SIMULATION OF SOLAR HOT-WATER SUPPLY AND AIR-CONDITIONING/VENTILATION SYSTEM

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ABSTRACT

As the solar thermal system with the floor heating and the hot-water supply system need low temperature of 40-50 degC, the effectiveness of solar collector is high. However, in the summer season, floor heating is unnecessary, and so there emerges a lot of surplus solar heat. By utilizing such surplus heat in summer as heat source for desiccant dehumidification activated with hot water at a temperature of about 70 degC [1)], it would be possible to use a solar heat collecting system efficiently all year round. Therefore, a new solar thermal system was developed with the purpose of utilizing solar heat with high efficiency all year round. In this paper, we reported that the field measurement in winter and the numerical simulation using TRNSYS for the annual performance evaluation of the developed solar thermal system ware carried out. As a result, it was found that annual system COP was as high as over 4, and it is possible to reduce running cost by about 9% by installing the cheaper midnight heating operation control based on the weather forecast of the following day.

INTRODUCTION

A solar heat collecting system combined with floor heating can improve solar heat collection efficiency, because heat collection temperature can be as low as 40-50 degC. However, it is the problem that the surplus heat energy is generated in summer, as solar heat source usually persists throughout the summer period. In addition, as the outdoor air is humid in the summer and intermediate seasons in Japan, it is necessary to dehumidify the air when the outdoor air is taken for ventilation into the room. Therefore, utilizing such surplus heat in summer as heat source for desiccant dehumidifier activated with hot water at a temperature of about 70 degC leads to efficient solar thermal system for annual use.

In this study, the solar thermal system consists of desiccant dehumidifier and floor heating system with solar hot water collector and a closed water storage tank was developed. Then, the authors have conducted the "research on desiccant dehumidifiers" utilizing the surplus heat (Yoshie, Momoi et al., 2007, 2008, 2010), with the purpose of developing a solar thermal system that can be used all year round for the facilities of welfare, education, and housing.

This paper reports on the field measurement of the solar hot water supply, air-conditioning, and ventilation system that can be used for a year, which was developed by combining a floor heating system and a desiccant dehumidification system. This paper also reports on the evaluation results of the operational behavior and the system performance of the developed system based on annual numerical simulation.

OUTLINE OF EXPERIMENT FACILITIES

Fig. 1 and Photos 1-4 show the outline of the field experiment facilities, and Table 1 shows the specifications of buildings, equipment, and devices. For a solar thermal system, variable water volume system for storing heat with water was adopted, to make heat collection temperature (hot water temperature) variable, and the heated water is stored in closed tanks with thermal stratification. In case sunlight is insufficient, the water is heated with the electrical heat pump water heater as an auxiliary heat source. The stored hot water is used for hot water supply (showers and washing stands) through the year, for desiccant dehumidifier in the summer and intermediate seasons, and for floor heating in the winter season. For showers, the hot water in the tank is directly used, while for washstands, clean water is heated through the heat exchanger with the hot water in the tank. The outline of operation modes is as follows:

Solar heat collecting + floor heating: In winter, heat is collected at a low temperature (60 degC), and hot water is supplied to floor heating panels. Surplus hot water is supplied to the upper part of a low-temperature water tank (500 ℓ × 2, connected in series). The hot water is stored with thermal stratification until the water temperature at the bottom of the tank becomes a certain temperature (50 degC). Then, the mode is switched to high-temperature heat collecting (80 degC), and hot water is stored in a high-temperature water tank (500 ℓ × 2, connected in series) with thermal stratification. For floor heating, water flow rate is controlled so that the retun water temperature is constant.

Solar heat collecting + desiccant: In the summer and intermediate seasons, high-temperature heat collecting (70 degC) is conducted for the regenerative air of the desiccant dehumidifier, and hot water is stored in the entire tank (500 ℓ × 4, connected in series) with thermal stratification. The water flow rate to the hot water coil in the desiccant dehumidifier is controlled so that the retun water temperature is constant [2).]

Water discharge for preventing the freezing of the heat collector: In winter, if there is a risk that the heat collector will freeze (the heat collecting plate will become 0 degC or lower) or it becomes boiling temperature due to control failure, water is automatically discharged from the heat collector with air pressure.

Reheating: If the amount of hot water at 50 degC or higher becomes 10% or less of the entire hot water tank, it is heated with the auxiliary heat source at 80 degC, until the amount reaches 25% (500 ℓ) of the entire hot water tank.

Midnight heating: The system receives operation control information regarding necessary heating water volume and operation start time during the cheaper electric power hours at midnight from the external host computer. The water is heated at 80 degC. In this experiment, this mode was not used.

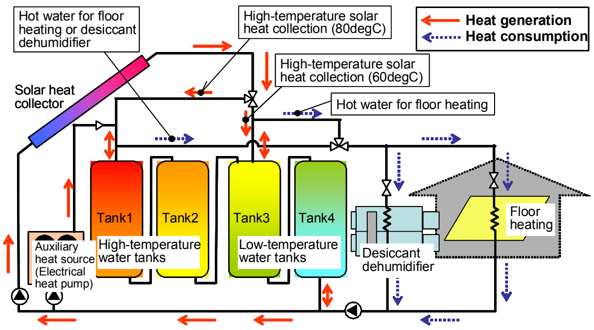

Figure 1 Solar thermal system with floor heating and desiccant dehumidifier for annual use

Photo 1 Solar heat collector

Photo 2 Water tanks and auxiliary heat source

Photo 3 Desiccant dehumidifier

Photo 4 Room with floor heating system

Table 1 Specifications of buildings and devices

Building	Target rooms: 2 laboratories (top floor of a 3-story RC-structured building); total floor area: 77.6 m^2, ceiling height: 2.3 m; room volume: about 180 m^3, opening area (vacuum insulation glass): 10.5 m^2 (south window) and 1.2 m^2 (north window)
1. Solar heat collector	Single-plate, glass, flat, selective absorption film, heat collecting plate; area: 30 m^2 (2 m^2 × 15 sheets); direction: 7° from south toward west; inclination angle: 40°; Valve for discharging water at the time of overheating; heat collection temperature during the summer and intermediate seasons: 80 degC; heat collection temperature during the winter season: 60 or 80 degC; variable water volume PID control
2. Hot water storage system	[Hot water tank] Stainless closed type (thermal stratification type); capacity: 2,000 ℓ (Two 500-liter low-temperature tanks and two 500-liter high-temperature tanks are connected in series) [Auxiliary heat source] Heat pump type midnight electric water heater; rated COP: 3.8; heating power: 24.6 [kW] (average); heating temperature: 80 degC [Control] ・Flow passage control system (electric valve) installed ・Variable water volume control (PID) pump installed ・System for discharging water for preventing the freezing of the heat collector with air pressure ・Remote control function for heating at midnight
3. Floor heating equipment	Hot water circulating floor heating panel; about 45 m^2 (3 piping systems); specified floor surface temperature: 28 degC; specified return water temperature: 38 degC; variable water volume PID control
4. Desiccant dehumidifier	Silica gel rotor type + indirect evaporative cooling system; heat exchange efficiency of hot water coil: 0.8; Air flow volume: 600 m^3/h (outside air: 100 m^3/h + circulating air: 500 m^3/h), regenerative air flow volume: 500 m^3/h; variable water volume PID control
5. Hot water supply equipment	Washstands (mixing faucet): 2 piping systems; shower booth: 1 piping system

RESULTS OF FIELD MEASUREMENT

Fig. 2 shows the results of winter continuous measurement for the period from Jan. 24 to 26, 2008. The weather was fine, and the outside air temperature varied from sub-zero to 8 degC (Fig. 2). Hot water at a temperature of 30-50 degC is supplied from the bottom part of the hot water tank to the solar heat collector or the auxiliary heat source, and the temperature of each device is kept 50-65 degC or 80 degC. The water flow rate of the solar heat collection was up to 8 ℓ/min, and when the hot water amount in the tank decreased at dawn, the water was heated with the auxiliary heat source with water flow rate being up to 5 ℓ/min (Fig. 3). In addition, hot water was supplied to the floor heating equipment with water flow rate being 1-6 ℓ/min, while keeping the return water temperature at 38 degC (Fig. 4). The temperature of the water supplied to the floor heating equipment decreased, and the return water temperature decreased to less than 38 degC. Therefore, the control system was improved so that water is heated appropriately with the auxiliary heat source. Solar heat collection efficiency [3], which was calculated every hour from the incident solar radiation on the heat collection area and the solar heat collection amount, was 20-40% (Fig. 5). Table 2 shows the monthly total of heat output of the heat collector and the auxiliary heat source and heat consumption at the load side, solar heat collection efficiency, solar percent [4], and system COP [5] in the period from Nov. 2007 to Jan. 2008. Solar heat collection efficiency was about 30%, which indicates that solar heat could be gained effectively. From Nov. to Jan., outdoor air temperature decreased and floor heating hours increased [6], and so floor heating amount and heat loss of the water tanks increased. Accordingly, amount of heat for electrical auxiliary heating increased about two times between Nov. and Jan., and total heat output also increased. On the other hand, since amount of heat for solar heat collection decreases between Nov. and Jan., solar percent declined from about 55% in Nov. to about 29% in Jan. For the same reason, system COP declined from about 4.7 in Nov. to about 3.2 in Jan.

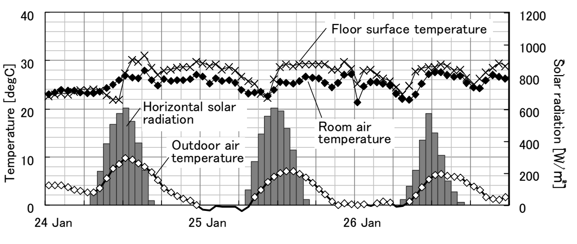

Figure 2 Outdoor air temperature, solar radiation and floor surface and air temperature in the room

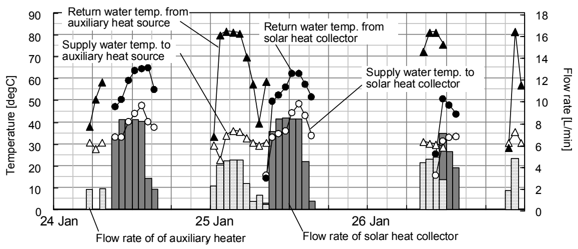

Figure 3 Supply and return water temperature and flow rate of solar heat collector and auxiliary heater

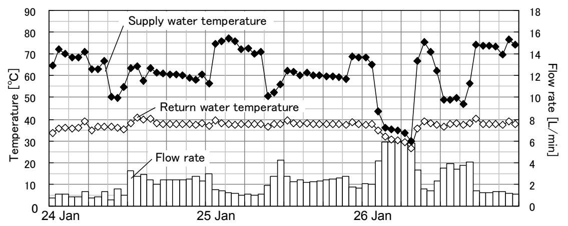

Figure 4 Supply and return water temperature and flow rate of floor heating system

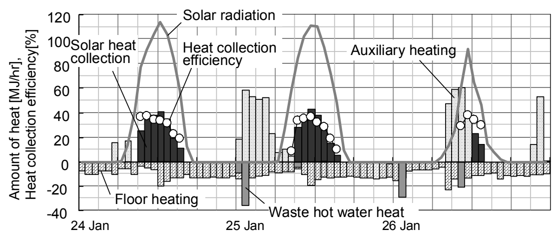

Figure 5 Heat balance and solar heat collection efficiency

Table 2 Monthly total of heat output and heat consumption at the load side

	Nov.	Dec.	Jan.
Incident solar radiation [GJ/month]	9.64	9.7	7.6
Amout of heat for solar heat collection [GJ/month]	3.2	2.92	2.14
Amout of heat for auxiliary heating [GJ/month]	2.58	4.91	5.17
Total heat output [GJ/month]	5.77	7.83	7.3
Amout of heat for floor heating [GJ/month]	-1.79	-4.19	-5.11
Amout of heat for hot water supply [GJ/month]	-3.45	-2.4	-0.67
Heat loss of water tank [GJ/month]	-0.53	-1.23	-1.52
Solar heat collection efficiency [%]	33.2	30.1	28.1
Solar percent [%]	55.4	37.3	29.3
System COP [-]	4.7	3.8	3.2

OUTLINE OF SIMULATION FOR SOLAR THERMAL SYSTEM

For simulation, the dynamic heat load calculation software TRNSYS16 was used, and a model was designed for the system shown in Fig. 1. The target system is composed of the 6 elements: a solar heat collector, thermal stratification hot water tanks, auxiliary heat source equipment, floor heating equipment, a desiccant dehumidifier, and hot water supply devices.

In the summer and intermediate seasons (May to Oct.), heat is collected in the high-temperature hot water tank at a high temperature (80 degC) as the heat source for desiccant regeneration. In the winter season (Nov. to Apr.), heat is collected in the low-temperature hot water tank at a low temperature (50 degC) as the heat source for floor heating. Only when solar heat is collected excessively, heat is collected in the high-temperature tank at a high temperature (80 degC). Water flow rate of solar heat collection is controlled so that heat collection temperature (return water temperature) is constant.

Table 3 shows the simulation conditions. The floor heating equipment selects the high-temperature or low-temperature tank to receive hot water according to the temperature of the upper part of the tank [7), and water flow rate is controlled with the return water temperature. For the desiccant dehumidifier, the hot water in the upper part of the high-temperature tank is supplied to the hot water coil inside the desiccant dehumidifier with a constant water flow rate. It was assumed that there is no heat load due to hot water supply.

The two cases were studied. In one case [8), solar heat collection amount is estimated on the following day, and midnight electrical heating time is controlled. In the other case [9), midnight electrical heating is not conducted, and reheating is carried out only when it runs out of hot water in daytime.

Calculation was conducted at 1 hour intervals for 1 year, with a one-month preliminary calculation. For meteorological data, Expanded AMeDAS Reference Weather Year of 2000 yr versions of Tokyo was adopted, and measured values were used for the input variables of each component. For example, the solar heat collection efficiency was given from the measurement result of Fig. 6.

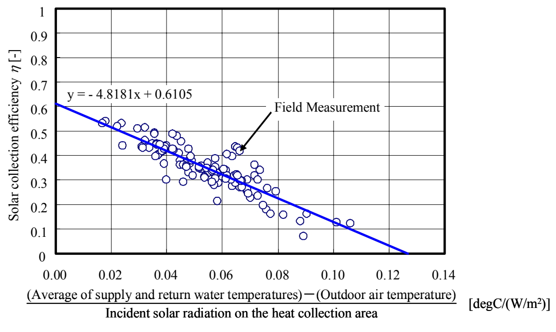

Figure6 Operational behaviors in winter

Table 3 Simulation conditions

1.	Solar Heat collector	Area: 30 m^2; solar heat collection efficiency: η = 0.61－4.18($\Delta\theta$ /I); $\Delta\theta$: (Average of supply and return water temperatures)－(Outdoor air temperature) [degC]; I : incident solar radiation on the heat collection area [W/m^2]; Heat collection temperature during the summer and intermediate seasons: 80 degC; Heat collection temperature during the winter season: 60 or 80 degC; Maximum water flow rate: 8.3 [ℓ/min]
2.	Hot water storage system	Capacity: 2,000 ℓ (Two 500-liter low-temperature tanks and two 500-liter high-temperature tanks are connected in series); thermal transmittance: 0.59 W/m^2 degC (thermal insulation); heating power of the auxiliary heat source: 24.6 [kW] (average); heating temperature: 80 [degC]; maximum water flow rate: 8.0 ℓ/min
3.	Floor heating equipment	Floor heating area: 45 m^2; operation time: 9:00-17:00 (winter only); specified floor surface temperature: 28 [degC]; specified returned water temperature: 35 [degC]; maximum water flow rate: 50 [ℓ/min]
4.	Desiccant dehumidifier	Operation time: 9:00-17:00 (summer and intermediate seasons only); heat exchange efficiency of hot water coil: 0.8; water flow rate: 2.5 ℓ/min; processing air flow rate: 600 m^3/h (outside air: 100 m^3/h + circulating air: 500 m^3/h), regenerative air flow rate: 500 m^3/h
5.	Others	Indoor air conditioner; operation time: 9:00-17:00 (summer only); specified room temperature in the summer season: 28 [degC]; total heat output in the room: 34.5 [W/m^2]; air ventilation: 2.0 [1/h] (including desiccant ventilation in summer)

RESULTS OF ANNUAL SIMULATION

Operational behavior of the simulation model

Figs. 7 and 8 show the winter and summer-time operational behaviors with the daytime reheating mode in the winter and summer seasons, respectively. The calculation and the above-mentioned measurement of the winter cannot be simply compared, because the duration of the floor heating is different. On Jan. 25, the temperature of the low-temperature tank was high, and so heat was collected with return water temperature being 80 degC. On Jan. 27, since heat was not collected on the previous day, the temperature of the low-temperature tank was low, and heat was collected with return water temperature being 50 degC. On a fine day (Jul. 17) in summer, heat was collected at 80 degC, and on a day with low solar radiation (Jul. 18), the hot water inside the tank was consumed through the heat was released at the hot water coil of the desiccant dehumidifier, and so reheating by the auxiliary heater was conducted frequently. Fig. 9 shows the summer-time operational behavior with the midnight heating mode. Operation was controlled appropriately according to solar radiation and remaining hot water amount on the following day, and reheating at daytime was not conducted.

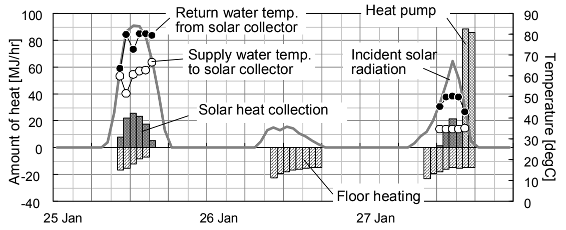

Figure7 Operational behaviors in winter (daytime reheating mode)

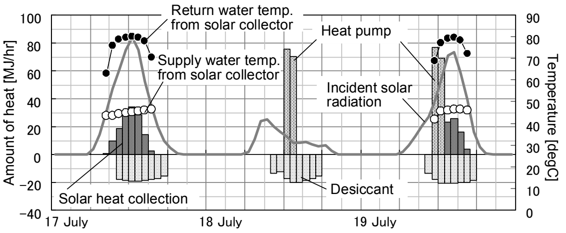

Figure 8 Operational behaviors in summer (daytime reheating mode)

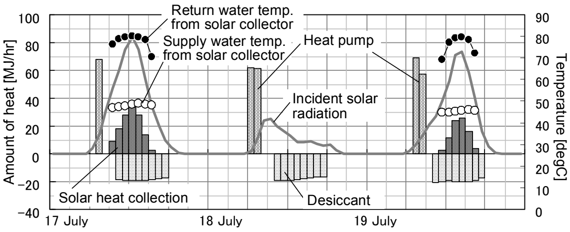

Figure 9 Operational behaviors in summer (midnight heating mode)

Solar percent

Fig. 10 shows monthly total heat balance and solar percent. In Apr. and Nov., heating load is low, and so the additional heating with an electrical heat pump was not conducted. Accordingly, collected heat covered total heat consumption, and solar percent was 100%. In the winter season, even in Jan. when outside air temperature is the lowest and floor heating is frequently used, amount of heat for the electrical heat pump was small and solar percent was as high as 82.9%. In the summer season, the heat release due to the desiccant operation increases and heat consumption augments, and so amount of heat for the electrical heat pump increased and solar percent decreased. In Aug., the weather was stable and the solar heat collection amount was large, and so solar percent was relatively high.

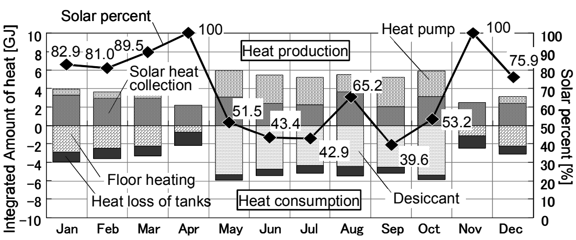

Figure 10 Monthly total heat balance and solar percent (daytime reheating mode)

Solar heat collection efficiency

Fig. 11 shows monthly solar heat collection amount and efficiency. Solar heat collection efficiency varied from 20 to 25% through the year. In Apr. and Nov. when heat consumption is low, the temperature of the entire tank becomes high, and so it is considered that the temperature of the water supplied to the solar heat collector increases and the solar heat collection efficiency declines. When there is the heat load due to the hot water supply, the temperature of the bottom part of the tank, which is supplied clean water, decreases to the temperature of the clean water, and then the solar heat collection efficiency increases. However, in this simulation, the heat load due to the hot water supply was not taken into account. Accordingly, the solar heat collection efficiency was lower than the results of the field measurements.

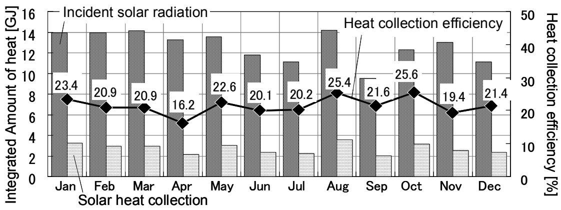

Figure 11 Monthly solar heat collection amount and efficiency (daytime heating mode)

System coefficient of performance (COP) and running cost

Fig. 12 shows system COP [10]. In the summer season in which the auxiliary heat source (Electric heat pump) is frequently used, system COP decreased, but its annual average was as high as over 4. In the winter season, the system COP with the midnight heating mode was lower than that with the daytime reheating mode, because of the heat loss at the water tank and excessive heating. It can be expected that by progressing midnight heating control programs, it is possible to optimize operation.

Fig. 13 shows the running cost of the system. The running cost was calculated under the assumption that cost is 14.17 yen/kWh during daytime (8:00-22:00) from Jul. to Sep., 12.81 yen/kWh during daytime from Oct. to Jun., and 7.45 yen/kWh during nighttime (22:00-8:00). In the summer and intermediate seasons in which the operation time of the auxiliary heat source is long, the running cost of daytime reheating is about 1,000 yen/month larger than that of midnight heating. The annual average cost was about 47,000 yen at daytime reheating and about 43,000 yen at midnight heating. The annual average cost of the midnight heating became to be about 9% lower than that of daytime reheating. It was found that the midnight heating is effective for reducing utility costs, although the system COP decreases slightly.

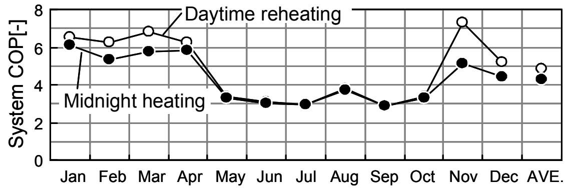

Figure 12 System COP (Comparison between daytime reheationg and midniht heating)

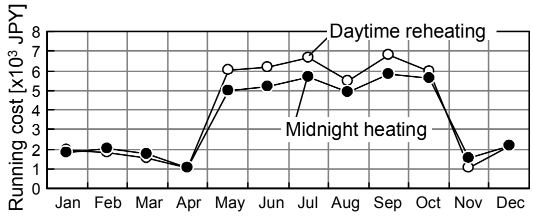

Figure 13 running cost of sysetem

CONCLUSION

A new solar thermal system was developed with the purpose of utilizing solar heat with high efficiency all year round. Field experiment facilities were constructed, and their outlines and the results of continuous field measurement in winter were summarized. In addition, annual simulation was carried out, with a model for field experiment facilities. Solar percent, solar heat collection efficiency, whole system COP, and running cost were calculated, and then performance of the solar thermal system was evaluated from simulation results. Annual system COP was as high as over 4, which indicates that this system is effective from the aspect of energy. In addition, it was found that it is possible to reduce running cost by about 9% by installing the midnight heating operation control based on the weather forecast of the following day. From now on, the authors plan to discuss the combination of midnight heating control and a desiccant dehumidifier, optimize the system further.

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ENDNOTES

1) As temperature is higher, dehumidification performance is better. A temperature of over 60 degC is necessary.
2) In this study, the desiccant dehumidifier is always driven in rating output, not controlled by the temperature and humidity of the supply air.
3) Solar heat collection efficiency [%] = Solar heat collection amount [GJ] / Incident solar radiation on heat collection area [GJ] × 100
4) Solar percent [%] = Solar heat collection amount [GJ] / Total heat output (Solar heat collection amount + Heat pump heating amount) [GJ] × 100
5) System COP [-] = Total heat output (solar heat collection amount + Heat pump heating amount) [GJ] / Total electric power consumption [GJ]
6) Operation time was 280 hours in Nov., while operation time was as long as 528 hours in Dec. and 522 hours in Jan.
7) When indoor air temperature is less than 22 degC, floor heating is started. If the temperature of the upper part of the tank 3 is over 45 degC (temperature of circulating water for floor heating + 10 degC), the system switches to the mode of floor heating with the low-temperature tank, in which water is supplied from the upper part of the tank 3. If the temperature is less than 45 degC, the system switches to the mode of floor heating with the high-temperature tank, in which water is supplied from the upper part of the tank 1.
8) The time for heating the water, whose amount is calculated by subtracting the remaining hot water amount and the water to be heated on the following day estimated from weather data from total tank capacity, and the operation of the electrical heat pump is started before 8:00 with the heating time to spare.
9) When the water temperature in the upper part of the tank 1 becomes less than 55 degC, the electrical heat pump is operated until the water temperature in the upper part of the tank 2 reaches 75 degC.
10) Electric power consumption was estimated from actual measurement data.

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