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Solar Energy 78 (2005) 427–440
SOLAR ENERGY
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A study on the design and analysis of a heat pump heating system using wastewater as a heat source

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Received 10 December 2003; received in revised form 3 March 2004; accepted 21 July 2004
Available online 11 September 2004

Communicated by: Associate Editor Joseph Khedari

Abstract

In this study, the compression heat pump system using wastewater, as a heat source, from hotel with sauna was designed and analyzed. This study was performed to investigate the feasibility of the wastewater use for heat pump as a heat source and to obtain engineering data for system design. This heat pump system uses off-peak electricity that is a cheap energy compared to fossil fuel in Korea. For this, the charging process of heat into the hot water storage tank is achieved only at night time (22:00–08:00). TRNSYS was used for the system simulation with some new components like the heat pump, which we create ourselves.

As a result, it was forecasted that the yearly mean COP of heat pump is about 4.8 and heat pump can supply 100% of hot water load except weekend of winter season. The important thing that should be considered for the system design is to decrease the temperature difference between condenser and evaporator working fluids during the heat charging process by the heat pump. This heat pump system using wastewater from sauna, public bath, building, etc. can therefore be effectively applied not only for water heating but also space heating and cooling in regions like as Korea.

Keywords: Heat pump; Hot water heating; Wastewater; Off-peak electricity; TRNSYS

1. Introduction

Wastewater discharged from saunas and public baths is relatively adequate in quantity and temperature and thus can be used as an efficient heat source for a heat pump (KEPRI, 1998). A heat pump system using wastewater as a heat source allows to use low-cost off-peak electricity, has no outdoor unit to make noise or spoil the appearance of the building where it is installed, and combines cooling/heating and hot water heating in a single unit. In addition, it has outstanding energy saving effect since it is operated at high COP without air pollution. Several types of heat pump systems are widespread in northern developed countries (Stuij and Stene, 1994). In Japan (Baek et al., 2001), a simulation study of district cooling/heating systems using sewage water as an energy source shows that, compared with conventional air-source heat pumps, wastewater source heat pumps

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0038-092X/$ - see front matter
doi:10.1016/j.solener.2004.07.009

Nomenclature

M_{day}	water consumption during day (peak time) (m^3)
T	temperature (K)
V	storage tank volume (m^3)

Greek symbols

η	rate of the thermal storage to daily heating load
γ_i	control function
Δ	dead band

Subscripts

co	condensing
ev	evaporating
hw	hot water
i	inlet
o	outlet
set	setting value
sto	storage
wst	wastewater

could help reducing energy consumption by 34%, lowering the emission of carbon dioxide (CO_2) by 68% and controlling the generation of nitrogen oxides (NO_x) by 75%.

The purposes of this study are to evaluate the efficiency and design of a heat pump hot water system that operates during night time hours and uses as a heat source, wastewater discharged from saunas and public baths, to investigate the properties and potential amount of wastewater discharged from hot spring and accommodation facilities in Yuseong area (KIER, 2001), and to perform design and analysis of a heat pump water heating system based on the investigation.

2. System design

A heat pump system using off-peak electricity is a water heating system designed to heat low-temperature (about 301 K) hot spring water during night time hours (22:00–08:00) and use, as a heat source, its wastewater stored in a wastewater storage tank (hereinafter abbreviated as WST). Heated spring water is stored in a hot water storage tank (hereinafter abbreviated as HWST) and supplied when needed.

2.1. Hot water heating load and wastewater amount

In this study we used the heat pump system of the Hotel "K" that uses hot spring wastewater as a heat source (hereinafter abbreviated as HPSW). Hotel "K" is a large hotel with a total area of 19,977 m^2, 2 basements, 10 floors, 144 rooms, and sauna facilities. The hotel's cooling/heating facilities include two 450RT double effect absorption chillers, three 4 ton/h steam boilers, and a single 425 ton wastewater tank. The hotel's basements contain two sets of a 0.424 m^3 WST and a 0.115 m^3 HWST for the hotel's own uses and for use of sauna, respectively.

The hotel supplies both low (301 K) and high (319 K) hot spring water temperature, 62.5% of which is low-temperature. The system's water heating load is the amount of energy needed to heat low-temperature hot spring water to a higher level of temperature.

Table 1 shows the mean consumption of low-temperature spring water used for every 2 h each day of the week during winter (November–February). There is a notable difference between the mean consumption of hot water used on week days (282 m^3) and on weekends (366 m^3). It was found that the hot water consumption during spring (March–May) and during fall (September–December) was respectively 75% and 50% of the consumption during winter as a result of investigation. The pattern of thermal water use by time of the day was nearly identical to that seen in winter. Critical to determining the capacity of the storage tank for this system is the hourly distribution and the ratio of hot water consumption during peak-off time (22:00–08:00) and peak time (08:00–22:00), which was founded to be 22%:78%, as shown in Table 1.

As described above, the system hot water heating load is the amount of energy needed to heat low-temperature thermal water to a higher level of temperature. Table 2 shows the daily hot water heating loads needed to supply hot water for the Hotel "K". The temperature of hot water supplied is set to be 323 K.

2.2. Design of a heat pump system (KOPEC, 1996)

Existing water heating system with HWST, where an oil or electric heater is used to heat water, minimizes the capacity of the storage tank by storing high-temperature hot water. However, the heat pump is not capable of producing hot water at a temperature of over 328–333 K. Like this system, systems that require an instant supply of hot water exceeding the heating capacity require a storage tank to play the role of a buffer tank. In case there is an adequate amount of thermal water, it is desirable that the storage temperature should be set at a temperature to allow supply of hot water without mixing with cold water (city water).

Table 1
Amount of hot water consumption (m^3) for every 2 h each day of the week during winter

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Mean	Ratio	Remarks
22–0	28	29	41	16	57	62	0	33.3	0.068	Night time
0–2	10	0	0	0	0	0	0	1.4	0.003	
2–4	0	0	0	0	0	0	0	0.0	0	
4–6	42	24	37	36	37	26	29	33.0	0.067	
6–8	36	42	37	29	37	46	38	37.9	0.077	
8–10	43	29	49	42	52	58	90	51.9	0.106	Day time
10–12	42	62	58	39	41	84	88	59.1	0.121	

Table 2
Daily hot water heating loads (10^3 MJ)

Season	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Mean	Remarks
Winter	24.9	26.2	27.5	23.9	27.2	33.1	34.2	28.1	
Spring/autumn	18.7	19.7	20.6	17.9	20.4	24.8	25.6	21.1	75% of winter
Summer	12.5	13.1	13.8	11.9	13.6	16.6	17.1	14.1	50% of winter

The following formula applies for calculating the thermal storage capacity (V_{sto})

$$V_{sto} = M_{day} * \eta, \quad (1)$$

where M_{day} is the daily hot water consumption (or load) (ton), and η is the rate of the thermal storage to daily heating load.

The temperature of hot water supplied by this system is below 298 K, so both heating load and the amount of hot water in storage should be considered simultaneously when calculating the thermal storage rate, η.

Fig. 1 shows a diagram of the system, which is consists of a heat pump, a storage tank, a wastewater filtering device, etc. When η is less than 1, this system is called "partial thermal storage mode" which can be operated the heat pump in day time if it is necessary.

The design conditions to determine the capacity of each major component of the system are presented in Table 3. This is based on the amount of hot water used during the intermediate seasons when hot water is used for the longest time.

Hot spring wastewater discharged from buildings is passed through a filtering device before entering the WST. Once the heat pump is operated during night time, the high-temperature wastewater in the top of the WST flows into the evaporator and undergoes heat exchange to lower its temperature. Then, the low-temperature wastewater flows again into the bottom of the WST. The low-temperature spring water in the bottom of the HWST flows into the condenser is heated up and then flows again into the top of the HWST. At this time, wastewater circulates into the evaporator, which may lead to evaporator contamination (scale accumulation). To prevent it, a brush-type heat-exchanger cleaner is installed in the evaporator.

Wastewater flows in through the top of the WST and flows out as overflow from the bottom. Low-temperature spring water flows into the HWST through the bottom and flows out from the top. In order to improve the COP of the heat pump and increase the heat storage and discharge efficiency of the HWST, diffusers designed for thermal stratification within the tank should be attached to all the pipes connected to the HWST and the WST.

2.2.1. Heat pump control

The control of heat pump operation is done by detecting the temperature of hot water in the bottom of the HWST and the temperature of wastewater in the top of the WST. Details are as follows.

- When the heat pump is turned ON ($\gamma_i = 1$).

[(Time 22:00–08:00)$\wedge(T_{wat} \geqslant T_{wat.set})\wedge(T_{wat} \geqslant T_{wat.set})$]
Then
γ_i=1
Otherwise
γ_i=0(Heat pump OFF)

- When the heat pump is turned OFF ($\gamma_i = 0$).

[(Time 22:00–08:00)$\wedge(T_{wat} < T_{wat.set})\wedge(T_{hw} > (T_{hw.set} - \Delta T_{hw}))$]
Then
γ_i=1
Otherwise
γ_i=0(Heat pump OFF)

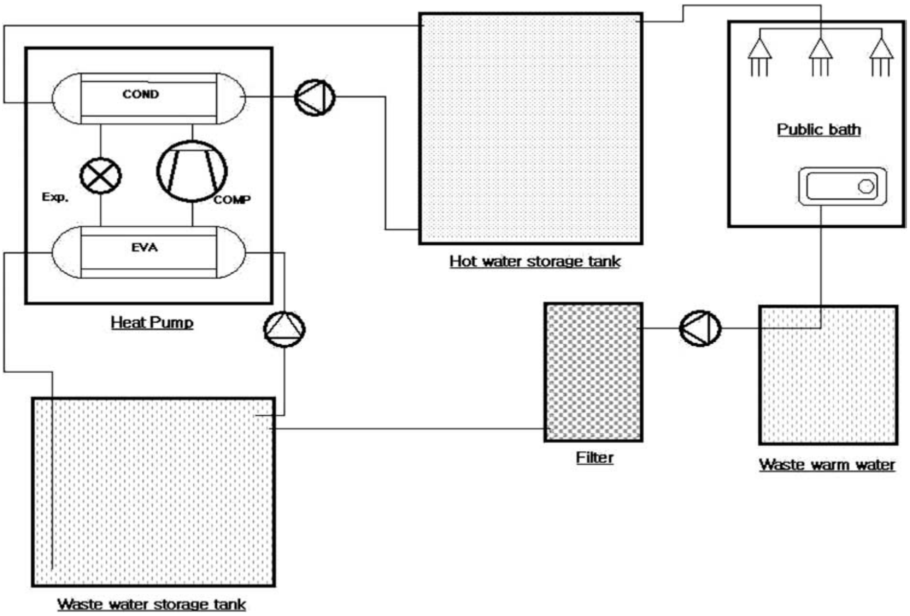

Fig. 1. Schematic diagram of heat pump system with HWST.

Table 3
Design conditions

Item	Design condition	Remarks
Heating temperature	323 K	
Daily hot water consumption	229.5 m^3	Spring/autumn
Daily heating load	88,235 GJ	Weekday: 4655, weekend
Heat storage rate	100%	Day time load rate: 78%
COP	5.0	Wastewater temperature: 291 K; hot water temperature: 323 K
Wastewater recuperation rate	150%	Recuperation of wastewater (water consumption)
Wastewater temperature	301 K	

where γ_i is the control function, T_{hw} the bottom temperature of HWST, $T_{hw,set}$ the storage setting temperature, T_{wst} the upper temperature of WST, $T_{wst,set}$ the setting temperature of WST, ΔT_{wst} the dead band temperature (=3 K), and ΔT_{hw} the dead band temperature (=5 K).

2.3. Heat pump performance

The performance of the heat pump was evaluated based on the performance data provided by a heat pump manufacturer. For simulation purposes, it is represented in the following formula (Baek, 1994).

$$\mathrm{COP} = a_0 + a_1 T_{ev} + a_2 T_{ev}^2 + a_3 T_{co} + a_4 T_{co,o}^2 + a_5 T_{ev} T_{co,o}, \quad (2)$$

where a_0 = 1.087197467509E+01, a_1 = 2.087855864386E−01, a_2 = 1.023086839024E−03, a_3 = 2.084584766312E−01, a_4 = 1.333333651207E−03, a_5 = 2.705972535643E−03, T_{ev} is the evaporating temperature (K), and $T_{co,o}$ the water temperature of condenser outlet (K).

2.4. Capacity of system components (KOPEC, 1996)

As this system is designed to heat all hot water heating loads during the intermediate seasons at night time hours from 22:00 to 08:00, the capacity of the heat pump should therefore be sufficient to produce the heat capacity corresponding to the design loads generated for 10 h. In addition, as this system uses heat recuperated from the WST to produce hot water, the appropriate capacity and hot water heating temperature and the temperature of wastewater to be used should be determined by considering the energy balance between the HWST and the WST. Considering that hot wastewater used as a heat source is generated in proportion to the use of thermal water during day hours, it is desirable to have suffi-

Table 4
Capacities of major components

Components	Capacity	Remarks
Hourly HP	2533 MJ	Daily hot water load=21,109 MJ; allowance =20%/R-134a
HWST	200 m^3	The optimum capacity is 179 m^3 (12% higher)
WST	280 m^3	
Water flow rate in condenser	120,000 $kg\,h^{-1}$	Pump capacity: 7.5 kW
Wastewater flow rate in evaporator	93,200 $kg\,h^{-1}$	Pump capacity: 5.5 kW

cient WST capacity to utilize wastewater during night time hours.

Table 4 shows the capacity of each major component of the system. Each capacity was measured according to the design conditions specified in Table 3.

When the system is designed to such specifications, the hourly mean charging and discharging storage for design loads for intermediate seasons has the distribution as shown in Fig. 2.

Fig. 3 is a comparison of the accumulated amount of loads with that of thermal charging energy according to season of the year. Under the same design conditions, the rate of dependence on thermal charging energy for winter loads is 75%. It is expected that, in the intermediate and summer seasons, 7–7.5 h of charging during night time hours will satisfy 100% of the day time loads.

3. Energy analysis

3.1. System configuration for simulation (Baek, 1994)

This study employed the well-known TRNSYS 14.1 as a simulation tool for theoretical analysis. Fig. 4 shows the configuration of the TRNSYS desk for the overall system. To simulate the heat pump component, we developed a new component named Type 95. For system control, Type 49 (microprocessor controller) was used which allows multi-factorial control.

3.2. Operation control

A change in the heat pump operation conditions (condensing and evaporating temperatures) leads to a change in the heat pump cycle. In this system, the

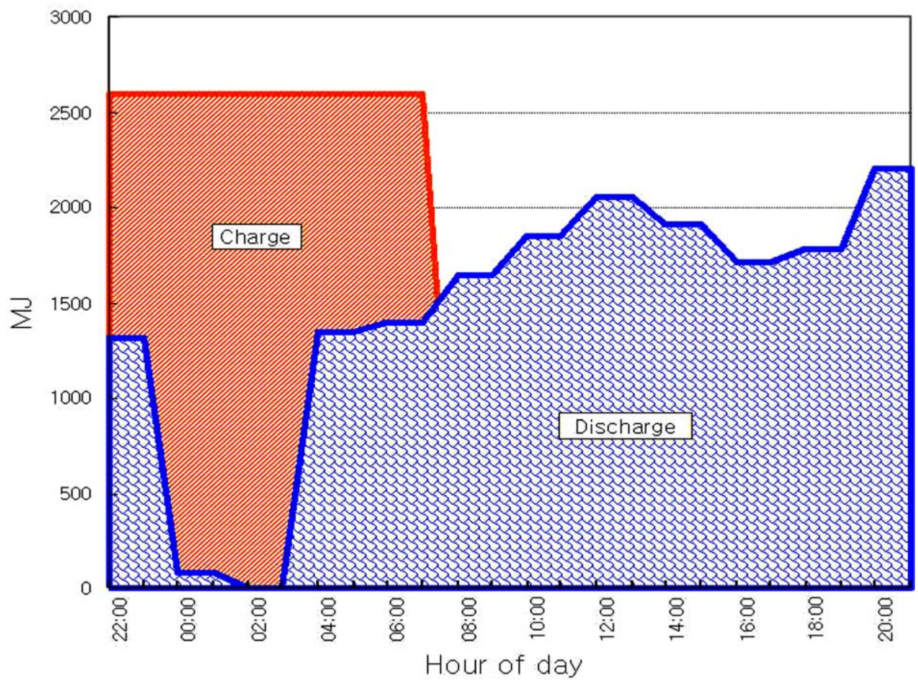

Fig. 2. Hourly charged into and discharged from HWST.

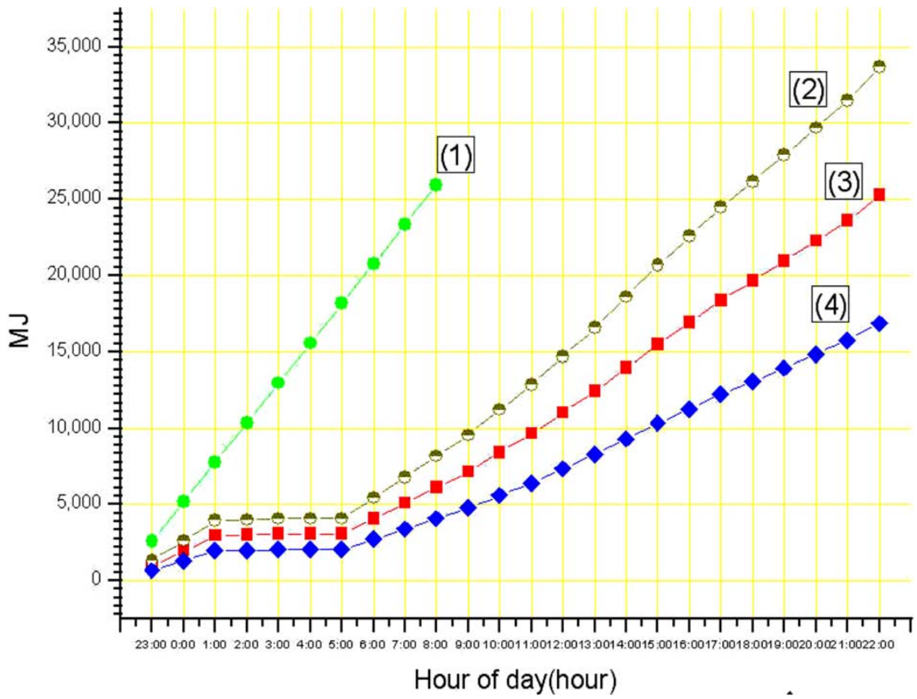

Fig. 3. Comparison of daily accumulated thermal charging into and discharging from storage according to season (1) accumulated amount of thermal charging (2)–(4) accumulated amount of heat loads respectively in winter, spring and autumn, summer season.

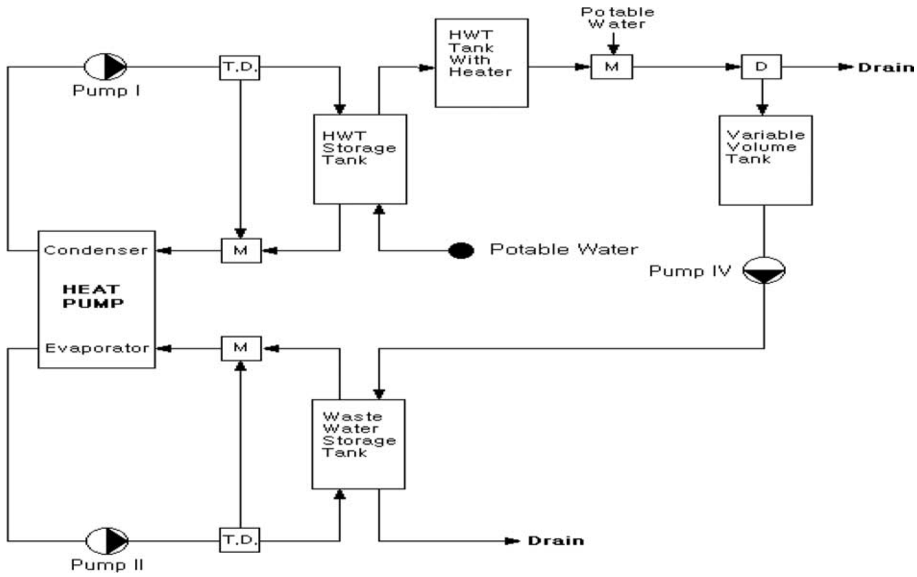

Fig. 4. TRNSYS simulation model.

temperature of the accumulator goes high after the operation of the heat pump while the condensing temperature goes much higher owing to thermal water recirculated to the condenser. On the contrary to this, the temperature of the evaporator goes down gradually as the wastewater in the WST circulates to the evaporator. Taking into consideration these operating characteristics of this heat pump system, the two following operating methods have been established (Fig. 4).

3.2.1. Operating method I

The first operating method is to heat the water in the accumulator by circulating a constant flow of water in the accumulator and WST directly to the condenser and evaporator. As a result, the operating conditions are changed.

3.2.2. Operating method II

The second operating method is to maintain the condenser outlet water temperature at a constant level. Changes in condensing temperature can be minimized by maintaining the temperature of hot water flowing into the HWST above a certain level and re-circulating a part of hot water when the temperature is less than that.

3.3. Energy analysis

Simulations for energy analysis of the system were performed for one year from October 1 to September 30. System control was done based on "Operating Method I" and the time step (Δt) was set to 15 min.

The temperature of thermal water remains constant regardless of seasons, therefore the heating loads vary according to thermal water load. In the case of Hotel K, the day time hot water load pattern remains constant through the seasons, so the system's thermal behavior has a recurring cycle of one week in each season.

Figs. 5–7 show the system's thermal behavior for one week in each season in term of the hot water temperature of the condenser outlet (1), the mean temperature of the HWST (2), the bottom temperature of the WST (3), the wastewater temperature of the evaporator inlet (4), and COP (5). Under the control conditions, the heat pump operates during night time. During day time the temperature of the HWST goes down due to the supply of low-temperature thermal water, while the change of temperature of the WST exhibits a weekly cycle. One of the heat pump's operating conditions, temperature changes in thermal water and wastewater flowing into the condenser and evaporator vary with time, which implies that changes in COP vary widely over time.

The system's behavior on a weekday (Wednesday 22:00–Thursday 22:00) and weekend (Saturday 22:00–Sunday 22:00) in each season was examined in order to monitor more closely the status of the heat pump operation. The results are given in Figs. 8–13. Regardless of the temperature before the beginning of the night time hours, the final temperature of the hot water HWST increased to 323 K during night time hours. This implies that the heat pump has a sufficient design capacity.

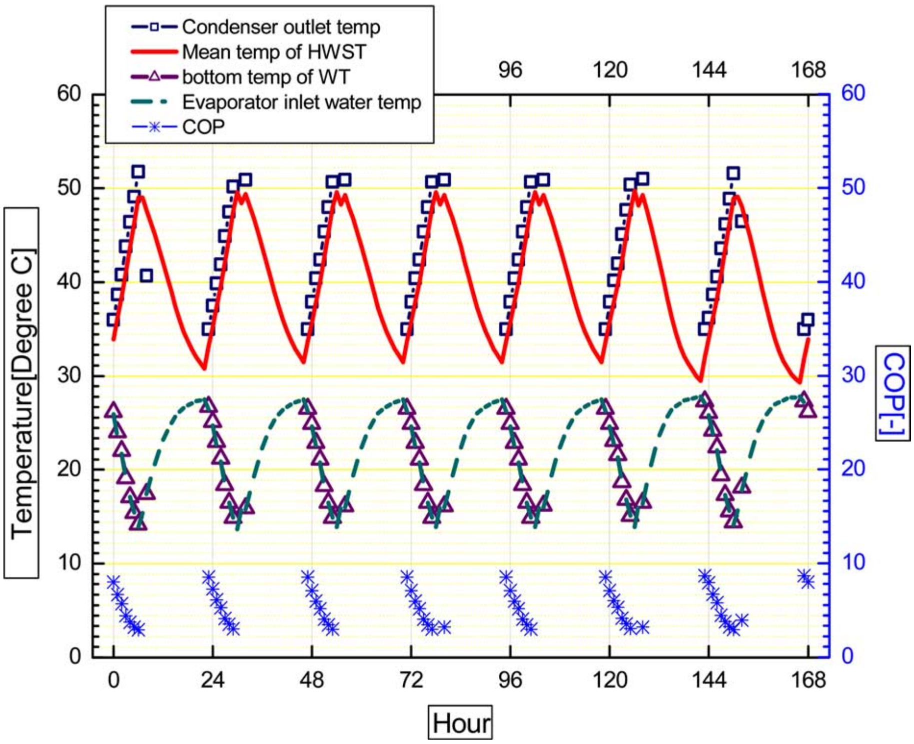

Fig. 5. Operating status for 1 week in spring and autumn.

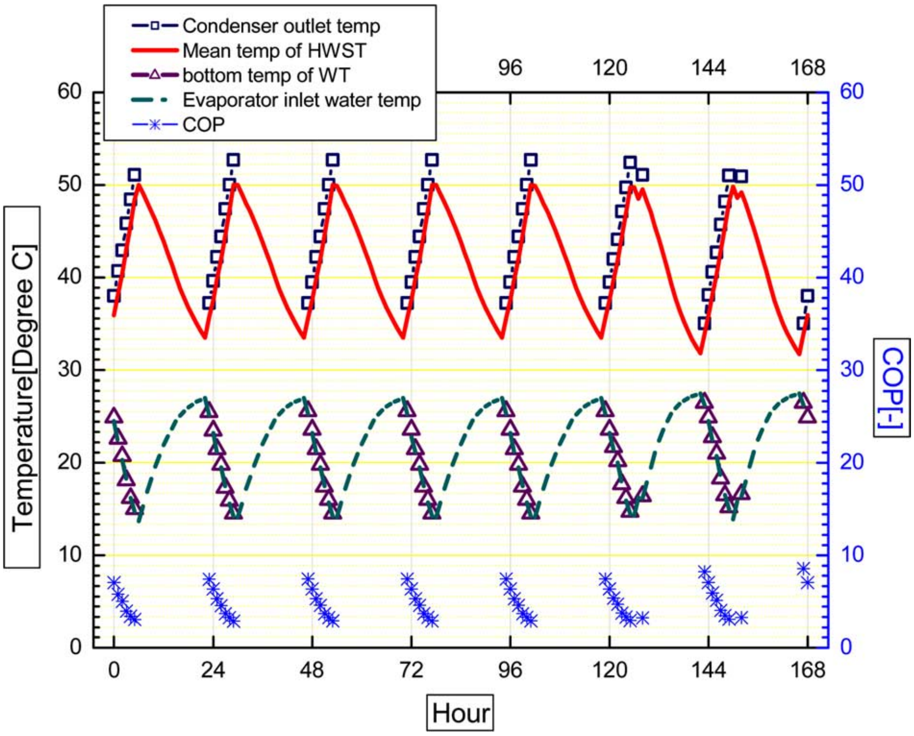

Fig. 6. Operating status for 1 week in spring and autumn.

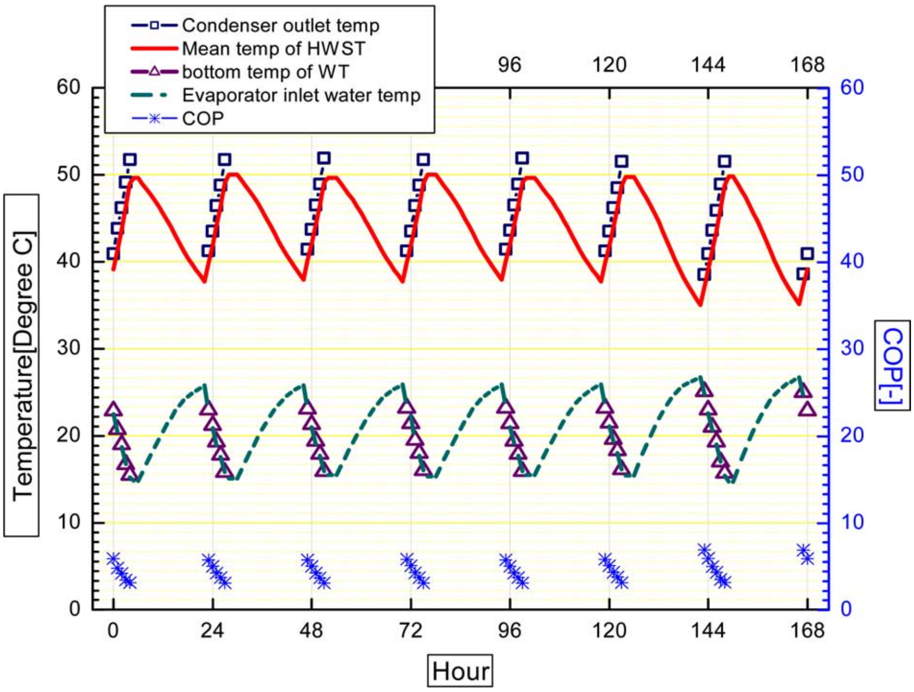

Fig. 7. Operating status for 1 week (summer).

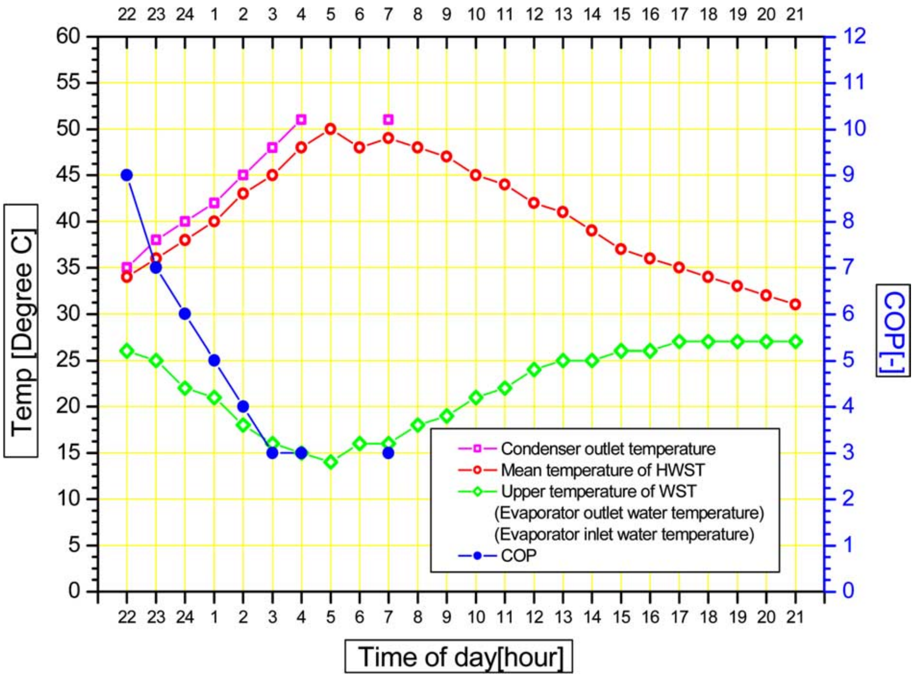

Fig. 8. Heat pump COP and operating temperature in weekday (July in winter).

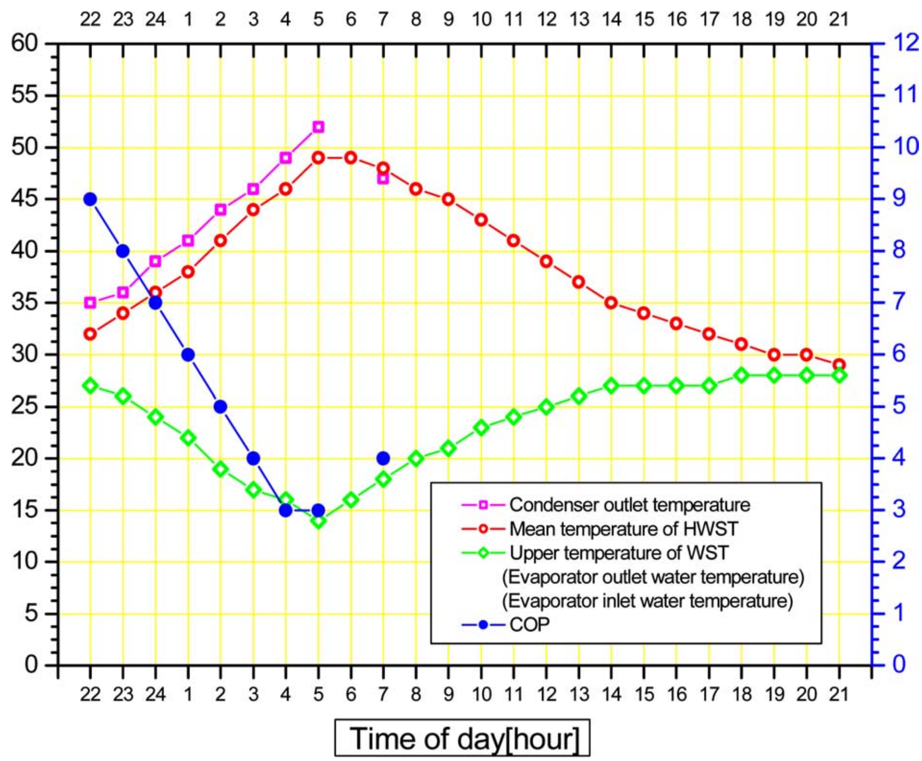

Fig. 9. Heat pump COP and operating temperature in weekend (winter).

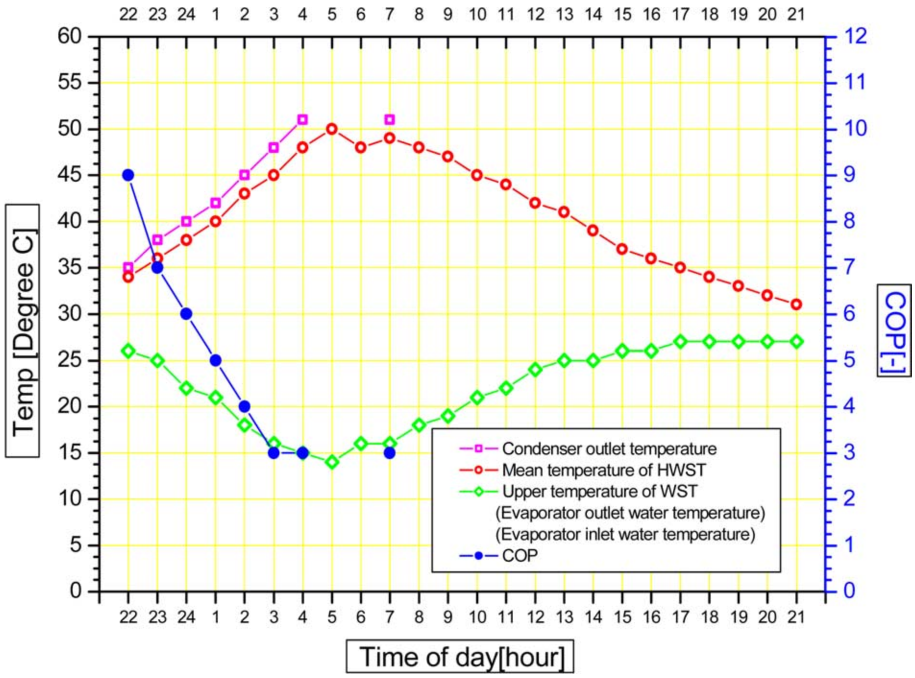

Fig. 10. Heat pump COP and operating temperature in weekday (July in spring and autumn).

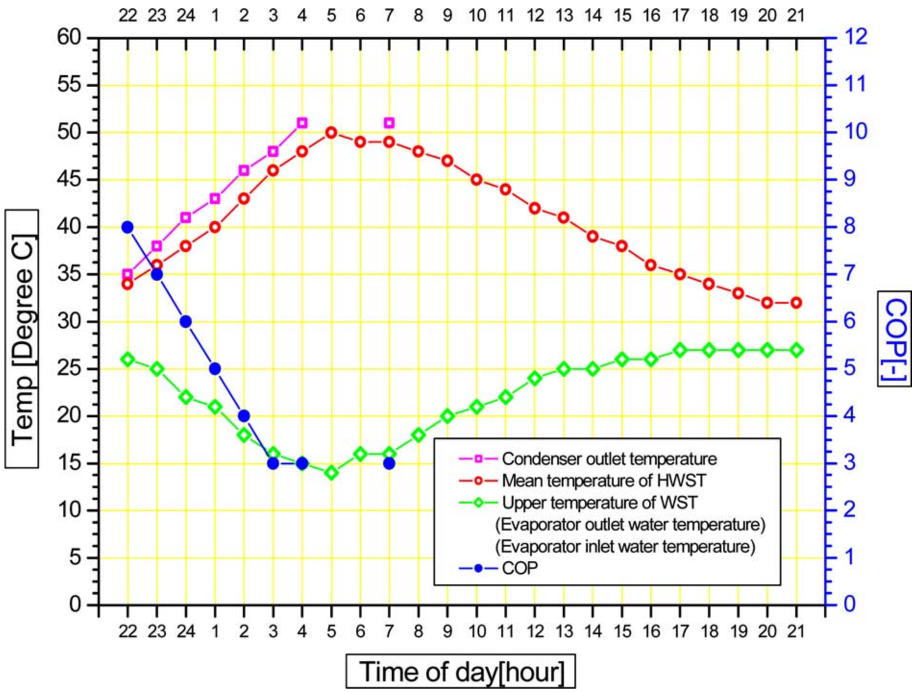

Fig. 11. Heat pump COP in weekend (spring/autumn).

It was found that the heat pump's daily operating hours were 8.4 h on weekdays and 8.8 h on weekends in winter, and 5.2 h on weekdays and 6 h on weekends in summer. This indicates that the operating hours var-

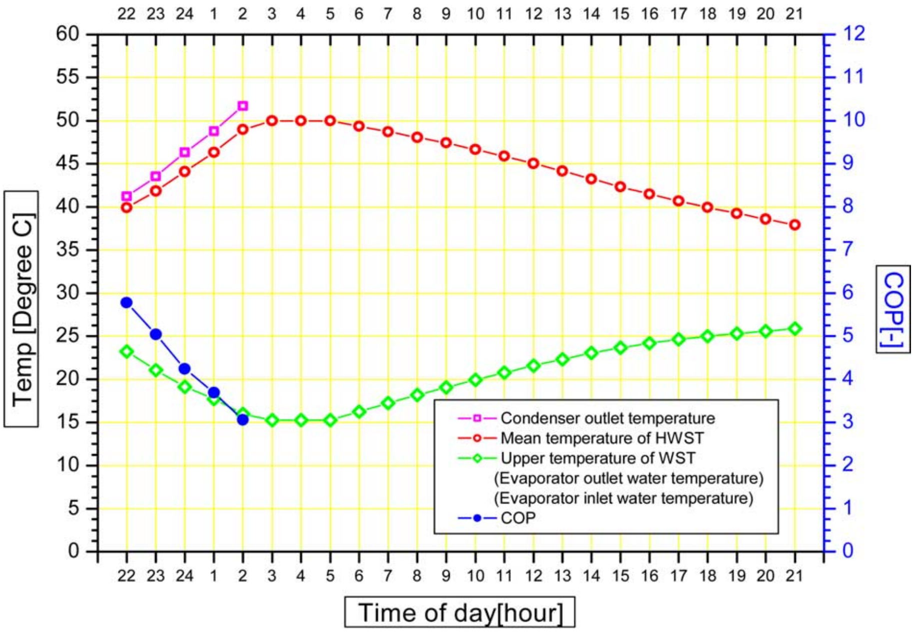

Fig. 12. Heat pump COP in weekday (summer).

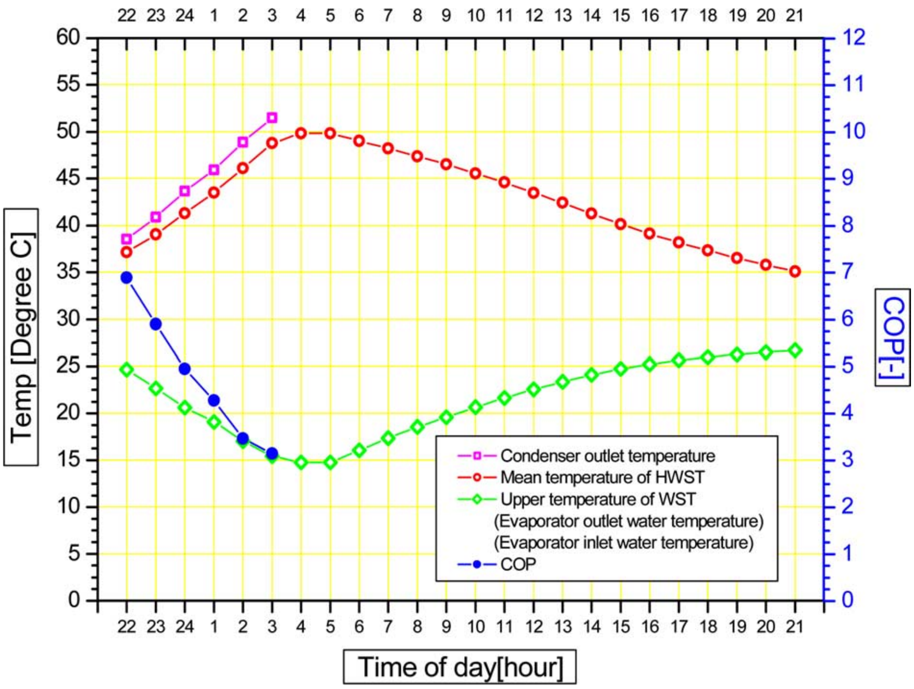

Fig. 13. Heat pump COP in weekend (summer).

ied according to the hot water load during day time hours.

It was also found that the heat pump's COP was 8.4 in maximum at the beginning of operation during night time hours but was later decreased to 2.9 in minimum at the end of charging storage. This is indicative of the irregular operation of the heat pump, which is the problem of "Operating Method I" that uses relatively simple control methods. In the case the range of change is extremely wide, "Operating Method II" should be employed, which can control the temperature of hot water and wastewater flowing into the heat pump's condenser and evaporator.

The COP of the heat pump performance is lower in summer than in other seasons. In particular, the performance is noticeably low at the beginning of operation. As a result of comparing the thermal behavior of the accumulator and the waste tank, the waste tank showed a constant temperature distribution regardless of seasons. When heat accumulation was completed, the temperature of the top of the waste tank decreased to 286 K, but then increased to 301 K with the influx of spring wastewater during night time hours. On the other hand, the minimum temperature of the accumulator showed differences according to hot water load during day time hours. The HWST temperature was 29° on weekends in winter but it was 38° on weekdays in summer when the hot water load is minimum, showing a difference of 9° between them. An increase of residual thermal energy in HWST leads to not only an increased heat loss of the HWST but also decreased performance of the heat pump. Therefore, adequate control of HWST temperature should be considered for this system.

3.3.1. Monthly and seasonal energy balance analysis

Table 5 shows a comparison of the results of energy analysis by weekdays, weekends and seasons. It was found that the heat pump produced almost 100% of the hot water load, except on weekends in winter (82%) and on weekends in intermediate seasons (97%). As a criterion for the design of this system, the heat pump was set to provide 100% of the mean hot water load for intermediate seasons. However, it was further found that it also provided 100% of the hot water load for weekdays in winter. This is owing to the fact that the actual operating COP was much higher than the design criterion for heat pump COP.

Table 6 and Fig. 14 show the results of energy analysis by months. It is thought that the heat pump provided 100% of the hot water load during the period

Table 5
Comparison of energy analysis results by weekdays, weekends and seasons

Season		Daily hot water load (MJ)				Daily input energy (MJ)		COP
		Total load	HP supply		Aux.	HP	Pump	
			Q	Ratio (%)				
Winter	Weekday	25,841	25,841	100	25,423	5209	396	4.97
	Weekend	33,507	27,346	82	27,003	5400	417	5.07
Spring/autumn	Weekday	19,374	19,374	100	18,956	3978	298	4.88
	Weekend	25,130	24,407	97	24,002	4996	374	4.89
Summer	Weekday	12,916	12,916	100	0	2880	208	4.49
	Weekend	16,753	16,753	100	16,335	7027	259	4.78

Table 6
Monthly energy analysis results

Month	Hot water (MJ)				Input energy (MJ)		COP
	Heating load (MJ)	HP supply		Aux. energy (MJ)	HP	Circulation pump	
		Energy (MJ)	Ratio (%)				
1	864	818	95	46	163,274	12,466	5.02
2	787	736	93	51	147,456	11,268	5.00
3	872	814	93	58	163,375	12,466	4.99
4	636	636	100	0	130,507	9806	4.88
5	650	650	100	0	133,462	10,015	4.88
6	637	637	100	0	130,647	9799.2	4.88
7	438	438	100	0	95,893	6951	4.57
8	434	434	100	0	95,202	6886	4.57
9	428	428	100	0	93,690	6793	4.58
10	650	650	100	0	133,635	10,018	4.87
11	839	785	94	53	157,568	12,031	4.99
12	880	817	93	63	163,472	12,506	5.01
Total	8120	7847	97	273	1,608,181	1,21,010	4.89

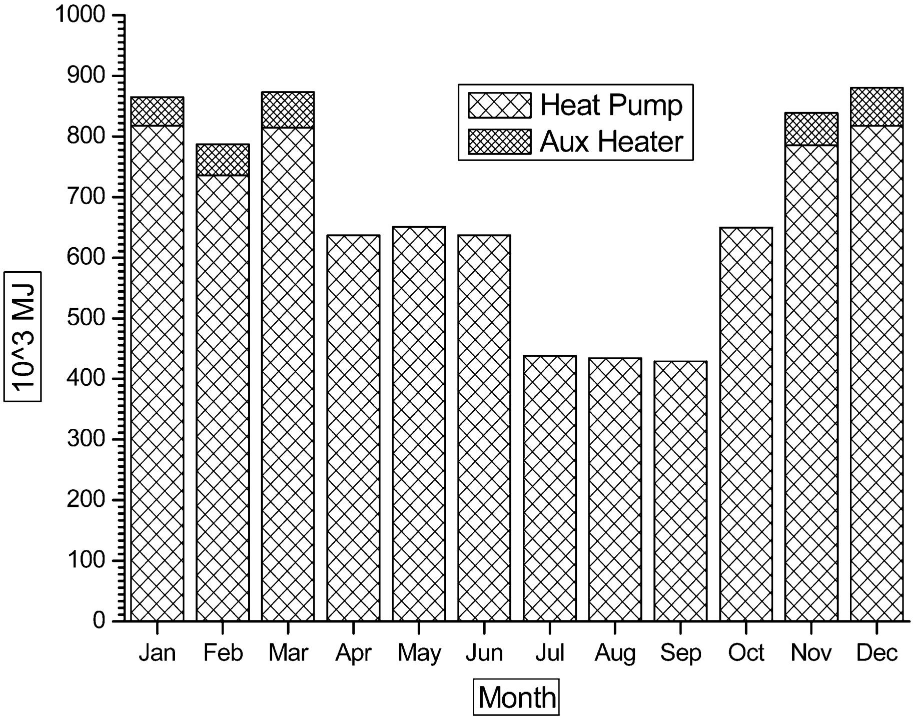

Fig. 14. Monthly energy supply by heat pump and auxiliary heater.

from April to October. As in the previous analysis, the mean COP of the heat pump was slightly lower compared to that in winter. The power required to run the heat pump was 1.6 GJ annually, while the power required to circulate the hot water and wastewater in the condenser and evaporator was 0.12 GJ.

4. Conclusion

In this study a heat pump system for instant hot water supply, using wastewater discharged from saunas and public baths as a heat source, was designed and an energy analysis was performed in order to evaluate the efficiency of the system. The system was designed using a simple method which does not control the temperature of hot water and wastewater flowing into the heat pump's condenser and evaporator. Energy analysis was performed by computer simulation using TRNSYS. The analysis results are as follows.

First, the yearly mean operating COP of the heat pump was 4.5–5.0 which has higher value than that of conventional heat pump system using ambient air heat source.

Second, the heat pump's COP change very widely, which has a maximum value at the beginning of operation during night time hours and a minimum value at the end of charging storage. Therefore, the system needs to be re-configured to control the temperature of hot water and wastewater flowing into the heat pump.

Third, the heat pump could provide over 90% of the instant hot water load and satisfy 100% of the hot water load, except for on weekends in winter.

It is therefore concluded that this system is particularly suitable for countries with climate similar to that of Korea with a correction of temperature control flowing into the evaporator and condenser, respectively. The operating cost saving resulting from the night time operation is an additional advantage of the system.

Acknowledgement

This work was made possible thanks to financial support from the provincial of Daejeon as a part of local energy development project.

References

Baek, N.C., 1994. Study on the heat pump system using waste water as a heat source. Energy R&D 16-1.

Baek, N.C. et al., 2001. Development of off-peak electric water heater using heat pump (1999-E-ID01_P11), pp. 3–7.

KEPRI, 1998. Technical Report TR.94YJ01.J1998.33, Program development of design and energy analysis for thermal cool storage systems, pp. 235–239.

KOPEC, 1996. Development of design method, installation standard and optimum operation criteria of cold storage system for cooling.

KIER, 2001. Feasibility study on heat pump system using waste thermal hot water as a heat source. Korea Institute of Energy Research, Internal report.

Stuij, B., Stene, J., 1994. HPC-AR3 Part 1-Analysis, International heat pump status and policy review. pp. 59–64.

TRNSYS 15.2, 1996. University of Wisconsin-Medison, TRNSYS 15.2 Reference manual.