Simulation for optimization of a household system using solar collectors to heat radiant floors and hot water tanks

Weirong Zhang*

Abstract: The introduction of renewable energy, solar energy in particular, is one of the most useful strategies for improving building energy efficiency. The objective of this study is to explore the total efficiency of a solar collector combined with a gas-driven auxiliary boiler to supply hot water for both residential use and radiant floor heating. The simulation results, based on TRNSYS17, were validated first by comparing them to the measurement results, which have been confirmed. Another objective of this study was examining how to optimize the use of solar energy. In a combined system, solar collectors are considered reasonable for any of the three options: radiant floor heating, residential water use, or for a combination of the two. Energy efficiency of a gas-driven auxiliary boiler varies depending on the inlet water temperature, which also affects the system performance, and therefore impacts the primary energy consumption. System control strategies depend on several elements including weather conditions, the domestic water use schedule, outlet water temperature from the floor heating, and the hot water tank's temperature. The total primary energy consumption is considered as the index to evaluate the whole system performance.

1. Introduction

When it comes to residential energy efficiency solar energy is commonly considered to be the first option, as it has been widely used for providing household hot water [1]. Hydronic underfloor heating systems are often adopted for residences as a thermally comfortable way of heating [2]. Both the domestic water system and underfloor heating system require hot water, which can be partly provided via solar energy [3]. The problem, therefore, is how to maximize the use of limited solar energy: should it be used for the underfloor system or be stored in a hot water tank for household use? This study investigates the most efficient use of water heated with solar energy. The first question we need to examine is by introducing solar energy how much primary energy can be saved? This is quantified using an evaluation index. In this study, dynamic simulation (TRNSYS ver.17) was used to calculate the energy demand in February under standard winter conditions. Simulation results have been compared to experimental results to confirm its reliability. Usually the schedule of the underfloor heating system, the household water demand, the boiler coefficient, which is determined by the inlet water temperature, and the volume and insulation effectiveness of the tank are all factors that affect the amount of primary energy. The two basic systems that we will discuss include 1) the solar energy collected directly for radiant floor heating, and 2) the heat of the outlet water from the underfloor heating system for storage in a tank combined with the solar energy aiming to improve the boiler coefficient performance.

2. System description

Two basic systems are discussed in this study. System 1 is often adopted in housing designs that incorporate solar energy (see Fig. 1 (a)). In these applications, when radiant floor heating is in use, collected solar energy is only introduced to the floor heating system when the temperature of heat medium from the solar collector is higher than that of the heating system. (Fig. 1(a): ① →② →③ →④ →⑤ →⑥). When the floor heating is not in use, the solar heat will heat the hot water tank for future household water use (Fig. 1(a): ①→②→⑦→⑧→⑤→⑥).

System 2 aims to improve the boiler coefficient performance. A gas boiler is used in both system 1 and 2, with the coefficient defined as equation (1). The correlation between inlet heat medium temperature Ti and boiler coefficient c is obtained through experiments under various conditions.

$$c = 0.0021T_i^2 - 0.3767T_i + 94.833 \qquad (1)$$

Equation (1) shows that a low inlet temperature leads to high boiler coefficient performance and thus the primary energy demand can be reduced. Outlet water temperatures, however, can sometimes be very high. In system 2, outlet water first warms the cold water in the hot water tank under the condition that the temperature is higher than that of the

* Associate Professor, Department of Architecture, Tokyo Polytechnic University
Received Sept. 28th, 2015

tank's water (Fig. 1(b): ⑨→⑩→③→④→⑪→⑫). After exchanging heat with the hot water tank water, the outlet water temperature will be lower, thus obtaining a higher boiler coefficient. In this case, solar energy is only stored via the hot water tank and used for household purposes (Fig. 1(b): ①→②→③→④→⑤→⑥).

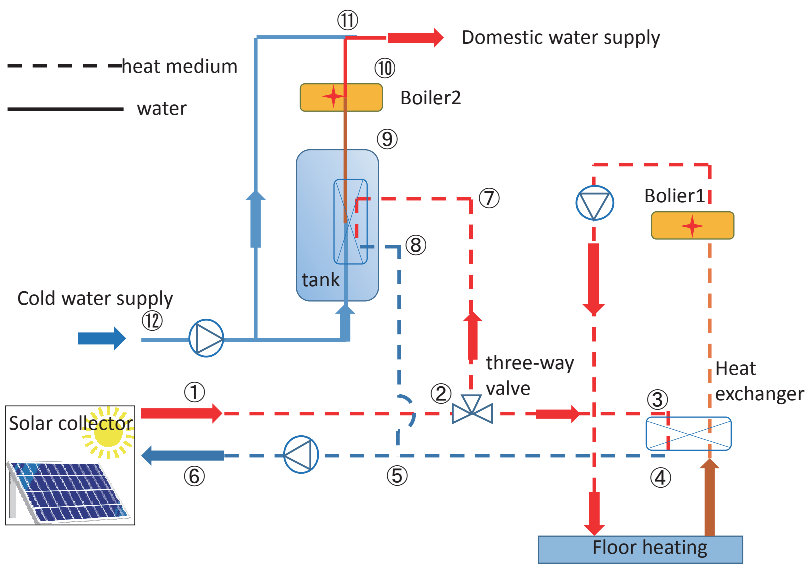

Fig. 1(a) System1: solar energy is first used for floor heating. Only when the radiant floor heating is not being used solar energy is stored as heat in the household hot water tank.

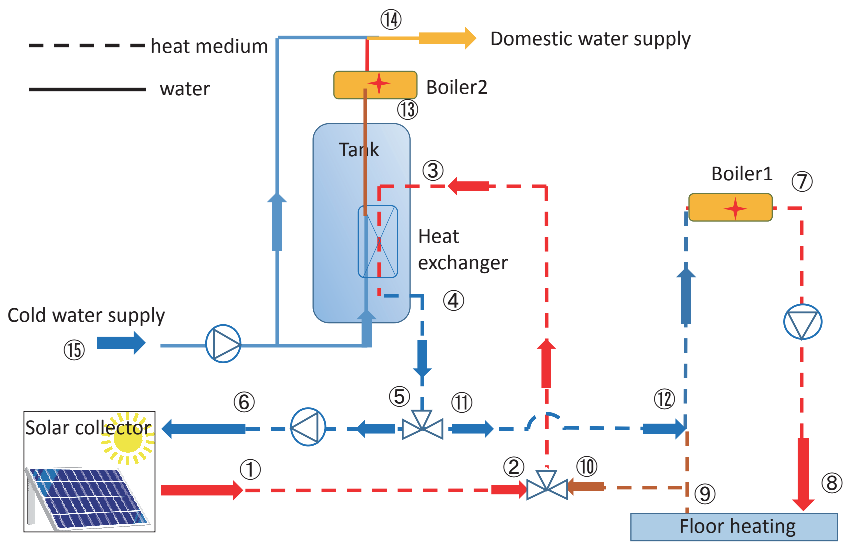

Fig. 1(b) System 2: solar energy is only used to heat the hot water tank. High outlet water temperatures from the radiant floor heating are used to heat the hot water tank to improve the boiler coefficient performance.

In both system 1 and system 2, when the temperature of hot water from the tank is higher than the supply temperature, the tank water will be mixed with cold water to match the preset temperature. When the tank's water temperature is low, it will be heated to the preset target temperature by boiler 2.

The total energy demand of boiler 1 (for radiant floor heating) and boiler 2 (for domestic water use) is considered to be the system energy demand. The lower this value is the more energy efficient the system is.

3. Building simulation

3.1 Simulation model

Fig. 2 illustrates the 3D model and the ground plan of the 1st floor of a standard residential house defined by IBEC [4]. The standard model has two floors with a total area of 120 m^2 located in Tokyo, Japan. Underfloor radiant heating is only installed in the living room at a laying rate of about 70%. The house is well insulated with a low heat loss coefficient of 2.7 W/m^{2}K. The U value of all the external walls is set as 0.383W/m^{2}K. Air change rate is approximately around 0.5 per hour. A general flat plate solar thermal collector with an effective area of 4 m^2 is set facing the south and tilted at 45^o in both the experiment and simulation. The mass flow rate of the heat medium in the solar collector is 120 kg/h.

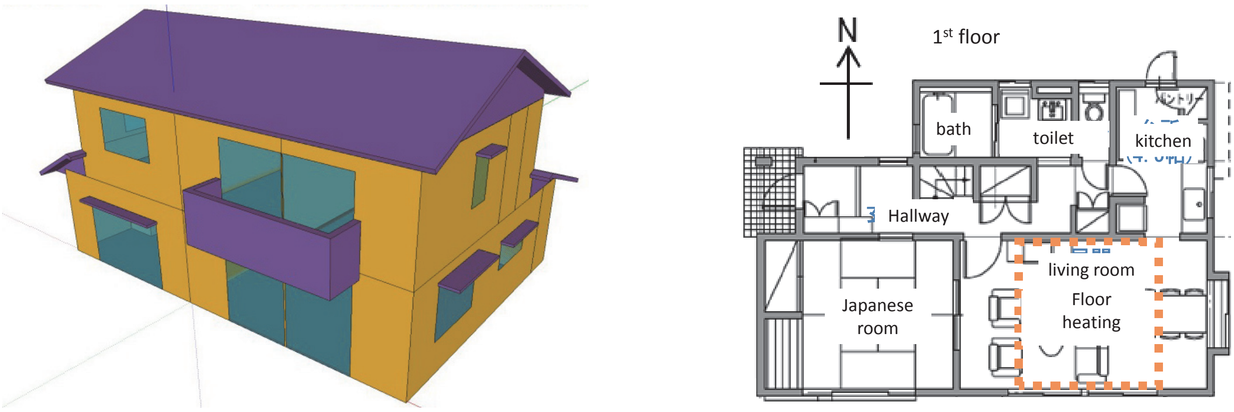

Fig. 2 IBEC standard residential model

3.2 Validating the simulation with experimental data

An experiment for evaluating the performance of system 1 was carried out in a real house between March 1 and April 30, 2011. The experimental data were used to validate the simulation model in this study. Fig. 3 shows the outlet and inlet water temperatures of the solar collector on April 1. The simulation results approximately matched the experimental results. Fig. 4 shows the temperature of the living room and floor's surface on April 1 The inlet water temperature for the floor heating is set high, at about 60^{o}C during the rising term in the experiment, the control strategy of which is confidential and thus was not completely set in the simulation. A steady feed water temperature of 45^{o}C was set as the condition in the simulation. This can explain the temperature difference from 7 AM to 8 AM between the experimental and simulation results. More details of the experimental data and validation results can be found in previous studies [5-6].

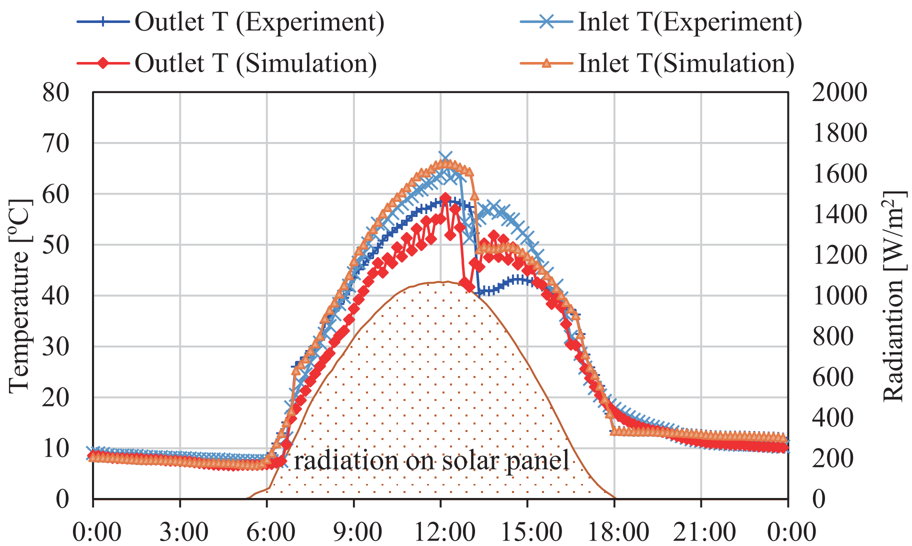

Fig. 3 Inlet and Outlet temperatures of the solar collector (2011.4.1)

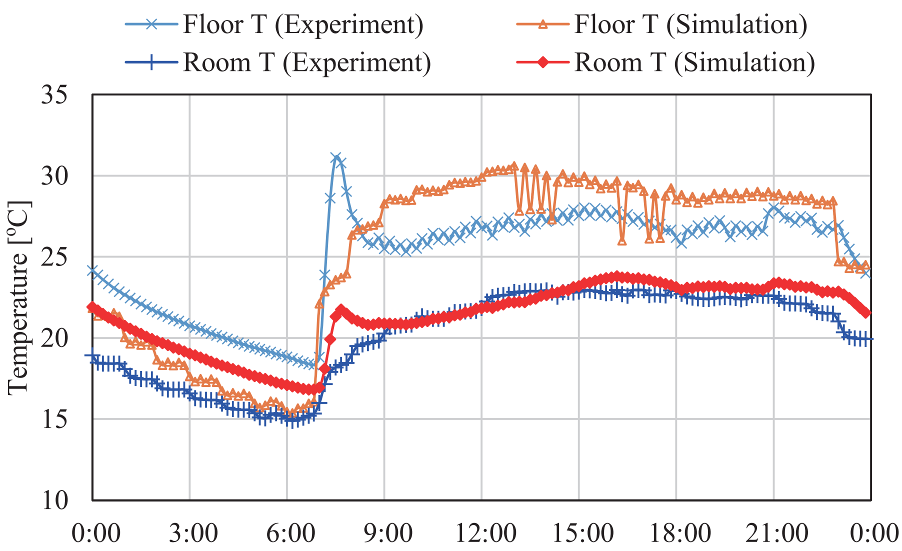

Fig. 4 The floor temperature and living room temperature (2011.4.1)

3.3 Simulation conditions

The common conditions of the simulations are summarized in Table 1. Fig. 5 illustrates the schedule of domestic water use for all the simulation cases. Fig. 6–Fig. 8 illustrate the schedule of lighting, occupants, and devices respectively. Weekdays and weekend days were not distinguished in this simulation. Simulations are listed in Table 2. The primary energy consumption is affected by several factors as mentioned above. In this paper, we only compare the value of system 1 (case 1) and system 2 (case 2) under the absolutely same conditions. Case 0 is set as a base to compare with case 1 and case 2. No solar energy is involved in case 0. In other words, all heat requirements are met through two gas boilers: one for the radiant floor heating and the second one for the domestic water supply system.

Table 1 Summary of calculating conditions

Floor heating schedule	Preset temperature of living room: 20±0.5°C, Calculation period: 1/15–2/28 Schedule of floor heating: 6:00–10:00, 18:00–22:00
Weather data	AMeDas standard weather data (Tokyo)
Setting of solar thermal system	Area of panel: 4 m^2, Slope of panel: 35°, Azimuth of panel: 0° (South)
	Heat loss coefficient of tank: 2.43[W/K], Tank volume: 90L, 1.6m height
	Solar pump OFF: Tank temperature >70°C
Physical properties of heat medium	Specific heat: 3.85 [kJ/kg・K]
	Mass flow rate: 120 kg/h
Setting of gas boiler	Domestic water boiler coefficient: 0.95 Feed water temperature: 40°C
	Floor heating boiler coefficient: Equation (1) Feed water temperature: 60°C

Table 2 Simulation cases

Case	Case 0	Case 1	Case 2
System description	No solar energy	System 1	System 2
Heat transfer	No heat transfer	From solar collector to floor heating or tank	From floor heating to tank From solar collector to tank
Aim	To compare with case 1 and case 2	To effectively use the solar energy and reduce the primary energy consumption	To improve the boiler coefficient and reduce the primary energy consumption

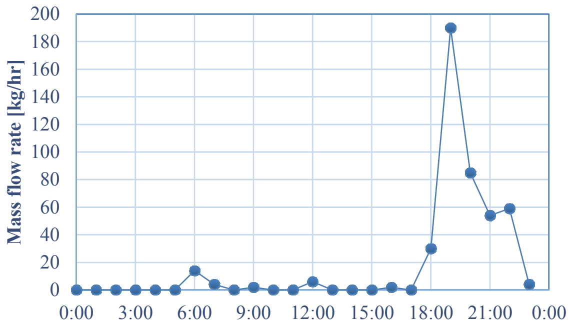

Fig. 5 Daily schedule of domestic water supply

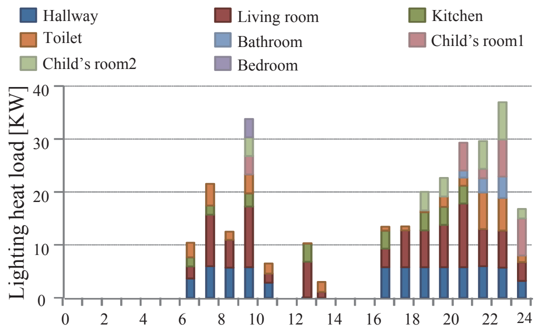

Fig. 6 Daily schedule of lighting heat load

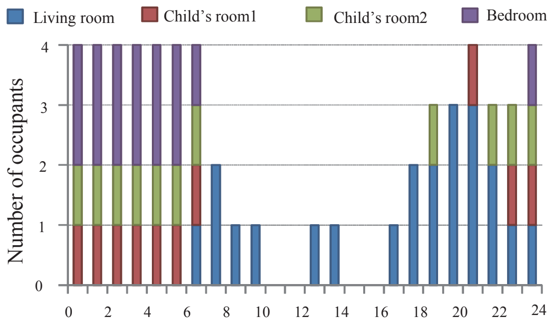

Fig. 7 Daily schedule of occupants

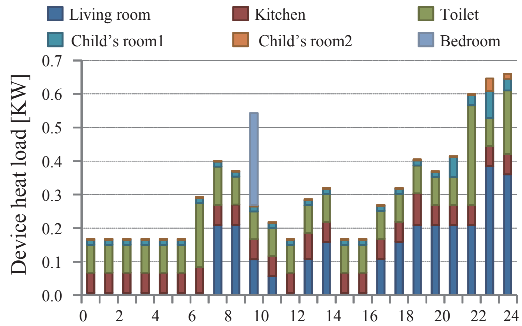

Fig. 8 Daily schedule of device heat load

3.4 Simulation results and discussion

The integral value of the primary energy demand in February of case 0–case 2 was calculated and illustrated in Fig. 11. By comparing the results of case 0 and case 1, the energy demand for floor heating in case 0 and case 1 are exactly the same, which is contrary to the control strategy of system 1. The intention of collected solar energy is that it be fully used for radiant floor heating, but the results showed that all the solar energy was instead stored in the hot water tank, leading to lower energy consumption for domestic water use. This conclusion can also be proved in Fig. 12, which shows the outlet temperature of the solar panel and floor heating in a typical day with enough solar radiation. Because the floor heating is only being used from 6:00–10:00 during the day, according to the daytime schedule of occupants in IBEC standards, the outlet temperature of the solar collector is lower than that out of the floor heating.

Fig. 9 shows the air temperature of the living room and outdoor air temperatures in case 0, case 1, and case 2 between Feb. 26 and Feb. 28. The inlet temperature of the floor heating is maintained at 60^{o}C, which means that air temperatures in the three cases are exactly the same. Fig. 10 shows the boiler coefficient for floor heating. By reducing the inlet temperature of heat mass, the boiler coefficient in system 2 is 5% higher than that in system 1 during most of the running time.

By comparing the results of case 1 and case 2 in Fig. 11, it can be seen that although the boiler coefficient rises in case 2, by introducing the outlet water from the floor heating to the tank, the total primary energy consumption is higher than that of case 1. The reason is that when both solar energy and outlet water from heating are directed to the tank, the tank temperature can easily increase, especially when the domestic water is not being used. In this situation, the solar thermal system will turn off; thus solar energy cannot be efficiently collected. At the same time, because the tank maintains high temperatures during the day, but is minimally used, the heat loss is more than that of case 1.

Although the results of system 2 are not as good as was expected due to the setting schedule, the volume of the tank, and the other setting simulation variables, improving the boiler coefficient is still considered to be one of the most useful ways to improve the overall energy efficiency of the system. In other cases, for example, when the tank volume is large enough to contain more water for solar heat energy storage, or a large amount of domestic water is in need, system 2 is expected to have a better performance.

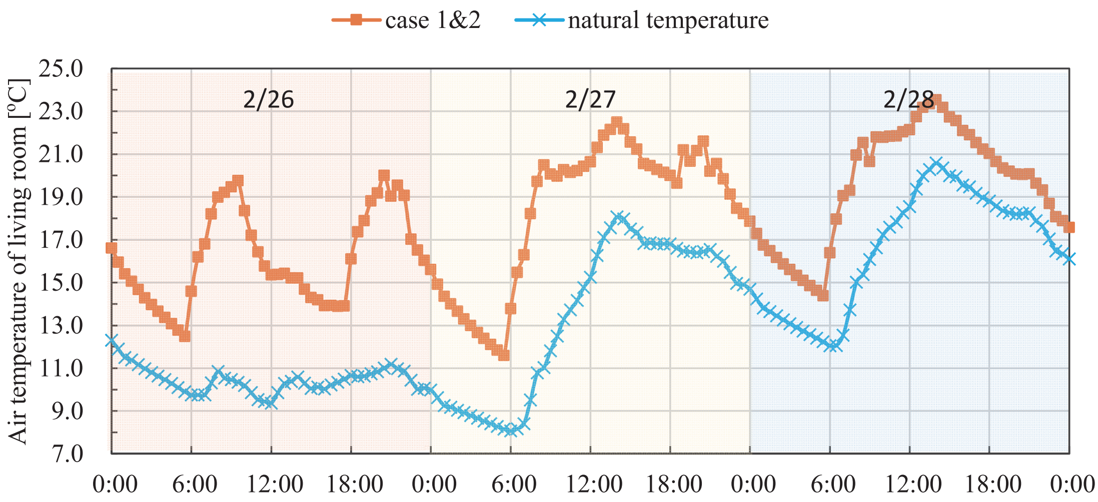

Fig. 9 Air temperature of living room (Feb. 26-28)

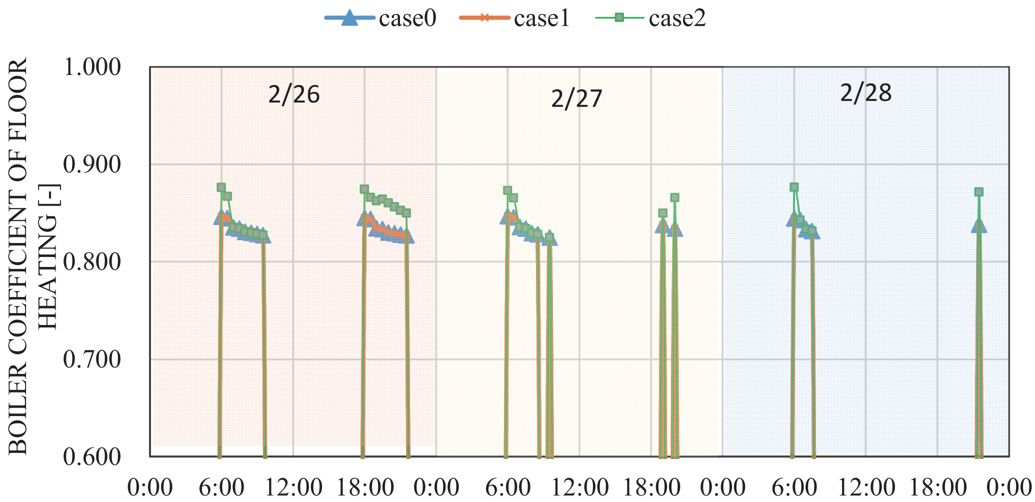

Fig. 10 Boiler coefficient (Feb.26-28)

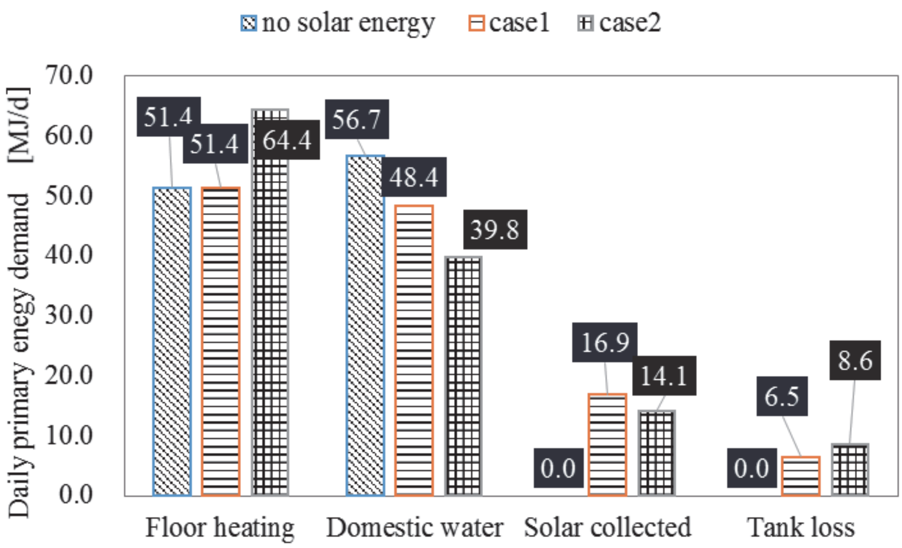

Fig. 11 Daily primary energy demand in February

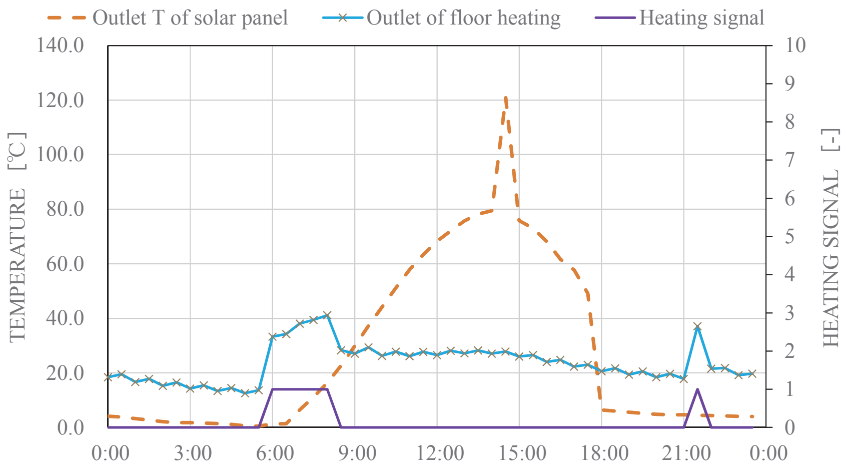

Fig. 12 Outlet temperature of solar panel and floor heating in system 1 (2/1)

4. Conclusion

This study compared two solar heat energy systems to support both the underfloor radiant heating and domestic water supply use in a residential energy simulation. Reducing the outlet water temperature from the radiant flooring can improve boiler coefficient performance, but at the same time it may reduce how much solar energy can be collected if the storage volume is too small. Solar energy may not always be directly used for underfloor radiant heating even though it was designed for it, especially in those residences that are well insulated. In these cases, temperatures are high on warm, sunny days when a lot of solar energy can be collected; on these days, however, the demand for floor heating is diminished. On cloudy and cold days, when there is high demand for floor heating, there is a decrease in supply of solar energy.

In future studies, the sensitivity of the heating schedule, domestic water schedule, tank volume, and insulation will be investigated in order to propose the most energy efficient system control strategy under various conditions.

References

[1] SZOKOLAY, Steven Vajk. Solar energy and building. 1977.

[2] A. K. Athienitis, Y. Chen. The effect of solar radiation on dynamic thermal performance of floor heating systems. Solar Energy, 2000, 69.3: 229-237.

[3] TABB, Phillip. Solar energy planning: a guide to residential settlement. 1984.

[4] Institute for Building Environment and Energy Conservation (IBEC): http://www.ibec.or.jp/

[5] Y. Nakagawa, T. Omori, J. Kim, W. Zhang, S. Kato. Prediction of Thermal Environment and Energy in Smart House using Simulation, PART 1: Construction of Evaluation Model for Standard. SHASE Conference Proceeding 2013. 197-200.

[6] K. Lin, S. Kato, W. Zhang, Y. Shimanuki. Study on Household Equipment System Using Solar Collectors (Part 1) Accuracy Evaluation for Floor Heating System and Hot Water Supply by Measurement and Simulation. SHASE Conference Proceeding 2014. 109-112.