HYBRID AIR-CONDITIONING BASED ON NATURAL AND MECHANICAL VENTILATION IN OFFICE BUILDING

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ABSTRACT

The performance of a hybrid air-conditioning system which utilizes wind-induced cross ventilation is investigated. The characteristics of flow and temperature fields are examined using CFD simulation under various conditions of inflowing outdoor air, i.e. air temperature, air exchange rate and width of the opening for cross ventilation. In this simulation, the room air controlling system (VAV system) which is used to keep the task zone at a target temperature, is reproduced through changing the supply airflow rate of the air-conditioning system. Cooling load of the mechanical air-conditioning system is analyzed based on the results of these simulations. When the inflowing outdoor air flows in the lower part of the room, it does not mix with the room air and cools the task zone well.

INTRODUCTION

Hybrid air-conditioning (AC) is based on the concept of utilizing both natural and mechanical ventilations when a large volume of outdoor air can be used directly (without conditioning) for controlling air-temperature and humidity in a room. The hybrid air-conditioning system studied in this paper is based on the concept of task/ambient air-conditioning, as shown in Figure 1. The task zone is conditioned precisely with the aid of the mechanical air-conditioning system and the remaining ambient zone is conditioned by natural cross ventilation. This is a valid system from the view point of improving indoor air quality (IAQ) and achieving energy conservation. The ventilation effectiveness and energy conservation have been partly reported in the preceding paper[1].

A CFD (Computational Fluid Dynamics) simulation was carried out for room airflow in this research. The boundary conditions (B.C.) of the CFD concerning the room air-conditioning

Fig. 1 Concept of Hybrid Air-conditioning (cooling) System based on Task-ambient Air-conditioning
(VAV (variable air volume) AC system) is changed within the simulation process in order to keep the average temperature of the task zone at the target temperature. In other words, the simulation leads to a condition where the average task zone temperature is kept at the target temperature by changing the supply air volume of the air-conditioning system. With this simulation, we can estimate how much cooling heat is consumed by the air-conditioning system to keep the task zone at the target temperature and can analyze the details of the flow and temperature fields in that condition.

METHODS

In the office setting (as shown in Fig. 2), flow and temperature fields are calculated based on a 3-D CFD simulation, using the standard k-ε model. The standard k-ε model is confirmed as a valid tool by comparing the results of room airflow simulation with experimental results[2]. The width of the calculation area is set as half of the 3.6 m office module (1.8 m), considering

![Fig. 2 Office Model for Analysis](by CFD, half space of the symmetrical office module)

<table>
<thead>
<tr>
<th>Table 1 Boundary &amp; Calculation Conditions for CFD</th>
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<tr>
<td>Supply opening</td>
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<tr>
<td>$U_{in, avg} = U_{in, std} + \Delta U$</td>
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<tr>
<td>$\Delta U = \frac{\Delta Q}{(T_{task} - T_{target}) \times V_{task}}$</td>
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<td>$\Delta Q = \frac{(T_{task} - T_{target}) \times V_{task}}{t_{rel}}$</td>
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- $T_{task}$: average temperature of the task zone [°C]
- $T_{target}$: targeted temperature [°C]
- $U_{in}$: supply air temperature [°C]
- $\Delta U$: acceptable difference between $T_{task}$ and $T_{target}$ [°C]
- $U_{in, avg}$: new velocity at the supply opening [m/s]
- $U_{in, std}$: old velocity at the supply opening [m/s]

<table>
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<tr>
<th>Table 2 Heat Sources in Office Model (Floor area used for calculation = 19.4 m²)</th>
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<tr>
<td><strong>Cooling load (W)</strong></td>
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<td>----------------------</td>
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<tr>
<td>400</td>
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</table>
the symmetrical configuration. Hybrid air-conditioning is modeled as the inflowing outdoor air flows into the room from the upper opening of the window \((0.5 \times 1.8 \text{ m}; \text{Fig. 2, left})\), and is exhausted through the opening at the other side \((0.5 \times 1.8 \text{ m}; \text{Fig. 2, right})\), while the mechanical AC is still operating. The cooled air of the mechanical AC is supplied by five floor supply openings \((0.1 \times 0.2 \text{ m})\) and then exhausted through four ceiling exhaust openings \((0.1 \times 1.2 \text{ m})\).

The CFD simulation, incorporating the VAV AC controlling system to the boundary conditions (B.C.), was carried out as shown in Figure 3. In the relaxation loop of the simulation, the average temperature of the task zone is compared with the target temperature. In this research, the target temperature is set at 26°C and the task zone as shown in Figure 4. If the difference between them is greater than acceptable value \(\delta\) (taken as \(\pm 0.04°C\) in this research), additional heat for keeping the average temperature of the task zone to the target temperature is calculated. Then, the supply airflow rate of the room air-conditioning system is changed accordingly considering the additional heat whereas the supply air temperature is set at a constant value of 19°C.

The boundary and calculation conditions for the CFD simulation are shown in Table 1 and the given heat generation rate in the office in Table 2. The effects of human bodies are considered only as heat sources which are given on the floor in the office. One simplified shape body is arranged in the center of the office to investigate the flow field around it.

### ANALYZED CASES (Table 3)

Cases analyzed are grouped into three as shown in Table 3. The cases in Group I were carried out to examine the effect of changing the outdoor air temperature of the cross ventilation, but keeping the airflow volume constant. The cases in Group II were carried out to examine the effect of changing the outdoor airflow rate, but maintaining the outdoor air temperature. Finally in Group III, the cases were carried out to examine the effect of changing the opening area of the window for natural cross ventilation. Case C in Group I also belongs to the other two groups of II and III, and is used as the standard case.

![Table 3 Analyzed Cases](image)

1) Supply air volume in VAV mechanical air-conditioning is simulated through the CFD so as to achieve the average temperature of 26°C within the task zone.

2) Archimedes number of inflowing outdoor air is defined as \(Ar = g \cdot \beta \cdot \Delta \Theta \cdot L \cdot U^2\), where, \(g\) is the gravitational acceleration \([\text{m/s}^2]\), \(\beta\) is the coefficient of volumetric expansion \((=1/300 \text{ [°C]})\), \(\Delta \Theta\) is the temperature difference between the inflowing outdoor air and the temperature at the task zone [°C], \(L\) is the vertical-width of window opening [m] and \(U\) is the velocity of inflowing outdoor air [m/s].
RESULTS

Flow and temperature fields are shown only for the cases of Group I on the account of limited space.

Flow Fields

The flow fields of Group I are shown in Figure 4. The vertical sections including the human model are shown. The inflowing outdoor air temperatures of Case A (Ar number of the inflow through the window = -4.83) and Case B (Ar = -4.36) are set at 18.8°C and 19.5°C respectively. The results show a tendency for the inflow air to drop near the window opening because of the negative buoyancy effect in the room. The air tends to flow near the floor at low speed, and rises along the wall surface, exiting through the opposite end of the room, as shown in Figure 4. There is an anti-clockwise air circulation in the room.

In Cases C (Ar. = -3.36), D (Ar. = -2.35) and E (Ar. = -1.34), the inflowing outdoor air

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Fig. 4 Flow Fields of Group I
(Sections including human model are shown)

Fig. 5 Temperature Fields of Group I
(Sections including human model are shown)
temperature are set at 21.0°C, 22.5°C, and 24.0°C respectively. The inflowing air does not drop near the window opening and directly flows deeper into the interior direction with the increase of inflowing air temperature, as shown in Figure 4. The inflow air mixes well with the indoor air. Clockwise air circulation is formed at the left side by the comparatively strong inflowing jet. There is rising stream around the human model which generates heat. The dropping pattern of the inflow jet from the window can be roughly explained by the Archimedes number.

Temperature Fields

Figure 5 shows the temperature distributions of Group I. The average task zone temperature is kept perfectly at 26°C by utilizing the under-floor VAV AC system. The under-floor AC system is thus very effective for the hybrid air-conditioning system based on the task/ambient zoning.

In Cases A and B, the former does not need AC cooling energy, and the latter needs only 9% of the total cooling load. There is not a big difference in the temperature distribution between them and both cases show a tendency to form temperature stratifications inside the room. These temperature stratifications can be utilized to conserve energy in designing an energy efficient air-conditioning system.

In Cases C, D and E, with the increase of outdoor air temperature, inflow air tends to flow further into the room and to mix well with the indoor air. The air volume of the air-conditioning, which is supplied at the constant temperature of 19°C, increases to keep the average temperature of the task zone at 26°C. With the increase of air volume of AC, the temperature gradient becomes steep at the task zone.

Characteristics of Cooling Load for Mechanical Air-conditioning System

Figure 6 shows the cooling loads of the mechanical AC system to maintain the average temperature of 26°C only at the task zone.
It also shows the cooling loads with the assumption of perfect mixing condition. The difference of the two indicates the effect of the temperature stratification in the room on the cooling loads for the task zone. With the increase in the temperature of the inflowing outdoor air, the cooling loads in both conditions increase at a constant rate. In comparison to the assumed perfect mixing condition, the cooling load required to maintain this temperature only at the task zone is 470 W lower, which is about one third of the total heat generation rate (1700 W) in the room. The comparatively cooler inflowing outdoor air does not mix well with the indoor air, but tends to flow lower towards the task zone and makes the average temperature of the task zone lower than the room averaged temperature. When the temperature of the outdoor air is at 18.8°C, the temperature of the task zone can be maintained at 26°C without using the mechanical AC system.

In Group II, as shown in Figure 7, with the increase of the volume of the inflowing outdoor air, the cooling load of the air-conditioning system for maintaining the temperature at 26°C only at the task zone decreases at a constant rate. In comparison to the assumed perfect mixing condition, the cooling load required to maintain this temperature is 450 W lower.

In Group III, as shown in Figure 8, with the increase of the window area (vertical width of the opening), the cooling load of the mechanical AC system decreases at a constant rate in comparison with the assumed perfect mixing case where the cooling load is constant despite the change in the opening area. This can be deduced from the fact that when the window area becomes bigger, the inflow jet of the outdoor air does not flow deeper into the upper part of the room (the ambient zone) which is comparatively warmer than the room averaged temperature; instead it drops down and flows towards the lower part of the room (the task zone) and thus reduces the cooling load of the mechanical AC system needed to achieve the temperature of 26°C at the task zone.

CONCLUSIONS

1. By keeping the air temperature at the task zone constant, when the temperature of the inflowing outdoor air increases, there is a tendency for the inflow jet to flow deeper into the room and mix well with the indoor air. These findings can be roughly explained by the Archimedes number of the inflowing outdoor air.
2. When the temperature of the inflowing outdoor air increases, the air volume from the AC system increases in response, thus creating a big temperature gradient at the task zone.
3. Knowledge of the formation of temperature stratifications inside a room is useful for determining the energy-saving principle in designing an energy efficient air-conditioning system.
4. The cooling load of the mechanical AC system increases with the increase of the temperature of the inflowing outdoor air and with the decrease of the inflowing outdoor air volume. In the case of varying the window opening area (vertical width of the opening), the opening should be made larger from the viewpoint of energy conservation.

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REFERENCES