Influence of Air Exchange through Small Openings Between Rooms
- Consideration of Resident’s Lifestyle -

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Abstract
This paper investigates the indoor thermal environment, and determines existing problems in energy efficiency and comfort with an emphasis on the importance of the position of small openings, taking into account the resident’s lifestyle.

Measurements were performed in a well-insulated and airtight house in Japan. The distribution of velocity and temperature at the center-plane of the living room, wall surface temperature and the temperature across the five undercut doors were measured under the condition that all interior doors and exterior doors were closed. The measured results agreed well with the predicted results by CFD analysis. Further, by these CFD simulations, it can be seen that there has been significant improvement in the indoor thermal environment after adjusting the small openings to the optimal position.

Next, the open and closed status of interior doors in winter and summer was estimated based on the measured room temperatures over a long period. The results show that interior doors are usually closed in winter and during the summer period when the air-conditioning system is in operation, while they are open when the air conditioning system is not in use. Generally speaking, it is more effective for installing uppercut doors to improve the indoor thermal conditions both in summer and winter than undercut doors, and thus the effect is strongly influenced by the resident’s lifestyle.

Keywords: air exchange; airflow; airflow distribution; simulation; comfort

Introduction
In Japan, residential houses are insulated and airtight for energy conservation and comfort. In these houses, uncontrolled air exchanges are significantly reduced.

Several studies have dealt with mechanical ventilation systems for the proper distribution of conditioned air and the creation of a comfortable thermal environment in a residential house (Murakami et al., 1993) (Farhad and Andy. 2000). However, there has been little focus on the influence of airflow through small openings between rooms, particularly, through undercut doors.

This paper investigates the characteristics of airflow and temperature distribution, considering the influence of air exchange through undercut doors, and examines existing problems in energy savings and the indoor thermal environment (Bogaki et al., 1998) (Daniel and Curtis 1997). The CFD model was used to determine the optimal position of the small openings, which helps building designers to identify how to provide maximum comfort and a healthy environment with minimum energy use. Furthermore, based on room air temperature measured over a long period, the open and closed status of interior doors was estimated and its influence on the improvement obtained by the method proposed in this paper is discussed.

Building Descriptions
The first plan of the tested house is shown in Figure 1. The two-story steel frame prefabricated house (3.18 m for the 1st floor and 2.72 m for the 2nd floor ceiling height) is located in Nishinomiya, Hyogo, Japan. With a 1st floor area of 121.19 m² and 11 rooms, this residence has a European-style room, a toilet, a bathroom, a lavatory, a laundry, a Japanese-style room, a living room, a kitchen, a dining room, a storehouse and a master bedroom. In addition, the 2nd floor of the building contains an attic with a 30.5m² rectangular floor for storage and ducting. The house is well insulated with low-e glass (2.64 W/m²K) and doors...
are classified as second class by Japan Industrial Standard in air-tightness ($\leq 5.0 \text{ cm}^2/\text{m}_2$). This house, whose exterior walls are constructed with FS panels, has a 100 mm thick insulation layer filled with glass wool ($< 0.35 \text{ W/m}_2\text{K}$). The roof and ceiling are insulated by 100 mm thick rock wool and loose-filled glass wool enclosed by aluminum foil.

An elderly occupant spends most of her time either in the bedroom or the living room. The dining room is used mainly for meals. The Japanese-style room mainly reserved for guests, is seldom used. Therefore, measurement of the thermal environment focused on the living and dining rooms.

In Nishinomiya, the annual mean temperature is 16.3°C. January and February, with a mean temperature of about 5°C, are the coldest months of the year, while August is the hottest month at 27.3°C. Mean relative humidity is between 60% and 75%.

**Description of Heating and Air Conditioning Systems**

Radiant floor heating systems are considered an economical and comfortable heating system because of the free use of space, no need for cleaning, no noise, no dust and low temperature heating. Thus, radiant floor heating panels are installed, except for the Japanese-style room. Hot water from a gas boiler is circulated through the piping grid. The room temperature can be regulated independently. The house has a central air-conditioning and ventilating system to distribute outside conditioned air into six rooms, which are the living room, the dining room, the bedroom, the Japanese-style room, the European-style room and the kitchen.

*Figure 2* shows a schematic diagram of the air conditioning system. Fan-coil units are installed in the attic, and the inlets and outlets are positioned in the ceiling. Depending on the number of occupants in the house, the ventilating system is designed to supply the minimum outside air according to the standard of 35 m$^3$/h each person (hereinafter, "minOA air-conditioning"). Outside air is supplied to the six rooms mentioned above and is exhausted through outlets in the toilets and the lavatory. Heat is recovered from the exhausted air by the total-heat exchanger.

**Procedures of Measurement**

The measurement period is January 1997 to October 2001. Two kinds of measurements were carried out. First one, short-term measurement for three days, was performed to investigate the indoor thermal environment and energy consumption of the house in winter and summer. In the second kind of measurement, the room air temperatures and humidity during one whole year were measured to understand how the occupant's lifestyle influences the thermal conditions. *Figure 3* shows the measured points of the temperature and relative humidity. In this paper, we selected the results on August 22, 1999 for summer and the results on February 25, 2000 for winter as the short-term measurement.

(1) **Short-term Measurement**

Considering the occupant's lifestyle, the short-term measurements were mainly taken in the living room (W 3.0 m × L 7.0 m × H 2.5 m) and the dining room (W2.0m × L 5.0 m × H 2.5m), during which the minOA air conditioning was in operation. All the doors and windows were closed to minimize the influence of outside wind and to maintain the indoor thermal environment of each room. In winter, a curtain partitioning the living and dining rooms is usually used to retain the living room warmth, while it is not used in summer (*Figure 1*). Therefore, the partition curtain was not used during measurements in summer. In addition, the radiant floor heating in the dining room is only used during meals for energy conservation. Therefore, the floor heating in the dining room was not used during measurement in winter.
The measured items are as follows:
1. Distribution of indoor air temperature and velocity
   Before measurement, all interior and exterior doors were closed. Thermal anemometers were used to measure the distributions of air velocity and air temperature during minOA air conditioning operation. The distribution of air temperature and velocity was measured on the A-A sectional plan (see Figure 1). Furthermore, the distribution at the boundary between the living and dining rooms was also measured in summer.
2. Velocity and direction of airflow across undercut doors and door cracks to the Japanese-style room
   The living and dining rooms were checked for major leakage by closing interior doors and measuring airflow through the small openings and the cracks. The air velocity and the direction through the small openings were obtained using an anemometer and a smoking incense stick.
   Five points were selected at equal intervals for a given opening, and air velocity through small openings and cracks was measured at each point by the anemometer.
3. Temperature variations across undercut doors
   Air temperature across the four undercut doors was recorded every 10 minutes by thermal recorders.
4. Airflow rate through inlets and outlets
   The airflow rate through the inlets and outlets was measured by an airflow meter during minOA air conditioning operation.
5. Surface temperatures of walls, ceilings, floors and windows
   The surface temperature of the building elements enclosing the living and dining rooms was measured by thermal recorders every 10 minutes.

(2) Long-term Measurement
   Next, in order to find how energy savings and indoor environment are influenced by the occupant’s lifestyle, such as the open-close status of the windows and doors, room air temperatures were measured over a long period, and monthly electricity power consumption and gas consumption were examined according to the actual bill. Figure 3 shows the measured points.

Measured Results
(1) Short-term Results
   The distribution of the indoor air temperature and velocity is shown in Figures 4 and 5. The velocity and direction of the airflow through undercut doors and door cracks to the Japanese-style room are listed in Table 1. The direction of the airflow is shown by the arrow symbols (Huang et al. 2000).
   In general, it is quite difficult to measure air velocity lower than 0.1m/s exactly due to the limited precision of the instrument. However, we could check the airflow directions using a smoking incense stick and confirmed that the measured values of airflow are significantly smaller than 0.1m/s. Since the main purpose of this paper is to study the room airflow patterns in winter and summer, the instrument accuracy does not significantly affect the following conclusions.
   Table 1 also gives the temperature variations across undercut doors and the airflow rate through inlets and outlets (Christopher et al. 2000).

   In winter, significant temperature difference cannot be seen in the living room (Figure 4). But the air temperature from the lobby, 10.8°C, is significantly lower than in the living room (Table 1). The cold air from unheated rooms forms drafts through undercut doors and influences the distribution of airflow and temperature, which makes occupants uncomfortable. The temperature near the lobby decreases to 17.0°C due to the draft at the right and lower part in Figure 4.
   Figure 5 shows that in summer, the temperature in the living room ranges from 28.6°C to 29.5°C, slightly
Table 1. Measured Airflow and Temperature at Openings in Winter

| Location                          | Size1(m) | Size2(m) | Air velocity(m/s) | Airflow (m³/h) | Temperature (˚C) |
|----------------------------------|----------|----------|-------------------|----------------|-----------------|
| Inlet                            | 0.250    | 0.250    | 0.11              | 26.0           | 27.1            |
| Outlet                           | 0.500    | 0.250    | 0.00              | -              | -               |
| Japanese style room => Living room| 0.005    | 2.000    | 0.56              | 20.3           | 15.9            |
| Lobby => Living room              | 0.750    | 0.005    | 0.77              | 16.7           | 10.8            |
| Lavatory <= Living room           | 0.700    | 0.015    | 1.36              | 51.3           | 16.9            |
| Corridor <= Living room           | 0.750    | 0.017    | 0.79              | 36.3           | 16.1            |
| Bedroom <= Living room            | 0.750    | 0.006    | 0.52              | 7.0            | 18.4            |
| Storeroom => Dining room          | 1.280    | 0.005    | 0.38              | 8.6            | 17.2            |
| Inlet in Dining room              | 0.080    | 0.080    | 1.30              | 30.0           | 26.8            |
| Kitchen => dining room            | 0.750    | 0.005    | 0.19              | 2.6            | 17.1            |
| Small window in Kitchen => Dining room| 0.005 | 0.500    | 0.27              | 2.5            | 17.1            |

Measured Airflow and Temperature at Openings in Summer

| Location                          | Size1(m) | Size2(m) | Air velocity(m/s) | Airflow (m³/h) | Temperature (˚C) |
|----------------------------------|----------|----------|-------------------|----------------|-----------------|
| Inlet                            | 0.250    | 0.250    | 0.16              | 36.0           | 27.5            |
| Outlet                           | 0.500    | 0.250    | -0.01             | -6.0           | 29.0            |
| Japanese style room => Living room| 0.005    | 2.000    | 0.52              | 18.7           | 27.0            |
| Lobby => Living room              | 0.750    | 0.005    | 0.49              | 6.6            | 27.4            |
| Lavatory <= Living room           | 0.700    | 0.015    | 1.10              | 41.6           | 28.6            |
| Corridor <= Living room           | 0.750    | 0.017    | 0.91              | 41.8           | 28.6            |
| Bedroom <= Living room            | 0.750    | 0.006    | 0.35              | 6.3            | 29.0            |
| Storeroom => Dining room          | 1.280    | 0.005    | 0.13              | 4.5            | 27.2            |
| Inlet in Dining room              | 0.080    | 0.080    | 1.56              | 36.0           | 23.0            |
| Kitchen => dining room            | 0.750    | 0.005    | 0.37              | 5.0            | 29.0            |
| Small window in Kitchen => Dining room| 0.005 | 0.500    | 0.71              | 6.4            | 29.0            |

hot. However, judging from the relatively low temperature at the right and lower part in Figure 5, a large amount of air from the inlet of the dining room with lower temperature (Table 1), seems to be exhausted directly through undercut doors to the lavatory and corridor, and thus it is not used effectively. Hot air is always located at the upper level of rooms, but the position of the small openings for ventilation is located at the bottom of the doors. Therefore, the hot air cannot be exhausted effectively through the openings. This causes the indoor temperature to rise.
(2) Comparison with CFD Simulation

In order to gain insight into factors affecting the indoor thermal environment and energy efficiency, a number of CFD simulations were performed.

The small openings (at the bottom of the doors) are provided as shown in Figure 6 (henceforth "Type A"). In all the CFD simulations in summer and winter, the inside surface temperatures were assumed as the average of the measured values. The input values used in the simulations were principally based on the measured data in the summer of 1999 and in the winter of 2000 as described above. In order to meet a mass balance in the input data regarding airflow, the exhaust airflow rate through the undercut of the master bedroom door was adjusted.

STREAM, a CFD simulation program for 3D fluid analysis based on the k-ε model, was used for the analysis.

The airflow distribution on the A-A sectional plane of the living room are shown in Figure 4 for winter, and Figure 5 for summer (numbers in parenthesis). The simulation results agree well with the measured results shown in Figures 4 and 5 as a whole, while the computed air velocity and temperature under the inlet were overestimated probably due to the specific characteristics of the diffuser used in operating the air-conditioning system.

As shown in Figure 5, the temperature at the upper part of the room is higher than that at the lower part of the room in summer, when the inter-room openings are located at the bottom of the doors. For energy saving and comfort, the situation should be improved. Thus, in the following section, the undercut doors are changed to the uppercut doors (Sasaki, Yoshino et al., 2000).

(3) Influence of Small Opening Position

Varying the positions of the small openings is followed by the change of mass airflow rate through the openings due to temperature differences between rooms (Sasaki et al. 2000). Therefore, the airflow rate through the small openings was estimated based on the conventional ventilation calculation (Tanaka et al. 1999) (Grenville et al. 2000) between rooms. From these two, the change of mass airflow rate through the small openings at different positions, by assuming that the \( \alpha \) values do not change when the position of the openings is changed. Table 2 shows the mass flow rate at the openings when they are located at the top of the doors. (Type B calculations; the positions of the small openings are changed to the top of doors.)

The CFD calculation was performed using the calculated airflow in Table 1. The effects of the opening position on the distribution of airflow and temperature were examined by the CFD simulations, shown in Figures 8 to 11. Figures 8 to 11 show the results for summer, and Figures 12 and 13 for winter.

Figure 8 shows the computed results of the temperature distribution over 29°C in summer when the exhaust openings are at the bottom of the doors, while Figure 9 shows the computed results when they are changed to the top of the doors. From these two figures, it can be seen that the area governed by the

| Room name             | Factor | Airflow (winter) | Airflow (summer) |
|-----------------------|--------|------------------|------------------|
| Japanese-style room   | 0.823  | 18.1             | 19.2             |
| Living room          |        |                  |                  |
| Lobby                 | 0.741  | 16.9             | 6.8              |
| Living room          | 0.797  | -7.3             | -5.7             |
| Bedroom              |        |                  |                  |
| Living room          | 0.824  | -52.1            | -43.9            |
| Living room          | 0.815  | -35.4            | -38.9            |

Table 2. Coefficient at Small Openings and Airflow

Unit: m³/s

Fig. 7. Airflow Rate on the First Floor
high temperature over 29°C becomes less if the small openings are located at the upper positions.

Figure 10 shows the computed streamlines of the airflow when small openings are at the bottom of the doors. In this figure, the cold air is partially exhausted through the undercut doors to the lavatory and the corridor. The air is not mixed sufficiently. As seen in Figures 8 and 9, the reason for the temperature rise is that the openings are located at the bottom of the doors in the living room.

Figure 11 shows the computed streamlines when the small openings are at the top of the doors. The air with lower temperature, which comes from the dining room, is not directly exhausted because the opening positions are at the top of the doors.

The computed results clearly show that the position change reduces the indoor temperature in summer and lessen the influence of draft on occupants.

The results in winter are shown in Figures 12 and 13. Figure 12 shows the computed results of the temperature distribution when the exhaust openings are located at the bottom of the doors, and Figure 13 shows the computed results when they are changed to the top of the doors. In Figure 12, the mean temperature difference between the living and dining rooms is significant, at about 1.5°C, because the floor heating in the dining room was not in use during the measurement. Although the draft from the dining room affects the temperature distribution at the lower levels of the living room, the influence is minimized by the partition curtain.

In Figure 13, the temperature at the upper level of the living room reduces by about 0.2°C, but the temperature at the lower levels increases by about 0.4°C. This leads to the cold airflow decrease from the dining room through the gap under the curtain. The area influenced by the draft from the dining room is significantly reduced.

Life Style and Open-closed Status of Interior Doors

As discussed above, the position of small openings plays an important role in the indoor thermal conditions. In the actual situation, however, whether the occupant usually keeps interior doors open or closed - will determine the effect of adjusting the position of small openings on improving the indoor thermal environment. Therefore, we estimated the actual situation using the results of the long-term
measurement. On the assumption that the interior doors are closed, we examined whether or not the measured temperatures agree with computed temperature by a dynamic load calculation program. The results give us some information regarding the open-closed status of the interior doors. In this paper, only the room temperatures in the living room and bedroom are shown (Figures 14 to 17).

Figures 14 and 15 show that the computed results agree well with the measurement in winter. The small differences might be due to the use of the standard solar radiation values in Tokyo as the inputs of solar radiations to the simulations. Therefore, we can conclude that the interior doors were kept closed for most of the winter season, in order to maintain indoor thermal comfort and avoid drafts from unheated rooms into living zones.

In summer, the occupant frequently left the doors open to obtain good natural ventilation under suitable external condition. However, the interior doors were closed when the air conditioning system was in use. Figures 16 and 17 confirm such situation. In Figure 16, the calculated room air temperature is in better agreement with the measured results if the windows and doors of the bedroom are assumed open compared with the result when the windows and doors of the bedroom are assumed close. Contrary to this, in Figure 17, the calculated results with the windows and interior doors assumed closed agree with measured values better than the case of open doors when the air conditioner is in use.

From these results, we can conclude that installing uppercut doors has a significant effect in winter, but it becomes very little under the natural ventilation condition. When the air conditioning system was in use, the occupant usually closed the interior doors and windows to obtain good thermal conditions in the air-conditioned room. Thus, the uppercut door proposed in this paper is still effective when the air-conditioning system is in operation. Although the effect depends on the situations such as seasons, it plays an important role in improving the room’s thermal environment.

Conclusion

It is important for building designers to carefully locate small openings for inter-room air exchanges in highly airtight houses.

In this paper, we investigated the characteristics of the indoor airflow and temperature distributions both in summer and winter. In summer, the hot air in the upper space of the rooms cannot be smoothly exhausted through the undercut doors, which leads to temperature rise. On the other hand, in winter, the cold air from unheated rooms crosses the undercut doors into living zones, which makes the occupants uncomfortable. The CFD calculation simulated these results.

To improve indoor thermal environment for energy conservation and comfort, we located the small openings at the top of the doors and carried out the simulations. The computed results showed a greater
improvement on the distribution of indoor airflow and temperature.

In addition, the open and closed status of interior doors in winter and summer was estimated based on the measured room temperatures over a long period. The results show the interior doors are usually closed in winter and during the summer period when the air-conditioning system is in operation, while they are open when the air conditioning system is not in use. Generally speaking, it is more effective to install uppercut doors to improve the indoor thermal conditions both in summer and winter than undercut doors, and thus the effect is strongly influenced by the resident’s lifestyle.

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