Reduction of Energy Consumption by AC due to Air Tightness and Ventilation Strategy in Residences in Hot and Humid Climates

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Abstract
This paper proposes strategies for reducing energy consumption for cooling in residences in hot and humid climates. Based on the results of fieldwork measurements and questionnaire surveys, a simulation of indoor thermal environments in consideration of air conditioner operation was carried out, in order to evaluate energy consumption by air conditioners. This simulation program takes into account both heat and moisture transfer in building materials. In order to simplify the calculation and due to lack of measurement of ventilation volumes, the ventilation volumes are assumed as constant values depending on open or closed windows. The combined effects of building air-tightness and the opening time of windows for ventilation were examined. Making an entire building airtight results in a small reduction in energy consumption, as the air-conditioned area increases. Meanwhile, simply making an air-conditioned room airtight is more effective for reducing cooling energy consumption. Irrespective of this, nighttime ventilation of non-air-conditioned spaces is quite effective in reducing sensible cooling load. Thus, introduction of not only a high degree of insulation but also air-tightness along with well controlled ventilation is required to achieve energy savings in hot and humid climates.

Keywords: windows and doors opening period (ventilation operating time); air-tightness; energy consumption for air conditioners; hot and humid climate

1. Introduction
In countries with a tropical climate, such as Indonesia, energy consumption is increasing more rapidly than ever1). Domestic energy consumption has been affected because air conditioners (henceforth AC) are now used not only in offices but also in residences to provide a comfortable indoor thermal environment. This is one reason for the increase in energy consumption2).

In order to reduce energy consumption by AC in tropical regions, researchers have previously considered strategies such as natural ventilation, façade design and solar shading. Wang and Wong used a computer simulation program3, 4) to consider the impact of ventilation strategies and façade design in naturally ventilated buildings in Singapore. Garrilho et al. also investigated ventilation strategies in apartment buildings in Beijing and Shanghai through computational fluid dynamics (CFD) simulations, to show the utilization of night ventilation to cool the building walls5). The advantages of buildings utilizing natural ventilation have been studied by many researchers. For example, Murakami considered natural ventilation in a porous building model in a hot and humid environment by means of CFD simulation6). Other investigations have studied the effects of combining air conditioning and window opening periods in several climate regions. Mui and Wong investigated the neutral temperature in an office building in the subtropical climate of Hong Kong7), to show that a lower temperature was preferred in such a region. Kubota and Ahmad conducted a field survey on AC use and window opening periods in Malaysia8), and revealed extended use of AC at night. In the latest study, both simulations and field studies were used to assess the impact of various ventilation strategies. This is significant, as there have been few studies until now on the relationships between residents’ air conditioning usage, ventilation strategies and building structure, that were based on the results of field surveys on residents’ air conditioning usage.
The authors have been investigating the indoor thermal environment of existing residences in Indonesia\textsuperscript{9, 10, 11}. Measurements of the thermal environment, and a questionnaire survey of residents, were both carried out. The results of the field survey showed that 50\% of the middle-income respondents, and 88\% of the high-income respondents used AC\textsuperscript{9}. (An AC unit costs between one and two times the monthly income of the middle-income respondents.) This indicates that the percentage of people who think that AC is necessary increases as the income bracket becomes higher. It seems that once they start to use AC, they are unwilling to stop using it. The energy consumption by residences with AC was nearly twice that of residences without it.

According to the result of the questionnaire survey of residents, at least one AC unit was installed in the bedroom, and residents usually used it during the night to ensure a comfortable sleep. They kept the AC on throughout the night until they arose in the morning. The room temperature typically dropped down to around 23°C during the night\textsuperscript{9}.

The low room temperature was the result of a low set-point temperature, usually between 18 to 26°C. Traditionally, houses in Southeast Asia have many openings and are open to the outside for ventilation\textsuperscript{15}. When AC is installed, however, the residents close these openings to prevent cool air from escaping. Unfortunately, the current air-tightness of the residences is usually insufficient, and consequently energy consumption for cooling has been increasing. Furthermore, the insufficient insulation of the houses also provides poor thermal resistance, which obliges residents to set low target temperatures, results in very low room temperatures, and necessitates the sustained use of AC\textsuperscript{10}. Judging from the use of AC, the increase in energy consumption for cooling in residences could become a serious problem in Indonesia.

In order to improve both the indoor environment where AC is in use, and to decrease energy consumption for cooling, a more effective use of AC is desired, along with building designs suitable for cooling.

In hot and humid climates, both temperature and moisture impact energy consumption by AC. Since porous (hygroscopic) building materials are often used, the ab-/desorption properties of wall surfaces should be considered when evaluating latent cooling load, as they can have a significant effect on energy consumption by AC.

In this study, by using a simulation program that takes into account AC operation and the ab-/ desorption of moisture by building elements, room temperature and humidity were calculated from the viewpoints of energy consumption and indoor thermal comfort. The effects of air-tightness and ventilation strategy were examined. The simulation program was examined through a comparison of the calculated and the measured room air temperatures and humidity ratios. Estimated ventilation rates were used as inputs. Although the ventilation rates were not measured in the real buildings, the air velocities estimated from the ventilation rates which were used in the simulation were in reasonable agreement with the measured air velocity in a house\textsuperscript{11}.

2. Survey Area and Climate

The surveyed area was in Surabaya City (7°S 113°E), which is located in the eastern part of Java Island in Indonesia. This island has both dry and wet seasons; the dry season is from April to November, while the wet season is from December to March. The monthly average temperature ranges from 26 to 28°C, with an annual mean temperature of 27.1°C\textsuperscript{13}. The hottest months are October and November. The monthly average relative humidity is from 60 to 85\%. This paper mainly reports on results measured and surveyed in Feb., during the wet season.

3. Field Survey of Thermal Environment

3.1 House Plan and Details for Investigation

Two houses, one with and another without air conditioning units are analyzed in this study. A typical floor plan and a section of the surveyed houses are shown in Fig.1. This type of residence is now quite common in urban areas in Java, Indonesia. There is a living room (LR: R2), a kitchen (R1), two bedrooms (BR: R3 and R5), and a bathroom (R4). There is also an attic space (R6). The walls are constructed from 120 mm-thick bricks, finished with 10 mm-thick mortar; the ceiling is made of 20 mm-thick plywood, the roof is made of 30 mm-thick clay tiles, and the floor is a concrete slab, finished with 10 mm-thick ceramic tiles. Insulation is not present in the ceiling, or the roof. The door is made of wood 40 mm-thick. External windows are made of 4 mm-thick, clear float glass, and do not have mosquito screens. There are also small, external
upper windows. Internal fixed windows with mosquito screens are installed above every partition door between rooms. The upper panes on the windows and doors in the rooms without AC are left permanently open.

The house with AC has units installed in the bedroom (R5) and the living room (R2). The attic space (R6) has been included with the other five rooms in performance calculations.

3.2 Measurement of Indoor Environment
3.2.1 Outline of the Field Survey

In order to understand the thermal environment in both houses, one with and one without AC, the survey was conducted in both the wet and dry seasons in Feb. 2001 and Jul. 2002. The temperature and humidity in the living room (R2) and the bedrooms (R3 and R5) were measured. In addition to the measurements, a questionnaire survey of residents was carried out regarding their impressions of the indoor thermal environment, strategies to achieve thermal comfort, and their use of AC.

The outdoor temperature, relative humidity, and the global solar radiation were measured at a selected house close to the surveyed area. The results in Feb. have been used for comparative purposes in calculations in this paper.

4. Results of Field Survey
4.1 Outdoor Thermal Environment

Fig.2. shows the outdoor temperature, the humidity ratio and the global radiation measured in Feb. 2001 (wet season). These are the average values measured over the period from Feb. 15 to Mar. 2, 2001 (wet season). These are the average values measured over the period from Feb. 15 to Mar. 2, 2001 (wet season). These are the average values measured over the period from Feb. 15 to Mar. 2, 2001 (wet season).

The average temperature and relative humidity were 28.1°C and 76% respectively in Feb. There were squalls in the evening, resulting in a temperature drop to 27°C at 18:00. The solar radiation decreased at around 15:00 because of the squall.

4.2 Outdoor Air Flow

The outdoor air flow data used for this assignment was obtained from the meteorological station in Juanda, which is the nearest station to the surveyed area. The wind direction and velocity were measured 3 meters above the ground-level. Fig.3. shows the wind velocity and the ratio of calm periods in Feb. 2004, extracted from meteorological data. The wind velocity starts to increase at 07:00, and reaches a peak of over 5 m/s at 13:00 or 14:00, then decreases toward nightfall. The wind speed in the night is around 2.5-3.5 m/s, and is half of that of the daytime. There is also a contrast to be found in the ratio of calm periods, which is lower in the day and higher in the night. The ratio of the calm period is less than 10% in the daytime, increasing throughout the evening until it exceeds 80% between 02:00 and 07:00. In this area the wind blows more during the daytime, and less during the nighttime.

4.3 Thermal Environment in House without AC

Fig.4. shows the measured temperature and relative humidity in the living room (LR:R2) and the bedroom (BR:R3) of House 1, which has no AC. The residents stayed in the living room during the daytime, and the bedroom during the nighttime. The living room temperature rose to 32.4°C at 14:00, and the bedroom temperature did not fall below 28°C during the nighttime. Thus, the residents lived under relatively hot conditions both day and night.

According to the questionnaire survey, the residents opened the windows and doors after they got up at 06:00. Consequently both room temperatures rose relatively rapidly after 07:00 in line with changes in the outdoor temperature. The temperature in the bedroom increased more slowly than in the living room, probably because the opening area onto the outside, and the amount of the solar radiation coming into the room, is small, compared to the living room. During the nighttime, the openings are closed against mosquitoes and for security reasons. While the living room temperature continued to decrease until morning, the bedroom temperature remained around 29°C, an uncomfortable environment for sleeping.

4.4 Thermal Environment in House with AC

Fig.5. shows the bedroom temperature and relative humidity measured in House 2, where AC is installed. Fig.6. shows the frequency of AC use during the measurement period.
The residents started to use the AC around 12:00 to 15:00 for a nap, and after 21:00 until 06:00 for sleeping. The frequency of the AC use exceeds 90% during the nighttime (Fig. 6.). Obviously the residents use the AC to create a comfortable sleeping environment. This is reinforced by the questionnaire results (for 18 households, multiple answers allowed), that show more than 80% of the residents use AC during sleeping time, while 39% use it before sleeping. The other reasons for using AC, including, for example 'for guests', 'after coming home', 'after taking a bath', 'while studying' etc., did not exceed 30%.

The temperature when the AC was turned on during the night was around 28-30°C (see the mark "ON" in Fig. 5.). After that, the temperature dropped rapidly to 24°C, although AC continued to be used until the next morning. Sometimes the temperature during the nighttime fell below 24°C, which seems too low for sleeping. The residents wore T-shirts and shorts with low clo values, and some of them did not use a blanket at the start of sleeping.

When the AC was turned on or off, the room temperature and humidity changed rapidly (see the marks "ON" and "OFF" in Fig. 5.). Both temperature and humidity rise to the level of the air outdoors as soon as the AC is turned off at around 06:00, mainly because the residents also open the door and windows at the same time. Moreover, since the air-tightness of the houses is insufficient, the room temperature easily increases when the AC is turned off in the evening. As a result, the residents tend to use the low set-point temperature in order to lower the room temperature quickly.

5. Simulation of Thermal and Moisture Conditions

In hot and humid climates, both temperature and moisture impact energy consumption by AC. Since porous (hygroscopic) building materials are often used, the ab-/desorption properties of wall surfaces should be considered when evaluating latent cooling load, as they can have a significant effect on energy consumption by AC.

In this study, room temperature and humidity were calculated by using an original simulation program that takes into account the ab-/desorption of moisture by building elements and AC operation.

5.1 Outline of Simulation

(1) Heat and moisture balance: The heat and moisture balance of the rooms and the building elements are simulated. In calculating room temperature and humidity, the heat fluxes and vapor flux into the room are considered (Appendix A).

(2) Ventilation rates: The ventilation rates are indicated in Tables 2. and 3. The value in brackets shows the air change rate, meaning the ratio of ventilation rate divided by the room volume.

The value in Table 2. shows the ventilation rates between the object room and the connected room, when all the openings are closed at night and when the AC is in operation. In Table 3., the ventilation rates are shown when the doors and windows are open during the daytime.

The constant value of volume of ventilation was used as the input data. These values were estimated tentatively to obtain agreement between the measured and calculated temperatures.

(3) Material properties: The material properties used in the simulation are listed in Table 1. (4). The simultaneous transfer of heat and moisture are taken into consideration in calculations of the temperature and humidity of the porous building materials used in the ceilings and walls (5). The surface of the floor tiles is assumed to be non-permeable to vapor.

(4) Model of AC: In this simulation program, the energy consumption of AC compressors is calculated (6). A simplified model of a heat pump is used, based on the heat and mass balances of the refrigeration cycle (7) (Appendix B). For evaluation of the effects of various measures to reduce energy consumption, the energy consumption for cooling and sensible and latent heat loads are used.

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Table 1. Material Properties

| Material | Thermal conductivity [W/mK] | Heat capacity [MJ/mK] | Porosity * air density [vol/vol]*(kg/m³) | Moisture conductivity [kg/(m²*K)] | y=(v=α/α0) |
|----------|-----------------------------|-----------------------|------------------------------------------|----------------------------------|-------------|
| Concrete | 1.6                         | 1.9                   | 0.039                                    | 0.47                             | 6900        |
| Mortar   | 1.4                         | 2.3                   | 0.032                                    | 2.6                              | 8100        |
| Plaster board | 0.22                   | 0.98                  | 0.065                                    | 0.47                             | 4000        |
| Soil     | 0.73                        | 1.9                   | 0.039                                    | 0.47                             | 6900        |
| Tile     | 1.3                         | 2.6                   | 0.052                                    | 0.45                             | 8100        |
| Brick    | 0.31                        | 1.3                   | 0.14                                     | 7.5                              | 900         |
| Insulation | 0.048                      | 0.085                 | 0.35                                     | 9.8                              | 2.8         |

Table 2. Ventilation Rate [m³/hour] When All Openings are Closed

| Room | Outdoor | Connected rooms | Outdoor | Connected rooms |
|------|---------|----------------|---------|----------------|
| 1    | 162 (6) | 540 (20)       | 54 (2)  | 540 (20)       |
| 2    | 632 (8) | 918 (12)       | 220 (3) | 689 (92)       |
| 3    | 135 (5) | 154 (5.7)      | 54 (2)  | 76 (2.8)       |
| 4    | 18 (2)  | 27 (3)         | 9 (1)   | 77 (8.5)       |
| 5    | 135 (5) | 141 (3)        | 54 (2)  | 38 (1.4)       |
| 6    | 198 (3) | 198 (3)        | 0       | 0              |

Table 3. Ventilation Rate [m³/hour] When All Openings are Opened

| Room | Outdoor | Connected rooms | Outdoor | Connected rooms |
|------|---------|----------------|---------|----------------|
| 1    | 324 (12)| 1080 (20)      | 108 (4) | 1080 (20)      |
| 2    | 918 (12)| 1653 (22)      | 612 (8) | 1530 (20)      |
| 3    | 216 (8) | 230 (8.5)      | 108 (4) | 189 (7)        |
| 4    | 27 (3)  | 153 (17)       | 18 (2)  | 153 (17)       |
| 5    | 216 (8) | 1683 (8.5)     | 108 (4) | 189 (7)        |
| 6    | 198 (3) | 198 (3)        | 0       | 0              |
(5) Validation of simulation program: In order to validate the program, the simulated temperature and humidity ratios in House 1 and House 2 are compared with the measured values.

5.2 Outdoor Conditions Used in Simulation

The outdoor temperature, humidity, and global solar radiation levels, measured between 17 and 23 Feb. in 2001, are used as the outdoor condition inputs. The measured solar radiation is separated into direct and diffuse components by using Bouguer and Berlage equations.[10] The input data are used repeatedly with a cycle of one week. The calculations are continued until the ground temperature becomes independent of the initial conditions. The outdoor temperature and humidity levels, averaged over the measured period, are used as initial conditions, and the ground temperature at a depth of 5 m is assumed to be the same as the average outdoor temperature.

5.3 Ventilation Rates in Simulated Houses

The ventilation rate and the air change rate are shown in Tables 2. and 3. These values were estimated to obtain agreement between the measured and calculated temperatures in all measured rooms. In each room, the incoming and outgoing airflow volumes are equal.

Cross ventilation is generally considered important in the common houses in Indonesia. The houses have many openings and thus the air tightness is low. Thus it is difficult to estimate the ventilation volume in a field survey. Because the main purpose of this study is to estimate the effect of the air-tightness installed in a very low airtight building, it is not important to estimate the ventilation volume exactly.

Factors which affect the ventilation rates are the condition of the openings (open/closed) and the outdoor wind velocity and direction. According to meteorological data, the period when the outdoor wind velocity is high corresponds to the period when the residents open the windows (06:00-21:00). Thus, the two patterns of ventilation were assumed depending on whether the windows were open or closed, and the constant values were used in this simulation, where the outdoor wind conditions becomes independent of the initial conditions. The outdoor temperature and humidity levels, averaged over the measured period, are used as initial conditions, and the ground temperature at a depth of 5 m is assumed to be the same as the average outdoor temperature.

5.4 Use of AC

In calculations performed to evaluate measures intended to reduce energy consumption by AC, it is assumed that one AC unit is installed in the bedroom (R5) in House 2, and that it is used from 21:00 to 06:00, and from 14:00 to 16:00. The set-point temperature is assumed to be 25.5°C. The cooling and moisture loads of the AC are calculated taking into account the heat and moisture balance between the indoor/outdoor air and the heat pump (Appendix B). Two residents spend their time in the living room during the day, except from 14:00 to 16:00 when they move to the bedroom for a nap (Fig.7). When residents remain in the bedroom, it is assumed that the AC is in constant use.

5.5 Consideration of Energy Reduction by Air-Tightness and Ventilation Control

The air-tightness and ventilation schedule were examined.

Two cases of air tightness are considered; one in which air-tightness between the air-conditioned room and other rooms is high (Fig.8. Case 2), and another in which air-tightness is increased between the outdoors and the entire house (Fig.8. Case 3). In total, three cases are examined, including a non-airtight case (Fig.8. Case 1). In this program, the air change rate when air-tightness is improved is assumed to be 0.5 times/hour; the ventilation rates are 38 m$^3$/h in the living room and 4.5 m$^3$/h in the bedrooms.

To determine energy savings achievable by changes in the ventilation schedule, calculations are performed for 4 patterns of ventilation schedule (Fig.9.). Generally, residents open apertures during daytime to maintain airflow inside the house. Fig.9. shows the

**Fig.7. The Number of Persons Staying in the Rooms**

**Fig.8. Image of Improvement in Air-Tightness**

**Fig.9. Ventilation Schedule**
assumed ventilation patterns. Pattern A corresponds to the typical situation in Indonesia. The residents open windows during the daytime and close them at night. In pattern B, the openings in the air-conditioned room are closed all day long, whilst all rooms are closed in pattern C. In pattern D, the windows are closed in the air-conditioned room, and the openings in the non-air-conditioned rooms are closed during daytime and open at night, providing nighttime ventilation.

Based on these three cases of air-tightness and the four ventilation schedule patterns, simulations were carried out for the twelve resulting combinations.

5.6 Other Preconditions of Houses Being Measured

Many factors need to be considered to achieve energy saving from AC use. For example, cutting solar radiation into the air-conditioned room, and insulating walls to reduce heat flow, appear effective. The houses being studied have been well designed to shade solar radiation. However, even now, housing insulation is not common in Indonesia. According to the simulation results for the houses being studied, a considerable amount of heat flows into rooms through the thin wooden ceilings, and considerably less flows through the brick walls. In order to separate the effects of the air-tightness and ventilation patterns, it is better that other variables be minimized. Therefore, the simulation pre-supposes 50 mm-thick insulation for the ceiling.

6. Results and Discussion

6.1 Comparison between Measured and Calculated Results

For purposes of validation of the simulation program, the calculated temperature and humidity ratio were compared with the measured results in Figs. 10. to 12. In this simulation program, the ventilation rates were adjusted to correlate the calculated and measured results. Furthermore, they are treated as constant values dependent on the opening or closing of windows, which is assumed to be at the same time each day. Other factors that influence ventilation rate, such as the outdoor wind speed and direction, are not included in these calculations, due to the lack of measurement data.

In the bedroom (R5) of House 1, where no AC is installed, the calculated room temperature replicates the measured data closely (Fig. 10.). The calculated humidity ratio also closely matches the measured ratio on average, and becomes even closer to the outdoor humidity ratio as the day progresses. The influence of the ventilation rate becomes greater than the other factors.

Figs. 11. and 12. show the results in House 2, in which an AC is used. The calculated temperatures and humidity ratios agree closely with the measured values on average. However, the humidity ratios in both the living room (R2) and bedroom (R5) in House 2 are also close to the values measured outdoors. When the room is air conditioned, the humidity ratio tends to be lower as a result of dehumidification by the AC.

These results of the simulation program considering the ab-/desorption properties of wall surfaces have a good agreement in temperature and humidity ratios of both houses with and without AC.

6.2 Strategy for Reduction of Energy Consumption

6.2.1 Effect of Air-Tightness

The calculated sensible and latent loads are shown along with energy consumption for the 12 cases in Fig. 13. Case 1-A corresponds to the non-airtight

![Fig.13. Sensible and Latent Loads and Energy Consumption (Values in Case 1-A are Set at 100 for Reference) (Current case) (Improvement in airtightness of entire house) (Improvement in airtightness of only air-conditioned room alone)](image)

![Fig.14. Temperature and Humidity Ratios in Room 2, a Non-Air-Conditioned Room in Case 1-A, 3-B, 3-C and 3-D](image)
At night when the outdoor temperature is lower than the conditioned rooms at night decreases due to ventilation. The temperature in the non-air-conditioned rooms is high compared with that of the air-conditioned room, the latent load is larger. Therefore, an effective energy saving step is to reduce the ventilation rate, not only between the air-conditioned room and the outdoors, but also between the air-conditioned and non-air-conditioned rooms.

6.2.2 Effect of Ventilation Pattern

Next, the results are compared among Patterns A, B, C, and D from the viewpoint of ventilation patterns (Fig.9.). In all cases of different degrees of air-tightness (in Cases 1, 2 and 3), energy consumption is decreased compared with Pattern A, the default ventilation pattern. It is clear that any ventilation during the daytime, when the room is not air-conditioned, introduces the hot outdoor air into the rooms, which causes an increase in the cooling load.

6.2.3 Combined Effects of Air-Tightness and Ventilation Pattern

In Cases 1-C, 2-C, and 3-C, in which the openings in non-air-conditioned rooms are closed all day long, energy consumption is 0.5 to 2.3% higher than in Cases 1-B, 2-B, and 3-B, which use daytime ventilation. Although the sensible load decreases, the latent load increases by 0.6 to 15.3%. The greater latent load causes an increase in energy consumption. Since human bodies in the connected non-air-conditioned rooms generate heat and moisture loads (Fig.9.), both the temperature and humidity ratios become higher when the openings are closed all day long (Fig.14., 3-C). On the other hand, both the temperature and humidity ratios are decreased when there is ventilation between the rooms and outdoors during the nighttime in Case 3-D (Fig.14., 3-D). When ventilation between the air-conditioned and non-air-conditioned rooms is minimized (Cases 2-A, 2-B, and 2-C), the moisture flow from adjoining rooms with high relative humidity is also minimal, and thus latent load does not increase. Since there is significant ventilation between the inside and outside in Cases A, B, and D, the humidity ratio in the rooms approaches the outdoor humidity, and the latent heat load does not increase.

In Cases 1-D, 2-D, and 3-D, which utilize nighttime ventilation, energy consumption is the least of all the cases considered. The temperature in the non-air-conditioned rooms at night decreases due to ventilation at night when the outdoor temperature is lower than that in the rooms, so reducing the sensible load. In one case (Case 2-D), the reduction of energy consumption is not large (Fig.14.), since the ventilation rate is restricted by partial air-tightness.

These results indicate that nighttime ventilation in non-air-conditioned rooms is effective when there is a large amount of ventilation between the air-conditioned and non-air-conditioned rooms.

7. Conclusion

This paper proposes strategies for reducing energy consumption for cooling in residences in hot and humid climates. The combined effects of the air-tightness applied to low air-tight houses and the opening time of windows for ventilation are evaluated by using the numerical simulation of indoor thermal environments in consideration of air conditioner operation based on the results of a fieldwork survey.

Cross ventilation is generally considered important in the common houses. The houses have many openings and thus the air tightness is low. Improvements in the air-tightness of air-conditioned rooms are very effective in decreasing energy consumption. This is because the heat and moisture loads carried in from the outdoors through ventilation are reduced. However, since improvements in the air-tightness of the entire house increase the air-conditioned area, the net reduction in energy consumption for cooling is small.

Irrespective of the degree of air-tightness, nighttime ventilation of non-air-conditioned rooms is useful for reducing sensible load.

Appendix A: Simulation Model of Indoor Temperature and Humidity

1. Heat and moisture balances of the room air

In calculating the room temperature and humidity ratio, the following governing equations are used:

\[ \frac{\partial T}{\partial t} = c_p \rho \frac{\partial T}{\partial t} + Q_v + Q_w + Q_s + Q_a + Q_{air} \quad (1) \]

\[ \frac{\partial Y}{\partial t} = M_v + M_w + M_w + M_a + M_{air} \quad (2) \]

Here, the heat and vapor fluxes are expressed by the following equations (3)-(13): heat flux from the walls (3), heat flux through air exchange with the outside (4), heat flux through air exchange with other rooms (5), solar radiation (6), internal heat generation by human bodies and lighting (7), cooling by an AC (8), vapor flux from walls (9), vapor flux through air exchange with the outside (10), vapor flux through air exchange with other rooms (11), moisture generation due to human bodies (12), dehumidification by an AC (13),

\[ Q_v = c_p \rho \frac{\partial T}{\partial t} + Q_w + Q_s + Q_a + Q_{air} \quad (4) \]

\[ Q_v = c_p \rho \frac{\partial T}{\partial t} + Q_w + Q_s + Q_a + Q_{air} \quad (5) \]

\[ Q_v = c_p \rho \frac{\partial T}{\partial t} + Q_w + Q_s + Q_a + Q_{air} \quad (6) \]

\[ Q_v = c_p \rho \frac{\partial T}{\partial t} + Q_w + Q_s + Q_a + Q_{air} \quad (7) \]

\[ M_v = M_w + M_w + M_w + M_a + M_{air} \quad (8) \]

\[ M_v = M_w + M_w + M_w + M_a + M_{air} \quad (9) \]

\[ M_v = M_w + M_w + M_w + M_a + M_{air} \quad (10) \]

\[ M_v = M_w + M_w + M_w + M_a + M_{air} \quad (11) \]

\[ M_v = M_w + M_w + M_w + M_a + M_{air} \quad (12) \]

\[ M_v = M_w + M_w + M_w + M_a + M_{air} \quad (13) \]
2. Heat and moisture balance in porous materials

Building materials such as bricks are porous materials. Heat and moisture transfers in porous materials are shown in equations (14) and (15), representing hygroscopic materials in which the vapor transfer is dominant and the water transfer is ignored. The boundary condition of the material’s surface is shown in equations (16) and (17).

\[
\begin{align*}
(c_v \cdot \rho_v + \kappa_v) \frac{\partial X}{\partial t} &= \kappa_v \frac{\partial^2 X}{\partial \theta^2} + \rho_v \frac{\partial \theta}{\partial t} \quad (14) \\
(c_v \cdot \rho_v + \kappa_v) \frac{\partial X}{\partial t} &= \kappa_v \frac{\partial^2 X}{\partial \theta^2} + R_v \rho_v \frac{\partial \theta}{\partial t} \quad (15) \\
-\kappa_v \frac{\partial X}{\partial t} \bigg|_{\partial \text{wall}} &= \alpha' \omega - \theta \omega \quad (16) \\
-\kappa_v \frac{\partial X}{\partial t} \bigg|_{\partial \text{wall}} &= \alpha' \omega - \theta \omega \quad (17)
\end{align*}
\]

Here, \(\kappa\) and \(\nu\) are shown in \(\kappa=\alpha \omega / \lambda X\) and \(\nu=\alpha \omega / \theta \). They are the parameters which show the characteristics of absorption and desorption of the porous materials. \(\kappa\) (kg/(m³·kg/kg (DA))) is the amount of absorption and desorption per unit of humidity ratio of the room air, and \(\nu\) (kg/(m³·K)) is the amount of absorption and desorption per unit of temperature of the room air. The values of \(\kappa\) and \(\nu\) are shown in Table 1.

Symbols

- \(A\): Area [m²], \(c\): specific heat [kJ/kgK], \(\epsilon\): porosity [m³/m³], \(\dot{F}\): heat generation from human body [W/person], \(F\): solar radiation [W/m²], \(M\): moisture flux [kg/s], \(N\): number [-], \(Q\): heat flux [W], \(R\): heat of adsorption [kJ/kg], SC: solar shading coefficient [-], \(\tau\): time [s], \(V\): volume [m³], \(\dot{\alpha}\): moisture transfer coefficient [m³/kg s kJ/kg (DA)], \(\dot{\beta}\): temperature [degrees C], \(\epsilon\): contact factor [-], \(\eta\): efficiency [-], \(\theta\): relative humidity [%], \(\kappa\): thermal conductivity [W/m K], \(\lambda\): moisture conductivity associated with a moisture content gradient [kg/m² (kg/kg)'], \(\rho\): amount of ab/desorption of porous material per humidity ratio [kg/m³·kg/kg (DA)], \(\sigma\): solar shading coefficient [-], \(\gamma\): density [kg/m³], \(\omega\): rate of moisture content [kg/m³].

Subscripts:

- a: air, ac: AC, h: human, l: light, m: material, o: outside, ro: room 1, r: room 2, so: solar, sup: supply air by AC, sur: surface, vo: ventilation between outside and room, vr: ventilation between rooms, w: wall, wi: window.

Appendix B: Model of AC

The schematic model of AC is shown in Fig. B1.

The heat exchanged at the condenser \(Q_C\) is given by the following equation:

\[Q_C = Q_{E} + L_{\text{com}} + Q_{\text{loss}} \quad (18)\]

Here, the heat exchange at the evaporator \(Q_E\) and the energy consumption by the compressor \(L_{\text{com}}\) are approximated as linear functions of the saturation temperature \(T_{sat}\) and the condensing \(T_{cond}\) temperatures.

\[Q_E = A_1 \cdot T_{sat} + A_2 \cdot T_{cond} + A_3 \quad (19)\]

\[L_{\text{com}} = B_1 \cdot T_{sat} + B_2 \cdot T_{cond} + B_3 \quad (20)\]

At the same time, \(Q_E\) and \(Q_C\) are expressed in another form based on the heat exchange between the coil surface and the inlet air, equations (21) and (22).

\[Q_C = \frac{G_{\text{sol}} \cdot c_{\text{sol}} \cdot T_{\text{sol}}}{Q_{\text{E}}} - \frac{G_{\text{com}} \cdot c_{\text{com}} \cdot T_{\text{com}}}{Q_{\text{E}}} \quad (21)\]

\[Q_E = \frac{G_{\text{sol}} \cdot c_{\text{sol}} \cdot T_{\text{sol}}}{Q_{\text{E}}} - \frac{G_{\text{com}} \cdot c_{\text{com}} \cdot T_{\text{com}}}{Q_{\text{E}}} - (D_1 \cdot T_{\text{sat}} + D_2) \quad (22)\]

The values of \(Q_E, Q_C, L_{\text{com}}, \theta_{\text{sat}}\) and \(\theta_{\text{cond}}\) are obtained by solving equations (18)-(22) simultaneously.

By making use of these values, the coil surface temperature \(\theta_{\text{sat}}\) is decided by the following equation:

\[\theta_{\text{sat}} = \frac{Q_{\text{E}}}{G_{\text{sol}} \cdot c_{\text{sol}} \cdot T_{\text{sol}} - G_{\text{com}} \cdot c_{\text{com}} \cdot T_{\text{com}}} \quad (23)\]

Finally the temperature and humidity ratios of supplied air are obtained as follows:

\[\frac{\theta_{\text{sat}}}{\theta_{\text{cond}}} = \frac{1-\epsilon}{1-\epsilon} \left(\frac{\theta_{\text{sat}}}{\theta_{\text{cond}}}\right) \quad (24)\]

\[X_{\text{sat}} = \frac{\theta_{\text{sat}}}{\theta_{\text{cond}}} \left(1-\epsilon\right) X_{\text{cond}} \quad (25)\]

Symbols

- c: specific heat [kJ/kgK], \(G\): air flow [kg/s], \(HE\): enthalpy [kJ/kg], \(L\): energy consumption [W], \(Q_{\text{E}}\): front area of heat exchanger [m²], \(Q\): heat flow [W], \(X\): humidity ratio [kg/kg (DA)], \(\alpha\): heat transfer coefficient [m³/kg s kJ/kg (DA)], \(\epsilon\): contact factor [-], \(\theta\): temperature [degrees C], \(\eta\): efficiency [-], \(\kappa\): thermal conductivity [W/m K], \(\lambda\): moisture conductivity associated with a moisture content gradient [kg/m² (kg/kg)'], \(\rho\): density [kg/m³], \(\omega\): rate of moisture content [kg/m³].

Subscripts:

- a: air, d: dry-bulb temperature, c: condenser, com: compressor, E: evaporator, ex: heat exchanger surface, ia: inlet air, lss: loss from refrigerant pipe, o: outside, r: refrigerant inside heat pump, ro: room: s: saturation, sup: supply air.

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