Exergy analysis of solar thermal energy utilization for buildings: comparison between Multiple source & Multiple use Heat Pump (MMHP) and Solar Water Heater (SWH) systems for winter season

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Abstract. In recent years, there are various utilization methods of solar thermal energy and it is hard to find which system is the best to utilize energy as work from the viewpoint of energy concept alone. Therefore, we conducted exergy analysis of two different solar energy utilization methods: one is a multiple source & multiple use heat pump we have developed; and the other is a conventional solar water heater. In order to clarify the performance gap depending on the solar radiation between the multiple source & multiple use heat pump and the solar water heater, exergy analysis was carried out on a clear-sky day and a daily average under the condition of equal exergy output. The results show that the performance of the solar water heater highly depends on the weather conditions, on the other hand, the multiple source & multiple use heat pump shows high performance regardless of the weather conditions.

1. Introduction

Energy analysis of a system based on the first law of thermodynamics is common in the field of building environmental engineering. However, energy analysis based on only the first law of thermodynamics, but exergy analysis considers both the first and second laws of thermodynamics. Thus, exergy analysis can quantify the wasted part of energy which is called as anergy and it enables us to quantify the efficiency of a system’s operation [1].

The utilization of natural energy is attracting attention as a counter measure against the depletion of fossil fuels and global warming issues. In particular, various methods of utilizing solar thermal energy have been studied from the viewpoint of energy. However, it is difficult to judge which system can effectively utilize solar thermal energy with energy analysis alone. Therefore, it is necessary to perform analysis from the point of exergy. In this research, we conducted exergy analysis of two solar energy utilization methods, both of which are connected with floor heating: one is a multiple source and multiple use heat pump (hereinafter, MMHP) [2] we have developed and the other is a solar water heater (SWH). By performing energy and exergy analyses under the condition of the same exergy output, the exergy utilization efficiency (output exergy / total input exergy), the natural exergy utilization efficiency (input exergy from nature / input power) [3,4], the conventional exergy efficiency (output exergy / input power) and the exergy consumption in both systems are investigated.

2. Basic theory of exergy [5]

In this research, we performed exergy analysis under a steady-state assumption. In the calculation, the outdoor air temperature was set as the environmental temperature which is regarded as a reference state. The governing equations for the steady-state exergy analysis are expressed in Equations (1) – (3).
Equation (1) is the energy balance equations that describes the first law of thermodynamics. Next, Equation (2) is the entropy balance equation based on the second law of thermodynamics. Lastly, the exergy balance equation expressed in Equation (3) can be obtained by calculating \([\text{Energy balance equation}] - \text{[Entropy balance equation]} \times \text{[Environmental temperature]}\).

\[
\begin{align*}
\text{Inflow energy} &= \text{Outflow energy} \quad (1) \\
\text{Inflow entropy} + \text{Generated entropy} &= \text{Outflow entropy} \quad (2) \\
\text{Inflow exergy} - \text{Consumed exergy} &= \text{Outflow exergy} \quad (3)
\end{align*}
\]

3. Outline of both systems

3.1. System overview of MMHP [2]

The MMHP is installed in an experimental house located on the Kashiwa campus of the University of Tokyo. Figure 1 shows the schematic of MMHP system and Table 1 shows the specifications of the MMHP. The water loop of the MMHP is connected with a sky-source heat pump (hereinafter, SSHP) and a ground heat exchanger (hereinafter, GHX), it supplies warm and cool heat to heating devices such as air conditioning and floor heating by exchanging heat. The water loop temperature is kept around 17 °C which is close to the ground temperature. The SSHP is a technology that can collect and reject thermal energy by using the solar panel as an evaporator and condenser, respectively. The detailed configuration of the panel is graphically presented in Figure 2. There is a solar heat collector on the top surface, a refrigerant passage at the center of the pipe with the fins that formed under the panel. The fins exchange heat with air by natural convection. The evaporative temperature of refrigerant is set higher than the outdoor air temperature during the heat collecting operation, and lower during the air heat collecting operation. Although PV cells are installed in the SSHP, in this research the power generation of PV cells is not considered. The SSHP and the GHX were used as heat sources, and only a floor heating heat pump (hereinafter, FHHP) was operated as a heating device. The performance of the MMHP was evaluated by using the measured data obtained from the thermal energy of the GHX and the SSHP.

3.2. System overview of solar water heater

| Table 1. Specifications of MMHP |
|---------------------------------|
| **SSHP**                        |
| Panel direction: South-facing   |
| Heat collecting area: 8 m²      |
| Refrigerant: R32                |
| Heat collecting capacity: 5 kW  |
| **GHX**                         |
| Type: double helix type         |
| Depth: 15 m                     |
| Number: 3                       |
| **FHHP**                        |
| Floor heating area: 47 m²       |
| Nominal capacity: 5 kW          |

Figure 1. Diagram of MMHP

Figure 2. Configuration of SSHP panel [2]
Figure 3 shows a simplified system diagram of the solar water heater and Table 2 shows the specification of the solar heat collector and the thermal storage tank. The efficiency of the solar heat collector was assumed to be a vacuum tube type. In order to fully utilize the solar heat, the solar water heater is equipped with a first thermal storage tank that stores hot water from 40 °C to 65 °C and a second thermal storage tank that stores hot water from 40 °C to 90 °C. At first, the solar heat is stored in the first thermal storage tank, then it is stored in the second thermal storage tank when the hot water temperature of the first thermal storage tank exceeds 65 °C. In addition, when the hot water temperature in the thermal storage tank falls to 40 °C or lower, an auxiliary heating is taken until it reaches 45 °C by using the heat pump water heater as an auxiliary heat source.

Figures 4 and 5 show examples of operating conditions of the solar water heater. In the daytime, the solar heat is collected by the solar heat collector in the first thermal storage tank, and the heat is extracted from the first thermal storage tank and supplied to the floor heating system (Figure 4). Also, when the hot water temperature in the first thermal storage tank falls to 40 °C or lower, the auxiliary heating of the heat pump water heater is performed until it reaches 45 °C, it is to prevent the hot water temperature in the first storage tank from significantly decreasing (Figure 5).

### Table 2. Specification of solar water heater

| Component          | Specification                            |
|--------------------|------------------------------------------|
| Solar heat collector | Heat collecting area: 8 m² Amount of refrigerant: 3.5 ℓ Type: Vacuum tube |
| Thermal storage tank | Amount of water: 300 ℓ Two of the heat storage tanks Thermal insulation performance: $K_A = 2.85$ W/K |
| Auxiliary heat source | COP=3 (CO2 Refrigerant) |

3.3. Overview of ambient conditions and floor heating operation

We compared the solar water heater and the MMHP on the basis of a weekly average (March 20th – March 26th, 2018) and also on the basis on March 25th which was the sunniest day in March, 2018. Ambient conditions such as outdoor air temperature, solar radiation on inclined surface and so on were measured at one-minute intervals. Figures 7 to 9 show the operating data of the SSHP, the GHX, and the solar heat collector. Regarding the solar heat collector, the amount of energy and exergy gain varies depending on the solar radiation. On the other hand, the amount of energy and exergy of the SSHP and the GHX is comparatively stable regardless of the weather conditions throughout the week.
Both systems supply the heat only to the floor heating and the total exergy output of the floor heating was set equal for both systems. Figure 10 shows the schedule of the floor heating operation of both systems on March 25th. Both systems supply the heat to only the floor heating and the total exergy output of the floor heating was set equal for both systems. Since the exergy output of the floor heating of both systems is equal, the energy output of the solar water heater was smaller than that of the MMHP as the hot water supply temperature of the solar water heater was higher. The floor heating of the solar water heater was set to keep the floor surface temperature at 27 °C, and the FHHP outputted to floor heating so that the floor surface temperature could be maintained between 21 °C and 23 °C by setting the hot water supply temperature at 27 °C.

4. Results
The results of the MMHP are obtained from the field experiment while that of the solar water heater are attained from calculations under the same weather and room conditions. The pressure loss of the pipe was considered as the same condition in both systems. Figures 11, 12 and Table 3 show the exergy consumption patterns and the amount of exergy consumption of both systems (MJ) on March 25th and...
with the weekly average (March 20th – March 26th). Since the outdoor air temperature of the week (March 20th – March 26th) was lower than that of March 25th, in order to maintain the room temperature, the weekly average exergy output of the floor heating of both systems was larger than on March 25th. The exergy consumption of the FHHP was the largest in the MMHP. The exergy consumption of the FHHP was 45.5% on March 25th and 39.6% with the weekly average for the total exergy consumption in the MMHP. This is because the FHHP was operated so that the floor surface temperature was always maintained between 21°C and 23 °C, the operation time was longer than the other systems of the MMHP. On the other hand, the exergy consumption of the thermal storage tank was the largest in the solar water heater. The reason for this is that the exergy consumption due to heating operation by the heat pump water heater and the movement of heat in the thermal storage tank was performed intermittently. The exergy consumption of the thermal storage tank was 64.0% on March 25th and 74.1% with the weekly average for the total exergy consumption in the system.

Table 4 and 5 show the heat gain, the heat output, the daily total power input of both systems and each evaluation index of both systems on March 25th and with the weekly average. The daily total power input of the MMHP and the solar water heater were 3.81 kWh and 3.63 kWh on March 25th, which was a fine day, but the weekly average total power input of the MMHP and the solar water heater were 5.75 kWh and 7.86 kWh, the total power input of the MMHP was smaller than that of the solar water heater. Nevertheless, the weekly average natural exergy of the solar water heater and the MMHP were 9.88 MJ and 4.87 MJ, the solar water heater input more the electric power than that of the MMHP. The reason can be explained as the exergy utilization efficiency of the solar water heater and the MMHP were 24.56% and 36.66%, so that, the total exergy consumption of the solar water heater was larger than that of the MMHP. Since the natural exergy gain of the solar water heater was affected by the weather condition, there was a difference of natural exergy gain between 19.19 MJ (March 25th) and 9.61MJ (the weekly average). Also, the natural exergy utilization efficiency and the conventional exergy efficiency of solar water heater depend on solar radiation. Regarding the MMHP, the natural exergy gain from the SSHP and the GHX is 4.20 MJ on March 25th and 4.87 MJ with weekly average, and the MMHP obtained the amount of the natural exergy regardless of the weather condition, the natural exergy utilization efficiency and the conventional exergy efficiency of the MMHP on March 25th did not differ significantly from those as the weekly average. The amount of natural exergy acquisition of the MMHP is insulated from the influence of the weather condition. Since MMHP acquires geothermal heat from the GHX and the solar heat and atmospheric heat from the SSHP stably, similar results are obtained between on March 25th and with the weekly average in any of the evaluation index.
5. Summary
Exergy analyses on the multiple source & multiple use heat pump (MMHP) and the solar water heater were conducted to investigate the utilization of solar thermal energy. Considering the influence of solar radiation equally, both systems were compared on clear-sky day (March 25th) and on a weekly average (March 20th – March 26th).

The results of this research are listed below:

1) Under the condition of the same exergy output quantities in both systems, the solar water heater required less total power on March 25th, which was the sunniest day of March 2018. But, regarding the weekly average, the total power input of the MMHP was less than that of the solar water heater.

2) The solar water heater acquired natural exergy of 19.73 MJ on March 25th and 9.88 MJ as the weekly average. The amount of natural exergy was dependent on the weather condition. As a result, the system performance of the solar water heater differed quite a lot. Since exergy consumption in the system is larger, the exergy utilization efficiency was less than that of the MMHP. Also, the exergy consumption of the thermal storage tank was the largest in the solar water heater.

3) From the SSHP and the GHX, the MMHP utilized natural exergy of 4.20 MJ on March 25th and 4.87 MJ as the weekly average, the MMHP acquired the natural exergy consistently regardless of weather conditions. Therefore, all the evaluation indices were not much different on either case of on March 25th or the weekly average. The MMHP shows high performance from the view point of energy and exergy.

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