Simulation Study on Solar House with Floor and Hot Water Heating System

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Abstract
In this study, a two storied single family house with solar floor and domestic hot water heating system is simulated to examine the usefulness of the simulation for predicting the indoor thermal environment and energy consumption to evaluate the system performance throughout a year. The effects of the solar floor and hot water heating system were evaluated with comparison of the simulated results for the cases with and without solar heating system. The results showed that the solar house provided comfortable environment with an average annual total purchased electric power of 40.4 GJ/year, which was lower than that of the house without solar heating system by 17%. In addition, the effect of tilt angle of solar collector on the total energy performance of this house was examined to discuss the suitable angle in considering roof design of the house. It was found that the effect of collector tilt angle on the solar energy contribution was much smaller than the difference in solar radiation on the tilt angle. This implies the flexibility in designing the roof shape of solar houses.

Keywords: simulation; single family house; solar floor heating; solar hot water heating; energy performance; collector tilt angle

Introduction
Using solar energy is very important for reducing energy consumption and averaging heat load in buildings. A way of effective solar heating system for small scale application such as single family house is to simplify the system structure. The solar space and hot water heating system combined with floor heating system using thermal mass of concrete floor is an example of a simple solar heating system. The advantage of such type of solar space heating system is that heat storage tank is not necessary, therefore the control of the heat storage and heat reclaim is not necessary. Instead of complicated control system, the passive thermal behavior of the floor slab controls the heating effect.

The tilt angle of solar collector in active solar space heating system is often discussed from the view of architectural design, as the high tilt angle for both space and hot water heating is useful for collecting solar energy in winter. However, a high tilt angle may conflict with roof design of the house.

This paper describes an annual performance of the solar house with the effect of solar floor and hot water heating system using the detailed system simulation results. The tilt angle of solar collector is also examined.

The simulation model house is a single family solar house with active solar heating system built in 1985. The house has been lived by a family for 19 years until now (Roh et al., 2004; Udagawa et al, 2003; Roh et al., 2002; Udagawa, 1998; Udagawa, 1987). Simulation method has been validated using the monitored data in long term. The simulation was carried out using a generalized simulation tool EESLISM developed by the author (Udagawa, 1990; Udagawa et al., 1999).

Solar heating system
The house is located in a residential area near the central part of Tokyo where both space heating and cooling are necessary and is well insulated to satisfy the recommended thermal insulation level for the thermal insulation area in which Tokyo is included.

Figure 1 shows the floor plan of the house faced to almost south. The house is two storied with a floor area of 164 m² (Udagawa et al., 2003; Roh et al., 2002). Light steel frame construction with light weight concrete panel for outside wall and roof slab is used. This type of construction is commonly used for single family house or small multi family house designed and constructed by several major housing company in Japan. The thermal insulation of wall is 59 mm of phenol foam and the windows are double glazing. Movable insulation panels are provided to increase the thermal resistance during night. The total heat loss coefficient is estimated to be 1.74 W/m²K.

Figure 2 shows the system diagram of the solar system. The solar collector is flat plate type with selective surface absorber. Six collector units with a total collector area of 11.5 m² are installed on the roof slab. The collector is
also faced to south almost as like the house (Azimuth: 18° to east). The solar energy is used for both DHW heating and floor heating in the heating season from November to April and for only DHW heating in other season. Two tanks for solar heating and auxiliary heating with electricity are for only DHW supply. For the space heating, only thermal mass of the concrete floor with 300 mm thickness is used for storing the collected solar heat.

Rooms L, D and S in Figure 1 is used as living space. A part of the living space is provided with the ceiling height of 5.4 m and the space is continued to above space of the second floor.

Heat pump room air conditioners are used in each room for space heating and cooling. The cooling is necessary in Tokyo, whereas the cooling season does not last so long comparing with the heating season. While the two room air conditioners in Room L and D are used daily from morning to night and the room air conditioner in Room CB is used in morning and evening. All other air conditioners are used only a few days in a year.

**Simulation method**

The detailed system simulation of the model house is carried out using the weather data and the data estimated from the living behavior of the occupants. The simulation tool named EESLISM has been used to estimate the building thermal behavior and the solar system performance.

Figure 3 shows the system model for the simulation by EESLISM. As shown in Figure 3, all the important system components as well as the flow path of the solar heat collecting and heating are input to describe the whole system. The simulation model for solar collector is based on the steady state model using the test data from the manufacturer. The heat storage tanks are simulated using the multi node model with uniform distribution. As the building thermal model, a multi room model using the finite difference calculation model for unsteady state heat conduction is used. Long wave radiation exchanges between room surfaces are considered in the building thermal model. The radiant floor heating simulation model is also included. The whole system simulation model consisting of both room thermal model and mechanical component models is used in EESLISM. All system components are based on the heat balance. The simulation is carried out for a year using the standard weather data of Tokyo by Expanded AMeDAS Weather Data (Architectural Institute of Japan, 2000). The time interval of 1 hour is used.

The solar system is worked by the difference between the collector temperature and the water temperature of...
the bottom in the storage tank at the temperature difference of 15°C. To prevent the over heating, the solar system is designed to be stopped when the water temperature of the top in the storage tank is over 90°C for the simulation.

The solar energy is used for both DHW heating and floor heating in the heating season, from November to April. However, in other season, from May to October, the floor heating system is switched to DHW heating system only. Electric DHW heater in the auxiliary heat storage tank is operated from 1:00 to 6:00 by midnight electric power and heats up the water to the set point as shown in Table 1. While DHW is supplied only from the solar storage tank at the daytime, the auxiliary heat storage tank is also used in other time throughout a year.

Total room number in this simulation is 19 as shown in Figure 3. The room air temperature set point is used with the estimated heating and cooling hours for Rooms L, D and CB as shown in Figure 3. The scheduled heating hour in the simulation for Rooms L and D is from 5:00 to 24:00. For Room CB, the heating is assumed in morning and evening as shown in Table 2. The scheduled cooling hour in the simulation for Rooms L and D is from 17:00 to 24:00 and for Room CB is from 21:00 to 24:00. As the room temperature set point, an operative temperature expressed with the weighted average of room air temperature and room surface temperature is used. As the data for the internal heat generation, the hourly schedule of the household appliances is estimated from the daily average household energy, 60 MJ/day. The domestic hot water use schedule is determined from the typical hourly schedule of the DHW use for the simulation.

In order to estimate the electric power consumed by the air conditioners from the simulated heat loads, the COP for the room air conditioner in each room is assumed. The COP value of 3.0 is used for the three room air conditioners in Rooms L, D and CB.

The simulation cases are shown in Table 3. Five cases on the different tilt angle of solar collector and a case without the solar heating system are examined. The effects of solar floor and DHW heating are evaluated with the simulation results in the case of the tilt angle of 60° and the case without solar heating system.

| Case          | Tilt angle of solar collector |
|---------------|------------------------------|
| 15 deg.       | 15°                          |
| 30 deg.       | 30°                          |
| 45 deg.       | 45°                          |
| 60 deg.       | 60°                          |
| 75 deg.       | 75°                          |
| Without solar | -                            |

Table 3. Simulation Cases.

Fig.3. Simulation Model.
The effect of solar heating system
As shown in Table 3, the simulation case without solar heating system was included to estimate the effect of the solar floor heating and hot water heating system. In order to ensure the thermal comfort level of two simulation cases, the operative temperature was used as a set point for space heating with the room air conditioners.

The effect of solar hot water heating system
Figure 4 shows the hourly results of the solar heat collecting system and the electric hot water heater with the solar heating system in winter. Figure 5 shows the hourly results of the electric hot water heater without the solar heating system in winter. DHW heating load of electric DHW heater with the solar heating system is lower than that without the solar heating system. Figures 4 and 5 show the difference of the distribution of water temperatures in the electric DHW heater.

Figure 6 shows the comparison of the electric powers for DHW with and without the solar heating system. The electric power consumption of the model house is lower than that of the case without the solar heating system.

The effect of solar floor heating system
Figure 7 shows the example results of room thermal condition of Room L with a floor area of 17 m². The difference in the room air temperatures for the two cases in Figure 7 shows the thermal effect of the solar floor heating. Using the solar floor heating, the air temperature to satisfy the requirement of the thermal comfort level is lower than that without solar floor heating. The heat load of the room air conditioner in the case without the solar system is greater than the solar heating case as shown in Figure 7. The total heating load with the solar floor heating system is slightly greater than that in the case without solar floor heating. The difference in Figure 7 shows the effects of the heat supply from the solar heated floor.

Figure 8 shows the comparison of the total electric power for room air conditioners in Rooms L, D and CB with and without the solar heating system. The difference shows the effect of solar floor heating system.

Figures 9 and 10 show the simulation results of the
daily variations. As shown in Figure 9, the collector efficiency is around 50% in heating season. In other season, from May to October, the collector efficiency is around 30% because of the collected solar energy used only for DHW heating. As shown in Figure 10, the midnight electric power consumption of the case with solar heating system is smaller than that of the case without solar heating system. The difference of the ordinary power consumption is very small in comparison with that of the midnight power consumption.

Figure 11 shows an annual performance of the model house with solar floor heating and hot water heating system. Annual total energy is 48.7 GJ/year and the breakdown of the annual energy is shown in Figure 11. The solar energy is 21.7 GJ/year and the auxiliary energy is 27.0 GJ/year. The solar energy used to the floor and DHW heating is 17.7 GJ/year and the loss from the storage tank and pipes is 4.0 GJ/year which corresponds to 18% of the total solar energy. The auxiliary energy used to the space heating and cooling and the DHW heating is 21.4 GJ/year and the loss from the tank is 5.6 GJ/year. The space heating load of the model house is 19.3 GJ/year and the solar floor heating load is 9.9 GJ/
year which corresponds to 51% of the total space heating load. The DHW heating load is 14.8 GJ/year and the solar DHW heating load is 7.8 GJ/year which is 53% of the total DHW heating load. The space cooling load is 5.0 GJ/year which corresponds to 13% of the total useful energy. The total useful energy is 39.1 GJ/year and the total loss is 9.6 GJ/year.

Figure 12 shows an annual performance of the model house without solar heating system. Electric DHW heater load and the room air conditioner space heating load with the solar heating system are 46% and 63% of those without the solar heating system, respectively.

Tilt angles of solar collector

The tilt angle of solar collector is important for the building design. The roof may not be inclined to the optimum angle for the solar collector. Architects may consider that the solar collector is a part of the roof for good outside view. Whereas it is said that the higher tilt angle of solar collector is effective in winter, the collector tilt angles of 15°, 30°, 45°, 60° and 75° were examined. The effect of the tilt angle on the total energy performance of the solar house were discussed using the simulation results. For the comparison, the house without solar system was also included.

Figures 13 and 14 show the comparison of solar collector outlet water temperature and hot water temperature of the top in the solar storage tank. In winter, the difference of the water temperatures by the tilt angle is small, as the collected solar energy is used for both the floor heating and to heat the solar storage tank. In summer, water temperatures in the solar storage tank showed the large difference.

Figures 15 to 18 show the comparison of the simulated monthly results. The solar radiation on the collector shows the large difference from April to August as shown in Figure 15. Nevertheless the other simulation results such as collected solar energy, space and DHW heating loads and electric power show the small difference. As the solar system is controlled to be stopped when the water temperature of the top node of the solar heat storage tank exceeding 90°C to prevent the over heating and higher collecting temperature decreases the collector efficiency, the collector efficiencies of the low tilt angles are almost same as that of the high tilt angles in summer. Figure 16 shows the differences in solar floor heating, however the effects on the heating load for the air conditioners are very small. Figure 17 shows the DHW heating load with the solar heating and the electric water heater. As shown in Figure 15, lower collector tilt angle
is advantage in summer. The difference in the collected solar energy is not large. The consumed electric powers for heating and DHW are shown in Figure 18. The monthly data show almost same values except for the DHW electric power in summer.

Figures 19 and 20 show the comparison of the yearly simulation results. While the collector tilt angle of 30° is the largest value for the solar radiation on collector
surface and the collected solar energy, the difference in the collected solar energy is very small. Whereas the differences in monthly data of solar DHW heat supply and DHW auxiliary load in summer were found, small difference was shown from the yearly simulation results of the heat loads and total energy consumption. Comparing of total electric power consumptions excepting household energy with and without solar heating system, the total electric energy with the solar heating system with the 60° tilted collector is 18.6 GJ/year, which is lower than that without the solar heating system by 69%.

Conclusions

Using the model solar house built in 1985, the effect of solar floor heating and DHW heating was evaluated using the detailed year round simulation. In addition, six cases were simulated to examine the effect of collector tilt angle on the solar heating system performance. From simulated results of indoor thermal environment and energy consumption, the solar house provided comfortable environment with an annual total electric power of 40.4 GJ/year with the 60° tilted collector, which is lower than that of the house without the solar heating system by 17%. This is due to the effect of the solar floor and DHW heating system.

The difference of the energy consumption by the tilt collector angle was small comparing to the difference in the solar radiations on collector. This implies the flexibility in designing the roof shape of solar houses.

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