforated duct system. With the all-air perforated duct system, the supplied airflow was 116 l/s and 61 l/s with the 73 W/m² and 38 W/m², leading to air change rates of 5.5 l/h and 2.9 l/h, respectively. With the PVRP and LVRP systems, the total supply airflow rate was 42 l/s with 38 W/m² and 73 W/m² and the air change rate was 2.2 l/h. In addition, the supply airflow rate was determined as Category II for low-polluting buildings based on EN 16798-1:2019 [41]. The recommended ventilation rate is 2 l/s, m² for this category. The rest of the cooling load was covered by the radiant panel, as shown in Table 2.

The total water mass flow rate was kept constant with different heat gain conditions. To cover the different cooling loads with heat gains of 73 W/m² and 38 W/m², the inlet water temperatures were 15 °C and 23 °C at 73 W/m² and 38 W/m², respectively. The local airflow from the personalized ventilation unit to each workstation was 7 l/s with the PVRP system [31], so the airflow rate supplied by the DCV was 28 l/s. The supply air temperature of the personalized ventilation unit was warmed due to the heated window and the surrounding room air. The temperature of fresh air from the personalized ventilation ATD was 20 °C. With the LVRP system, the local airflow rate from each of the two low velocity units was 15 l/s [33], so the rest airflow from the DCV was 12 l/s.

The parameters of the designed experimental cases are shown in Table 3. The cases of these experimental conditions were selected to reveal the characteristics of airborne transmission. To investigate the airborne transmission between sitting persons in a closed office space with different air distribution methods, four important influential parameters were varied systematically: the heat gain level in the room (38 W/m² and 73 W/m²), the breathing pattern of the infector, the desk partition walls, and the air distribution methods. The desk partition wall used in the test was 75 cm above the desk between two workstations, as shown in Fig. 3.

2.3. Evaluation indices

A Wells–Riley mode [42] is assumed that the indoor condition is fully-mixed and steady and as follows:

\[ P = \frac{C}{S} = 1 - e^{-\left(\frac{Q}{S} \cdot S\right)} \] (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 (m³/h), \( t \) is the total exposure time (h), and \( Q \) is the room ventilation rate (m³/h).

However, the indoor conditions are not uniform everywhere. The non-uniformity factor needs to be included in the probability model. According to the dilution-based evaluation of airborne infection risk estimation proposed by Zhang and Lin [43], the airborne infection risk model is based on the Wells-Riley model and modified for the not fully mixed condition. The revised Wells-Riley model is as follows:

\[ D = \frac{C_{\text{infector}}}{C_{\text{exposed}}} \] (2)

\[ C_{\text{quantum}} = \frac{q}{D \cdot P_{\text{infector}}} \] (3)

\[ N_{\text{quantum}} = \int_0^T P_{\text{exposed}} C_{\text{quantum}}(t) \, dt \] (4)

\[ P_{D} = 1 - e^{-N_{\text{quantum}}} \] (5)

where \( C_{\text{infector}} \) and \( C_{\text{exposed}} \) are the airborne contaminant concentrations at the infectious point and exposed position respectively (ppm); \( C_{\text{quantum}} \) is the airborne quantum concentration at the exposed position (quanta/m³); \( D \) is the dilution ratio at the exposed position; \( P_{\text{infector}} \) is the breathing rate of the infector (m³/s); \( N_{\text{quantum}} \) is 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; \( P_{\text{exposed}} \) is the breathing rate of the exposed person (m³/s).

### Table 3

<table>
<thead>
<tr>
<th>Case</th>
<th>Heat gain Air distribution method</th>
<th>Supplied airflow rate</th>
<th>Desk partition wall</th>
<th>Breathing pattern of manikin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38 W/m²</td>
<td>PVRP</td>
<td>total 42 l/s, PV: 7 l/s × 2</td>
<td>no partition</td>
</tr>
<tr>
<td>2</td>
<td>38 W/m²</td>
<td>DCV: 28 l/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>73 W/m²</td>
<td>LVRP</td>
<td>total 42 l/s, LV: 15 l/s × 2</td>
<td>no partition</td>
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<tr>
<td>4</td>
<td>73 W/m²</td>
<td>DCV: 12 l/s</td>
<td></td>
<td></td>
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<tr>
<td>5</td>
<td>73 W/m²</td>
<td>Perforated duct</td>
<td>61 l/s</td>
<td>no partition</td>
</tr>
<tr>
<td>6</td>
<td>73 W/m²</td>
<td>LV: 15 l/s × 2</td>
<td></td>
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<tr>
<td>7</td>
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<td>LV: 15 l/s × 2</td>
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<td>73 W/m²</td>
<td>LV: 15 l/s × 2</td>
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</table>
3. Results

3.1. The effect of air distribution on the infection risk

Based on the assumptions of a fully-mixed air space and steady-state conditions, Fig. 4 shows the infection probability with three air distribution methods calculated using the Wells–Riley model before the experiments. According to Equation (1), the infection probability is only concerned with the airflow rate when the indoor air is fully mixed, not with air distribution methods. Therefore, the infection probability is the highest (2 %) with the PVRP and LVRP systems in this study due to the lower airflow rate after 102 min. As could be expected with the perforated duct system, the infection probability decreased compared to the air-water systems with the increasing airflow rate. The relative difference of the infection probability between 61 l/s (1.38 %) and 116 l/s (0.73 %) was 47 %.

However, the air distribution affects the spatial and temporal concentrations in the room space. Fig. 5 shows the tracer gas distribution with two micro-environment and one fully mixed air distribution methods from t = 0–102 min at different measured locations. The tracer gas was used to dose the test room starting at t = 0 min, and afterward the concentration started to build up. In the first stage when the concentration had not reached the steady-state conditions, the tracer gas concentration rose with time. In the second stage, the concentration started to build up. In the first stage when the concentration had not reached the steady-state conditions, the tracer gas concentration rose with time. In the second stage, the concentration became stable for each location until the end of the test.

With the perforated duct system, the concentration of the inhaled air of the exposed person was slightly higher than two micro-environment systems with airflow rate of 61 l/s. This is because the local airflow of micro-environment systems protects the trace gas transmission from the infector compared with the fully mixed condition.

With two micro-environment systems (PVRP and LVRP), the inhaled concentration of the exposed person was much lower than at the other locations in the test room. Moreover, compared to the LVRP system (15 l/s per person), the SF6 concentration with the PVRP system was slightly lower at the exposed person even with less local airflow rate (7 l/s per person). Due to the background ventilation being supplied downwards over the corridor area and far from the infector, the tracer gas concentration on the corridor side was lower than on the window side. However, the concentration with the perforated duct system was quite uniform at each location.

For the two micro-environment systems, the air change efficiency is around 65 % [28,30], and the tracer gas concentration reached constant at 41 min. For the perforated duct system with the higher airflow rate, the stable time is 21 min with 116 l/s and 40 min with 64 l/s.

Fig. 6 shows the variation of the dilution ratio (Equation (2)) over time at different locations. Under dynamic condition, the dilution rate decreased rapidly. This is because the tracer gas concentration at every location was quite low at the beginning of the test. With the increase of the tracer gas indoors, the dilution rate decreased to a constant level.

For the micro-environment (Fig. 6), for example, for the PVRP system, the dilution rate at the point of the inhaled air was larger than on the corridor and window side due to the higher local airflow rate in the breathing zone. At the steady-state condition, the dilution ratio at the point of the inhaled air was a little higher than that on the corridor side and is the smallest at the window side. This is because the local airflow rate from each personalized ventilation is only 7 l/s and the rest of 28 l/s of airflow was supplied at the corridor side. This leads to a quite similar air change rate in the breathing zone of an exposed person and in the corridor area.

With the dilution ratio, the airborne infection risk of the inhaled air of the exposed person, corridor, and window were calculated according to Equation (6), as shown in Fig. 7. Under dynamic condition, the infection risk increased more rapidly than in the steady state condition. Under steady-state conditions, the infection risk increased linearly. The quantum generation rate of a COVID-19 infector was assigned to be 5 quanta/h [42] for office work.

Compared to the results with the standard Wells–Riley model, the infection probability of the dilution-based model varied significantly at different measured locations. With two micro-environment systems, the infection probability was 2 % calculated in the fully mixed conditions after 102 min, however, the corresponding values of the actual conditions were only 0.5 % and 0.6 % for exposed person with the PVRP and LVRP systems, respectively.

The infection risk was the lowest for the inhaled air of the exposed person.
person with all systems. This indicates that indoor air is not fully mixing in the test room with any of the analyzed air distribution methods. It should be noted that with the micro-environment systems, the variation in the infection risk at the different locations was larger than the perforated duct system. The infection risk of the exposed person was 38%, 26%, and 11% lower than that on the window side with PVRP, LVRP, and perforated duct system, respectively. This means that the micro-environment systems are able to better mitigate the airborne transmission risk in the inhaled air than the perforated duct. The infection risks at the inhaled air measurement point were 0.6% and 0.5% with the LVRP and PVRP systems, respectively. This result shows that PVRP system was slightly superior to the LVRP system for the protective effect. With the PVRP and LVRP systems, the infection risk in the corridor area was lower than the window area but was a similar level to that with the perforated duct system.

With the perforated duct system, the infection risk of the exposed person decreased from 0.7% to 0.4% when the airflow rate increased from 61 l/s to 116 l/s after 102 min. Compared with the micro-environment systems (0.5%–0.6% with 42 l/s), the infection risk of the exposed person with the perforated duct with airflow rate of 61 l/s (0.7%) was higher but lower with an airflow rate of 116 l/s (0.4%).

### 3.2. The effect of the heat gain on the infection risk

Fig. 8 shows the infection risk under the circumstance of different air distribution methods and two different heat gain levels (38 and 73 W/m²) at the end of the test (102 min). The difference in the infection risk at the inhaled air measurement point and on the window side can be ignored in the PVRP system with different heat gains. The infection risk of the exposed person was around 0.67% with the PVRP system under 38 and 73 W/m². This means that the infection risk was kept the same by the heat gain level in the PVRP system. With the LVRP system, the infection risk of the exposed person under 73 W/m² was slightly higher (0.81%) than under 38 W/m² (0.71%). A possible reason for this could be that the protective effect created by the low velocity unit is disturbed...
by the strong convection flow from the heated window with 73 W/m² to an extent, and then bringing in a more uniform thermal environment. With the perforated duct system, as we expected, the infection risk was much higher with 38 W/m² than with 73 W/m² because of the different volume of the supplied airflow. The infection risk of the exposed person was 0.89 % and 0.44 % with 38 and 73 W/m² and the relative difference was 50 %.

3.3. The effect of the desk partition wall on the infection risk

Fig. 9 shows the effect of the desk partition wall on the infection risk with different air distribution methods at 102 min (the end of the test).
With two micro-environment systems, the relative difference at the inhaled air measurement point with and without partition walls was minor, about 7%, and only 2.4% with the perforated duct system. Therefore, the effect of a desk partition wall on mitigating airborne transmission risk is quite limited. This makes the air distribution analysis critical to the airborne transmission indoors.

3.4. The effect of the breathing patterns on the infection risk

Fig. 10 shows the effect of the breathing patterns of the infector on the infection risk with different air distribution methods at the end of the test. Whether the infector (breathing manikin) exhaled through the nose or mouth the infection risk was quite similar with three air distribution methods at the inhaled air measurement point. Particularly with the PVRP system, the risk was not much different when the infector exhaled through the nose and exhaled through mouth. In the corridor area, the risk was slightly higher for the mouth exhaled test gas than for the nose exhaled test gas for the three systems. On the window side, however, the potential risk from the mouth exhaled test gas was lower than from the nose exhaled test gas with the PVRP and perforated duct system, but higher with the LVRP system.

4. Discussion

This study investigated the airborne transmission between face-to-face occupants in an office room with two local micro-environment and one mixing air distribution methods. Both the spatial and temporal distribution of the tracer gas concentration as well as the infection risk results indicated that the micro-environment system can prevent airborne transmission effectively with local ventilation solutions. Under dynamic conditions (with the infector commencing to release droplets), the dilution ratio was much higher, and the infection risk was lower. This means the air jet from the personalized ventilation (PVRP) system and the installed low velocity unit (LVRP) over the workstation can entrain the convective boundary layer existing around the human body and reach the breathing zone of the exposed person to prevent airborne transmission. Therefore, a steady state may have not been achieved in the short term (less than 30 min). The micro-environment solution had significantly lower concentration levels than that with fully mixed steady-state conditions. After the concentration reached a steady state, the dilution ratio was nearly similar everywhere.

With the PVRP or LVRP system analyzed in the mock-up office, the local airflow and radiant panel would create a clean and comfortable micro-environment around the occupants. Compared with the fully mixed air distribution, the un-uniform air distribution focuses more on the occupied zone and brings fresh air directly to the breathing zone. This leads to a low infection risk for the exposed person. The previous studies show there are benefits from the combined system with basic air distribution methods and advanced ventilation technologies, such as personalized ventilation [20,44]. In this study, the infection risk was smaller with an airflow rate of 42 l/s with the micro-environment systems than that 61 l/s with the mixing ventilation. This indicates that the increase of the airflow rate is not the only relevant solution to reduce infection risk indoors. Based on REHVA COVID-19 guidance [42], with Category II ventilation rates (2 l/s/m²) according to ISO 17772-1:2017 [45] and EN 16798-1:2019 [41], the probability of infection is below 5% within 8 h for open-plan offices. In this study, the infection risk is 0.5%–1% after 100 min, therefore, after 8 h, the infection risk would be 2.5%–5%, which fulfills the requirement of the REHVA guidance.

The advanced ventilation technologies with lower airflow rates have the potential to reduce airborne transmission. Furthermore, higher airflow rates mean higher energy consumption and higher investment costs. Therefore, in renovated buildings, it is more important to analyze ventilation efficiency and the local concentration in the breathing zone.

The results of the present study show that the heat gain levels indoors have a limited effect on contaminant transmission with a micro-environment system. With increasing heat gains, the cooling capacity of radiant panels was increased but the airflow rate was kept constant. In this way, thermal comfort can be maintained [31,33]. With the perforated duct system, the risk level is reduced by increasing airflow rate. However, the higher local draft risk may occur with higher airflow rate. Therefore, the general airflow condition indoors is a key factor in airborne cross-infection. As a result, the micro-environment system is more robust to the variation of the indoor environment and the breathing parameters. In practical application, however, the indoor heat gains and their distribution are varied. This may result in different infection risks than those reported in this study. This means that the results are only applicable to the given experimental set-up.

The results of the present study show that a desk partition wall has only a limited effect on the infection risk. However, the partition wall is effective against coughing for a short time [23] but not normal breathing activity for a long time. Thus, investments in partition walls do not reduce the infection risk and should not be the first option in the office.

The previous study [46] shows that the breathing patterns would affect the cross-infection risk with displacement ventilation, and exhaling through the mouth or the nose may disperse airborne pathogens in a completely different way. However, this study indicates that the breathing patterns do not have a significant influence on the infection risk with micro-environment systems.

The air distribution was noticed to play a significant role in airborne transmission with the different room layouts and that is why the dilution ratio was introduced to analyze the effect of air distribution on infection risk. The infection risk level was varied in different parts of the room. Therefore, the micro-environment air distribution had benefits when it came to controlling the airborne infection risk for an exposed person than the fully mixed air distribution. The Wells–Riley approach was limited to well-mixed conditions and cannot spatially and temporally evaluate the airborne infection risk, as it would overestimate or underestimate the airborne infection risk.

The breathing process of the exposed person was not considered in this study. Moreover, the experiments were conducted in a steady-state thermal environment, and the effect of the occupants’ movement indoors on airborne transmission was not taken into account. Finally, the breathing parameters in real life would be varied due to age, gender and metabolic rate, etc., which may also have some effect on the infection risk.

This study focused only on a double layout in an office with two people. Therefore, the investigation of more people in the same or larger room, e.g., a meeting room could be one additional topic for future research. For short-term events (less than 30 min), the airborne cross-
infection maybe different with and without a partition wall between workstations, which should be further analyzed.

5. Conclusion

This study investigated the airborne transmission risk between occupants sitting face-to-face in a simulated office. The effect of the air distribution method, the desk partition wall, and the breathing pattern on the airborne transmission was investigated at two heat gain levels (38 W/m² and 73 W/m²). The adaptation of micro-environment systems (PVRP and LVRP) can help supply the local airflow from a personalized ventilation or low velocity unit to the occupant breathing zone directly. The perforated duct system as an all-air system can achieve a nearly fully mixed environment.

Based on the results, the tracer gas concentration was lower with the micro-environment systems and the lowest infection risk occurred at the inhaled air measurement point with micro-environment. The infection risk of the exposed person was around 0.5 % with the micro-environment systems (42 l/s) and 0.7% (61 l/s) with the perforated duct system after 102 min. The heat gain levels affect the infection risk a little with the micro-environment systems. The infection risk is decreased from 0.7% to 0.4 % with a double airflow rate when the heat gain increased with the perforated duct system. A desk partition wall did not have a significant effect on the infection risk. Moreover, the breathing patterns did not influence the infection risk of the exposed person with the three air distribution methods.

CRediT authorship contribution statement

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

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References


