Energy use by air-conditioner in residences under hot and humid climates

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ABSTRACT

The purpose of this paper is to propose strategies of reducing energy consumption for cooling in residences under hot and humid climate such as Indonesia. Based on the results of field survey, a simulation of the indoor thermal environment considering the operation of an air-conditioner was carried out, in order to evaluate energy consumption by the air-conditioner. This simulation program takes into account both heat and moisture transports in the walls. The effects of air tightness and thermal insulation were examined. The results show that an increase in insulation on ceilings or roofs is essential to reduce the heat flow caused by the strong solar radiation. This is also true for the houses without air-conditioners. Increase in air tightness of only the air-conditioned room can effectively reduce electricity consumption, mainly due to the latent heat load.

1. INTRODUCTION

The countries under tropical climate such as Indonesia, air-conditioners have been prevailing not only in offices but also in residences for a comfortable indoor thermal condition (IEA, 2000, Statistics Indonesia). Traditionally, the houses in Southeast Asia used to have many openings and be open to the outside for ventilation. Since the current air tightness of the houses is not enough, the energy consumption for cooling has been increasing. The results of our field survey (Uno et al., 2003a & b) showed that the energy consumption of the residences installed with an air-conditioner was nearly twice as much as that in the house without an air-conditioner. In the houses with air-conditioners, at least one air-conditioner was installed in the bedroom, and the residents usually used it during night to have a comfortable sleep. Since the residents keep the air-conditioner on all night until they get up in the morning, the room temperature falls down around 23 degrees C during nighttime. This low temperature is the result of the low set point temperature. The temperatures reported by residents were from 18 to 26 degrees C, lower than the realized temperatures. Because the thermal resistance of houses is not sufficient, the room air cannot be reduced efficiently, which results in long use of the air-conditioner. In order to both improve the indoor environment under the use of air-conditioners and decrease energy consumption for cooling, an effective use of the air-conditioners along with the design of the house suitable for cooling are highly required. In hot and humid climate, not only temperature but also moisture influences the energy consumption by air-conditioners. In this paper, using a simulation program that takes into account the operation of the air-conditioner and the moisture adsorption by the building elements, the room temperature and humidity are calculated from viewpoints of energy consumption and indoor thermal comfort.

2. AREA AND CLIMATE

The surveyed area is in Surabaya City (7°S 113°E) (Figure 1), which is located in the east part of Java Island in Indonesia. Figure 2 shows the monthly average temperature and relative humidity (JMA, 2001). This paper mainly reports the measured and surveyed results in February, the wet season.

3. ANALYSIS OF THERMAL AND MOISTURE CONDITIONS

3.1 Measured and Simulated House

The typical plan of the measured houses is

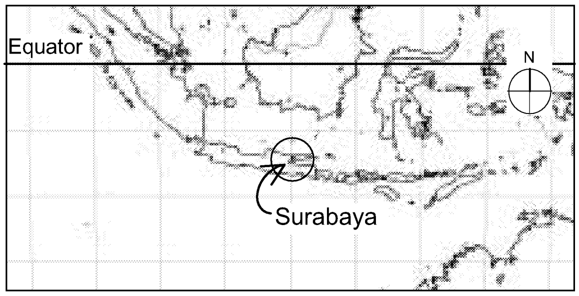

Figure 1 Location of Surabaya, Indonesia

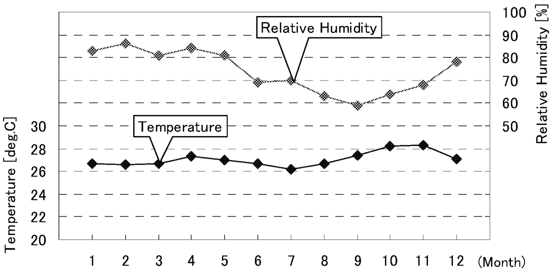

Figure 2 Monthly average temperature and relative humidity (2001) (JMA, 2001)

shown in Figure 3. Two houses, one with and another without air-conditioners are analyzed in this paper. There are a living room (Room 2), a kitchen (Room 1), a bathroom (Room 4) and two bedrooms (Rooms 3 and 5). Also there is an attic space (Room 6). The materials of the building elements are listed in Table 1. The insulation is attached neither to the ceilings nor the roofs. In the house with air-conditioners, they are installed in the bedroom (Room 5) and the living room (Room 2).

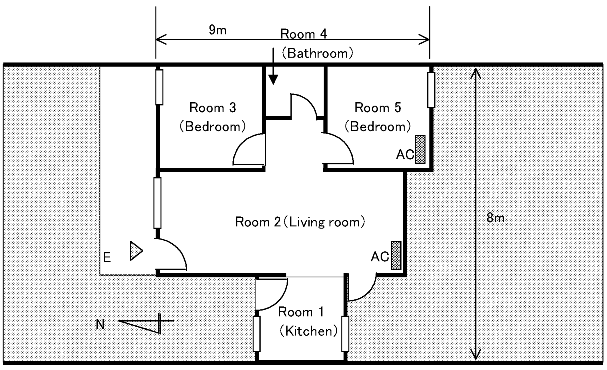

Figure 3 Typical plan of surveyed house

Table 1 Material of building element

	Material (thickness)	Finish (thickness)
Roof	Clay tile (3cm)	
Ceiling	Plaster board (2cm)	
Wall	Brick (12cm)	Mortar (1cm)
Floor	Concrete (10cm)	Ceramic tile (1cm)

3.2 Mathematical Model

3.2.1 Fundamental Equations of Heat and Moisture Transfer in Porous Materials

The equations (1) and (2) (Hokoi et al., 2002) are the conservation equations for energy and moisture in a porous material that consists of solid, liquid water, vapor and dry air. It is assumed that the moisture transfer in liquid phase is negligible.

Energy balance: $$c\gamma\frac{\partial\theta}{\partial t}=\lambda\frac{\partial^2\theta}{\partial x^2}+R\frac{\partial\omega}{\partial t} \quad (1)$$

Moisture balance: $$c'\gamma'\frac{\partial X}{\partial t}=\lambda'\frac{\partial^2 X}{\partial x^2}-\frac{\partial\omega}{\partial t} \quad (2)$$

t: time [s], θ : temperature [degrees C], c: heat capacity of material [J/kgK], γ : density of material [kg/m^3], λ : thermal conductivity [W/mK], R: enthalpy for phase change of adsorbed water [J/kg], ω : moisture content [kg/m^3], X: humidity ratio [kg/kg(DA)], c': porosity [m^3/m^3], γ' : air density [kg/m^3], λ' : vapor conductivity [kg/ms(kg/kg(DA))]

3.2.2 Energy and Moisture Balance of Room

In calculating a room temperature (equation (3)), the following heat fluxes into the room are considered; the heat flux from walls (Q_w), the heat flow by air exchange with outside or other rooms (Q_{vo} and Q_{vr}), the solar radiation (Q_{so}), the internal heat generation by human bodies (Q_h), and cooling by the air-conditioner (Q_{ac}). Regarding the moisture balance of the room (equation (4)), the vapor fluxes from walls (M_w), the vapor fluxes from the outside and the connecting rooms (M_{vo}, M_{vr}), the moisture generation from human bodies (M_h) and the dehumidification by the air-conditioner (M_{ac}) are considered.

$$\rho_a V_{ro1}\frac{\partial\theta_{ro1}}{\partial t}=Q_w+Q_{vo}+Q_{vr}+Q_{so}+Q_h+Q_{ac} \quad (3)$$

$$\gamma_a V_{ro1}\frac{\partial X_{ro1}}{\partial t}=M_w+M_{vo}+M_{vr}+M_h+M_{ac} \quad (4)$$

where,
ρ : volumetric specific heat [J/m^{3}K], V: volume of room [m^3], Q: heat flux [W], M: moisture flux [kg/s], V_R: amount of ventilation [m^3/s], Subscript a: air, ro: room air, o: outdoor, w: wall

3.2.3 Mathematical Model for Air-conditioner

Figure 4 illustrates the schematic diagram of an air-conditioner. Based on the heat and moisture balances of the refrigeration cycle, the air-conditioner is mathematically formulated (Ito et al. 1985).

3.3 External Conditions

The external temperature, humidity and the global solar radiation measured from 17th to

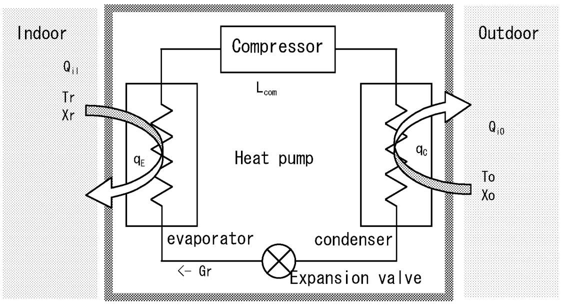

Figure 4 Air-conditioning system

23rd February in 2001, are used as the input outdoor conditions. The input data are assumed to change with a weekly cycle. The calculation is repeated until the ground temperature shows a cycle change. The outdoor temperature and humidity averaged over the measured period are used as initial conditions of the building elements, while the average outdoor temperature is used as the ground temperature at the depth of 5 m.

Table 2 Air exchanges rate

(a) Infiltration rate

	House with air-conditioner		House without air-conditioner	
	Room and outside	Room and other rooms	Room and outside	Room and other rooms
Room 1	2	20	6	20
Room 2	3	9	8	12
Room 3	2	2.8	5	5.7
Room 4	1	8.5	2	8.5
Room 5	2	1.4	5	5.7
Room 6	3	0	3	0

(b) Ventilation rate *

	House with air-conditioner		House without air-conditioner	
	Room and outside	Room and other rooms	Room and outside	Room and other rooms
Room 1	2	20	6	20
Room 2	5	11	4	10
Room 3	2	4.2	3	2.8
Room 4	1	8.5	1	8.5
Room 5	2	6.1	3	2.8

*This value added that in (a) during the ventilation period.

4. SIMULATED RESULTS

4.1 Comparison between Measured and Calculated Room Temperature and Humidity

The air exchanges rates used in the computation are given in Table 2. The values of the air exchange rate were adjusted so that an agreement between the measured and calculated temperatures (not humidity) is obtained. The air-conditioners are installed in the living room (Room 2) and the bedroom (Room 5), if the house is air-conditioned.

4.1.1 House without Air-conditioner

First of all, the calculation for the house without air-conditioner is curried out to clarify the influence of the hygroscopicity (absorption/ desorption) of building materials, for two cases. In Case A, the hygroscopicity is taken into account, while not considered in Case B. Figures 5 and 6 show the comparison between the measured and calculated temperatures and humidity ratios in Room 5 (bedroom) of the house without an air-conditioner. Since the values of the air exchange rate is decided so as to get a good agreement between the measured and the calculated temperatures in Case A, the calculated room temperature in case A is closer to the measured results than that in Case B. During daytime, the air temperature calculated in Case B is higher than that in Case A by 0.8 degrees K. This is because the ceiling temperature rises up during daytime due to the solar radiation, and also because the moisture evaporates at the ceiling surface and decreases the surface and room temperatures. The humidity ratio calculated in Case A is also close to the measured value during daytime, while that in Case B is rather closer to the outdoor one. This is because that the ventilation between the room and the outdoor is dominant in determining the room condition in Case B, where the absorption is not considered. Also, a better agreement of the humidity ratio in Case A supports the validity of the present calculation.

4.1.2 House with Air-conditioner

Next, a house with air-conditioners is examined. Figures 7 and 8 show the room temperatures and humidity ratios in the living room (Room 2), and those in the bedroom (Room 5) are given in Figures 9 and 10. The temperatures of both

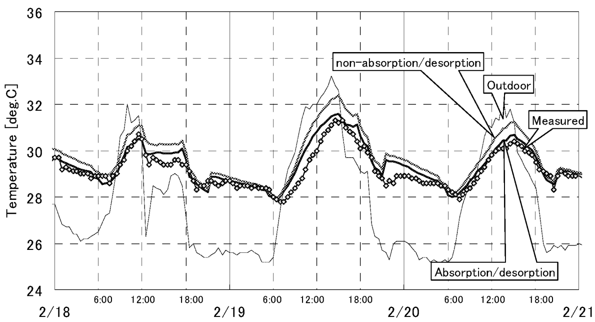

Figure 5 Comparison between measured and calculated temperatures in Room 5 without AC

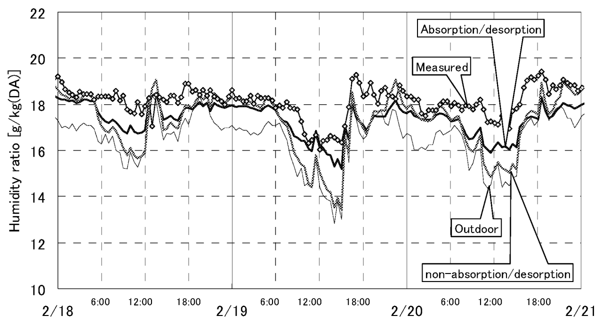

Figure 6 Comparison between measured and calculated humidity ratios in Room 5 without AC

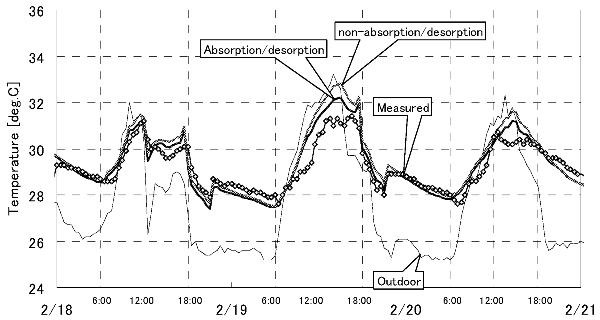

Figure 7 Comparison between measured and calculated temperatures in Room 2 with AC

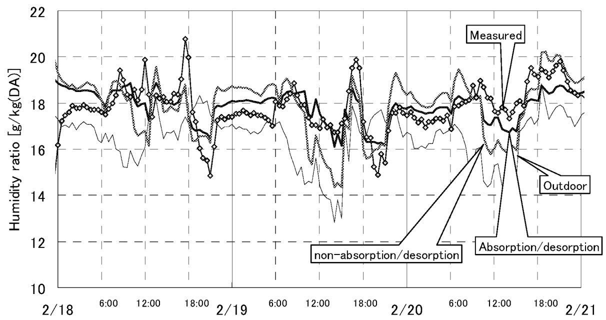

Figure 8 Comparison between measured and calculated humidity ratio in Room 2 with AC

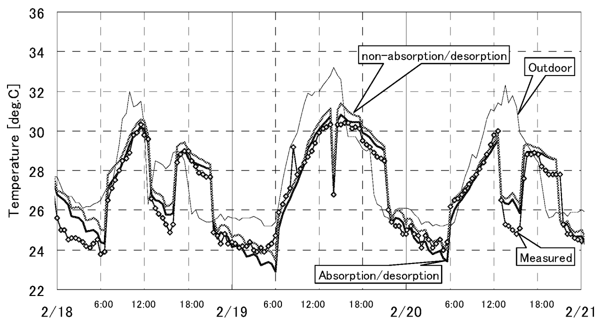

Figure 9 Comparison between measured and calculated temperatures in Room 5 with AC

Room 2 and Room 5 in Case B are higher than those in Case A due to the same reason as in the cases of the house without air-conditioners. On

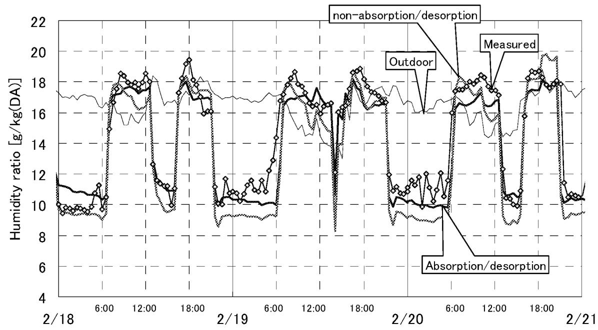

Figure 10 Comparison between measured and calculated humidity ratio in Room 5 with AC

the other hand, the humidity ratio in Room 5 differs only slightly between Case A and Case B. This is because the operation of the air-conditioner is the determining factor of the room condition. Furthermore, the humidity ratio of Room 2 in Case A is closer to the measured value during daytime when the air-conditioner is not operated. This again shows the influence of the hygroscopicity of the wall. From these results, it can be concluded that the calculated result considering the hygroscopicity of the walls can give a reasonable agreement with the measured results regarding both the temperature and the humidity ratio.

The simulation considering the absorption in this section will be called “Case 0” hereafter.

4.2 Improvement of Thermal Environment

4.2.1 Calculation Conditions

In order to improve the present situation, several simulations were carried out with the insulation and the air tightness changed. As criterion for an improvement, the energy consumption by the compressor is evaluated. Based on the surveyed results, it is assumed that the air-conditioner is used from 14:00 to 16:00 and from 21:00 to 5:00 AM. The room temperature is controlled between 24.5 and 25.5 degrees C during air-conditioning period. An air-conditioner is used only in Room 5 (bedroom).

The air exchange rates in Table 2 are used. The infiltration rate is corresponding to the air exchange rate when the all openings are closed. From 6:00 AM to 18:00 PM, the openings are open for ventilation and the ventilation rates in Table 2 (b) are added to the values in Table 2 (a). The openings in Room 5 are closed when the air-conditioner is operated. The simulated cases are listed in Table 3.

4.2.2 Effect of Insulation (Cases 0, 1 and 2)

Figures 11 and 12 show the calculated room temperature and humidity ratio in Rooms 2 and Room 5 (Cases 0, 1 and 2). In Case 1, the insulations put on the ceiling of the whole house, while to the ceiling only in Room 5 in Case 2. The temperatures in both Room 2 and Room 5 in Case 1, and that in Room 5 in Case 2 are kept lower than that in Case 0 (Figure 11), because of the insulation effect. The humidity ratio of Room 5 during an operation period of the air-conditioner in Cases 1 and 2 are higher than that in Case 0 by 0.3 g/kg(DA). This can be explained as follows. The air-conditioner controls only the room air temperature, not the humidity ratio. By increasing the thermal insulation, the heat flow into the room decreases. Thus, the operating time of the air-conditioner becomes shorter, and the amount of the moisture dehumidified from the room also decreases. As a result, the sensible heat load is reduced by 17 ~ 21 % while 15 ~ 20 % of the latent heat load (Figure 15).

4.2.3 Effect of Air Tightness (Cases 0, 3 and 4)

Figures 13 and 14 show the calculated room temperatures and humidity ratios in Room 2 and Room 5 in Cases 0, 3 and 4. In Case 3, the infiltration rates between the room and the outdoor are decreased in all the rooms, while in Case 4, only the infiltration rates between the Room 5 and other rooms and between Room 5 and the outdoor are partially decreased. The temperature in Room 2 during nighttime is higher than those in the other cases. Although the outdoor temperature drops during nighttime, the room temperature can not fall down when the air exchange ratio is decrease. In Case 3 the air exchange rate between Room 5 and Room 2 is the same as that in Case 0, it leads to the heat load of Room 5, and thus the sensible heat load

Table 3 Simulated cases

Case No.	Insulation		Infiltration	
	Room 5	Other rooms	Room 5	Other rooms
0				
1	X	X		
2	X			
3			X	X
4			X	
5	X	X	X	X
6	X		X	
7	X		X	X
8	X	X	X	

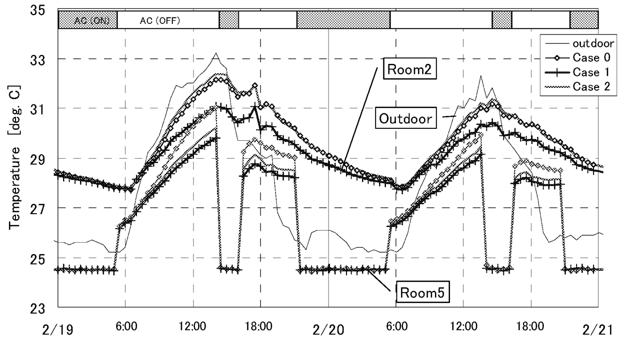

Figure 11 Calculated temperatures in Rooms 2 and 5

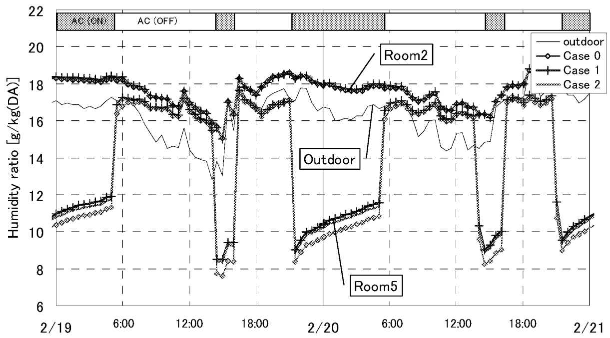

Figure 12 Calculated humidity ratios in Rooms 2 and 5

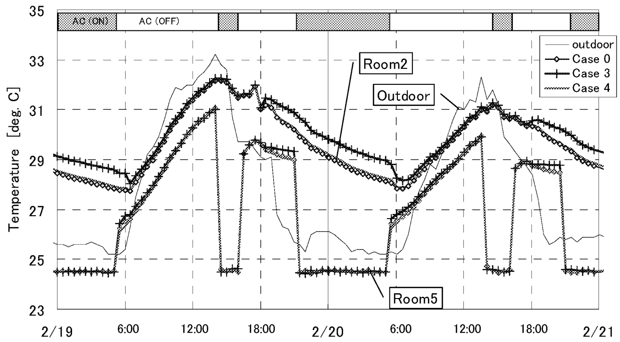

Figure 13 Calculated temperatures in Rooms 2 and 5

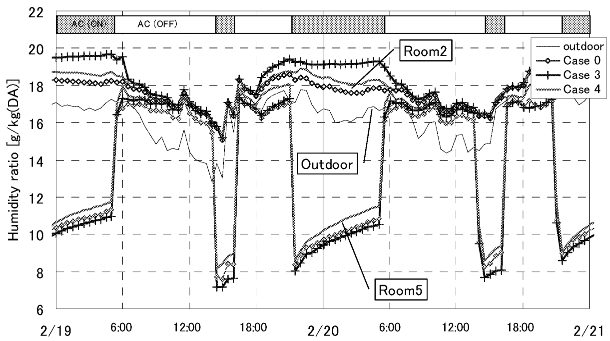

Figure 14 Calculated humidity ratios in Rooms 2 and 5

is reduced only few percent in Case 3. Therefore, to reduce the heat load, reduction in the air exchange rate of the air-conditioned room and an increase in the air exchange rate between the air-conditioned room are effective. In Case 3, the humidity ratio in Room 2 during nighttime is higher than other cases. This is because the air tightness causes the reduction of the moisture exhaust by the air exchange. In Case 4, the humidity ratio of Room 2 is slightly higher than that in Case 0. Since, the moisture in Room 2 cannot flow into Room 5 due to the increase in the air tightness of Room 5. The humidity ratio in Room 5 during the operating of the air-conditioner in Case 3 is lower than that in the other cases. This is caused by a longer operation of the air-conditioner. The temperature in non air-conditioned room becomes high in Case 3, and which makes the heat load in Room 5 larger. Then the air-conditioner must be operated longer, and it causes the humidity ratio lower. To increase the air tightness between the air-conditioned room and the outdoor leads to the reduction in the latent heat load by preventing the high humidity outdoor air from entering into the room. But, during nighttime, it is against reducing energy consumption by the air-conditioner to decrease the air exchange rates of all rooms without improving the air tightness between the air-conditioned room and the other rooms, since it is equivalent to air-condition all rooms. Although the air tightness is effective in the daytime, whether the air tightness should be increased or not must be decided in the night, taking the balance between the outside and set point temperatures into consideration.

4.2.4 Combined Effect of Insulation and High Air Tightness (Cases 5 to 8)

Figure 15 shows the reduction rate in the electric power consumed by compressor, the sensible and the latent heat loads from the values of Case 0. The reduction of the energy consumption is small in Cases 5 and 7. Even though the air-conditioned room is insulated, a large air exchange between the air-conditioned room and the non air-conditioned room causes the high latent and sensible heat loads. Thus the energy consumption cannot be decreased. The reduction rates in Case 6 and Case 8 clarify that the improvement in the air tightness only in the air-conditioned room can reduce the latent heat load significantly.

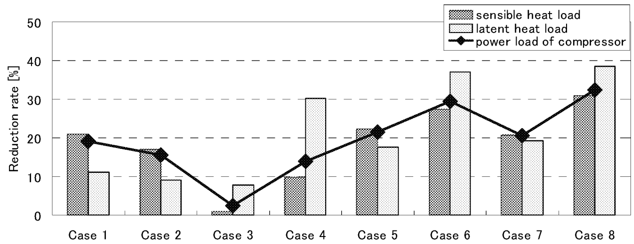

Figure 15 Reduction rate from Case 0 in sensible and latent heat loads, electricity consumption

5. CONCLUSION

The thermal environment of the residences was investigated in Surabaya, Indonesia. Then the thermal environment of the air-conditioned rooms was numerically analyzed in order to evaluate and reduce the energy consumption. The simulation program takes into account the operation of the air-conditioner. To evaluate the influence of the moisture on the cooling load, the absorption and desorption by the building materials are considered. By considering the hygroscopicity of the building elements, the simulated temperature and humidity agreed well with the measured values in both houses with and without air-conditioners.

The simulated results showed that an addition of the thermal insulation to the ceiling was very effective in reducing the heat flow from the ceiling. In addition to insulation, increasing air tightness of the air-conditioned room could reduce an electric consumption by the air-conditioner, which is mainly caused by a decrease in the latent heat load. Even if the air tightness of the whole houses is increased, the latent heat load is not decreased so much without the improvement in the air tightness between the air-conditioned room and the surrounding rooms. By the 5-cm-thick insulation on the ceiling and the partial reduction of the air infiltration rate of the air-conditioned room down to 0.5 times/hour, 33 % of the energy consumption is reduced.

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