Task Ambient Air Conditioning System with Natural Ventilation for High Rise Office Building (Part 1: Outline of System and Thermal Environment in Working Zone)

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Summary: A task ambient air conditioning system with natural ventilation was introduced to a high-rise office building. This paper reports the design concept, outline of this system and measurement results. Sufficient ventilation can be secured with the natural ventilation openings developed at this time, and the differences in the room temperature are small among various in-room places due to air flow along the ceiling surface. Judging from the PMV, the thermal comfort in the task zone is improved when temperature differences between the upper space and the lower space in the task zone are eliminated by task outlets and the feeling of air flow is given to occupants.

Keywords: task ambient air conditioning system, natural ventilation, thermal comfort
Category: indoor climate specific designs, ventilation, innovative technologies and solutions

1. Introduction
The task ambient air conditioning system with natural ventilation is intended to attain both occupants' thermal comfort and energy saving by dividing the thermal environment in the office into a general "ambient" zone and working "task" zones. The task zone is so controlled as to suite individual thermal preferences, and the ambient zone mitigates the thermal condition using natural ventilation. This system was introduced to an office building (195 m in height, 41 stories above the ground and 5 stores below the ground, 106,000 m\textsuperscript{2} in total floor area) in Osaka completed in December 2004. This paper reports the design concept and the outline of this air conditioning system, and measurement results of task ambient air conditioning during natural ventilation and during air conditioning (cooling).

2. Design Concept and Outline of System
2.1 Natural ventilation
The building site is located in a sandbank (Nakanoshima) where west prevailing wind flows along the river. For wind-induced ventilation in the horizontal direction by utilizing this west wind, natural ventilation openings were provided on the ceiling near the windows in the working zone of office (floor area: 1,426.5 m\textsuperscript{2}/floor) except the core on the south side. Each natural ventilation opening is 7.2 m in width and 0.4 m\textsuperscript{2} in effective opening area. Twenty-six natural ventilation openings were provided on each of the 14th to 17th floors (FL = GL + 59.63 to 72.53 m), and twenty-four natural ventilation openings were provided on each of the 27th to 35th floors (FL = GL + 123.03 to 153.13m).

Figure 1 shows the plan of the office floor. The working zone on each floor is non-partitioned, one large open space except those in the southwest area.

![Fig. 1 Plan of office floor](image_url)

Figure 2 shows the section of the entire building. Figure 3 shows the conceptual drawing of the task ambient air conditioning system with natural ventilation. Natural ventilation is introduced from the eaves of the outer building frame into the inside of the room as to
prevent intrusion of rainwater and mitigate strong wind.

utilized to the maximum extent in ambient air conditioning.

Table 1 shows the opening condition for the natural ventilation openings. Natural ventilation is controlled based on the wind velocity at the roof in many cases, but the correct wind velocity cannot be necessarily measured due to the effect of the wake area generated at the roof. In addition, because the wind velocity varies vertically in high-rise buildings, it is difficult to control natural ventilation openings on each floor based on the wind velocity at the roof. Accordingly, the natural ventilation openings were controlled based on the pressure difference between the indoor and the outdoor on the floor shown in Fig. 2 instead of the wind velocity at the roof, and the wind velocity at the roof was measured only for reference. Control of the natural ventilation openings is divided into 8 systems on each floor because the pressure difference between the indoor and the outdoor is different in each bearing. The natural ventilation openings are open when all opening condition items are satisfied in each system. When any one opening condition item is unsatisfied, the natural ventilation openings are closed. While the natural ventilation openings are open, the opening area is adjusted in two steps, "half open" and "completely open", due to the temperature difference between a zone near the window and an inner zone in the room so that draft is prevented.

Table 1 Opening condition for natural ventilation openings

<table>
<thead>
<tr>
<th>Pressure difference between indoor and outdoor</th>
<th>150 Pa or less (70 Pa or less during rainfall)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside air temperature</td>
<td>Range from 18°C to circulated air temperature</td>
</tr>
<tr>
<td>Outside air humidity</td>
<td>90%RH or less</td>
</tr>
<tr>
<td>Outside air enthalpy</td>
<td>Outside air &lt; In-room air</td>
</tr>
</tbody>
</table>

Figure 4 is the inner view of the natural ventilation openings. The in-room natural ventilation openings are so developed that the blow-off air flows along the ceiling surface so that the introduced outside air reaches deep inner places in the room. According to the results of several full-size experiments, the air flow reaches up to 7 m from the outlet of the natural ventilation openings when the blow-off air movement velocity is 2 m/s and blow-off air temperature is lower than room air temperature by 6°C. Natural ventilation openings are opened or closed fully automatically so that natural ventilation can be

2.2 Task ambient air conditioning

The task zone is air conditioned by floor outlets, and the ambient zone by ceiling outlets. Because the task zone and ambient zone are controlled individually, the thermal environment in the ambient zone can be mitigated while the independency in the task zone is maintained.

The newly developed task floor outlet is so designed
as to allow changeover between directional air flow and diffusive air flow, and the air volume is also changeable from "High" through "Low" to "Off" according to individuals’ preferences. One task floor outlet is provided to each person in principle. It was confirmed by the experiment performed in the environmental test laboratory about task ambient air conditioning and natural ventilation that the temperature difference of approximately 2°C was generated between the task zone and the ambient zone, and that the task zone was clearly formed.

The ambient zone is so designed as to mitigate the set room temperature (28°C in summer, 22 to 26°C in spring and fall, for example), utilize natural ventilation positively, and improve energy-saving. Table 2 shows the specification of the task ambient air conditioning.

Table 2 Specification of task ambient air conditioning

<table>
<thead>
<tr>
<th>Control method</th>
<th>Task</th>
<th>Ambient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>VAV</td>
<td>26</td>
<td>28</td>
</tr>
<tr>
<td>Blow-off temperature [°C]</td>
<td>16.98 (71%)</td>
<td>6.94 (29%)</td>
</tr>
<tr>
<td>Room temperature [°C]</td>
<td>39.80 (55%)</td>
<td>32.54 (45%)</td>
</tr>
</tbody>
</table>

Task floor outlet: 101 m³/h/unit (when set to "directional" and "Hi"), 113 m³/h/unit (when set to "diffusive" and "Hi")

3. Outline of Measurement

For verifying the performance of this air conditioning system, the temperature, relative humidity, air movement velocity and wind velocity were measured mainly with natural ventilation (in spring and fall) and with air conditioning (in summer). Table 3 shows the outline of measurement.

Table 3. Outline of measurement

<table>
<thead>
<tr>
<th>1. Measurement period</th>
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</thead>
<tbody>
<tr>
<td>Spring and fall:</td>
</tr>
<tr>
<td>From April 23 to May 1, 2005,</td>
</tr>
<tr>
<td>From October 23 to November 4, 2005</td>
</tr>
<tr>
<td>Summer:</td>
</tr>
<tr>
<td>From July 16 to July 22, 2005</td>
</tr>
</tbody>
</table>

2. Air conditioning
- Spring and fall: Natural ventilation + Task air conditioning + Ambient air conditioning (The natural ventilation openings were completely open manually, and only the task aid conditioning system was operating on April 23, October 23 and October 30.)
- Summer: Task air conditioning + Ambient air conditioning

3. Measured floor: 30th floor (FL = GL + 131.63 m)

4. Measurement points
- 2 concentration measurement areas (see Figs. 1): 144 points for temperature (18 points of 1.0 m in width and 2.5 m in depth with 0.5 m pitch, and 8 points in height direction at each point), 36 points for airflow velocity, 2 points for humidity and 2 points for globe temperature

- Entire room (see Fig. 1): 33 points for temperature (0.9 m in height), 4 points for temperature and humidity (1 point for each 0.9 m in height) and 14 points for temperature and air movement velocity (8 points for temperature and 3 points for air movement velocity in height direction)
- Air conditioner: Blow-off temperature, return temperature and heat quantity

5. Internal loads
- Human body: Person simulator 60 W x 2 bodies (on seats in concentration measurement areas) and black lamp 60 W x 1 10 units (on other seats)
- OA equipment: Personal computers in standby status
- Illumination: Lit

4 Verification of Natural Ventilation Performance (Measurement Results in Spring and Fall)

4.1 Relationship between wind velocity at roof and air change rate by natural ventilation

The wind velocity was compared between two anemometers installed in the east and west at the roof (GL + 200 m) and the Osaka District Meteorological Observatory (GL + 33 m). Figure 6 shows the relationship between the wind velocity at the roof and the wind velocity announced by the Osaka District Meteorological Observatory. The wind velocity in the east was almost equivalent to that announced by the Osaka District Meteorological Observatory, and the wind velocity in the west was almost half of the wind velocity in the east. As a result, it was judged that the wind velocity at the roof instead of the outside wind velocity though the measurement height was different and the negative load area generated at the roof gave some effect.

Figure 7 shows the relationship between the wind velocity at the roof and the air change rate by natural ventilation. The ventilation rate was obtained by multiplying the air movement velocity measured at the natural ventilation opening by the area. The air change rate was obtained by dividing the ventilation rate by the volume of the working zone.
excluding the southwest area. Inflow and outflow of the wind were judged visually by checking the tuft attached to the outlets of natural ventilation opening. It is regarded that the inflow air volume is larger than the outflow air volume because the inflow air volume from the natural ventilation openings (S9 and S10) in the southwest were excluded from measurement and the inflow air volume caused by the chimney effect from the elevator hall are ignored.

Some correlation can be seen between the wind velocity at the roof and the air change rate. Natural ventilation was performed at the air change rate of 2.5 to 4.5 ACH with the wind velocity at the roof of 2 m/s, 4.0 to 5.5 ACH with the wind velocity at the roof of 4 m/s, and 4.5 to 6.5 ACH with the wind velocity at the roof of 6 m/s.

4.2 Relationship between outside wind velocity and air movement velocity at natural ventilation openings

Figure 8 shows the relationship between the outside wind velocity on the west side and the air movement velocity at the natural ventilation openings. The outside wind velocity on the west means that of a wind on the due west obtained by making vector resolution of past wind velocities and directions recorded by the Osaka District Meteorological Observatory. Correlation was detected between the outside wind velocity and the air movement velocity at the natural ventilation openings while the natural ventilation openings were both half open and completely open. The ratio of the air movement velocity at the natural ventilation openings to the outside wind velocity was 0.47 in the half open status, and 0.73 in the completely open status.

4.3 Relationship between air movement velocity at natural ventilation opening and in-room air movement velocity

Figure 9 shows the relationship between the air movement velocity at the natural ventilation openings on the west side and the in-room air movement velocity (T5). A certain correlation can be found between them. There is wind of 0.2 to 0.3 m/s which can be recognized by people at the height of FL +1.1 m and FL +1.6 m with the air movement velocity at the natural ventilation openings of 2.0 m/s even at the distant of 16.2 m (T5) from the natural ventilation opening.

4.4 Room temperature under natural ventilation

Figure 10 shows elapsed changes in the outside air temperature, outside wind velocity, most frequent wind direction, the opening ratio of the natural ventilation openings and room temperature (T1, T2 and T3) near the window having largest temperature fluctuations on each day. The natural ventilation openings were operated fully automatically on all days except October 30. The natural ventilation openings were usually open by half or more on all days except October 24. Except on October 30 when the natural ventilation openings were completely open manually, the temperature difference in the east-west direction (T1 and T2) was 0.2°C on average and 1.6°C maximum, and the temperature difference in the north-south direction (T1 and T3) was 0.3°C on average and 0.9°C maximum. The difference in room temperature was maintained within 1.6°C even while only natural ventilation was provided.

![Fig. 10 External condition, openings ratio of natural ventilation openings, and room temperature (from October 24 to October 30, 2005)](image)

Figure 11 shows the room temperature distribution from 12:00 to 13:00 on October 30 while the west wind was stably blowing. It can be seen that the natural ventilation air taken from the natural ventilation openings on the west side flows along the ceiling surface is mixed with the room air, and exhausted together from the natural ventilation openings on the east side.
4.5 Air conditioning load reduction by natural ventilation

Fig. 12 shows the heat rate consumed by the air conditioning system on a floor (30th floor) with natural ventilation and a floor (15th floor) without natural ventilation. Because the interior layout and internal heating condition (heat generated by personnel, illumination and equipment) are almost equivalent between these floors, the effect of natural ventilation can be regarded as the difference in the heat rate consumed on these floors. The daily accumulated heat quantity was reduced by natural ventilation by 32 to 42%, and by 36% on average in the period from October 24 to October 28.

Fig. 12 Heat extraction by air conditioning system (from October 24 to October 30, 2005)

5 Verification of Task Ambient Air Conditioning Performance without Natural Ventilation (Measurement Results in Summer)

5.1 Temperature and air movement velocity distribution in task zone

The temperature and air movement velocity were measured while the status of the task floor outlets in the concentration measurement area was changed day by day. Table 4 shows the opening status of the task floor outlets on July 20 to July 22.

Table 4 Opening status of task floor outlets in concentration measurement area

<table>
<thead>
<tr>
<th>Date</th>
<th>July 20</th>
<th>July 21</th>
<th>July 22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening status</td>
<td>Closed</td>
<td>Directional</td>
<td>Diffusive</td>
</tr>
</tbody>
</table>

Task floor outlets were set to "diffusive" except in the concentration measurement area on every day.

Fig. 13 Outside air temperature (from July 20 to July 22, 2005)

Figure 14 shows elapsed changes in the temperature in the task zone. While the task floor outlets were closed, there were temperature differences of 0.5 to 0.7°C on average between "FL +0.1 m" and "FL +0.6 m" and between "FL +0.6 m" and "FL +1.1 m". The temperature differences were small between "FL +1.1 m" and "FL +1.6 m". While the task floor outlets were set to "directional", there was almost no temperature difference at "FL +1.1 m" or lower because the temperature was lower at "FL +0.6 m" than at "FL +0.1 m". There was temperature difference of 1.4°C on average between "FL +1.1 m" and "FL +1.6 m". It is thought that the thermal environment in the task zone (FL + approx. 1.1 m or less) is different from the ambient zone due to the directional air flow from the task floor outlets.

Fig. 14 Temperature in task zone

Figures 15 and 16 show the vertical temperature distribution and air movement velocity distribution in the upper and lower spaces in the concentration measurement area (averaged values from 13:00 to 14:00). The measurement point was the back of a seat (T8). While the task floor outlets were open (and set to "directional" or "diffusive"), the temperature decreased and the air movement velocity increased mainly at "FL +0.6 m" due to the effect of blow-off air flow. The temperature difference between the upper space and the lower space was almost equivalent in both the "directional" mode and the "diffusive" mode, but the air movement velocity at "FL +0.6 m" was higher in the "directional" mode.
Figures 17 and 18 show the temperature distribution in the concentration measurement area (averaged values from 13:00 to 14:00). While the task floor outlets were set to "directional", there was almost no temperature difference between the upper space and the lower space around the rear of the person simulator. As for the temperature difference between the upper space and the lower space, the temperature in the front of the person simulator was higher by 0.6 to 0.9°C because the air flow from the task floor outlets was blocked by the person simulator and the back of the seat. While the task floor outlets were closed, the temperature difference of approximately 1.2°C was generated around the person simulator between the upper space and the lower space.

5.2 PMV evaluation

Figure 19 shows elapsed changes of the PMV. The PMV calculation points were provided at FL +1.1 m in the front of the person simulator (T7) and in the rear of the person simulator (T8). In the rear of the person simulator, the PMV was approximately 0.5 while the task floor outlets were closed, and approximately 0.2 or less while the task floor outlets were open. As for the "directional" and "diffusive" modes, the task zone was near the neutral range in the "directional" mode because the air movement velocity was high. In the front of the person simulator, the PMV value was as large as approximately 0.4 while the task floor outlets were open because the air flow from the task floor outlets was blocked by the person simulator body and seat.

6 Conclusion

1. This paper presented the design concept and outline of the task ambient air conditioning system with natural ventilation introduced to a high-rise office building.
2. The following results were found by measurements mainly with natural ventilation:
   - The air change rate of 4.0 to 5.5 ACH was secured with natural ventilation while the wind velocity at the roof is 4 m/s.
   - Even only with natural ventilation, the two-dimensional difference in room temperature was 0.3°C on average and 1.6°C maximum.
   - With the natural ventilation openings developed this time, the air flow along the ceiling was supplied to the room.
   - The daily accumulated heat consumption was reduced by 36% by natural ventilation.
3. The following results were found by measurements with air conditioning (cooling, without natural ventilation):
   - The thermal environment different from that in the ambient zone was formed in the task zone by task floor outlets.
   - While the task floor outlets were open in the "directional" mode, the task zone was nearest the neutral range of thermal comfort.
   - The shape of the back of seats might give considerable effect on the air flow from the task floor outlets. It is thought that the thermal environment in front of the person simulator could be further improved because the air from the task floor outlet flows to the chair with a back near the opening.

References