Design Aspects and Experimental Performance Test of a Wastewater Heat Pump for the Mediterranean Climate

O. Ekren, M. Araz, A. Hepbasli, E. Biyik, and H. Gunerhan

***Abstract*—In this study, the performance of a wastewater heat pump system, which was designed and installed in Izmir, Turkey, is experimentally assessed. The wastewater temperatures utilized are about 9-14°C and 26-29°C in winter and summer seasons, respectively. It may be concluded that a wastewater source heat pump is more efficient than an air source heat pump in Izmir, Turkey, of which western coast has a Mediterranean climate. According to the results, by using wastewater source heat pump can provide heating and cooling efficiency up to 44% because of lower condensing and higher evaporation temperatures. Also wastewater source heat pump can use bigger portion of theoretical energy potential than air source heat pumps.**

***Index Terms*—Energy efficiency, heat recovery, sustainability, wastewater, wastewater source heat pump.**

I. Introduction

Recently, sustainability in buildings has attracted a lot of interest in the research community, and new approaches have been proposed through efficient energy systems as well as utilization of renewable energy systems. In this sense, heat pumps are part of the environmentally friendly technologies using renewable energy and also wasted heat in the buildings. Wastewater can be employed as a renewable heat source for heat pumps. This has been widely applied in North European countries in the past two decades. In the winter and summer seasons, wastewater from local building drainage systems shows relatively higher and lower temperatures, respectively, than traditional sources such as, groundwater, geothermal heat and outdoor air. Therefore, wastewater from the buildings can be utilized as hot or cold heat source for the heating or cooling systems.

II. Principle of Heat Pumps

Heat pump is a device that transfers heat from a low temperature heat source (cold side) to a high temperature working fluid (hot side) and can be used for the purposes of cooling/heating and also domestic hot water production in any buildings [1].

The main components of a vapor compression cycle heat pumps are a compressor, a condenser, an expansion valve, an evaporator and auxiliary equipment, as shown in Fig. 1. A heat pump system has both cooling (summer) and heating (winter) modes. According to their heat source, heat pumps can be classified as air source, ground source, water source [1], [2]. Furthermore, heat pumps are classified in monovalent, bivalent and multivalent. Monovalent means that heat pump heating system without supplemental heating during the heating season. Bivalent system is hybrid heat pump heating system (heating system with supplemental heating). Multivalent system can be used in tandem with a cogeneration (CHP) system in larger buildings [1].

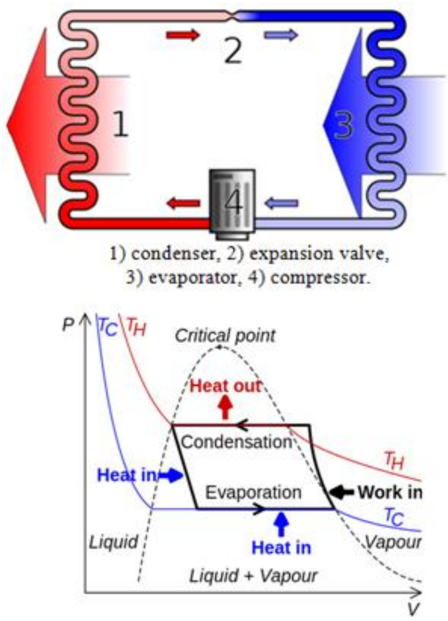

Fig. 1. A basic schematic and p-v diagram of heat pump [3].

III. Evaluation of Wastewater Heat Pump Utilization

Recently, heat pump (HP) system has been an efficient and economical method among the various conventional heating cooling systems. Among different heat sources such as water, air, and ground, wastewater is also very sustainable thermal energy source for HPs. When wastewater is used as thermal energy source, the heat pump system is called wastewater source heat pump (WWSHP). Selection of heat pump's thermal energy source depends on the source temperature in winter and summer periods. In this study, a WWSHP for the Mediterranean climate region is investigated. The Mediterranean climate zone is given in Fig. 2.

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O. Ekren is with the Solar Energy Institute, Ege University, 35100 Bornova, İzmir, Turkey (e-mail: orhanekren@gmail.com).

M. Araz, A. Hepbasli, and E. Biyik are with the Department of Energy Systems Engineering, Yasar University, 35100 Bornova, İzmir, Turkey (e-mail: {mustafa.araz, arif.hepbasli, emrah.biyik}@yasar.edu.tr).

H. Günerhan is with the Department of Mechanical Engineering, Ege University, 35100 Bornova, İzmir, Turkey (e-mail: huseyin.gunerhan@ege.edu.tr).

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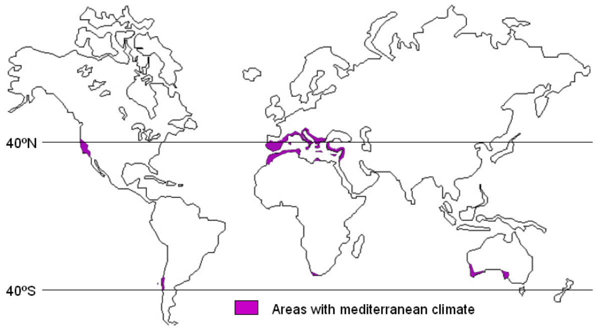


Fig. 2. The Mediterranean climate zone.

In Izmir-Turkey where the case study is conducted, the wastewater temperatures are about 14ºC and 28ºC during the winter and summer seasons, respectively [4].

The temperature of the heat source directly affects HP's efficiency. Commonly used heat source temperatures (i.e., air, ground, sea, lake or river water and wastewater) for heat pumps in the Mediterranean and other climates are given in Table I [5].

TABLE I: TEMPERATURE RANGE FOR COMMONLY USED HEAT SOURCES FOR HEAT PUMPS [5]

Thermal Source	Temperature Range (ºC)		Difference versus Wastewater temperature (ºC)	
	Winter	Summer	Winter (min)	Summer (max)
Air (ambient)	(-10)-15	26-45	19	-16
Ground Water	4-15	6-18	5	11
Lake Water	0-15	10-20	9	9
River Water	0-15	8-18	9	11
Sea Water	4-15	10-25	5	4
Ground	0-15	10-20	9	9
City Wastewater	*9-14*	*26-29*	-	-

A WWSHP may recover heat from wastewater in a building (bath, kitchen etc.) or outside the building from the urban wastewater distribution line or from a treatment plant. Why wastewater is used in HP;

(i) Temperature of the wastewater is constant during the winter and summer season [6].

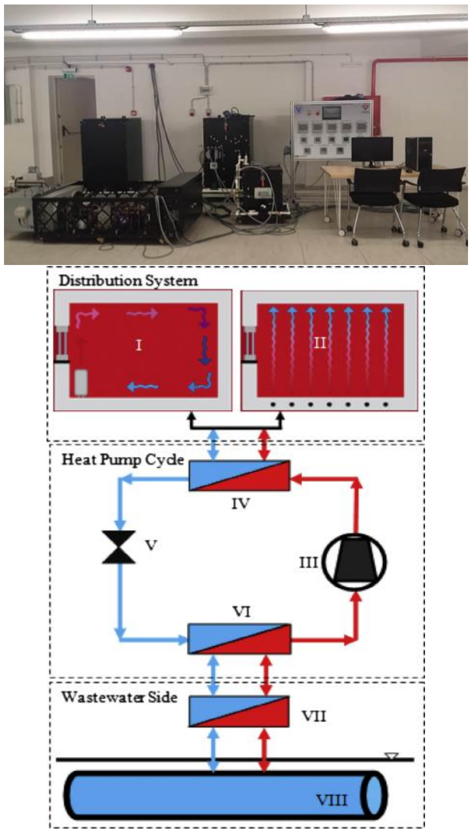
(ii) In any city, almost 40% of the produced heat is sent to the sewerage system as waste heat [6], and

(iii) The amount of wastewater is significantly high and its flow rate is almost constant over the year [6].

The WWSHP system provides cold or hot fluid for a volume of air or water. During the heating period, the waste heat is removed from the wastewater through the evaporator and transferred to the indoor by the condenser. On the other hand, during the cooling period, the heat is removed from the indoor and is transferred to the wastewater through the condenser. The wastewater side requires a specially designed heat exchanger which transfers heat from/to the wastewater efficiently. In daily basis, about 600.000 m^3 wastewater is produced [4]. It is calculated that, while the wastewater temperature changes only 1 ℃ about 700 MWh daily thermal energy can be extracted.

IV. A CASE STUDY OF WASTEWATER HEAT PUMP SYSTEM

In this study a solar energy assisted wastewater source heat pump (SEAWWSHP) system has been investigated. The SEAWWSHP experimental setup is in Izmir Turkey. Izmir has Mediterranean climate which is characterized hot and dry summers and mild to cool rainy winters. Average temperatures during the winter months are usually between 0 and 5 ℃. During summer, the average temperature between 35 and 40 ℃ from June to September [7]. A schematic illustration of a WWSHP is given in Fig. 3.



I: Fan-coil system, II: Floor heating,
III: Compressor, IV: Condenser/Evaporator,
V: Expansion valve, VI: Evaporator/Condenser,
VII: Wastewater HX, VIII: Wastewater line
Fig. 3. Schematic of experimental setup [8].

There are three cycles in the experimental system; a wastewater cycle, a heat pump cycle and a heating/cooling utilization cycle. At the wastewater cycle, there is a heat exchanger between waste and refrigerant. The waste water temperatures are about 9-14ºC and 26-29ºC in winter and summer seasons, respectively. The velocity of the wastewater is about 1 m/s as similar with city wastewater lines. Wastewater cycle is a closed loop cycle and in the winter period, a photovoltaic thermal (PVT) system can be used as an auxiliary thermal source for the domestic hot water production.

In the current system, wastewater to air and wastewater to water heating/cooling can be realized. In this paper, only wastewater-air mode for heating and cooling is evaluated. The capacities of the heat pump cycle may be varied from 1.5 to 5 kW using variable speed AC and DC compressors. R134a has been used as refrigerant in the HP cycle.

In summer, for the air source HPs, increasing the condensing temperature (ambient air) decreases HP's efficiency. Similarly, in winter, decreasing the evaporation temperature (ambient air) decreases HP's efficiency. The ambient average temperatures for Izmir are taken 35°C and 5°C in summer and winter seasons, respectively. Energetic efficiency of the WWSHP is given by COP

$$COP_{\text{heating}} = \frac{Q_{\text{hot}}}{W_{\text{comp,elect}}} \tag{1}$$

and

$$COP_{\text{cooling}} = \frac{Q_{\text{cold}}}{W_{\text{comp,elect}}} \tag{2}$$

where Q_{cold} is the heat removed from the cooled volume (cold reservoir) and Q_{hot} is the heat supplied to the heated volume (hot reservoir). $W_{\text{comp,elect}}$ is the electrical energy consumption of the compressor. Furthermore, for the WWSHP operating at maximum theoretical efficiency (i.e. Carnot efficiency) can be shown that

$$COP_{\text{carnot,heating}} = \frac{T_{\text{hot}}}{T_{\text{hot}} - T_{\text{cold}}} \tag{3}$$

and

$$COP_{\text{carnot,cooling}} = \frac{T_{\text{cold}}}{T_{\text{hot}} - T_{\text{cold}}} \tag{4}$$

where T_{cold} and T_{hot} are the evaporation and condensation temperatures of the cooling cycle, respectively. This yields a very close value to equivalent temperature values as the Gibbs free energy in both heat exchangers is almost negligible [9]. In addition, the percentage of COP_{Carnot} shows the potential that already has been used,

$$\%COP_{\text{carnot}} = \frac{COP}{COP_{\text{carnot}}} \times 100 \tag{5}$$

In Table II, analysis results of air and wastewater source heat pumps for heating and cooling mode are given.

TABLE II: HP COMPARISON BY HEAT SOURCES FOR SUMMER/WINTER

Wastewater Source HP-**Cooling Mode**	
Condenser wastewater inlet temperature(oC)	28.0
Condenser wastewater outlet temperature(°C)	33.0
Evaporation Temperature (°C)	10.0
Condensing Temperature (°C)	43.0
Condenser wastewater flow rate (kg/s)	0.29
Evaporator Capacity (kW)	5.00
Condenser Capacity (kW)	6.13
Compressor Capacity (kW)	0.91
COP_{cooling}	5.48
COP_{Carnot}	9.40
% COP_{Carnot}	58.1
Wastewater Source HP- **Heating Mode**	
Evaporator wastewater inlet temperature(°C)	14.0
Evaporator wastewater outlet temperature(°C)	9.0
Evaporation Temperature (°C)	10.0
Condensing Temperature (°C)	40.0
Evaporator wastewater flow rate (kg/s)	0.20
Evaporator Capacity (kW)	4.15
Condenser Capacity (kW)	5.00
Compressor Capacity (kW)	0.67
COP_{heating}	6.15
COP_{Carnot}	10.4
% COP_{Carnot}	58.9
Air Source HP- **Cooling Mode**	
Condenser air inlet temperature(°C)	35.0
Condenser air outlet temperature(°C)	40.0
Evaporation Temperature (°C)	10.0
Condensing Temperature (°C)	50.0
Condenser air flow rate (kg/s)	1.22
Evaporator Capacity (kW)	5.00
Condenser Capacity (kW)	6.40
Compressor Capacity (kW)	1.16
COP_{cooling}	4.30
COP_{Carnot}	8.10
% COP_{Carnot}	53.3
Air Source HP- **Heating Mode**	
Evaporator air inlet temperature(°C)	5.00
Evaporator air outlet temperature(°C)	1.00
Evaporation Temperature (°C)	0.00
Condensing Temperature (°C)	40.0
Evaporator air flow rate (kg/s)	0.75
Evaporator Capacity (kW)	3.92
Condenser Capacity (kW)	5.00
Compressor Capacity (kW)	0.92
COP_{heating}	4.26
COP_{Carnot}	7.80
% COP_{Carnot}	54.4

V. RESULTS AND DISCUSSIONS

It is known that in summer, for the air source HP increasing the condensing temperature (ambient air) decreases HP's efficiency, also in winter, decreasing the evaporation temperature (ambient air) decreases HP's efficiency. Since the wastewater temperature is lower than the air (ambient) temperature in the summer period in Izmir, the *COP* value for WWSHP in the cooling mode is higher (5.48) than the air source heat pump (ASHP) (4.30). Similarly, the wastewater temperature is higher than the air (ambient) temperature in the winter period in Izmir. Therefore, the *COP* value for WWSHP in the heating mode is higher (6.15) than the ASHP (4.26). When the evaporation temperature increases and the condensation temperature decreases, the *COP* of the HP increases.

According to the results, WWSHP has higher COP_{Carnot} in both cooling (9.40) and heating (10.4) modes than ASHP. This shows that wastewater source has a higher theoretical energy potential than air source. Also, the percentage of COP_{Carnot}, which shows the potential that already has been used, is higher for WWSHP in both cooling (58.1%) and heating (58.9%) modes than ASHP. This means that WWSHP uses bigger portion of theoretical energy potential than ASHP.

Wastewater allows us higher evaporation temperature and lower condensation temperature. The efficiency can be increased up to 44% by using wastewater as a heat source in HP. When the WWSHP is used, for the heating season yearly 4 months (November to February) and daily 10 hours operation saves yearly 300 kWh electricity and 36 $ (electricity cost is 0.12 $/kWh). For the cooling season with the daily 10 hours and yearly 5 months (May to September) operation savings will be 375 kWh and 45$. For the heating and cooling season total yearly savings are 675 kWh and 81$.

VI. Conclusions

According to the analysis and comparison it is concluded that in a heat pump,

1) WWSHP has higher evaporation and lower condensation temperatures compared to ASHP.
2) The efficiency can be increased up to 44% by using wastewater as a heat source.
3) For the heating and cooling seasons, total yearly savings are 675 kWh and 81$, respectively.
4) The wastewater source has higher theoretical energy potential than air source
5) The WWSHP can use bigger portion of theoretical energy potential than ASHP.

In the current study, WWSHP application in Izmir has been presented. This is the first experimental WWSHP study in Turkey. We have concluded that wastewater which is already has been using in north Europe is an efficient source for Turkey (Izmir). By using wastewater and solar energy coupled system as we realized heating and cooling efficiency can be increased. In future, we are planning to apply large scale WWSHP heating and cooling for some municipalities in Izmir.

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O. Ekren was born in Izmir, Turkey. He graduated from Dokuz Eylul University (DEU) as a mechanical engineer in 1999, from Izmir Institute of Technology (IZTECH) Energy Engineering program with the MSc degree in 2003 and from DEU Mechanical Engineering Department Thermodynamics program with the PhD degree in 2009. From 2000 to 2003, he studied as a research assistant at IZTECH. Dr. Ekren was worked in the USA as a visiting scholar in 2008 and 2011. He has been working at Ege University Solar Energy Institute as an Assoc. Prof. since 2014. His research areas are renewable energy sources, hybrid energy system sizing and optimization, refrigeration system energy efficiency, heat pumps and alternative cooling methods.

M. Araz was born in Karaman, Turkey on August 23, 1986. He received the B.S. degree in mechanical engineering from Ege University, Turkey in 2010, the M.S degree in 2013 and is currently a Ph.D. student in mechanical Engineering at Ege University.

He completed his military service in 2011. He has been working as research assistant at the Energy Systems Engineering Department of Yaşar University, in İzmir, since October 2012. He has worked as a scholarship student in the project entitled *Design of an Elevator Air Conditioning Unit Using R-1234yf*, which is supported by the Republic of Turkey Ministry of Science, Industry and Technology. His research interests are low global warming potential (LGWP) refrigerants, air conditioning systems, refrigeration technologies and clean energy systems. Mr. Araz is a member of Union of Chambers of Turkish Engineers and Architects the Chamber of Mechanical Engineers.

A. Hepbasli has dealt with energy-related issues for 35 years, is a professor and the head of Energy Systems Engineering Department at Yaşar University in Izmir, Turkey. Dr. Hepbasli joined Ege University, Izmir, Turkey in 1996 after about a ten-year period in industry, as the head of engineer, assistant manager for investments and maintenance manager. His research has been involved with energy, exergy, exergoeconomic and exergoenvironmental analyses and assessments of energy-related systems, energy/exergy efficiency and management, fluidized bed combustion systems, ground-source heat pumps, utilization and potential of renewable energy sources and sustainable energy technologies. Dr. Hepbasli is also a certified industrial energy manager in Turkey while he is the author or co-author of over 560 papers (over 275 SCI-based papers with an academic footprint of 35) on a national and international basis as well as several national and international books and book chapters. He has chaired and co-chaired many national and international conferences, symposia, workshops and technical meetings. He has served as a consultant for industry in cases involving his research area and is also a member in the international advisory board of various prestigious energy-related journals and an associate editor of Journal of Energy Engineering (ASCE) while also serving in many energy journals and industrial projects as a reviewer. In 2014, he became the Turkish expert of the Energy Configuration of the Horizon 2020 Programme Committee while also serving as an advisory committee member at Turkish Scientific Technology Research Institute (TUBITAK).

E. Biyik received the B.S. degree in electrical engineering (EE) from Bogazici University, Istanbul, Turkey in 2003 and the M.S. degree in EE, M.S. degree in applied math and the Ph.D. degree in EE from the Rensselaer Polytechnic Institute, Troy, NY, US in 2004, 2006, and 2007, respectively. From 2008 to 2012, he worked as a control systems engineer at GE Global Research Center, Niskayuna, NY, and developed advanced controls, estimation and optimization solutions for power systems, turbomachinery and energy management applications. Dr. Biyik is currently with the Energy Systems Engineering Department at Yasar University, Izmir, Turkey and also acts as a consultant for the GE Global Research. His research interests are in controls and optimization of energy systems, buildings, and power networks.

H. Gunerhan works as a lecturer at Ege University, Faculty of Engineering, Department of Mechanical Engineering. He got a PhD degree in 1999. He has worked as an associate professor at the same university since 2012. His study areas are heat transfer, thermodynamics, thermal energy storage and heat pumps.