Effect of Outdoor Temperature on Performance of All-air Wall Induction Unit in a Four-bed Hospital Ward

Shaoyu Sheng 1, Toshio Yamanaka 1, Tomohiro Kobayashi 1, Narae Choi 1, Nobukazu Chou 2

1Osaka University, Department of Architectural Engineering, 2-1 Yamadaoka, Suita, Japan
2KIMURA KOHKI Co., Ltd, Production Department, 3-5-5 Chuoku Uehonmachinishi, Osaka, Japan

Abstract. The prototype all-air wall induction unit (IU) has the characteristics of displacement ventilation (DV) and windless air supply, which is considered ideal for hospital ward usage. The outdoor temperature, however, will affect its ventilation and thermal performance. This study conducted a full-scale experiment. IUs are vertically installed in the four corners of the experiment room, which is furnished as a Japanese hospital ward. An outdoor climate simulation chamber (OCSC) is installed on one side of the room to simulate the external window and sill under different outdoor temperature conditions. CO2 is generated from the patients’ breathing zone. As parameters, the temperature difference between the OCSC and the room air (or supply air), the IU’s windless characteristics. IU’s air supply velocity (volume) is restricted to maintain DV, which may result in insufficient thermal capacity. On the other hand, in the winter, downward airflow can undermine the DV’s concentration stratification by entraining pollutants to fall down, thereby decreasing ventilation efficiency. In the summer, excessive upward airflow pushes the concentration stratification layer down and may expose occupants to high pollutant concentrations. Therefore, this study will focus on outdoor temperature’s influence on the wall IU’s ventilation and thermal performance in a four-bed hospital ward. The full-scale experiments will be carried out in a room furnished as a typical four-bed hospital ward in Japan. An outdoor climate simulation chamber (OCSC) is installed on one side of the room to simulate the external window and sill under different outdoor temperature conditions. CO2 is used as the tracer gas to represent the pollutants emitted by a patient. As parameters, the temperature difference between the OCSC and the room air (or supply air), the IU’s supply area and volume, and the existence of cubic curtain around the hospital bed will be adjusted. The room’s steady-state temperature and CO2 concentration distribution under different conditions will be compared and analyzed. Based on the experiment results, the effect of outdoor temperature on the performance of wall IU in a four-bed hospital ward will be clarified. The improving methods for wall IU’s design, as for the supply area and supply rate, combine with cubicle curtain, and the insulation performance requirements of the building envelope will be proposed.

1 Background and Purpose

The all-all type induction unit (IU) works similarly to the active chilled beam terminal, wherein the high-velocity discharge jet has already been conditioned before being supplied into the IU, then mixed with the entrained air, and supplied into the room without exchanging the heat through the convective coil. It has the strengths such as savings the fan-power and re-heating energy consumption, water-pipe free, anti-condensation characteristics, and the radiation air conditioning effect [1]. Li et al. [2] [3] performed experiments to examine the performance of a ceiling mount all-air IU system. In their work, an analysis of the tracer gas concentration distribution (normalized concentration mainly less than 1, compared with the exhaust concentration) and air change efficiency (~0.7 in the entire room) shows that the IU has a satisfactory mixing ventilation performance. In order to further improve its ventilation performance, a prototype IU was developed for vertical (wall corner) mounts. In our previous study [4], the possibility and feasibility of establishing displacement ventilation by the wall IU was verified based on the full-scale experiment and CFD simulation. The wall IU’s improving design method was proposed by comparing the IU’s thermal and ventilation performance in the adiabatic experiment room.

However, during the summer or winter, an upward or downward airflow occurs near the exterior wall and windows due to the significant temperature difference. On the one hand, the cold draft may decrease the occupant’s thermal comfort during the winter due to the
2 Methodology

Full-scale experiments were conducted in the showroom of an air conditioner maker. Though the experiment room is insulated and uses OCSC to control the window’s inner surface temperature, experiments under winter-heating conditions were carried out in February 2022, and summer-cooling conditions were carried out in August 2022 to minimize the influence of the variable outdoor temperature.

2.1 Details of the all-air wall induction unit

Fig. 1 is an overview of the IU used in this research. As shown in Fig. 1(a) and (b), primary air (PA) from the air handling unit (AHU) is jetted out from the primary air nozzle and enters the induction chamber at a speed of 3–5 m/s. The high-speed airflow causes negative pressure on the induction chamber, enabling it to induct indoor air from the two sides of the IU and mix it with the primary air. This mixed air flows to the flow straightener and finally seeps out from the punching panel at the center of the IU’s surface into the room at a speed of approximately 0.2–0.5 m/s. The mixing ratio of the IU under the standard supply condition (full size, PA=220m³/h/unit) is approximately 4:6, which means that the PA from the AHU and the IA respectively account for 60% and 40% of the IU’s total supply airflow (SA) rate (airflow seepage from the punching panel). And the outlet area of the IU was adjusted as 2/3 outlet mode (66% open, 1400 mm in height) in this study to balance the supply volume and the ventilation performance. The adjustment changed the IU’s mixing ratio within a certain range (from 4:6 to 3:7) because of the variety of air nozzle velocity and the IU’s geometric. They were considered insignificant to affect the IU performance in this study.

2.2 Experiment room and equipment

Fig. 2 shows the experiment room layout and the distribution of measurement points. The experiment room was 7000 mm in length, 7000 mm in width, and 2600 mm in height. Four IUs were vertically installed in the wall corners, and a 550×550-mm-sized exhaust was in the center of the ceiling. The OCSC is installed on one side of the experiment room, and an individual air-conditioning system can control the temperature inside the OCSC. 3 mm polycarbonate (U=5.8W/m²·K) is installed between the room and OCSC to represent the 6 mm single glass with an area of 4.6m² under the summer-cooling condition. Similarly, 7 mm styrene panels (U=1.4W/m²·K) are used to represent the double glazing with the same area (4.6m²) under the winter-heating condition. The room’s other three walls were thermally insulated by polystyrene foam (50-mm thickness, 0.022 W/m·K) to decrease the effect of outdoor air temperature changes. The showroom is located on the third floor of a three-story office building. The second floor of this building is an office with 24-hour air conditioning. And the room’s ceiling is a chamber.
with 600 mm height, which exhibits a negligible change in temperature during the experiment. Therefore, this experiment room can be considered a middle unit with only one exterior surface (perimeter).

Four hospital beds with cubicule curtain systems were set inside the room. Cylinders (1500 mm length, 300 mm Ø, Fig.2) covered with a black cloth and a PVC heating cable (50 W) wrapped inside were used to simulate patients lying on the bed. In the winter experiments, pure CO2 gas was generated (1L/min) from one cylinder (near P6 in Fig.2) to represent the pollutants emitted from one patient. However, the gravitational deposition of CO2 may affect the experiment’s accuracy. Therefore, in the following summer experiment, CO2 and He gas were mixed in a 5:3 ratio to be used as the tracer gas (1.6L/min) since they have the same density as air. Black lamps (incandescent bulbs covered with dark purple glass) were set near the hospital bed 800 mm above the floor to simulate the heat generated by the electrical equipment (60W). The total heat generated inside the room was estimated to be 440 W.

Fig.3 shows the distribution of the measurement points. The room’s vertical temperature distribution is measured by the thermocouple from 54 points dispersed on six poles in 30-s intervals (Fig.3 (a) and (b)). For the CO2 concentration measurement, a total of 36 non-dispersive infrared (NDIR) gas analyzers (TR-576, T&D Corporation) points were dispersed on the same six poles as temperature measurement points (Fig.3 (c)) and recorded in 30-s intervals. Moreover, the inner surface temperature of the wall was measured by 24 points (denoted as “W” in Fig.3 (a) and (d)), the inner surface temperature of the OCSC was measured by 24 points (denoted as “C” in Fig.3(a) and (e)). The temperature and concentration of the IA, PA, SA, EA, and RA are recorded continuously during the experiment.

2.3 Parameters and experiment cases

The temperature difference Δθ between the OCSC and the room air (or supply air), IU’s air supply location (2/3 outlet mode and 1/2 air supply mode, Fig.1), supply volume, and the existing cubicule curtain, are adjusted as the parameters. It is important to note that OCSC temperature adjustment under the summer-cooling conditions is based on its difference from the IU’s SA temperature (temperature after mixing with the room air). In contrast, the winter heating conditions are based on its difference from the IU’s SA temperature adjustment under the summer-cooling experiment.

Considering the experiment method (tracer gas, definition of the temperature difference, air supply volume) has changed (improved), results and examination of the summer and winter experiments will be presented individually. The comparison between the winter and summer experiment results will only take place on a macro level.

3 Experiment results

Considering the experiment method (tracer gas, definition of the temperature difference, air supply volume) has changed (improved), results and examination of the summer and winter experiments will be presented individually. The comparison between the winter and summer experiment results will only take place on a macro level.
Normalized concentration \( C_N \), calculated by Function 1 is used to express the CO2 concentration. PA means the primary air supplied by the air conditioner, EA means the exhaust air, and \( \Phi \) means the measurement points.

\[
C_N = \frac{C_P - C_{PA}}{C_{EA} - C_{PA}} \tag{1}
\]

### 3.1 Winter-heating condition

**Fig.4** shows the indoor temperature and normalized concentrations distribution when the temperature difference between the room air and the OCSC (1.1 m height) is 18°C (Table 1 for reference). These temperature conditions correspond to the midwinter condition in Osaka, Japan, and the cases with different air supply conditions (2/3 outlets, PA=880 m³/h or 1/2 supply, PA=600 m³/h), with or without the cubicle curtain are compared. Furthermore, \( \Delta \theta \) is adjusted to around 10, 7, and 3°C while under 2/3 air supply mode, PA=600m³/h, and with the cubicle curtain surrounding the bed to investigate its influence on the indoor thermal and ventilation environment. The results are shown in **Fig.5**.

Under the midwinter condition (**Fig.4**), the vertical temperature difference in the occupied space (0.1 to 1.8 m above the floor) is around 3°C, and the temperature difference between the space near the hospital bed (0.6 m) and 1.7 m above the floor is within 2°C. If the IU is operating in 2/3 supply mode with a PA=600m³/h, regardless of curtain presence or not, vertical air temperature distribution has a similar gentle gradient. Meanwhile, the curtain’s block effect is highlighted when IU is under 1/2 supply mode with an 880m³/h rate. Without using the cubicle curtain, a significant temperature gradient in the vertical direction (about 6°C) was observed near the IU (P1, P2, P5, and P6, occupied zone), while this gradient is around 3°C if the curtain surrounded the bed.

With respect to the concentration distribution, the sinking of CO2 was observed in most of the experimental cases, (except for the case of the 1/2 air supply mode). In the space near the generation source (P6), the normalized concentration near the floor becomes larger than 3 and less than 1 near the other hospital beds. This is because while the plume carries up the pollutant (tracer gas) near the heating source (patient), part of the pollutant is affected by the downward airflow near the cold glass/wall surface and falls down to the floor. In cases (1/2)880-UC and (1/2)880-NC, the IU has the highest air supply velocity compared with the other cases. The supply air at high-speed offsets the influence of the downdraft near the wall, making the pollutants stay in the space around 1 m above the floor. In midwinter, although the downward flow near the cold glass/wall has an opposite effect on DV’s efficiency, the normalized concentration distribution in the entire room except the space near the pollution source, especially near other beds, is less than 1, and can be considered to be quasi-displacement ventilation. Otherwise, unlike in the adiabatic [4] and summer-cooling conditions (section 3.2), the presence or absence of the curtains has no particular effect on the concentration distribution.

**Fig.5** shows the indoor temperature and normalized concentration distribution when the room temperature (1.1 m from the floor) and the outside chamber air temperature differ by \( \Delta 3, 7 \), and 10°C, respectively. The U-shaped curtain is used in the analysis, and the volume of PA is kept at 600m³/h. When the temperature

### Table 1. Case number, parameters, and reference of the winter-heating experiment

<table>
<thead>
<tr>
<th>Case</th>
<th>Parameter abbreviation</th>
<th>PA volume (m³/h)</th>
<th>Air supply mode</th>
<th>Curtain shape</th>
<th>( \Delta \theta ) (°C)</th>
<th>OA (°C)</th>
<th>EA (°C)</th>
<th>PA (°C)</th>
<th>Wall inner (°C)</th>
<th>OCSC inner (°C)</th>
<th>OCSC air (°C)</th>
<th>Air 1.1m above the floor (°C)</th>
<th>Difference between OCSC surface and room air (°C)</th>
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<tbody>
<tr>
<td>Case1</td>
<td>(2/3)600-NC</td>
<td>600</td>
<td>2/3</td>
<td>No</td>
<td>17.65</td>
<td>7.18</td>
<td>29.47</td>
<td>39.25</td>
<td>27.27</td>
<td>24.09</td>
<td>12.87</td>
<td>30.52</td>
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<td>600</td>
<td>2/3</td>
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<td>10.26</td>
<td>29.70</td>
<td>39.45</td>
<td>28.43</td>
<td>25.31</td>
<td>14.09</td>
<td>30.00</td>
<td>Δ4.09</td>
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<td>2/3</td>
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<td>U</td>
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<td>26.99</td>
<td>32.35</td>
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<td>600</td>
<td>2/3</td>
<td>U</td>
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<td>12.11</td>
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<td>23.45</td>
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<td>21.94</td>
<td>20.09</td>
<td>23.15</td>
<td>Δ1.21</td>
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</table>

### Table 2. Case number, parameters, and reference of the summer-cooling experiment

<table>
<thead>
<tr>
<th>Case</th>
<th>Parameter abbreviation</th>
<th>PA volume (m³/h)</th>
<th>Air supply mode</th>
<th>Curtain shape</th>
<th>( \Delta \theta ) (°C)</th>
<th>OA (°C)</th>
<th>EA (°C)</th>
<th>PA (°C)</th>
<th>Wall inner (°C)</th>
<th>OCSC inner (°C)</th>
<th>OCSC air (°C)</th>
<th>SA (IU's surface temperature) (°C)</th>
<th>Difference between OCSC surface and room air (°C)</th>
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<td>598</td>
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<td>28.92</td>
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<td>No</td>
<td>14.92</td>
<td>31.05</td>
<td>27.76</td>
<td>18.22</td>
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<td>35.18</td>
<td>20.26</td>
<td>5.24</td>
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<td>2/3</td>
<td>U</td>
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<td>32.13</td>
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<td>18.98</td>
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<td>2/3</td>
<td>U</td>
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<td>27.08</td>
<td>18.63</td>
<td>25.94</td>
<td>30.83</td>
<td>34.52</td>
<td>20.27</td>
<td>5.11</td>
</tr>
<tr>
<td>Case8-b</td>
<td>(2/3)859-UC-10</td>
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<td>2/3</td>
<td>U</td>
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<td>28.39</td>
<td>25.69</td>
<td>18.50</td>
<td>24.92</td>
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<td>19.89</td>
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<td>2/3</td>
<td>U</td>
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<td>23.50</td>
<td>24.18</td>
<td>19.04</td>
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<td>300</td>
<td>2/3</td>
<td>U</td>
<td>14.75</td>
<td>31.69</td>
<td>28.55</td>
<td>18.66</td>
<td>27.30</td>
<td>31.97</td>
<td>35.27</td>
<td>20.51</td>
<td>5.93</td>
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</table>
difference between indoors and outdoors decreases, the gradients of the indoor air temperature become gentler. The vertical temperature distribution is almost uniform in the case of $A^3\vartheta$C (air temperature difference between the OCSC inner and the 1.1m height of the room’s center). Concerning the concentration distribution, these three cases have a stable distribution of DV. In the case of $7\vartheta$C and $10\vartheta$C differences, although there is still some concentration gathering near the generation source, the volume sinking down to the floor is dramatically decreased. When the temperature difference reaches $3\vartheta$C, the pollution rises and exhorts smoothly. According to Fig.5, when using double glazing, the conveying effect of the plume can overcome the influence of the down draft near the wall or glass if the temperature difference between indoor and outdoor air in winter is less than $10\vartheta$C.

### 3.2 Summer-cooling condition

Fig.6 shows the vertical temperature and concentration distribution under the different supply volumes and curtain conditions with a 2/3 air supply mode, respectively. The temperature difference between the OCSC (35$\vartheta$C) and the IU’s SA (20$\vartheta$C) is aimed to keep as $A\vartheta$ = 15 $\vartheta$C. The temperature gradients of the indoor air temperature become gentler. The vertical temperature distribution is almost uniform in the case of $10\vartheta$C and $7\vartheta$C differences. The height of the DV’s concentration stratification becomes larger than 2 around 1.8 m from the floor, reaches the maximum at around 2 meters, and decreases while $\vartheta$ = 15 $\vartheta$C, pollutants concentrate in the space near the wall or glass if the temperature difference between indoor and outdoor air in winter is less than $10\vartheta$C.

Based on the results in Fig.6, under the summer cooling condition ($A\vartheta$ = 15$\vartheta$C, single glass), the IU has excellent ventilation performance by stably establishing the DV. All the experiment cases show a normalized concentration of less than 0.5 in the occupied zone. Under the 2/3 air supply mode, surrounding the bed with a curtain can further reduce the pollutants’ diffusion; even the space near the generation source can maintain a normalized concentration of less than 0.3. Meanwhile, the vertical temperature difference in the occupied zone is less than $A\vartheta$ = 2.5$\vartheta$C, ensuring a comfortable thermal environment. This supply mode can achieve a stable and high-efficiency DV during the summer cooling. Fig.7 compare the influence of the temperature difference between the OCSC (OA) and the SA (indoor air temperature). A higher OA (exterior glass) temperature will push the stratification down, thereby increasing the temperature gradient. The height of the DV’s concentration stratification changes according to the temperature gradient of the room air. When the $A\vartheta$ = 5$\vartheta$C, pollutants concentrate in the space near the ceiling (mostly above 2 m height from the floor). Meanwhile, if the $A\vartheta$ = 15$\vartheta$C, the normalized concentration becomes larger than 2 and decreases while $\vartheta$ = 5$\vartheta$C, ensuring a comfortable thermal environment. This supply mode can achieve a stable and high-efficiency DV during the summer cooling.
getting close to the ceiling. The relationship between the heat load (windows or wall temperature) and DV’s stratification height of the IU needs further investigation. The current findings indicate that the IU can keep the vertical stratification of the DV at a satisfactory height (above 1.5 m) when using 6 mm single glass with a temperature difference of 15°C under a common air supply volume (around 600 m³/h). In wards where patients are always in bed, it is sufficient to keep their breathing zone clean.

4 Discussion and conclusions

Through the upward/downward airflow near the exterior window, the outdoor temperature clearly impacts the IU’s ventilation and thermal performance. On the one hand, in the summer, upward airflow near the high-temperature window or wall keeps the DV stable (image shown in Fig.9(a)), thereby increasing ventilation efficiency. However, excessive upward airflow can increase the indoor air temperature gradient and push the DV’s concentration stratification down. It is crucial to keep the occupant’s breathing zone below the DV’s concentration stratification by adjusting the IU’s air supply volume and temperature. On the other hand, cold draft occurs near low-temperature window or walls in the winter. Downward airflow decreased the DV’s efficiency by entraining the pollutants near the ceiling and falling into the occupied zone (image shown in Fig.9(b)). In addition, part of the clear SA from IUs rises to the upper portion of the room rather than supplementing the occupied zone. These make the flow field in the room complicated. The concentration stratification becomes blurred, thereby decreasing the DV’s efficiency.
This study examines the outdoor temperature's influence on the all-air wall IU's performance used in a four-bed hospital ward by full-scale experiments both in summer and winter. Conclusions were made as follows.

- This air terminal for DV has an ideal thermal performance: the vertical temperature gradient in the occupied zone is less than 2.5°C in summer and around 3°C in winter.
- In wards where patients are always in bed, the effect of the temperature difference will become more negligible.
- During the summer, IU has an excellent ventilation performance (normalized concentration in the occupied zone mostly less than 0.3) because the upward airflow strengthens the DV.
- A PA supply rate of around 600 m³/h is recommended for hospital ward usage in the summer. The height of DV’s stratification layer can be kept at a 1.5 m height when using the 6 mm single glass with a Δθ = 15 °C in/outdoor temperature difference.
- Even though the downward airflow influences the IU’s ventilation performance, the normalized concentration in the occupied zone mostly less than 0.3 because the upward airflow strengthens the DV.
- In midwinter, a high supply rate with a small supply area and the usage of a cubicle curtain are recommended. If the temperature difference is less than 10 °C, by using the double glazing, the plume’s conveying can overcome the influence from the down draft and stabilize the DV while using a moderate supply rate (600 m³/h).
- Surrounding the hospital bed with a cubicle curtain strengthens the DV in the summer and reduces the vertical temperature gradient near the bed in the winter.

Because the experiments carried out in the building are in actual use, and the time to carry out the summer and winter experiments differs by half a year that the experimental method had improved, this study focused more on qualitative than quantitative analyses. This is considered one of the limitations of this study. A more sophisticated winter-heating experiment is planned to allow a more in-depth comparison and analysis with the summer experiment. The relationship between the heat load and stratification height will be analyzed and figured out. In addition, the investigation using some comfort index will be carried out by experiment data and the CFD simulation results.

**References**