Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Energy and Exergy Assessment of Salihli Geothermal District Heating System

Leyla Ozgener[a], Arif Hepbasli[b] and Ibrahim Dincer[c]

[a] Graduate School of Natural and Applied Sciences, Mechanical Engineering Science Branch, Ege University, 35100 Bornova, Izmir, Turkey
[b] Department of Mechanical Engineering, Faculty of Engineering, Ege University 35100 Bornova, Izmir, Turkey
[c] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology (UOIT), 2000 Simcoe Street North, Oshawa, ON L1H 7K4, Canada

E-mail addresses: leylaozgener@mail.ege.edu.tr, hepbasli@bornova.ege.edu.tr, ibrahim.dincer@uoit.ca

Keywords: Exergy Analysis, Geothermal energy, District Heating

ABSTRACT

The present study undertakes an energy and exergy analysis of the Salihli geothermal district heating system (SGDHS) in Manisa, Turkey. In the analysis, actual system data obtained on 1 February 2004 directly from the system are used to assess the district heating system performance, through energy and exergy efficiencies. Energy and exergy losses within SGDHS are determined and compared (for a dead state temperature of 0°C). It is found that the exergy losses in the system are essentially due to the fluid flow and take place in the pumps and heat exchangers, as well as the exergy losses of the thermal water (e.g., geothermal fluid) and the natural direct discharge of the system. As a result, the total exergy losses account for 1.72% in pumps, 16.47% in the discharge and 23.62% in heat exchangers, based on the total exergy input to the entire SGDHS. The overall energy and exergy efficiencies of the system are found to be 53.73% and 58.20%, respectively. In addition, the efficiencies of the system elements are studied to evaluate the individual performances and performance improvement possibilities.

1. INTRODUCTION

Exergy analysis has been accepted as a powerful tool for system analysis, design and performance assessment of energy systems, e.g. Moran (1982), Kotas (1985), Bejan (1998), Szargut et al. (1998), Dincer (2002), Hasan et al. (2002), and Rosen and Dincer (2003).

In order to calculate exergy, the environment must be specified. Because of the lack of thermodynamic equilibrium in the surrounding nature, only its common components can be used for the abovementioned purpose. The ability of an energy carrier to do work expresses the general ability to be converted into other kinds of energy, and therefore exergy can be used not only to analyze the process of power plants and of other mechanical machines, but also to investigate technological process. An engineer designing a system is expected to aim for the highest possible technical efficiency at a minimum cost under the prevailing technical, economic and legal conditions, but also with regard to ethical, ecological and social consequences. Exergy appears to be an effective instrument to achieve all or some these objectives.

The studies conducted on the exergy analysis of geothermal systems may be divided into four groups, namely (a) general exergetic studies (Badvarsson and Eggers, 1972; Lee, 2001), (b) exergy analysis of geothermal power plants based on actual data (DiPippo and Marcille, 1984; DiPippo, 1994; Kanoglu and Cengel, 1999; Kanoglu, 2002; Cerci, 2003), (c) exergetic evaluation of geothermal fields in terms of their electric power potential (Quijano, 2000; Koroneous et al., 2004), and (d) exergy analysis of geothermal district heating systems, which has recently been performed by the authors (Ozgener et al., 2004a,b).

In the present study, the authors aim to conduct an energy and exergy analysis for the assessment and modeling of the entire geothermal district heating system and its essential components for performance evaluation and comparison purposes.

2. SYSTEM DESCRIPTION

The Salihli geothermal field is about 7 km far from the town Salihli (about 55 km far from the city Manisa, located in the western part of Turkey) and is abounded with considerably rich geothermal resources. It has a maximal yield of 0.087 m^3/s at an average reservoir temperature of 95°C, with a minimal capacity of 838 MW. The SGDHS was initially designed for a capacity to cover 20,000 residences equivalence. Of these, 2400 residences equivalence are heated by geothermal energy as of February 2004. The outdoor and indoor design temperatures for the system are 4°C and 22°C, respectively (Ozgener et al., 2004a).

Figure 1 illustrates a schematic of the SGDHS, where two hospitals and official buildings heated by geothermal energy were also included. The SGDHS consists mainly of three cycles, such as: (a) energy production cycle (geothermal well loop and geothermal heating center loop), (b) energy distribution cycle (district heating distribution network) and (c) energy consumption cycle (building substations)

At the beginning of 2004, there were seven wells ranging in depth from 70 to 262 m in the SGDHS. Of these, five wells were in operation at the date studied and two wells (K5 and K6) were out of operation. Four wells (designated as K2, K3, K4, and K7) and one well (K1) are production and balneology wells, respectively. The well head temperatures of the production wells vary from 56 °C to 115°C, while the volumetric flow rates of the wells range from 0.002 to 0.02 m^3/s. Geothermal fluid is sent to the primary plate type heat exchanger (between the geothermal fluid and the district heating water) and is cooled to about 44°C, as its heat is transferred to the district heating water.

The geothermal fluid (7) is discharged via natural direct discharge, no recharge to Salihli geothermal field production, but reinjection studies are expected to be completed in the near future. The temperatures obtained during the operation of the SGDHS are, on average, 96/44°C for the district heating distribution network and 62/43°C for the building circuit. By using the control valves for flow rate and temperature at the building main station, the needed amount of water is sent to each housing unit and the heat balance of the system is achieved. Geothermal fluid, collected from the four production wells at an average well heat temperature of about 96°C, is pumped to the inlet of the heat exchanger mixing tank later a main collector (from four production wells) with a total mass flow rate of about 47.62 kg/s. The geothermal fluid of intermingling molecules of different species through molecular diffusion was neglected in this study. As a result, not only irreversibility of the mixing tank was assumed equal to zero but also heat losses from the tank and main collector pipe line (5-6) through the mixing process were neglected based on the earlier works (e.g., Ozgener et al., 2004a).

3. ANALYSIS

In the analyses, both energy and exergy models are employed. To provide an efficient and effective use of energy, it is essential to consider the quality and quantity of the energy used to achieve a given objective. In this regard, the first law of thermodynamics deals with the quantity of energy and asserts that energy cannot be created or destroyed whereas, the second law of thermodynamics deals with the quality of energy i.e., it is concerned with the quality of energy to cause change, degradation of energy during a process, entropy generation and the lost opportunities to do work. More specifically, the first law of thermodynamics is concerned only with the magnitude of energy with no regard to its quality; on the other hand the second law of thermodynamics asserts that energy has quality as well as quality. By quality, it means the ability or work potential of a certain energy source having certain amount of energy to cause change, i.e., the amount of energy which can be extracted as useful work which is termed as exergy. (Dincer and Rosen, 1999; Rosen and Dincer, 2001). For a steady-state, steady-flow process, the three balance equations, namely mass, energy and exergy balance equations, are employed to find the heat input, the rate of exergy decrease, the rate of irreversibility, and the energy and exergy efficiencies, as listed in Table 1. The thermodynamic properties of water are obtained from the general thermodynamic tables and software.

For the overall geothermal system, the mass balance equation is written as follows:

$$\sum_{i=1}^{n} \dot{m}_{w_{tot}} - \dot{m}_d = 0 \quad (1)$$

where $\dot{m}_{w_{tot}}$ is the total mass flow rate at wellhead, $\dot{m}_r$ is the flow rate of the reinjected geofluid and $\dot{m}_d$ is the mass flow rate of the natural direct discharge.

The geothermal brine energy and exergy inputs from the production field are calculated using the following equations:

$$\dot{E}_{brine} = \dot{m}_w \left(h_{brine} - h_0\right) \quad (2)$$

$$\dot{E}x_{brine} = \dot{m}_w \left[\left(h_{brine} - h_0\right) - T_0\left(s_{brine} - s_0\right)\right] \quad (3)$$

The exergy lossed (destructions) in the heat exchanger, pump and the system itself are calculated as follows:

$$\dot{E}x_{HE,dest} = \dot{E}x_{in} - \dot{E}x_{out} \quad (4)$$

$$\dot{E}x_{dest,pump} = W_{pump} - \left(\dot{E}x_{out} - \dot{E}x_{in}\right) \quad (5)$$

$$\dot{E}x_{dest,system} = \sum \dot{E}x_{dest,HE} + \sum \dot{E}x_{dest,pump} \quad (6)$$

The energy efficiency of the SGDHS is calculated from

$$\eta_{system} = \frac{\dot{E}_{useful,HE}}{\dot{E}_{brine}} \quad (7)$$

The exergy efficiency of a heat exchanger is determined by the increase in the exergy of the cold stream divided by the decrease in the exergy of the hot stream on a rate basis as follows:

$$\varepsilon_{HE} = \frac{\dot{m}_{cold}\left(\psi_{cold,out} - \psi_{cold,in}\right)}{\dot{m}_{hot}\left(\psi_{hot,in} - \psi_{hot,out}\right)} \quad (8)$$

The exergy efficiency of the SGDHS is calculated from one of the following equations:

$$\varepsilon_{system} = \frac{\dot{E}x_{useful,HE}}{\dot{E}x_{brine}} \quad (9a)$$

$$\varepsilon_{system} = 1 - \frac{\dot{E}x_{dest,system} + \dot{E}x_{natural\ \mathrm{discharged}}}{\dot{E}x_{brine}} \quad (9b)$$

The exergy efficiencies and exergy destructions for the entire system and its major components are calculated using the above equations and are listed in Table 1.

4. RESULTS AND DISCUSSION

In this study, the restricted dead state was taken to be the reference environment at which the temperature and the atmospheric pressure are 0°C and 101.325 kPa, respectively. The exergy rate results given in Table 2 indicate that it is observed through analysis that the exergy destructions in the system particularly take place as the exergy of the fluid lost in the natural direct discharge of the system, the heat exchanger, and the pumps accounting for 23.62%, 16.47%, and 1.72%, respectively, of the total exergy input to the SGDHS as shown in Figure 2. Both energy and exergy efficiencies of the overall SGDHS are determined to be 53.73% and 58.20%, respectively.

The total energy input value is obtained to be 18426.52 kW for the day on 1 February 2004 (Ozgener et al., 2004a). The corresponding reference state (dead state) temperature is 0ºC. In conjunction with this, the total exergy input value is found to be 2771.16 kW for the same day.

It is important to note that in the geothermal district heating systems, the temperature difference between the geothermal resource and the supply temperature of the district heating distribution network plays a key role in terms of exergy loss. In fact, the district heating supply temperature is determined after the optimization calculation. In this calculation, it should be taken into account that increasing the supply temperature will result in a reduction of investment cost for the distribution system and the electrical energy required for pumping stations, while it causes an increase of heat losses in the distribution network. Unless there is a specific reason, the district heating supply temperature should be higher in order to increase the exergy efficiency of the heat exchangers and hence the entire system.

5. CONCLUSIONS

The following main conclusions may be drawn from the present study:

a) The values for energy and exergy efficiency for SGDHS are found to be 53.73% and 58.20%, respectively. In comparison with other local district heating systems (e.g., Balcova geothermal district heating system), the present system has higher energy and exergy efficiencies while its geothermal resources are categorized as low-quality geothermal resources. This is in fact due to the smaller amount of exergy destructions within system components and in the system in general.
b) Currently, reinjection is not applied in the SGDHS and is planned in the near future. After this is implemented, it will result in smaller amount of heat losses which will make the system more efficient.
c) Actual thermal data taken from geothermal district heating present a valuable database and source for further and future studies.
d) The data and analysis results are expected to be beneficial to the researchers and engineers working in the area of geothermal district heating systems.

NOMENCLATURE

$\dot{E}$	energy rate (kW)
$\dot{E}x$	exergy rate (kW)
Ex	exergy (kJ)
h	specific enthalpy (kJ/kg)
$\dot{I}$	irreversibility (exergy destruction) rate (kW)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\dot{Q}$	heat transfer (thermal energy) rate (kW)
s	specific entropy (kJ/kgK)
$\dot{S}$	entropy rate (kW/K)
$\dot{W}$	work rate, power (kW)
T	temperature (^{o}C or K)

Greek letters

η	energy (first law) efficiency (%)
ε	exergy (exergetic or second law) efficiency (%)
ψ	flow exergy (kJ/kg)

Subscripts

d	natural direct discharge
dest	destroyed
e	electricity
gen	generation
HE	heat exchanger
in	inlet
k	location
out	outlet
tot	total
w	well-head

Superscripts

CH	chemical
KN	kinetic
PH	physical
PT	potential

ACKNOWLEDGEMENTS

The authors are grateful to Manisa–Salihli Municipality for their technical arrangements. Special thanks are due to Mr. Z. Sukru Ogurtan from ORME Geothermal Inc. for providing operational data and support during the field study conducted in the Salihli geothermal district heating system.

REFERENCES

Badvarsson, G., and Eggers, D.E.: The Exergy of Thermal Water, *Geothermics*, **1**, (1972), 93-95.

Bejan, A.: Advanced Engineering Thermodynamics, *John Wiley & Sons*, New York (1998).

Cerci, Y.: Performance Evaluation of a Single-flash Geothermal Power Plant in Denizli, Turkey, *Energy*, **28**, (2003), 27-35.

Dincer, I., and Rosen, M.A.: Energy, Environment and Sustainable Development, *Applied Energy*, **64 (1/4)**, (1999), 427-440.

Dincer, I.: The Role of Exergy in Energy Policy Making, *Energy Policy*, **30**, (2002), 137-149.

DiPippo, R., and Marcille, D.F.: Exergy Analysis of Geothermal Power Plants, *Geothermal Resources Council Transactions*, **8**, (1984), 47-52.

DiPippo, R.: Second Law Analysis of Flash-binary and Multilevel Binary Geothermal Plants, *Geothermal Resources Council Transactions*, **18**, (1994), 505-510.

Hasan, A.A., Goswami, D.Y., and Vijayaraghavan, S.: First and Second Law Analysis of a New Power and Refrigeration Thermodynamic Cycle Using a Solar Heat Source**,** *Solar Energy*, **73**(**5)**, (2002), 385-393.

Kanoglu, M.: Exergy Analysis of a Dual-level Binary Geothermal Power Plant, *Geothermics*, **31**, (2002), 709-724.

Kanoglu, M., and Cengel, Y.A.: Improving the Performance of an Existing Binary Geothermal Power Plant: A Case Study. Transactions of the ASME, *Journal of Energy Resources Technology*, **121(3)**, (1999), 196-202.

Kotas, T.J.: The Exergy Method of Thermal Plant Analysis, Anchor Brendon Ltd, Tiptree, Essex. Great Britain (1985).

Koroneous, C., Bobolias, C., and Spachos, T.: Evaluation of Utilization Opportunities of Geothermal Energy in the Kavala Region, Greece, Using Exergy Analysis. *International Journal of Exergy*, **1(1)**, (2004), 111-127.

Lee, K.C.: Classification of Geothermal Resources by Exergy, *Geothermics*, **30**, (2001), 431-442.

Moran, M.J.: Availability Analysis: A Guide to Efficiency Energy Use, Prentice-Hall, Englewood Cliffs, NJ (1982).

Ozgener, L., Hepbasli, A., and Dincer, I.: Energy and Exergy Analysis of Salihli Geothermal District Heating System in Manisa, Turkey, *International Journal Energy Research*, (2004a), in press.

Ozgener, L., Hepbasli, A., and Dincer, I.: Thermo-mechanical Exergy Analysis of Balcova Geothermal District Heating System in Izmir, Turkey, *ASME-Journal of Energy Resources Technology*, (2004b), in press.

Quijano, J.: Exergy Analysis for the Ahuachapan and Berlin Geothermal Fields, El Salvador, *Proceedings*, World Geothermal Congress, May 28-June 10, Kyushu-Tohoku, Japan (2000).

Rosen, M.A., and Dincer, I.: Exergy as the Confluence of Energy, Environment and Sustainable Development, *Exergy, An International Journal* **1**(1), (2001), 3-13.

Rosen, M.A., and Dincer, I.: Exergy–Cost–Energy–Mass Analysis of Thermal Systems and Processes, *Energy Conversion and Management*, **4(10)**, (2003), 1633-1651.

Szargut, J., Morris, D.R., and Stewart, F.R.: Exergy Analysis of Thermal, Chemical, and Metallurgical Processes, Edwards Brothers Inc. USA (1998).

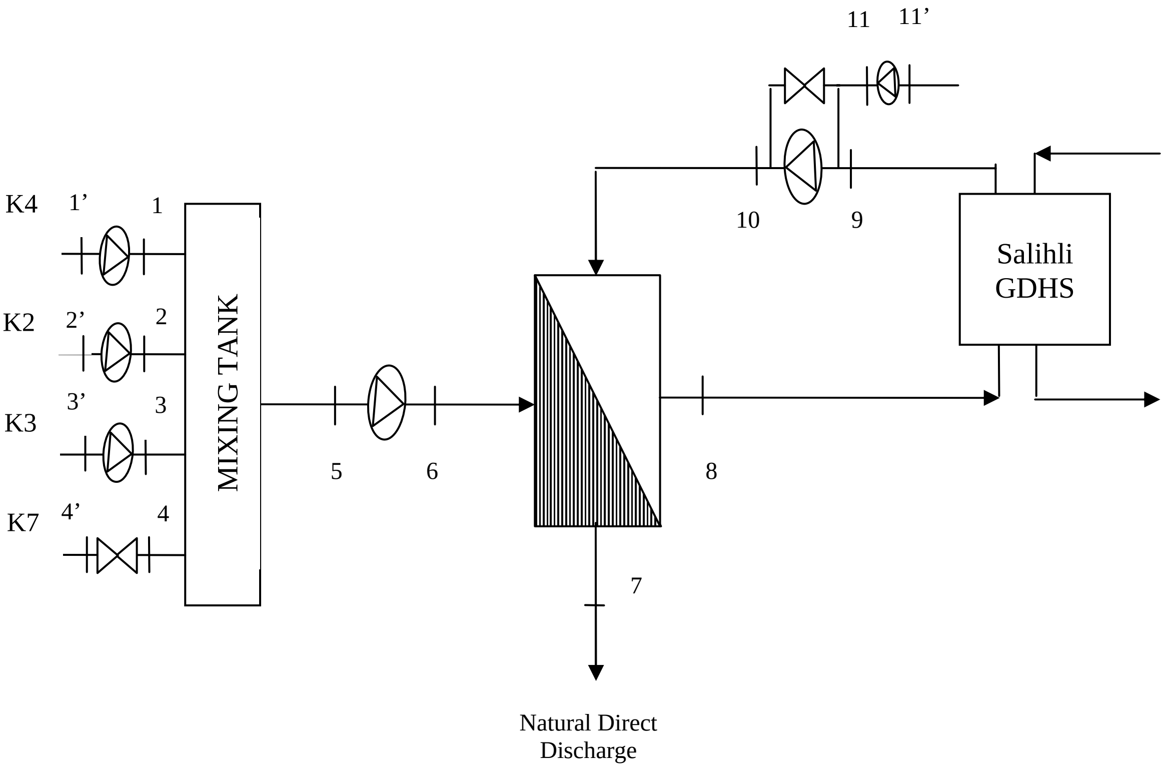

Figure 1: A schematic of the Salihli GDHS

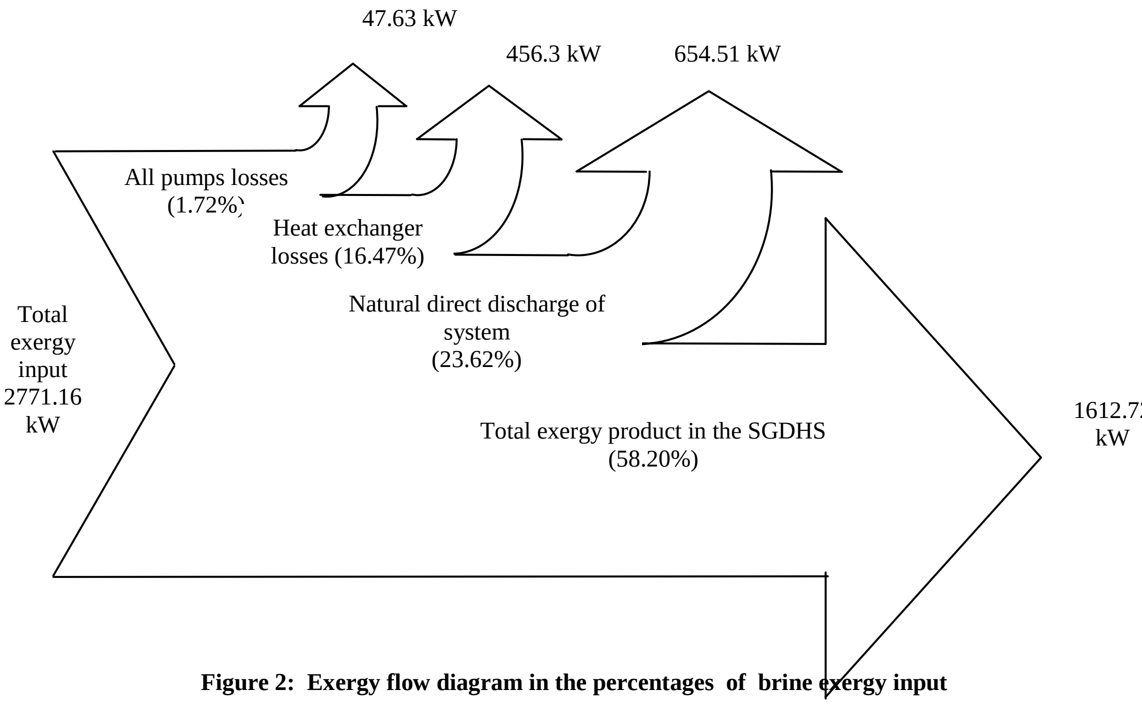

Figure 2: Exergy flow diagram in the percentages of brine exergy input

Table 1: The general balance equations for the system.

Item no	Title	Equations	Remarks
I	Mass balance	$\sum \dot{m}_{in} = \sum \dot{m}_{out}$	The general mass balance equation
II	Energy balance	$\dot{E}_{in} = \dot{E}_{out}$	The general energy balance equation pressed as the total energy input equal to the total energy output
		$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out}$	
		$\dot{Q} = \dot{Q}_{net,in} = \dot{Q}_{in} - \dot{Q}_{out}$	The rate of net heat input
		$\dot{W} = \dot{W}_{net,out} = \dot{W}_{out} - \dot{W}_{in}$	The rate of net work output
III	Exergy balance	$Ex = Ex^{PH} + Ex^{KN} + Ex^{PT} + Ex^{CH}$	The total exergy of a system
		$\psi = (h - h_0) - T_0(s - s_0)$	The specific exergy
		$\dot{E}x_{brine} = \dot{m}_w[(h_{brine} - h_0) - T_0(s_{brine} - s_0)]$	The exergy rate
IV	Destruction or irreversibilty	$\mathring{E}x_{heat} - \mathring{E}x_{work} + \mathring{E}x_{mass,in} - \mathring{E}x_{mass,out} = \mathring{E}x_{dest}$	The general exergy balance
		$\dot{E}x_{in} - \dot{E}x_{out} = \dot{E}x_{dest}$	
		$\sum \left(1 - \frac{T_o}{T_k}\right)\dot{Q}_k - \dot{W} + \sum \dot{m}_{in} \psi_{in} - \sum \dot{m}_{out} \psi_{out} = \dot{E}x_{dest}$	
		$\dot{I} = \dot{E}x_{dest} = T_0 \dot{S}_{gen}$	The exergy destroyed or the irreversibility
V	Efficiencies	$\eta = \frac{\dot{E}_{output}}{\dot{E}_{input}}$	The energy efficiency
		$\varepsilon = \frac{\dot{E}x_{output}}{\dot{E}x_{input}}$	The exergy efficiency

Table 2: Exergy destruction and exergy efficiencies for one representative unit of the SGDHS.

Item no	Component	Exergy destruction rate (kW)	Utilized power (kW)	Heat transfer rate or installed power (kW)	Exergy efficiency (%)	Energy efficiency (%)
1	Heat exchanger	456.3	10226.83	43961.38	77.95	-
2	K4 well pump	21.28	24.75	55	14.02	65 - 80
3	K2 well pump	12.51	20.25	45	38.22	65 - 80
4	K3 well pump	4.76	20.25	45	76.49	65 - 80
5	K7 well pump	-	-	-	-	-
6	Salihli booster pump	6.2	55	675	88.73	65 - 80
7	Salihli circulation pump	2.88	112.5	537	97.44	65 - 80
8	Heat exchanger and pumps	503.93	10468.52	45520.58	-	-
9	Overall system[a]	1158.44	1612.72	45520.58	58.20	53.73

[a] Based on the exergy (or energy) input to thermal water and water