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Thermo-Economic Analysis of a Ground-Source Heat Pump System for Hot Water Supply for a Hotel in Antalya

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Abstract: *Ground source heat pumps (GSHPs) or geothermal heat pumps (GHPs) are a highly efficient, environmentally friendly, renewable energy technology for space heating, cooling and hot domestic water supply for residential and commercial buildings. This technology is having popularity because of its ability to reduce primary energy consumption and thus diminish production of greenhouse gases. The purpose of this study is to present an energy and exergy analyses of a ground source heat pump system for hot water supply for a hotel in Antalya, Turkey. Then, a comparative thermo-economic analysis of the heat pump system is performed.*

Keywords: *Ground-source, geothermal, heat pump, exergy analysis*

1. Introduction

Heat pumps withdraw heat from a lower temperature source and seemingly pump it to warmer mediums. They do so by essentially "pumping" heat from a low temperature medium to a hotter one by including electricity energy the majority of the heat pumps in use utilize atmospheric air as a heat source. They are specified as air source heat pumps. On the other hand, ground source heat pumps (GSHPs) utilize the constant temperature of the soil. A GSHP uses the soil or ground water as a heat transfer medium. The GSHP systems can be installed using ground heat exchangers withdrawing heat from the soil or underwater heat exchangers extracting heat from a pond or lake when such a suitable water source near the building is available.

The advantages of GSHP systems were explained by Lund and Freeston [1], Akpinar and Hepbasli [2] and Hepbasli and Akdemir [3]. The constant temperature of the soil is the most important one. Lund and Freeston [1] and Lund et al [4] have reviewed the application of geothermal energy. Akpinar and Hepbasli [2] examined the exergy performance evaluation of two different GSHP systems in Turkey. Thermodynamic analysis of a vertical GSHP system was carried out by Hepbaslı and Akdemir [3]. Ozgener and Hepbasli [5] reviewed the works carried out on exergy research of GSHP systems. Fei and Ping fang [6] performed energy and exergy analysis of a GSHP system. In their works, the heat pump was mounted in a building in Wuhan city, China. A comprehensive exergy analysis of a GSHP system for heating and cooling modes is presented by Bi et al [7]. The main purpose of the work was to investigate potential energy saving components. They concluded that a thorough exergy analysis of a GSHP is very important issue. Chen and Hao [8] have performed exergy calculations of a ground-coupled heat pump system. The aim of the work was to assess the ground-coupled heat pump performance. Bi et al [9] investigated solar and GSHP systems. In another work, Bi et al [10] performed an experimental study for a solar GSHP system. Thermodynamic analysis of a GSHP system for district heating was given by Hepbasli [11]. An experimental investigation of ground source, solar source and air source heat pumps for domestic heating constructed in Elazığ, Turkey, and thermodynamic analysis of these systems were given by Dikici et al [12] and Dikici and Akbulut [13]. Exergy calculations and experimental research of heat pump systems were given by Bilgen and Takahashi [14]. With the aid of the exergy calculations, they developed a computer program to simulate and assess experimental systems. A domestic heat pump was simulated by using experimental data. Kaygusuz and Ayhan [15] made an experimental research on a solar assisted heat pump system, and assessed the results using the exergy calculations. Torres-Reyes et al [16] and Torres-Reyes and Cervantes de Gortari [17] presented an experimental and optimization study with a solar assisted heat pump system and gave the second law efficiency and the coefficient of performance based on the first law. Thermodynamic analysis of a ground-coupled heat pump system having two horizontal ground heat exchangers were given by Esen et al [18]. Hepbasli and Balta [19] made a work on modeling and performance evaluation of a heat pump system utilizing low temperature geothermal resources as a heat source in buildings. Energy and exergy analysis of a GSHP system for a public building in Wuhan city, China were investigated by Hu et al [20].

A comparison of air source heat pump versus ground source heat pump has been given by Wu [21]. Another experimental study about an air-to-water heat pump system together with an economic evaluation was given by Popa et al [22]. A review of domestic heat pumps was given by Staff ell et al [23] In this review, they gave recent technologies and the practical applications. The current status of GSHP were presented by Sanner et al [24]. GSHP systems and applications were also given in Omer [25]. In another work, Self et al [26] reviewed geothermal heat pumps systems and recent developments in this field. Another recent review was carried out by Lucia et al [27] about GSHP system for heating and cooling. A detailed literature-based review on GSHP technology concentrated on the ground-coupled heat pump systems was presented by Sarbu and Sebarchievici [28]. In this paper, a detailed description of the surface water, ground-water and ground-coupled heat pumps were given. An experimental study on air-to-air compact heat pump system was carried out by Kent [29]. Thermo-economic analysis of a water-to-water heat pump system was given by Koyun et al [30].

The aim of present study is to give an energy and exergy analyses of a ground source heat pump system for hot water supply for a hotel in Antalya, Turkey. Since most hotels and other establishments are open in summer season in Antalya, the heating demand of the hotel building is not needed in summer season. For this reason, only hot water supply of the hotel is provided by the GSHP system. The schematics of the GSHP considered are given in system description section 2. In the theoretical analysis section 3, the governing equations are given. Exergy destructions (exergy losses) in each of the system components are found to evaluate their own performances by indicating the potential improvements. The results drawn from the present work and irreversibility’s in the system elements are presented in section 4.1. A comparative thermo-economic analysis of the heat pump system is also given in section 4.2.

2. System Description

The schematic of the ground source heat pump system theoretically analyzed in this work is given in figure1.

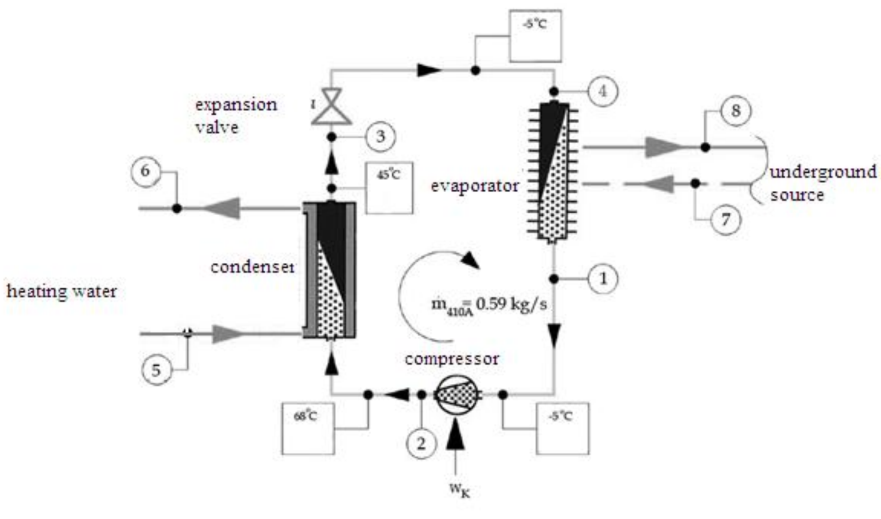

Figure1. *Schematic diagram of the ground source heat pump system*

The system considered has three individual sections: (i) the underground section (water-or sometimes water-antifreeze mixture when low temperatures below the freezing point temperatures of water are encountered), (ii) the refrigerant section and (iii) domestic hot water section. The system elements are consist of compressor, evaporator, condenser and throttling valve. The working fluid is R-410A. It is designed for hot water supply for a hotel in Antalya, Turkey. The condenser load in the heating mode is 85 kW. The mass flow rate of the refrigerant (R-410A) is 0.59 kg/s. The hot water flow rate is 2.5 kg/s and ground coupling circuit water flow rate is 5.79 kg/s. The efficiency of the compressor is assumed to be %80. The compressor power is 29.5 kW. The exergy and the exergy destructions (exergy losses) or the rate of irreversibility are specified by applying the governing equations for a control volume.

3. Theoretical Analysis

For a control volume, to specify the exergy and the exergy destructions (exergy losses) the governing equations are applied to system elements Cengel and Boles [31],[2,3,11].

The mass balance equation or continuity equation in the rate form can be given as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

Where $\dot{m}$ denotes the mass flow rate, and the indexes in denotes for inlet and out for outlet.

The total exergy of a system $\dot{E}_x$ composed of four parts, (i) physical exergy $\dot{E}_x^{PH}$, (ii) kinetic exergy $\dot{E}_x^{KN}$, (iii) potential exergy $\dot{E}_x^{PT}$, and (iv) chemical exergy $\dot{E}_x^{CH}$ Dincer [30].

$$\dot{E}_x = \dot{E}_x^{PH} + \dot{E}_x^{KN} + \dot{E}_x^{PT} + \dot{E}_x^{CH} \tag{2}$$

The specific exergy per unit mass can be expressed as

$$ex = ex^{PH} + ex^{KN} + ex^{PT} + ex^{CH} \tag{3}$$

Kinetic exergy $\dot{E}_x^{KN}$, potential exergy $\dot{E}_x^{PT}$ and chemical exergy $\dot{E}_x^{CH}$ were not taken into consideration in this work and physical exergy $\dot{E}_x^{PH}$ is the total exergy of the GSHP system.

The general exergy balance in the rate form can be written as

$$\dot{E}x_{heat} - \dot{E}x_{work} + \dot{E}x_{mass,in} - \dot{E}x_{mass,out} = \dot{E}x_{dest} \tag{4}$$

From equation (4), the exergy balance equation could be written as

$$\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k - \dot{W} + \sum \dot{m}_{in} ex_{in} - \sum \dot{m}_{out} ex_{out} = \dot{E}x_{dest} \tag{5}$$

With

$$ex = (h - h_0) - T_0(s - s_0) \tag{6}$$

Where Q_k holds for heat transfer rate, T_k temperature at position k, W stands for the rate of work, ex is the specific exergy per unit mass or flow specific exergy, h is the enthalpy, s is the entropy, and the subscript zero stands for dead state properties at P_0 and T_0.

The product of flow specific exergy Eq. (6) by the fluid mass flow rate yields the total exergy rate as:

$$\dot{E}x = \dot{m}[(h - h_0) - T_0(s - s_0) \tag{7}$$

4. Results And Discussions

4.1. Irreversibilities in the System Elements

The irreversibilities of each of the elements of the GSHP system may be found from exergy and entropy calculations at various points. The major property data, enthalpy and entropy values are evaluated using the thermodimamic charts of water and R-410A. In the exergy analysis, the dead sate properties of the refrigerant and water are taken at P_o=100 kPa and T_0=+7°C (Outlet temperature of the ground coupling circuit water).

Property data, temperature, enthalpy and entropy values of the GSHP system considered are given in Table 1.

Table1. *Property data, temperature, enthalpy and entropy values of the GSHP system*

State No.	T Temp. (°C)	h Enthalpy (kJ/kg)	s Entropy (kJ/kg K)
1.	-5	420	1.82
2.	68	460	1.82
3.	45	276	1.27
4.	-5	276	1.29
5.	30	125.72	0.4367
6.	38	159.16	0.5456
7.	10	42.01	0.1511
8.	7	29.42	0.1064

Exergy balance result of this ground source heat pump system are given in Table 2.

Table2. *Exergy balance result of the ground source heat pump system*

State no.	Fluid	T(°C)	$\dot{m}$(kg/s)	ex (kJ/kg)	$\dot{E}x$ (kW)
1.	R-410A	-5	0.59	-15.169	-8.9497
2.	R-410A	68	0.59	24.831	14.6502
3.	R-410A	45	0.59	-5.087	-3.001
4.	R-410A	-5	0.59	-10.69	-6.3071
5.	Water	30	2.5	3.657	9.1415
6.	Water	38	2.5	6.589	16.4725
7.	Water	10	5.79	-0.042	-0.2431
8.	Water	7	5.79	-0.11	-0.6369

Irreversibilities in each of the system element are presented in Table 3.

Table3. *Irreversibilities in each of the system element*

Component	**Irreversibility or exergy destruction (I) kW**
Condenser	10.3193
Compressor	5.9001
Throttling valve	3.3061
Evaporator	3.0364

The highest irreversibility occurs in the condenser. This is due to the relatively higher temperature differences between the refrigerant and circulation water which is a source of irreversibility. At the compressor exit, the temperature of the refrigerant at superheat phase causes to large temperature differences at the beginning of heat transfer process. The second largest exergy loss occurs in the compressor. This is can be attributed to the isentropic inefficiencies. The third highest exergy loss occurs in the throttling valve because of the irreversibilty of the process. Needless to say, the evaporator has the least exergy loss in the system. From these results, the following suggestions can be made for the potential energy efficiency improvement of this system. The temperature difference between the refrigerant and water circulating in the condenser may be decreased. The degree of superheat achieved at the end of the compression process must also be reduced. This will help to reduce the exergy loss in the condenser. Compressor irreversibility can be reduced by improving motors, valves, lubrication etc. The only one possible alternative to eliminate the exergy loss in throttling valve is to replace the throttling valve with a small turbine and thus, recover some shaft work from the pressure drop.

4.2. Thermo-Economic Analysis

Thermo-economic analysis of the GSHP system consists of the assessment of the heating systems both from thermodynamic and economic point of view. It aims to minimize the total cost of the system. The total cost consists of initial investment cost and operational cost.

Thermo-economic analysis of this GSHP system is performed as follows:

- Capital cost of the GSHP system is $24.000, and capital cost for natural gas and LPG boiler is $3530, and for fuel-oil 4 boiler is $1767.
- Economic life of the system is 10 years and total working time is 4380 hours.
- Initial investment cost and operational cost of the GSHP system and the boiler system for domestic hot water suplly are calculated. Then, the total cost of the each system is found.

The total cost C_t is calculated as:

$$C_t = C_{inv} + C_{op} \qquad (\$ / kWh) \tag{8}$$

Where C_{inv} is initial investment cost and C_{op} is operational cost.

The initial investment cost for the GSHP system is calculated from:

$$C_{inv} = \frac{CRF.C}{Q_k.4380} \tag{9}$$

Where CRF is capital recovery factor, C is capital cost and $\dot{Q}_k$ is the heating load of the system.

Capital recovery factor CRF can be calculated from:

$$CRF = \left[\frac{i \cdot (1+i)^n}{(1+i)^n - 1}\right] \tag{10}$$

Where i denotes annual interest rate and n is economic life of the system in years.

For the capital cost of the GSHP system of $24.000, and for LPG and natural gas boilers of $3530 and fuel-oil boiler of $1767, the initial investment costs of the systems are calculated from Equation (9) and given in Table 4.

The operational cost of the GSHP system is calculated from:

$$C_{op} = \frac{C_{el}}{COP_{HP}} \tag{11}$$

Where C_{el} is the cost of electricity (0.09918$/kWh), and COP_{HP} is the coefficient of performance of the heat pump system (2.88).

The operational costs of fuel-oil 4, LPG and natural gas boiler systems are calculated from:

$$C_{op} = \frac{C_f}{\eta} \tag{12}$$

Where C_f is the cost of fuel per kWh, η is the efficiency of the boiler. C_f is 0.0660187 $/kWh for fuel-oil 4, 0.119465 $/kWh for LPG and 0.019698 $/kWh for natural gas. The boiler efficiencies for fuel-oil 4, LPG and natural gas are 0.80, 0.92 and 0.90, respectively.

The operational costs and total costs of the GSHP system are also presented in Table 4.

It must be noted that natural gas is not exist in Antalya. Therefore natural gas is not a viable option for Antalya. The results for natural gas is given for comparison. From this table, although initial investment cost for the GSHP system is bigger than that of costs of the boiler systems, total cost of the GSHP system is less than (other viables options) fuel-oil 4 and LPG boiler systems. In addition to environmentally friendly, renewable energy technology, the GSHP system considered is also an economic option.

Table4. *The initial investment, operational and total costs of the systems*

Costs	C_{inv} ($ /kWh)	C_{op}($ /kWh)	C_t($ /kWh)
GSHP	0.003777	0.03443	0.033821
Fuel-oil 4	0.0002782	0.0632	0.06348
LPG	0.0005561	0.11946	0.1200
Natural gas	0.0005561	0.021880	0.02244

5. CONCLUSION

In this work, an energy and exergy analyses of a GSHP system for hot water supply for a hotel in Antalya, Turkey has been performed. Irreversibility in each of the GSHP systems components are qualified. From these results, it is found that the highest irreversibility occurs in the condenser. This is due to the relatively higher temperature differences between the refrigerant and circulation water which is a source of irreversibility. For the potential energy efficiency improvement of this system, the temperature difference between the refrigerant and water circulating in the condenser may be decreased. This will help to reduce the exergy loss in the condenser.

A comparative thermo-economic analysis of the GSHP system with other fuel-oil 4 and LPG boiler systems revealed that the ground source heat pump system considered is also an economic option among other viable options.

Nomenclature		Indices	
$\dot{E}x$	rate of exergy (kW)	dest	destroyed
ex	specific exergy (kJ/kg)	el	cost of electricity
h	specific enthalpy (kJ/kg)	HP	heat pump
I	rate of irreversibility (kW)	i	annual interest rate
$\dot{m}$	mass flow rate (kg/s)	in	inlet
s	specific entropy (kJ/kg K)	inv	investment
T	temperature (°C or K)	k	location
C	capital cost	KN	kinetic
$\dot{Q}$	heating load (kW)	n	economic life
		op	operation
		out	outlet
		PH	physical
		PT	potential
		t	total
		0	dead state
		Abbreviations	
		COP	coefficient performance
		CRF	capital recovery factor
		GHP	geothermal heat pump
		GSHP	ground source heat pump

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