Influence of the air renovation rate on the risk of cross infections in a hospital room with a combined radiant and mixing ventilation system

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Abstract
This study aims to test how mixing ventilation combined with a hydronic radiant floor system performs removing airborne exhaled contaminants using two different air renovation rates. The two selected renovation rates are 2 ACH and 7.5 ACH. Temperature and velocity probes are used to evaluate temperature and velocity profiles in the room. A tracer gas (CO₂) is used to measure the risk of cross infection between two breathing thermal manikins. One of the manikins (P) represents a lying person over a horizontal surface and its breathing represents the only source of contaminants into the chamber. The other one (HW) represents a standing person near P. The concentration of exhaled contaminants reaching its breathing zone is studied.

Temperature and air velocity profiles show that a nearly completely air stability situation is reached at the occupied zone. This stability is influenced by the air renovation rate performed. Tracer gas measurement results show a similar distribution of exhaled contaminants but with some discrepancies for both tests conducted. A higher tracer gas concentration reaches the nearby zone of HW manikin when the air renovation rate is increased from 2 to 7.5 ACH. This can lead to a higher cross infection rate.

The obtained results suggest that that a higher ventilation rate not necessary leads to a decrease of the airborne cross infection risk for the occupants in an enclosed area.

Keywords - Airborne Cross Infection; Breathing; Hydronic Radiant Systems; Ventilation

1. Introduction

A significant increase in the study of ventilation performance in indoor public places such hospitals is being taken place in recent times [1–3]. New ventilation methods have been tested to provide better ventilation and energy efficient systems [4–6]. Hospitals are potentially risky places for airborne cross infection between patients, health workers and visitants [7].
One of the major sources of contaminants which can transmit pathogens is breathing. Breathing exhaled air contents droplets in which nuclei can contain several pathogens. Cause of the small size of the droplets exhaled, tracer gases are a good tool to study the spreading of these contaminants [8,9]. Usually, mixing ventilation is used to remove airborne contaminants [10]. Energy efficient systems like hydronic radiant floors and ceilings may be an alternative to provide comfort conditions and reduce ventilation rates [11,12].

This study aims to test how mixing ventilation combined with hydronic radiant systems performs removing airborne exhaled contaminants using two different air renovation rates

2. Methods

The experiments have been taken place into an isolated experimental chamber. People in the chamber are represented by two breathing thermal manikins. One of them (P) aims to represent a lying person at supine position over a horizontal surface, such a patient in a hospital ward. The other one (HW) represents a standing person near the first one, such a health worker. P manikin represents the only contaminant source of the room while the presence of contaminants into the breathing zone of HW is studied. The two breathing manikins, inhaling through the mouth and exhaling through the nose, have their mouths aligned in a vertical plane. A complete description of the distribution of the chamber can be seen in Figure 1 and Figure 2.

![Diagram of the experimental chamber](image)

Fig. 1. Horizontal section of the experimental chamber. (D) Four-way mixing diffusers. (R) Exhaust grilles. (Pt) Vertical pole. (L) Lamps.
Conditioned clean air at neutral conditions (24°C) is supplied to the room through four four-way mixing diffusers and extracted by four exhaust grills placed in the corners of the room. This study proposes two different experiments modifying the ventilation rate of the chamber. Test 1 is performed under a ventilation rate of 2 ACH (61.2 m³/h) while Test 2 is performed under a ventilation rate of 7.5 ACH (229.5 m³/h). During both tests the hydronic radiant system maintains a surface floor temperature of 17 °C.

Temperature of the two manikins is controlled to maintain it at 34 °C on their surface. Manikins’ breathing corresponds with the one of a man of 1.70 m height and 70 kg weight using the expressions obtained from the research of Gupta [13]. Breathing orifices of the manikins corresponds with circles of 20 mm² for each nostril and 126 mm² for mouth. More information about the geometrical design and performance of the two breathing manikins can be found at [14,15].

Tests have been conducted once stationary conditions have been obtained inside the experimental chamber. Experimental chamber conditions are considered stationary when the temperature fluctuations inside the room remain under 0.5 °C. Each test has been performed during 2 hours.

Air velocity along the height of the room has been measured at five different points using a vertical pole (Pt) near the standing manikin, Figure 1 and Figure 2. The velocity probes, TSI 8475, have an accuracy of 1%.

Air temperature along the height of the room has also been measured at the same five points where the air velocity is registered. The exact heights of the temperature and velocity probes along the pole can be seen at Figure 2. Temperature has been registered using J type thermocouples with an
accuracy of 2%. Temperature measurement frequency is 1 Hz for each probe.

To measure contaminants propagation and evaluate HW cross infection risk, the breathing of P is seeded with 45000 ppm of CO\textsubscript{2} as tracer gas. This concentration is the one of a resting breathing [16]. Four CO\textsubscript{2}METER SprintIR 5% NDIR CO\textsubscript{2} probes with a 1% accuracy have been distributed around the experimental chamber to measure tracer gas concentration. Three of them have been placed near the breathing zone of the HW, as can be seen at Figure 3, the remaining one at the air exhaust of the room. Measurement frequency for each probe is 1 Hz.

![Fig. 3. CO\textsubscript{2} probe positions at the breathing area of HW.](image)

3. Results and discussion

Absolute air velocity measurements along the vertical probe of the experimental chamber have been processed and their average value ($\bar{u}_i$) at each measurement point during each test have been obtained together with the standard deviation ($\sigma_i$). Results have been summarized in Table 1.

Table 1. Absolute average air velocity along the vertical pole (Pt) for the two tests performed. ($H_R = z/H$) represents the normalized height of each probe respect to the total height of the room.

<table>
<thead>
<tr>
<th>Probe</th>
<th>$z$, (m)</th>
<th>$H_R$</th>
<th>$\bar{u}_i$, (m/s)</th>
<th>$\sigma_i$</th>
<th>$\bar{u}_i$, (m/s)</th>
<th>$\sigma_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0.1</td>
<td>0.04</td>
<td>0.00</td>
<td>0.00</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>P2</td>
<td>0.6</td>
<td>0.22</td>
<td>0.00</td>
<td>0.00</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>P3</td>
<td>1.1</td>
<td>0.40</td>
<td>0.01</td>
<td>0.02</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>P4</td>
<td>1.7</td>
<td>0.62</td>
<td>0.03</td>
<td>0.02</td>
<td>0.10</td>
<td>0.03</td>
</tr>
<tr>
<td>P5</td>
<td>2.3</td>
<td>0.84</td>
<td>0.08</td>
<td>0.02</td>
<td>0.30</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Average air velocities along the height of the room for the two experiments performed are represented in Figure 4.

Fig. 4. Absolute average air velocity measurements along the vertical pole (Pt).

Results show that the air velocity values obtained at the occupied zone of the chamber, up to a normalized height of $H_R=0.656$, are relatively low in both cases. However, these velocity values are higher in the upper part of the room, close to the ceiling, for both cases. It seems clear the existence of an air stability region in the occupied zone that was also visualized in preliminary experiments using smoke. It is observed that the air velocity vertical profile is always higher in Test 2 than in Test 1.

Measurements obtained at the zone between the breathing points of the P and HW, placed at 0.394 and 0.558 in normalized height respectively, approximately at the interval between P3 and P4, shows that air velocity remains under 0.1 m/s at both experiments.

Temperature measurements conducted along the vertical pole have been obtained. Average temperature at each measurement point ($\overline{T_i}$) and the exhaust air temperature ($\overline{T_r}$) are used to obtain relative temperatures ($T_{ri}$), using Equation 1.

$$T_{ri} = \frac{\overline{T_i}}{\overline{T_r}}$$

(1)

Results for Test 1 and Test 2 are summarized at Table 2.
Table 2. Temperature measurements along the vertical pole.

<table>
<thead>
<tr>
<th>Probe</th>
<th>( H_R )</th>
<th>( \bar{T}_i ),(^{(\circ \text{C})} )</th>
<th>( T_{Ri} )</th>
<th>( \sigma_i )</th>
<th>( \bar{T}_i ),(^{(\circ \text{C})} )</th>
<th>( T_{Ri} )</th>
<th>( \sigma_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0.04</td>
<td>21.2</td>
<td>0.83</td>
<td>0.03</td>
<td>21.2</td>
<td>0.87</td>
<td>0.07</td>
</tr>
<tr>
<td>P2</td>
<td>0.22</td>
<td>22.7</td>
<td>0.91</td>
<td>0.06</td>
<td>22.2</td>
<td>0.94</td>
<td>0.06</td>
</tr>
<tr>
<td>P3</td>
<td>0.40</td>
<td>23.7</td>
<td>0.95</td>
<td>0.06</td>
<td>22.7</td>
<td>0.96</td>
<td>0.05</td>
</tr>
<tr>
<td>P4</td>
<td>0.62</td>
<td>24.1</td>
<td>0.96</td>
<td>0.03</td>
<td>23.5</td>
<td>0.99</td>
<td>0.04</td>
</tr>
<tr>
<td>P5</td>
<td>0.84</td>
<td>24.3</td>
<td>0.97</td>
<td>0.03</td>
<td>23.4</td>
<td>0.99</td>
<td>0.05</td>
</tr>
<tr>
<td>Exhaust</td>
<td>1.00</td>
<td>25.0</td>
<td>-</td>
<td>0.04</td>
<td>23.7</td>
<td>-</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Average relative temperatures along with the relative height of the probes are represented in Figure 5 for the two experiments conducted.

Fig. 5. Relative temperature distribution along the height of the experimental chamber.

Results show that the temperature profile along the height of the room is similar in both cases. The influence of the hydronic radiant floor is notable in the lower part of the room, where the minimum temperature value is registered. Test 2 provides a higher relative temperature values for all the points considered. This fact indicates that higher ventilation rates approximate temperature values registered along the vertical pole with the exhaust one, improving temperature homogeneity along the height of the room.

A vertical temperature gradient at the lower part of the room is present in both experiments. It shows a maximum value of 8.33 \(^{\circ} \text{C/m} \) in Test 1 and 5.51 \(^{\circ} \text{C/m} \) in Test 2 between probes positions P1 and P2. The slope of the gradient decreases with height being 1.81 \(^{\circ} \text{C/m} \) in Test 1 and 3.64 \(^{\circ} \text{C/m} \) in Test 2 between P3 and P4, which is the interval between the breathing
regions of the two manikins. Moderate positive temperature gradients such as the obtained at this research do not induce convective air flows [17].

Average concentration measurements of CO₂ \( (c_i) \) as tracer gas at three different positions near the HW manikin are obtained together with the standard deviation \( (\sigma_i) \) of its values. Relative average tracer gas concentration \( (c_{Ri}) \) has been obtained against tracer gas concentration into the exhaust \( (c_r) \) using Equation 2.

\[
c_{Ri} = \frac{\bar{c_i}}{\bar{c_r}}
\]  

(2)

All these results together with the relative height of each CO₂ probe are summarized in Table 3 for Test 1 and Test 2.

Table 3. CO₂ concentration at three different heights close the HW manikin.

<table>
<thead>
<tr>
<th>Probe</th>
<th>( H_R )</th>
<th>( \bar{c_i}, ) (ppm)</th>
<th>( \sigma_i )</th>
<th>( \bar{c_{Ri}}, ) (ppm)</th>
<th>( \sigma_{Ri} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>0.39</td>
<td>366.8</td>
<td>0.89</td>
<td>19.93</td>
<td>263.4</td>
</tr>
<tr>
<td>CM</td>
<td>0.55</td>
<td>359.5</td>
<td>0.87</td>
<td>29.98</td>
<td>290.1</td>
</tr>
<tr>
<td>CH</td>
<td>0.64</td>
<td>448.9</td>
<td>1.09</td>
<td>41.71</td>
<td>395.0</td>
</tr>
<tr>
<td>Exhaust</td>
<td>1.00</td>
<td>413.6</td>
<td>-</td>
<td>11.21</td>
<td>307.4</td>
</tr>
</tbody>
</table>

Relative CO₂ concentration against relative height is shown for both experiments in Figure 5.

![Fig. 5. Relative CO₂ concentration at the breathing zone of the standing manikin](image)

Fig. 5. Relative CO₂ concentration at the breathing zone of the standing manikin
Results show similar vertical concentration gradients for both tests but with some discrepancies. At the height of the chest of HW (CL), 0.02 m above the P’s mouth, the contaminant concentration is less than 1 for the two tests, which is considered lower than the value for a fully mixed air situation. There is an air stability of the air in the exhalation region of P generated by the temperature stratification provoked by the cool floor and the lack of air turbulence even when the airflow rate is high, corresponding to 7.5 ACH. This air stability makes the exhaled contaminants flow to the upper part of the room without mixing with the air surrounding HW. The clean air close to the floor is induced to the chest of HW by thermal stratification. This phenomenon also generates a low exposure level (CM) to the HW, below 1 for the two tests studied. The separation distance between the two manikins is enough to have no interference between the exhalation of P and the microenvironment around HW. However, at a higher position, above the head of HW manikin (CH), the contaminant concentration value is higher than 1, and the standard deviation increases especially for test 2. In that part of the room the air from the diffusers induces the exhaled contaminants, which are mixed with the clean air of the room, increasing the contaminant concentration above the head of HW (CH). The increase of the contaminant concentration for test 1 (2ACH) at this position is lower than for test 2 (7.5 ACH) due to the stronger influence of the air from the diffusers that induces more air from the stable region of the exhalation. The elevated flow rate of the air induces air from the lower part of the room driving it to the upper part and transporting the exhaled contaminants. The increasing of standard deviation with height also explains the distribution of exhaled contaminants in the upper part of the room, out of the stability region.

When using 2 ACH (test 1) the lack of air movement induced from the diffusers, produce a lock up phenomenon that maintains the contaminants above the patient. Many authors [18,19], for similar conditions of positive temperature gradient, have reported a lock-up phenomenon of the exhaled contaminants due to the air stability generated at the height of the exhalation of the source manikin. This makes the transport of contaminants in the air to other areas, such as to the microenvironment of HW difficult. For test 2 (7.5 ACH) there is a similar contaminant distribution, especially in the lower part of the room, due to the temperature gradient generated by the cool floor.

4. Conclusions

This study evaluates the influence of renovation rates in airborne contaminants removal when a mixing ventilation system is combined with a hydronic radiant floor system. Test 1 evaluates a very low ventilation rate, 2 ACH with the aim of comparing it with Test 2, which uses a common ventilation rate of 7.5 ACH.

Results obtained from measurements of absolute velocity and temperature along the height of the room show a positive vertical
temperature and velocity gradient generated by the cool hydronic floor and influenced by the ventilation rate used during each test. Higher ventilation rates lead to an increase of absolute air velocity and its variation with time inside the chamber, especially in the upper part.

CO\textsubscript{2} measurements show a similar distribution of exhaled contaminants but with some discrepancies. In both cases there is an air stability in the lower part of the room that generates low concentration values of contaminants in the region near the HW. However, the airflow generated by the diffusers in the upper part of the room induces a mixing flow that conduces to an increase value of the contaminant concentration above the head of the HW. This behavior is especially observed for test 2, using 7.5 ACH. While for test 1, 2 ACH, the concentration values above the head of the HW are still low. This study demonstrates that a higher ventilation rates does not necessarily lead to a better situation in terms of cross infection risk and contaminant exposition of people inside indoor places. Studying the dispersion of exhaled contaminants, special care should be taken on possible stability regions generated by the ventilation systems and on the temperature and velocity gradients that are generated in indoor environments.

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References