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Experimental Exergetic Performance Evaluation of a Wastewater Source Heat Pump System (WWSHP)

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Abstract
Heat pumps (HPs) have been used as an environmentally friendly technology for heating and cooling purposes since decades. They are not only named after the source (i.e. air source heat pumps), their efficiencies do also depend on the source that is being used. Wastewater (WW), discharged from buildings to sewerage systems, reserve huge amounts of thermal energy which can be used as heat source in HPs. It can also be considered as a sustainable and renewable source in big cities. WW represents a much more efficient source than air when used in HPs, having higher temperatures than air in winter and lower temperatures than air in summer.

In the present study, a wastewater source heat pump system (WWSHP) installed at Yasar University, Izmir, Turkey was experimentally investigated. In the first part of the study, the whole system along with each component was exergetically analyzed while exergetic destructions and efficiencies in each component were determined to present possible improvements. In the second part of the study, an appropriate building was selected for the WWSHP and was evaluated from the primary energy transformation to the building envelope using the low exergy approach and some exergy-based indicators.

Keywords - wastewater; heat pump; exergy; lowex; sustainability

1. Introduction

HPs can be considered as a part of the environmentally friendly technologies using renewable energy and have been widely used for years as a clean and energy efficient heating and cooling solution in buildings. Based on the type of the heat source, HP technology includes water-source, air-source, and ground-source HPs [1]. In addition to these sources, WW can be used for heating and cooling buildings with HPs and can be seen as a renewable heat source for HPs. It presents large potential, especially in urban areas [2-4]. The main characteristics of WW make it a very good heat source for HPs.

These main characterstics can be listed as follows: (i) there is a huge amount of WW produced every year in cities, (ii) WW temperature is higher than outdoor temperature in winter and lower than outdoor temperature in summer, (iii) the fluctuations on WW temperature during the whole heating and cooling season are very low [5]. WW from local residential drainage systems exhibits relatively high temperatures during the heating season, being about 14 °C in the Cigli district, Izmir, Turkey. WW, therefore, offers an ideal basis for utilization of heat. In summer, the WW temperatures are over 20°C, being between 28-29 °C in the same district. Therefore, it represents a much more efficient heat source than air, when used in HPs [6]. According to the measurement data of Beijing Gaobedian WW treatment plant (WWTP), the WW temperature is 13.5 to 16.5 ℃ in winter, which is about 20℃ higher than outdoor temperature; while in summer the WW temperature is 22 to 25℃, which is 10℃ lower than outdoor temperature [5]. The heat loss via WW for a traditional building in Switzerland accounts to 15% of its demand and 6000 GWh of thermal energy is lost via WW every year in Switzerland. At present, there are more than 500 WWSHP installed around the world, with a capacity range of 10 kW – 20 MW [4]. Due to the huge potential of WW, numerous studies have been conducted and found in the literature. In [7], an urban WWSHP system, which consisted of a filth block device, a wastewater heat exchanger (WWHE), a HP unit, and other components, such as pumps, fans, and end user devices, is designed and tested. The overall COP values of the system, which was built in 2008, was found to 4.3 in the heating mode and 3.5 in the cooling mode. Li and Li [8], performed energy and exergy analyses of a WWSHP system, which was designed, constructed and tested in Harbin Engineering University, and assessed its performance. They determined the exergy losses of the whole system and for all main components. Based on the results, it was stated that the performance of the WWSHP was higher than that of the GSHP under the same condition. The highest exergy loss occurred in the compressor regardless of winter or summer conditions. It was followed by the evaporator, the expansion valve and the condenser in the winter. The heating and cooling COP values were found to be 3.8 and 3.34, respectively, while the exergy efficiency of the whole system was found to be 64 %. In [6], a comprehensive review of WWSHP systems was conducted and the authors concluded that the majority of the studies in the literature were energetically evaluated, while there were only a few studies related to exergetic performance of WWSHPs.

In the present study, the data obtained from the experimental system were utilized for modeling purposes. In the first part of the study, the whole system along with each component was exergetically analyzed while exergetic destructions and efficiencies in each component were determined to present possible improvements. In the second part of the study, an appropriate building was selected for the WWSHP and was evaluated from the primary energy transformation to the building envelope using the low exergy approach and some exergy-based indicators.

2. System Description

The schematic of the experimental WWSHP system is given in Fig. 1, while its pictures are given in Fig. 2.

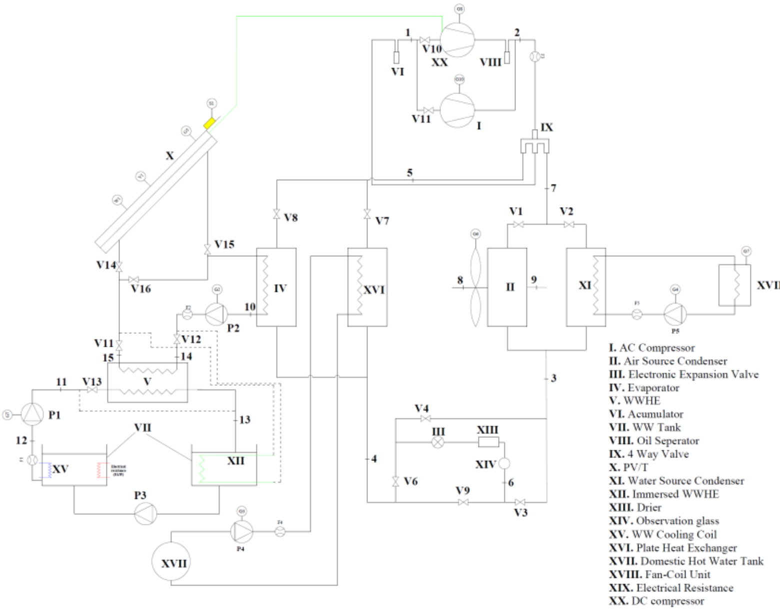

Fig. 1. Schematic of the WWSHP

Fig. 2. Photos of the WWSHP system.

The system consists of three main sub-systems, namely (i) a WW system, (ii) a WWSHP, and (iii) an end user system. The WW sub-system consist of three main parts: PV/T system, WWHEs and WW tanks. A local wastewater drainage system, through which WW flows, was not utilized because the designed and constructed WWSHP system could not be connected to it. Therefore, two 500 L tanks, where water was stored and circulated by pumps, were used to simulate it. An eight kW resistance and cooling coil is located in one of the tanks in order to keep the WW temperature constant and so that the system can reach to steady state conditions. For transferring heat from/to the WW, two different WWHEs, a plate heat exchanger and an immersed heat exchanger, connected in parallel were used in the system. In the HP sub-system, we have two compressors (1 AC and 1 DC), three water source and one air source heat exchangers, an electronic expansion valve, a four-way valve and some other auxiliary equipments such as the drier, oil separator and etc. In the end user system, we have a fan-coil unit which is connected parallel to the air source heat exchanger and a domestic hot water (DHW) tank. In the present study the WWSHP system is operated in heating mode and valves 1, 3, 6, 8, 10, 11, 12, 13 and 16 are open. The air source heat exchanger is used as the condenser, while the DC compressor and plate type WWHE were selected as the main units. On the other hand, the PV/T system is excluded from this study (it is by-passed both electrically and thermally). The refrigerant is compressed to the condenser by the DC compressor, where it transfers heat to the indoor air. After that, it enters to the electronic expansion valve and its expanded to the evaporator pressure. The refrigerant enters the evaporator in two-phase state and absorbs heat from the clean water in the intermedium cycle. The temperature of the water in the intermedium cycle is decreased in the evaporator and is than sent to the WWHE. In the WWHE WW is used to heat the intermedium water and pumped back to the WW tank. During this process, temperatures, pressures, flow rates and power consumptions were continuously measured at the shown locations in the schematic and recorded in the data loggers.

For the second part of the study, a family house with a volume of 326.7 m^3 and a net floor area of 121 m^2 is considered as a case study [8]. The plan and panoramic view of the house is given in Fig. 3.

Fig. 3. Plan and panoramic view of the selected house [9,10].

3. Modeling

The following assumptions are made during the analyses:

(a) All processes are steady state and steady flow with negligible potential and kinetic energy effects and no chemical or nuclear reactions.

(b) Water properties are used instead of wastewater.

(c) The pressure losses in the pipelines and heat exchangers are neglected.

(d) Air is taken as an ideal gas at given conditions.

(d) The mechanical and electrical efficiencies of the pumps are taken as 82% and 88%, respectively.

(e) The values for the dead (reference) state and pressure are taken to be 21.34 °C and 101.325 kPa, respectively.

General energy, entropy and exergy balance equations given below are used and then further reduced to specific equations for each component (for each control volume) [11,12,13]. It should be noted that all the equations below, except (5) are in rate form.

$$\sum m_{in} = \sum m_{out} \quad (1)$$

$$E_{in} = E_{out} \quad (2)$$

$$S_{out} - S_{in} = S_{gen} \quad (3)$$

$$Ex_{in} - Ex_{out} = Ex_{dest} \quad (4)$$

The exergy transfer by mass is determined by (5) and (6), while (7) is used for calculating the exergy transfer rate by heat.

$$ex=(h-h_0)-T_0(s-s_0) \quad (5)$$

$$Ex = m(ex) \quad (6)$$

$$Ex_Q= \sum(1-T_0/T)Q \quad (7)$$

The COP of the WWSHP and the whole system can be found using (8) and (9):

$$COP_{WWSHP} = Q_{cond}/W_{comp,elec} \quad (8)$$

$$COP_{sys} = Q_{cond}/(W_{comp,elec}+\sum W_{pumps,elec}+W_{fan,elec}) \quad (9)$$

The exergy efficiency of each component can be found using (10):

$$\varepsilon = Ex_{output}/Ex_{input} \quad (10)$$

The overall exergy efficiency based on product/fuel basis can be calculated from

$$\varepsilon_{overall} = (\sum \text{Exergetic product})/(\sum \text{Exergetic fuel}) = \sum P_i/\sum F_i \quad (11)$$

The functional exergy efficiency of the WWSHP system and overall system can be calculated using the following equations:

$$\varepsilon_{WWSHP} = (Ex_8-Ex_9)/ W_{comp,elec} \quad (12)$$

$$\varepsilon_{sys} = (Ex_8-Ex_9)/(W_{comp,elec}+\sum W_{pumps,elec}+W_{fan,elec}) \quad (13)$$

Van Gool's improvement potential is as follows:

$$IP=(1-\varepsilon)(Ex_{in}-Ex_{out}) \quad (14)$$

$$RI = Ex_i/Ex_{tot} \quad (15)$$

For the second part of the study, the methodology and relations used are based on a pre-design analysis tool, which has been created during ongoing work for the IEA ECBCS Annex 37 to develop an understanding of exergy flows in buildings and to find further improvements possibilities of energy utilization in buildings [14,15]. In this approach, the total exergy efficiency of the system is defined as the ratio of the exergy demand of the room and total exergy input (16), while the exergy flexibility factor (EFF) is the ratio between the exergy demand of the emission system (e.g., radiator, fan-coil) and total exergy input (17).

$$\varepsilon=Ex_{room}/Ex_{tot} \quad (16)$$

$$EFF=(Ex_{heat}+P_{aux}+\Delta Ex_{room})/Ex_{tot} \quad (17)$$

All other necessary equations are given elsewhere [14,15] and have not been repeated here. The heat demand of the building is found to be 2744.7 W by Yıldırım and Hepbasli [10] and is used in this study. Also, there are not any devices for heat storage and domestic hot water (DHW) production. Therefore, the calculations for the estimation of heat demand, heat storage and DHW are not included in this study.

4. Results and Discussion

The WW temperature is set to 14 °C and kept nearly constant and water, air and refrigerant temperatures and pressures, water and refrigerant flow rates are recorded continously during the whole experiment. WW, intermedium water and air temperatures and evaporator, condenser a are shown in Fig. 4.

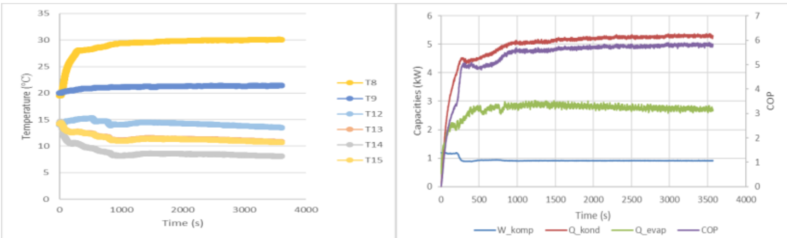

Fig. 4. Air, WW and intermedium water temperatures and energetic results.

Using the equations given in the previous section, the energetic and exergetic performance of the WWSHP system is assessed. The results are listed in Table 1, where P and F represent the exergetic product and exergetic fuel rates, respectively.

Table 1. Results.

Comp. No	Component	P (kW)	F(kW)	Ex_{dest} (kW)	IP (kW)	ε (%)	RI (WWSHP) (%)	RI (overall) (%)
I	Compressor	0.4117	0.6457	0.234	0.08483	63.75	67.38	41.56
II	Condenser	0.0724	0.1343	0.0619	0.02856	53.89	17.83	11
III	Expansion valve	0.5362	0.5496	0.0134	0.00033	97.57	3.848	2.37
IV	Evaporator	0.6284	0.6664	0.0380	0.00217	94.3	10.94	6.74
V	WWHE	0.226	0.2541	0.0281	0.00311	88.94		4.99
P1	WW Pump	0.0018	0.0864	0.0846	0.08287	2.075		15.03
P2	Intermedium Water Pump	0.0044	0.1075	0.1031	0.09885	4.115		18.31
I-IV	WWSHP	1.6487	1.996	0.3473	0.11588	82.6	100.0	61.67
	Overall	1.8809	2.444	0.5631	0.30071	76.96		100.0

The COP of the system is found to be 5.77, while that of the overall system is calculated as 3.61. The decrease is mainly related to the pumps, which cause approximately 38% of the total irreversibilities. As can be seen from the table, the greatest exergy destruction (irreversibility) occurred in the compressor, which is mainly related to the mechanical-electrical losses. The condenser has the lowest exergy efficiency in the WWSHP, while the electronic expansion valve has the highest efficiency. The exergy efficiency of the WWHE and evaporator are found to be 88.94% and 94.3%, respectively, which are considerably high compared to other equipments. Exergy efficiencies for WWSHP and the whole system are estimated as 82.60% and 79.96%, on product/fuel basis, while their functional exergy efficiencies are found to be 7.7% and 5.5%, respectively. The expansion valve has the smallest relative irreversibility (2.37%) and is followed by the WWHE (4.99%).

We next analyzed the system from a lowex perspective. In this method, the process begins with the power plant, through the generation of heat (WWSHP), via a distribution system, to the heat emission system and from there, via the room air, across the building envelope to the outside environment. For this study, the total building area was 121 m2 and the total volume of 326.7 m^3, while the indoor and outdoor air temperatures are given as 22ºC and, 1 ºC, respectively. The WWSHP described previously is considered as the heat generation device, while air heating/cooling option with supply and return temperatures of 35 ºC and 25 ºC and heat/loss efficiency of 95% was selected for the emissions system. All other selections were made according to Ref. [10]. The results of the analysis are illustrated in Fig. 5, where the usable flow of energy and exergy through the heating process from source to sink is given.

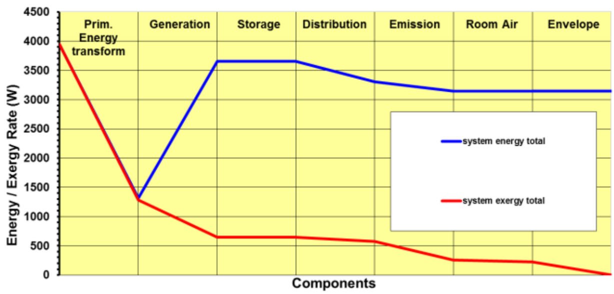

Fig. 5. Exergy and energy flow through components.

As it can be seen from the figure above, there is an increase in the energy flow in the generation section, while total exergy is continously decreased. This increase is due to the WWSHP. Also, the total system exergy reaches zero after all the stages, while there is still a remarkable amount of energy. The figure also indicates that the largest exergy destruction occurred at the primary energy transformation stage. The variations of energy and exergy loss rates through each component are illustrated in Fig.6. The exergy efficiency for the system and exergy flexibility factor are found as 5.66% and 14.51%, respectively.

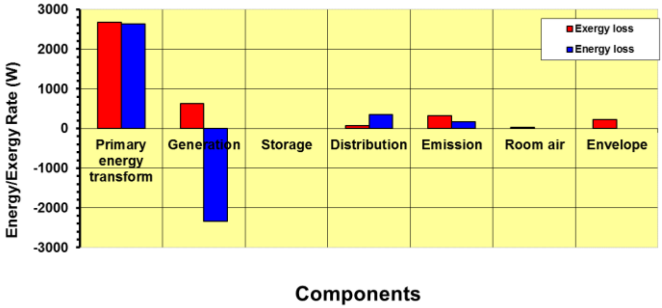

Fig. 6. Exergy and energy flows through components

5. Conclusion

In this study, we experimentaly evaluated the performance of a WWSHP system installed at Yasar University, Izmir, Turkey. For the assessment we have used two different methods. First, we exergtically analysed each component (compressor, condenser etc.) in the WWSHP system and calculated exergy destructions and exergetic efficiencies of all the components. Secondly, we have used the lowex approach to assess the performance of the system from the primary source to building envelope. The following remarks have been drawn from the results of the present study:

a) WW represents an efficient source for heat pumps due to its main characteristics.

b) Exergy efficiencies for WWSHP and the whole system are estimated as 82.60% and 79.96%, on product/fuel basis, while their functional exergy efficiencies are found to be 7.7% and 5.5%, respectively.

c) The biggest relative irreversibility and improvement potential occurred in the compressor, which is followed by the condenser.

d) The exergy efficiency of the whole system and exergy flexibility factor values are found to be 5.66% and 14.51%, respectively.

e) For further works, combined exergy analyses, such as technoeconomic and exergoenvironmental, can be conducted to have useful insights in the economics and environmental effects of the system.

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