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Energy and exergy analysis of geothermal district heating systems: an application

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Abstract

In this study we present an energy and exergy assessment and modeling of geothermal district heating systems for their system analysis, performance evaluation and optimization. A comprehensive case study is conducted in Balcova geothermal district heating system (BGDHS) in Izmir, Turkey and actual thermal data are collected and employed for analysis. Using actual system data, an assessment of the district heating system performance, energy and exergy efficiencies, and exergy destructions in the system is conducted in this regard. The exergy destructions in the overall BGDHS are quantified and illustrated using exergy flow diagram. Furthermore, both energy and exergy flow diagrams are exhibited for comparison purposes. It is observed through analysis that the exergy destructions in the system particularly take place as the exergy of the fluid lost in the pumps, the heat exchanger losses, the exergy of the thermal water (geothermal fluid) reinjected and the natural direct discharge (hot water distribution losses) of the system, accounting for 1.64%, 8.57%, 14.84% and 28.96%, respectively, of the total exergy input to the BGDHS. For system performance analysis and improvement, both energy and exergy efficiencies of the overall BGDHS are investigated and are determined to be 41.9% and 46%, respectively.

Keywords: Geothermal energy; Efficiency; Energy analysis; Exergy analysis; District heating system; Turkey

1. Introduction

It is known that geothermal energy is the energy contained as heat (the thermal energy) within the Earth's interior. The origin of this heat is linked with the internal structure of our planet and the physical processes occurring there. Geothermal energy is to some extent a renewable energy source since a geothermal resource usually has a projected life of 30–50 years. The life of a resource may be prolonged by a reinjection process, which may compensate for at least part of the fluid extracted by production [1–4].

Geothermal energy has been produced commercially for over 80 years and for four decades on the scale of hundreds of megawatts both for electricity generation and direct use. The utilization of geothermal energy has increased rapidly during the last 3 decades. In 2000, geothermal resources were identified in over 80 countries, and there are quantified records of geothermal utilization in 58 countries in the world [5].

Most of the world's geothermal power plants were built in the 1970s and 1980s following the 1973 oil crisis. The urgency to generate electricity from alternative energy sources and the fact that geothermal energy was

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Nomenclature

E	energy (kJ)
$\dot{E}$	energy rate (kW)
$\dot{\mathrm{E}}\mathrm{x}$	exergy rate (kW)
Ex	exergy (kJ)
ex	specific exergy (kJ/kg)
$\dot{F}$	exergy rate of the fuel (kW)
f	exergetic factor (%)
h	specific enthalpy (kJ/kg)
$\dot{I}$	irreversibility (exergy destruction) rate (kW)
IP	improvement potential rate (kW)
$\dot{m}$	mass flow rate (kg/s)
$\dot{P}$	exergy rate of the product (kW)
P	pressure (kPa)
$\dot{Q}$	heat transfer (thermal energy) rate (kW)
s	specific entropy (kJ/kg K)
$\dot{S}$	entropy rate (kW/K)
$\dot{W}$	work rate, power (kW)
T	temperature (°C or K)
ExP	exergy product rate (kW)
HExL	rate of heat exchanger losses (kW)
HEx	heat exchanger power (kW)
NDDS	natural direct discharge rate of system (kW)
SExI	specific exergy index (dimensionless)
TEI	total energy input rate (kW)
TExI	total exergy input rate (kW)

Greek letters

η	energy or first law efficiency (%)
ε	exergy or exergetic or second law efficiency
ψ	flow exergy (kJ/kg)
δ	fuel depletion rate (%)
ξ	productivity lack (%)
χ	relative irreversibility (%)

Subscripts

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

Superscript

CH	chemical
KN	kinetic
PH	physical
PT	potential
·	rate

essentially free adversely affected careful designs of power plants to maximize their efficiency for a given geothermal resource [6,7]. This change has had important consequences for energy and environmental policies [8]. As a result, energy policy has been an important part of sustainable development, given the significant role of energy in economic growth and environmental effects associated with energy use [9–11].

Since the first geothermally generated electricity in the world was produced at Larderello, Italy, in 1904 the use of geothermal energy for electricity has grown worldwide to about 7000 MW in 21 countries around the world. The USA alone produces 2700 MW of electricity from geothermal energy, electricity comparable to burning 60 million barrels of oil each year [6].

The world geothermal electrical capacity installed in the year 2000 was 7974 MW, with the generation of 49.3 billion kW h in the same year, and energy use growth in space heating since 1995 has been 12%. About 75% of the total energy production is utilized for district heating, and the reminder is for individual space heating in the world [7]. Although the majority of the districts heating systems are in Europe, particularly in France and Iceland, the USA has the highest rate of using geothermal energy for individual home heating systems, typically in Klamath Falls, Oregon and Reno, Nevada.

Note that geothermal heat is utilized in some creative ways; its use is limited only by the ingenuity. For instance, in Klamath Falls, Oregon, which has one of the largest district heating systems in the US [6], geothermal water is also piped under roads and sidewalks for snow melting and freeze protection purposes in freezing weather conditions. The cost of employing any other method to keep hot water running continuously through cold pipes would be prohibitive. Furthermore, in New Mexico and other places rows of pipes carrying geothermal water have been installed under soil, where flowers or vegetables are growing. In fact, this ensures that the ground does not freeze, providing a longer growing season and overall faster growth of agricultural products that are not protected by the shelter and warmth of a greenhouse.

There are also other countries, e.g., China, Japan, and Turkey using geothermal district heating systems.

Turkey's share worldwide thermal energy use is about 12.1% [4,12]. Before the 1960s geothermal resources were only used spontaneously in bathing and medical treatment in Turkey. Recently, the General Directorate of Mineral Research and Exploitation in Turkey has carried out some considerable geothermal energy research and explorations. In fact, the inventorial works chemical analyses of the hot springs and mineral waters were initiated in 1962. Geothermal district heating applications started in 1987 in Turkey with heating of 600 residences in Balikesir-Gonen in 1990, geothermal direct use applications increased as steeply as 185% from 1990 to 1995 [12]. Direct use of geothermal resources has expanded rapidly since 1964, from space heating of single buildings to district heating, greenhouse heating, industrial usage, modern balneology, and physical treatment facilities. Direct use installed thermal capacity increased from 160 MW in 1995 to 820 MW in 2000. The distribution of this installed thermal capacity of 820 MW by category is 392 MW for spaces heating (particularly in residences and thermal facilities), 101 MW for greenhouses, and 327 MW for bathing and swimming [13,14]. Today, the geothermal space heating capacity has increased at an average annual growth of 23% since 1983. The total number of geothermal space heating systems is currently 37 [14,15].

Utilization of district heating systems and combined heat and power systems is increasing due to reduced amounts of wastes, emissions, and recovery of energy in the world. It may also provide significant environmental and social benefits [16–20]. Several countries have adopted strategic energy policies, primarily focusing on improving sectoral energy use, creating an environmentally benign energy sector, making optimal use of local resources by diversifying the essential energy sources for electricity production, etc. In this regard, geothermal energy appears to be a potential solution to energy and environmental problems and a key tool for sustainable development. Also, geothermal energy systems are simple, safe, and adaptable systems with modular 1–50 MW plants capable of providing continuous baseload, load following, or peaking capacity and benign environmental attributes (negligible emissions of CO_2, SO_x, NO_x, and particulates, and modest land and water use). Because these features are compatible with sustainable growth of global energy supplies in both developed and developing countries, geothermal energy then becomes an attractive option to replace fossil and fossil fuels [21].

An exergy analysis has proven to be a powerful tool in the thermodynamic analyses of energy systems [22–27]. In order to calculate exergy, the reference environment must be specified. Exergy analysis is employed to detect and to evaluate quantitatively the causes of the thermodynamic imperfection of the process under consideration. Exergy analysis can, therefore, indicate the possibilities of thermodynamic improvement of the process under consideration, but only an economic analysis can decide the expediency of a possible improvement [25].

Exergy analysis is important for all energy resource utilization, because exergy is the part of the energy analysis. The theory of exergy analysis is essentially that of available energy analysis. The concepts of exergy, available energy, and availability are essentially similar. The concepts of exergy destruction, exergy consumption, irreversibility, and lost work are also essentially similar. Terminology does not appear to have been standardized [28]. Exergy is also a measure of the maximum useful work that can be done by a system interacting with an environment which is at a constant pressure P_0 and a temperature T_0. The simplest case to consider is that of a reservoir with heat source of infinite capacity and invariable temperature T_0. It has been considered that maximum efficiency of heat withdrawal from a reservoir that can be converted into work is the Carnot efficiency [29–31].

As far as the geothermal systems are concerned, these studies can be classified in three groups as follows: (i) exergy analysis of geothermal power plants (e.g., [7,32–35]), (ii) evaluation of geothermal fields using exergy analysis (e.g., [36,37]), and (iii) classification of geothermal resources by exergy (e.g., [39]). As can be seen from this classification, the concept of exergy was first used to analyze a geothermal power plant by Badvarsson and Eggers [32]. Their illustrative example, which compared the performances of single and double flash cycles based on a reservoir water temperature of 250 °C and a sink condition of 40 °C, gave exergetic efficiencies of 38.7% and 49%, respectively, assuming 65% mechanical efficiency [38].

Numerous studies (e.g., [2–4,7–9,12–15,32–41]) have recently been undertaken for geothermal systems to perform a large range of investigations from system basics to system energy and exergy analyses. The authors have conducted some preliminary works [40,41] for Balcova and Salihli geothermal district heating systems in Turkey. In this paper, the authors extend the previous work done on Balcova geothermal district heating system by considering four different days, namely 1 January 2003, 2 December 2003, 2 January 2004 and 2 February 2004 to cover a much wider range of application and operational conditions, investigating each essential component of the system from energy and exergy analysis point of view, and conducting a parametric study to see how both energy and exergy efficiencies of the system change with various operational data and weather conditions on various days. Furthermore, energy and exergy flows and efficiencies are compared for a better assessment and performance evaluation, which will result in some possible efficiency improvements.

2. Case study: Balcova geothermal district heating system

The Izmir-Balcova geothermal field covers a total area of about 3.5 km^2 with an average thickness of the aquifer horizon of 150 m. Assume that no feeding occurs, and 25% of the fluid contained in the reservoir is utilized. The field has a maximum yield of 810 m^3/h at a reservoir temperature of 118 °C (as detailed in Ref. [40]). The present district heating system consists of the Izmir-Balcova geothermal district heating system (IBGDHS) and the Izmir-Narlidere geothermal district heating system (INGDHS). The design heating capacity of the IBGDHS is equivalent to 7500 residences. The INGDHS was designed for 1500 residence equivalence but has a sufficient infrastructure to allow a capacity growth to 5000 residence equivalence. The outdoor and indoor design temperatures for the two systems are 0 and 22 °C, respectively [39]. Both IBGDHS and INGDHS are investigated here under BGDHS (for more details, see Ozgener et al. [40]). The BGDHS is presently run by a governmental body under the governorship of Izmir and is utilized only for district heating purposes.

Fig. 1 shows a schematic diagram of the BGDHS where hotels and official buildings heated by geothermal energy are also included. The BGDHS consists mainly of three cycles, such as: (a) energy production cycle through geothermal well loop and geothermal heating center loop, (b) energy distribution cycle through district heating distribution network and (c) energy consumption cycle through building substations.

As of the end of 2001, there were 14 wells ranging in depth from 48 to 1100 m in the IBGF, while 10 wells were working at the date studied. Of these, eight wells (designated as BD2, BD3, BD4, BD5, BD7, B1, B4, B5 and B10) and one well (BD8) are production and reinjection wells, respectively. The well head temperatures of the production wells vary from 95 to 140 °C, while the volumetric flow rates of the wells range from 30 to 150 m^3/h, respectively. The geothermal fluid is then sent to two primary plate type heat exchangers and is cooled to about 60–62 °C, as its heat is transferred to secondary fluid [40].

The primary geothermal fluid is reinjected into the well BD8 after transferring its heat, while the secondary fluid (i.e., clean hot water) is transferred to heat building circulation water through the substation heat exchangers. The average conversion temperatures obtained during the operation of the BGDHS are 80/57 °C for the district heating distribution network and 60/45 °C for the building circuit. Using the control valves for flow rate and temperature at the building substations, the required amount of water is sent to each housing unit to achieve the heat balance of the system. The geothermal fluid, collected from the eight production wells at an average well heat temperature of 117.9 °C, is pumped to a main collector (from eight production wells) with a total mass flow rate of about 212.16 kg/s.

As a matter of fact, in the present case study conducted in the BGDHS, the hourly recorded experimental thermal data of various parameters were taken from the system technical/operational staff. The pressures and temperatures of fluids (including water and geothermal) are measured by the technical staff with Bourdon-tube pressure gauges and fluid-expansion thermometers, respectively. The volumetric flow rates of the distribution networks are also measured by Danfoss MAG 3000 flowmeters. As known, the errors

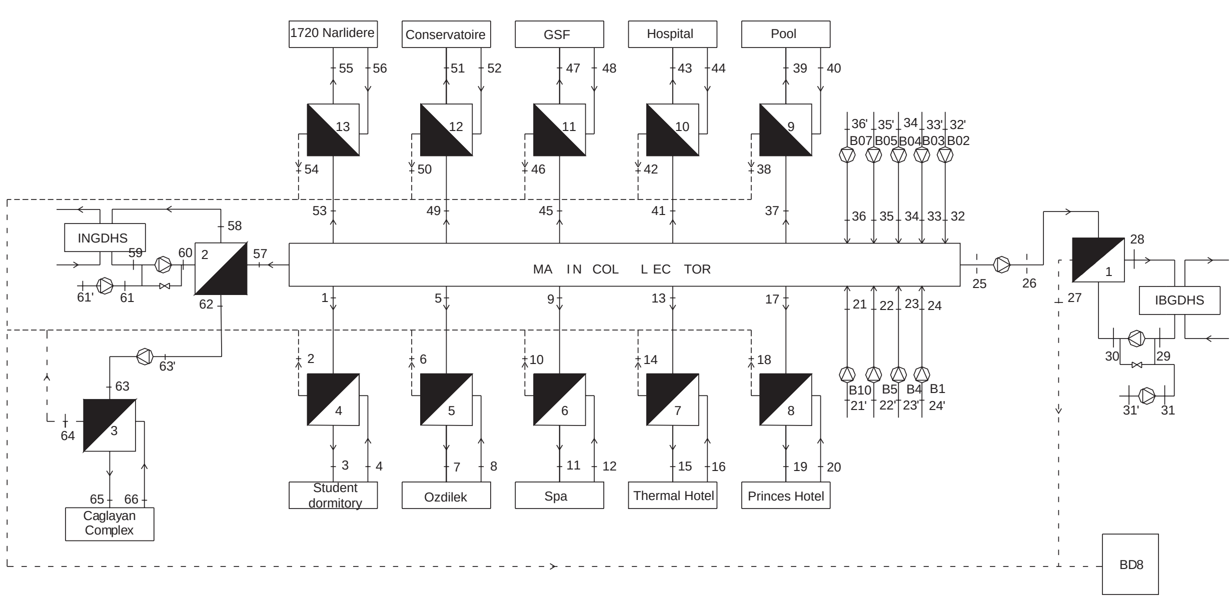

Fig. 1. Schematic diagram of the current BGHS.

Table 1
Total uncertainties of the measured and calculated parameters

Item no.	Description	Unit	Total uncertainty (%)
Measured quantities			
1	Temperature	°C	±1.97
2	Pressure	bar	±1.71
3	Volumetric flow rate	m^3/s	±0.32
Derived quantities			
1	Mass flow rate12345*		
	kg/s	±0.38	
2	Energy rate	kW	±0.43
3	Specific exergy	kJ/kg	±0.68
4	Exergy rate	kW	±0.78
5	Energy efficiency	%	±0.75
6	Exergy efficiency	%	±1.28
Uncertainty in reading values of table			±0.20

*The values of the flow meters installed in the system (Balcova geothermal district heating system) are considered as indicated in Fig. 1.

and uncertainties in data recording and experiments may arise from instrument selection, instrument condition, instrument calibration, environment, observation and reading and test planning. An uncertainty analysis was needed to prove the accuracy and reliability of the experimental data taken. Such uncertainty analysis is performed through the method described by Holman [42]. As a result, Table 1 shows the total uncertainties of these measured parameters measured as outlined in detail elsewhere [40].

3. Modeling

Recently, the concept of exergy has received great attention from scientists, researchers and engineers in various disciplines and has been applied to various utility sectors and thermal processes. Recently, much attention has been paid to the energy and exergy modeling techniques for energy- and exergy-use assessments in order to minimize losses and maximize energy savings and hence financial savings.

In the modeling both energy and exergy models are employed. As stated earlier [10,11], to provide an efficient and effective use of fuels 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 exergy to cause change, degradation of exergy during a process, entropy generation and the lost opportunities to do work. The first- and second-law efficiencies are often called *energy* and *exergy efficiencies*, respectively. It is expected that exergy efficiencies are usually lower than the energy efficiencies, because the irreversibilities of the process destroy some of the input exergy.

3.1. Mass, energy and exergy balance equations

For a general 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.

In general, the mass balance equation can be expressed in the rate form as

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

where $\dot{m}$ is the mass flow rate, and the subscript in stands for inlet and out for outlet.

The general energy balance can be expressed below as the total energy input equal to total energy output ($\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$), with all energy terms as follows:

$$\dot{Q} + \sum \dot{m}_{\text{in}} h_{\text{in}} = \dot{W} + \sum \dot{m}_{\text{out}} h_{\text{out}}, \tag{2}$$

where $\dot{Q} = \dot{Q}_{\text{net,in}} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}$ is the rate of net heat input, $\dot{W} = \dot{W}_{\text{net,out}} = \dot{W}_{\text{out}} - \dot{W}_{\text{in}}$ is the rate of net work output, and h is the specific enthalpy.

Assuming no changes in kinetic and potential energies with no heat or work transfers, the energy balance given in Eq. (2) can be simplified to flow enthalpies only:

$$\sum \dot{m}_{\text{in}} h_{\text{in}} = \sum \dot{m}_{\text{out}} h_{\text{out}}. \tag{3}$$

Unlike energy, exergy is not subject to a conservation law (except for reversible processes). Rather exergy is consumed or destroyed, due to irreversibilities in any real process. The exergy consumption during a process is proportional to the entropy created due to irreversibilities associated with the process.

The total exergy of a system Ex can be divided into four components, namely (i) physical exergy Ex^{PH}, (ii) kinetic exergy Ex^{KN}, (iii) potential exergy Ex^{PT}, and (iv) chemical exergy Ex^{CH}

$$\text{Ex} = \text{Ex}^{\text{PH}} + \text{Ex}^{\text{KN}} + \text{Ex}^{\text{PT}} + \text{Ex}^{\text{CH}}. \tag{4}$$

Here, we consider physical exergy only in this analysis and neglect chemical, potential and kinetic exergies due to the fact that no chemical reactions take place and that the changes in kinetic and potential exergies are negligible. Thus, the general exergy rate balance can be expressed as follows:

$$\dot{\text{E}}\text{x}_{\text{heat}} - \dot{\text{E}}\text{x}_{\text{work}} + \dot{\text{E}}\text{x}_{\text{mass,in}} - \dot{\text{E}}\text{x}_{\text{mass,out}} = \dot{\text{E}}\text{x}_{\text{dest}} \tag{5}$$

and more explicitly,

$$\sum\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k - \dot{W} + \sum \dot{m}_{in}\psi_{in} - \sum \dot{m}_{out}\psi_{out} = \dot{E}x_{dest}, \quad (6)$$

where $\dot{Q}_k$ is the heat transfer rate crossing the boundary at temperature T_k at location k, $\dot{W}$ is the work rate, ψ is the flow exergy, h is enthalpy, s is entropy, and the subscript zero indicates properties at the restricted dead state of P_0 and T_0.

The specific exergy and exergy rate equations for the geothermal fluid flow system can be defined as

$$\psi = (h-h_0) - T_0(s-s_0) \quad \text{and}$$
$$\dot{E}x = \dot{m}[(h-h_0) - T_0(s-s_0)]. \quad (7)$$

For exergy destruction (or irreversibility), the entropy generation $\dot{S}_{gen}$ is calculated first and used in the following equation:

$$\dot{I} = \dot{E}x_{dest} = T_0\dot{S}_{gen}. \quad (8)$$

3.2. Energy and exergy efficiencies

Basically, the energy efficiency of the system can be defined as the ratio of total energy output to total energy input

$$\eta = \frac{\dot{E}_{output}}{\dot{E}_{input}}, \quad (9)$$

where in most cases "output" refers to "useful" one.

Numerous ways of formulating exergetic (or exergy or second-law) efficiency (effectiveness, or rational efficiency) for various energy systems are given in detail elsewhere [23]. Here, in a similar way we define exergy efficiency as the ratio of total exergy output to total exergy input:

$$\varepsilon = \frac{\dot{E}x_{output}}{\dot{E}x_{input}}, \quad (10)$$

where "output" refers to "net output" or "product" or "desired value", and "input" refers to "given" or "used".

3.3. Specific exergy index (SExI)

Geothermal resources are generally classified according to their reservoir temperatures as low-temperature (>90 °C), intermediate-temperature (90–150 °C) and high-temperature (>150 °C) resources, while some may have slightly different ranges of the temperatures [38]. Since temperature itself is not sufficient for proper classification, some (e.g., [38]) suggest that two independent properties are required to define the thermodynamic state of a fluid clearly.

Geothermal energy is already in the form of heat, and from the thermodynamic point of view, work is more useful than heat because not all the heat can be converted to work. Therefore, geothermal resources can be classified to reflect their ability to do thermodynamic work. In this regard, Lee [38] proposed a new parameter, namely specific exergy index (SExI) for better classification and evaluation as follows:

$$\text{SExI} = \frac{h_{brine} - 273.16 s_{brine}}{1192} \quad (11)$$

which is a straight line on an h–s plot of the Mollier diagram. Straight lines of SExI = 0.5 and SExI = 0.05 can therefore be drawn in this diagram and used as a map for classifying geothermal resources by taking into account the following criteria:

1. SExI < 0.05 for low-quality geothermal resources;
2. 0.05 ⩽ SExI < 0.5 for medium-quality geothermal resources; and
3. SExI ⩾ 0.5 for high-quality geothermal resources.

Here, the demarcation limits for these indices are exergies of saturated water and dry saturated steam at 1 bar absolute.

In order to map any geothermal field on the Mollier diagram as well as to determine the energy and exergy values of the geothermal brine, the average values for the enthalpy and entropy are then calculated from the following equations [38]:

$$h_{brine} = \frac{\sum_{i=1}^{n} \dot{m}_{wi}h_{wi}}{\sum_{i=1}^{n} \dot{m}_{wi}}, \quad (12)$$

$$s_{brine} = \frac{\sum_{i=1}^{n} \dot{m}_{wi}s_{wi}}{\sum_{i=1}^{n} \dot{m}_{wi}}. \quad (13)$$

3.4. Exergetic improvement potential and some other thermodynamic parameters

In addition, van Gool [43] has also noted that maximum improvement in the exergy efficiency for a process or system is obviously achieved when the exergy loss or irreversibility ($\dot{E}x_{in} - \dot{E}x_{out}$) is minimized. Consequently, he suggested that it is useful to employ the concept of an exergetic "improvement potential (IP)" when analyzing different processes. This improvement potential on the rate basis, denoted IP, is given by Hammond and Stapleton [44]:

$$\text{IP} = (1-\varepsilon)(\dot{E}x_{in} - \dot{E}x_{out}). \quad (14)$$

Some other thermodynamic parameters for geothermal energy systems are also proposed as follows [45]:

- *fuel depletion ratio*: $\delta_i = \dfrac{\dot{I}_i}{\dot{F}_{Tot}}$, (15)

- *relative irreversibility*: $\chi_i = \frac{\dot{I}_i}{\dot{I}_{\text{Tot}}}$, (16)

- *productivity lack*: $\xi_i = \frac{\dot{I}_i}{\dot{P}_{\text{Tot}}}$, (17)

- *exergetic factor*: $f_i = \frac{\dot{F}_i}{\dot{F}_{\text{Tot}}}$. (18)

4. Results and discussion

Here, the balance equations are written for mass, energy and exergy flows in the systems which are treated as the steady-state steady-flow systems, and the respective energy and exergy efficiency equations are also written for the system and its components.

The temperature, pressure, and mass flow rate data for both geothermal fluid and hot water are given in accordance with their state numbers specified in Fig. 1. The exergy rates are calculated for each state and listed in Table 2. Note that state 0 indicates the restricted dead state for the geothermal fluid and hot water. In this study, the restricted dead state was taken to be the state of environment at which the temperature and the atmospheric pressure are 10.4 °C and 101.3 kPa on 2 January 2004, respectively, which were the values measured at the time when the geothermal district heating system data were obtained. Some investigators (e.g., [7,35]) also employed this type selection in the exergy analysis of geothermal power plants. For geothermal fluid, the thermodynamic properties of water are used. By doing so, any possible effects of salts and noncondensable gases that might be present in the geothermal brine are neglected [7]. 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:

$$\sum_{i=1}^{n} \dot{m}_{\text{w,tot}} - \dot{m}_{\text{r}} - \dot{m}_{\text{d}} = 0, \tag{19}$$

where $\dot{m}_{\text{w,tot}}$ is the total mass flow rate at wellhead, $\dot{m}_{\text{r}}$ is the flow rate of the reinjected geofluid and $\dot{m}_{\text{d}}$ is the mass flow rate of the natural direct discharge.

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

$$\dot{E}_{\text{brine}} = \dot{m}_{\text{w}}(h_{\text{brine}} - h_0), \tag{20}$$

$$\dot{\text{E}}\text{x}_{\text{brine}} = \dot{m}_{\text{w}}[(h_{\text{brine}} - h_0) - T_0(s_{\text{brine}} - s_0)]. \tag{21}$$

The exergy destructions in the heat exchanger, pump and the system itself are calculated using:

$$\dot{\text{E}}\text{x}_{\text{dest,HE}} = \text{Ex}_{\text{in}} - \dot{\text{E}}\text{x}_{\text{out}} = \dot{\text{E}}\text{x}_{\text{dest}}, \tag{22}$$

$$\dot{\text{E}}\text{x}_{\text{dest,pump}} = \dot{W}_{\text{pump}} - \left(\dot{\text{E}}\text{x}_{\text{out}} - \dot{\text{E}}\text{x}_{\text{in}}\right), \tag{23}$$

$$\dot{\text{E}}\text{x}_{\text{dest,system}} = \sum \dot{\text{E}}\text{x}_{\text{dest,HE}} + \sum \dot{\text{E}}\text{x}_{\text{dest,pump}}. \tag{24}$$

Based upon Eq. (9), the energy efficiency of the BGDHS is calculated from

$$\eta_{\text{system}} = \frac{\dot{E}_{\text{useful,HE}}}{\dot{E}_{\text{brine}}}. \tag{25}$$

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:

$$\varepsilon_{\text{HE}} = \frac{\dot{m}_{\text{cold}}\left(\psi_{\text{cold,out}} - \psi_{\text{cold,in}}\right)}{\dot{m}_{\text{hot}}\left(\psi_{\text{hot,in}} - \psi_{\text{hot,out}}\right)}. \tag{26}$$

Based on Eq. (10), the exergy efficiency of the BGDHS is calculated from one of the following equations:

$$\varepsilon_{\text{system}} = \frac{\dot{\text{E}}\text{x}_{\text{useful,HE}}}{\dot{\text{E}}\text{x}_{\text{brine}}} = 1 - \frac{\dot{\text{E}}\text{x}_{\text{dest,system}} + \dot{\text{E}}\text{x}_{\text{reinjected}} + \dot{\text{E}}\text{x}_{\text{natural discharged}}}{\dot{\text{E}}\text{x}_{\text{brine}}}. \tag{27}$$

The exergetic efficiencies and exergy destructions for the entire system and its major system components are calculated using the above equations and are listed in Table 2.

It is important to note here that exergy is always evaluated with respect to a reference environment (i.e., dead state). When a system is in equilibrium with the environment, the state of the system is called the *dead state* due to the fact that the exergy is zero. At the dead state, the conditions of mechanical, thermal, and chemical equilibrium between the system and the environment are satisfied: the pressure, temperature, and chemical potentials of the system equal those of the environment, respectively. In addition, the system has no motion or elevation relative to coordinates in the environment. Under these conditions, there is neither possibility of a spontaneous change within the system or the environment nor an interaction between them. The value of exergy is zero. Another type of equilibrium between the system and environment can be identified. This is a restricted form of equilibrium where only the conditions of mechanical and thermal equilibrium (thermomechanical equilibrium) must be satisfied. Such state is called the *restricted dead state.* At the restricted dead state, the fixed quantity of matter under

Table 2
Exergy rates and other properties at various system locations for one representative unit (for state numbers refer to Fig. 1)

State no.	Fluid	Phase	Temperature T (°C)	Pressure P (kPa)	Specific enthalpy h (kJ/kg)	Specific entropy s (kJ/kg K)	Mass flow rate $\dot{m}$ (kg/s)	Specific exergy ex (kJ/kg)	Exergy rate $\dot{E}x$ (kW)
0	Water	Dead state	10.4	101.30	43.80	0.1568	—		
1	Thermal water	Liquid	105	222.11	439.95	1.3623	11.2	54.440	609.73
2	Thermal water (re-injection)	Liquid	55	117.05	230.02	0.7671	11.2	13.279	148.73
3	Water	Liquid	80	148.67	334.71	1.0744	18.71	30.835	576.91
4	Water	Liquid	50	113.65	209.13	0.703	18.71	10.565	197.67
5	Thermal water	Liquid	105	222.11	439.95	1.3623	5.82	54.440	316.84
6	Thermal water (re-injection)	Liquid	80	148.67	334.71	1.0744	5.82	30.835	179.46
7	Water	Liquid	55	117.05	230.02	0.7671	9.72	13.279	129.08
8	Water	Liquid	50	113.65	209.13	0.703	9.72	10.565	102.69
9	Thermal water	Liquid	90	171.42	376.7	1.1917	4.88	39.564	193.07
10	Thermal water (re-injection)	Liquid	57	118.62	238.38	0.7952	4.88	13.672	66.72
11	Water	Liquid	85	159.11	355.71	1.1334	5.37	35.105	188.51
12	Water	Liquid	55	117.05	230.02	0.7671	5.37	13.279	71.31
13	Thermal water	Liquid	90	171.42	376.7	1.1917	5.42	39.564	214.44
14	Thermal water (re-injection)	Liquid	57	118.62	238.38	0.7952	5.42	13.672	74.10
15	Water	Liquid	85	159.11	355.71	1.1334	5.97	35.105	209.58
16	Water	Liquid	55	117.05	230.02	0.7671	5.97	13.279	79.28
17	Thermal water	Liquid	75	139.86	313.74	1.0146	25.47	26.821	683.13
18	Thermal water (re-injection)	Liquid	60	121.23	250.93	0.8303	25.47	16.269	414.37
19	Water	Liquid	70	132.47	292.78	0.954	19.12	23.044	440.60
20	Water	Liquid	50	113.65	209.13	0.703	19.12	10.565	202.00
21	Thermal water	Liquid	102.3	354.63	428.73	1.3321	34.55	51.784	1789.13
21′	Thermal water	Liquid	102	210.1	427.29	1.3287	34.55	51.308	1772.68
22	Thermal water	Liquid	106.7	354.63	447.3	1.3813	25.42	56.403	1433.76
22′	Thermal water	Liquid	106.4	228.1	445.87	1.3779	25.42	55.937	1421.92
23	Thermal water	Liquid	101.1	354.63	423.67	1.3186	8.51	50.552	430.19
23′	Thermal water	Liquid	100.8	205.57	422.22	1.3152	8.51	50.066	426.06
24	Thermal water	Liquid	101.4	486.36	425.04	1.3219	25.27	50.986	1288.41
24′	Thermal water	Liquid	101.1	206.68	423.49	1.3186	25.27	50.372	1272.89
25	Thermal water	Liquid	116.7	324.24	489.59	1.4913	78.49	67.503	5298.27
26	Thermal water	Liquid	117	557.28	491.02	1.4945	78.49	68.025	5339.30
27	Thermal water	Liquid	62	506.62	259.68	0.8553	78.49	17.930	1407.35
28	Water	Liquid	89.4	689.01	374.67	1.1847	150.78	39.519	5958.67
29	Water	Liquid	60.7	420.49	254.18	0.8391	144.85	17.024	2465.90
30	Water	Liquid	61	790.33	255.74	0.8428	150.78	17.535	2643.88
31	Water	Liquid	13.4	102.86	56.26	0.201	5.93	0.037	0.22
31′	Water	Liquid	13.1	102.83	55	0.1966	5.93	0.025	0.15
32	Thermal water	Liquid	133.9	404.53	562.72	1.6748	19.13	88.601	1694.94
32′	Thermal water	Liquid	133.6	401.87	561.44	1.6717	19.13	88.200	1687.27
33	Thermal water	Liquid	130.1	455.96	546.62	1.6349	19.98	83.815	1674.62
33′	Thermal water	Liquid	129.8	369.85	545.21	1.6317	19.98	83.312	1664.58
34	Thermal water	Liquid	136.5	506.63	573.96	1.702	41.82	92.129	3852.82
34′	Thermal water	Liquid	136.2	425.5	572.56	1.6989	41.82	91.608	3831.03
35	Thermal water	Liquid	120.4	557.28	505.45	1.5313	21.73	72.021	1565.01
35′	Thermal water	Liquid	120.1	300.51	503.92	1.5281	21.73	71.398	1551.48
36	Thermal water	Liquid	117.5	455.96	493.08	1.5	15.75	68.526	1079.28
36′	Thermal water	Liquid	117.2	282.89	491.6	1.4967	15.75	67.981	1070.71
37	Thermal water	Liquid	90	171.42	376.73	1.1917	3.66	39.594	144.91
38	Thermal water (re-injection)	Liquid	57	118.62	238.38	0.7925	3.66	14.437	52.84
39	Water	Liquid	85	159.11	355.71	1.1334	4.02	35.105	141.12
40	Water	Liquid	55	117.05	230.02	0.7671	4.02	13.279	53.38
41	Thermal water	Liquid	105	222.11	439.95	1.3623	51.95	54.440	2828.18
42	Thermal water (re-injection)	Liquid	65	126.32	271.85	0.8925	51.95	19.552	1015.74

Table 2 (*continued*)

State no.	Fluid	Phase	Temperature T (°C)	Pressure P (kPa)	Specific enthalpy h (kJ/kg)	Specific entropy s (kJ/kg K)	Mass flow rate $\dot{m}$ (kg/s)	Specific exergy ex (kJ/kg)	Exergy rate $\dot{E}x$ (kW)
43	Water	Liquid	80	148.67	334.72	1.0744	104.72	30.845	3230.04
44	Water	Liquid	60	121.24	250.93	0.8303	104.72	16.269	1703.70
45	Thermal water	Liquid	107.3	486.36	449.94	1.388	1.32	57.143	75.43
46	Thermal water (re-injection)	Liquid	78.7	303.97	327.76	1.0541	1.32	29.641	39.13
47	Water	Liquid	80	162.12	334.78	1.0744	2.09	30.905	64.59
48	Water	Liquid	61.7	212.78	258.18	0.8515	2.09	17.508	36.59
49	Thermal water	Liquid	110	486.36	461.35	1.4179	0.2	60.075	12.02
50	Thermal water (re-injection)	Liquid	50	113.65	209.13	0.703	0.2	10.565	2.11
51	Water	Liquid	65	263.44	272.02	0.8925	0.42	19.722	8.28
52	Water	Liquid	36.6	273.57	153.52	0.5264	0.42	5.030	2.11
53	Thermal water	Liquid	111.6	486.36	460.11	1.4355	9.4	53.845	506.14
54	Thermal water (re-injection)	Liquid	80	148.67	334.71	1.0744	9.4	30.835	289.84
55	Water	Liquid	81	303.97	339.09	1.0863	12.83	31.840	408.51
56	Water	Liquid	57.7	364.77	241.59	0.8014	12.83	15.124	194.04
57	Thermal water	Liquid	108	425.56	452.85	1.3957	16.3	57.870	943.28
58	Water	Liquid	90	496.49	377.04	1.1917	24.21	39.904	966.08
59	Water	Liquid	56	385	234.51	0.7798	24.21	14.168	343.02
60	Water	Liquid	56.3	618.08	235.96	0.7836	24.21	14.541	352.03
62	Thermal water (re-injection)	Liquid	58	398.2	242.87	0.8051	16.3	15.355	250.28
63	Thermal water	Liquid	58	398.2	242.87	0.8051	16.3	15.355	250.28
63′	Thermal water	Liquid	57.7	119.2	241.31	0.8013	16.3	14.872	242.41
64	Thermal water (re-injection)	Liquid	40	108.69	167.37	0.572	16.3	5.950	96.99
65	Water	Liquid	47	111.93	196.6	0.6642	29.84	9.037	269.66
66	Water	Liquid	37	107.6	154.85	0.5319	29.84	4.800	143.24
67	Thermal water (re-injection)	Liquid	64	364.77	267.93	0.8801	114.76	19.148	2197.46

consideration is imagined to be sealed in an envelope impervious to mass flow, at zero velocity and elevation relative to coordinates in the environment, and at the temperature T_0 and pressure P_0 taken often as 25 °C and 1 atm [22].

For analysis purposes, the actual thermal data for energy and exergy analysis and performance assessment purposes were taken from the BGDHS on 1 January 2003, 2 December 2003, 2 January 2004 and 2 February 2004, and the respective thermodynamic properties were obtained based upon these data. These 3 months are the key months where the heating demand is highest. We identified the above given days with the help of technical site staff and considered them as the representative days for performance analysis.

It is important to note that the number of the wells in operation in the Balcova geothermal field may vary depending on the heating days and operating strategy. Taking into account the eight productive wells for the day the actual data sets were taken, the specific exergy index (SExI) is found to be 0.07 using Eq. (11). This represents that the Balcova geothermal field falls into the medium-quality geothermal resource according to the Lee's classification [38].

Using Eq. (19), the total geothermal reinjection fluid (the geofluid reinjected into the well BD8) mass flow rate is 114.76 kg/s at an average temperature of 64 °C and the total production well mass flow rate is 212.16 kg/s, and the natural direct discharge of the system is then calculated to be 97.4 kg/s on 2 January 2004. It is observed that the distribution pipeline losses in the geothermal scheme are quite large and account for 45.9% of the total production well mass flow rate, due to the fact that the pipelines of the distribution network are old resulting in high flow losses (and leakages). In this regard, replacement of some pipelines and proper control of the flow are required for possible improvements.

To cover some leaks, the water was added by a pump (using a pressurized water tank) to this network up to the date studied, while recently, this application has been changed, and carbon steel pipes are being changed with glass reinforced plastics (GRP) pipes currently.

Table 3
Some exergetic, energetic and thermodynamics analysis data provided for one representative unit of the system

Item no.	Component	Exergy destruction rate (kW)	Utilized power (kW)	Heat transfer rate or installed power (kW)	P (kW)	F (kW)	Exergy (second law) efficiency (%)	Relative irreversibility χ (%)	Fuel depletion rate δ (%)	Productivity lack ξ (%)	Exergetic factor f (%)	Energy (first law) efficiency (%)
1	Heat Ex 1	617.38	18157.09	50364	3314.78	3931.95	84.3	40.85	7.13	8.63	45.36	—
2	Heat Ex 2	78.95	3422.18	5800	614.05	693	88.6	5.22	0.91	1.10	8.00	—
3	Heat Ex 3	26.88	1226.99	2310	126.42	153.3	82.5	1.78	0.31	0.38	1.77	—
4	Heat Ex 4	81.76	2350.32	3372	379.24	461.01	82.3	5.41	0.94	1.14	5.32	—
5	Heat Ex 5	110.69	1221.33	4651	26.39	137.38	19.2	7.32	1.28	1.55	1.59	—
6	Heat Ex 6	9.15	675.08	2200	117.2	126.36	92.8	0.61	0.11	0.13	1.47	—
7	Heat Ex 7	10.04	749.78	1700	130.3	140.34	92.8	0.66	0.12	0.14	1.62	—
8	Heat Ex 8	30.16	1600.02	3200	238.6	268.76	88.8	1.99	0.35	0.42	3.10	—
9	Heat Ex 9	4.33	506.31	1275	87.74	92.07	95.3	0.29	0.05	0.06	1.06	—
10	Heat Ex 10	286.1	8729.68	15700	1526.35	1812.44	84.2	18.92	3.30	4.00	20.91	—
11	Heat Ex 11	8.31	161.71	2326	28	36.3	77.1	0.55	0.10	0.12	0.43	—
12	Heat Ex 12	3.73	50.36	1117	6.17	9.9	62.3	0.25	0.04	0.05	0.11	—
13	Heat Ex 13	1.83	1251.43	1316	214.48	216.3	99.1	0.12	0.02	0.03	2.49	—
14	B10 well pump	11	27.45	45	16.45	27.45	59.9	0.73	0.13	0.15	0.32	65–80
15	B5 well pump	26.41	38.25	75	11.84	38.25	30.9	1.75	0.30	0.37	0.44	65–80
16	B4 well pump	9.62	13.75	55	4.13	13.75	30	0.64	0.11	0.13	0.16	65–80
17	B1 well pump	15.83	31.35	55	15.52	31.35	49.5	1.05	0.18	0.22	0.36	65–80
18	BD2 well pump	7.33	15	75	7.67	15	51.13	0.48	0.08	0.10	0.17	65–80
19	BD3 well pump	28.45	38.5	110	10.05	38.5	26.1	1.88	0.33	0.40	0.44	65–80
20	BD4 well pump	31.02	52.8	110	21.78	52.8	41.3	2.05	0.36	0.43	0.60	65–80
21	BD5 well pump	17.27	30.8	55	13.53	30.8	43.9	1.14	0.20	0.24	0.36	65–80
22	BD7 well pump	23.88	32.45	55	8.57	32.45	26.4	1.58	0.28	0.33	0.38	65–80
23	Balcova booster pump	26.98	68	200	41.03	68	60.34	1.78	0.31	0.38	0.78	65–80
24	Balcova circ. pump	14.02	192	480	177.98	192	92.7	0.93	0.16	0.20	2.21	65–80
15	Pressurized water tank (Balcova)	10.93	11	11	0.26	11	0.64	0.71	0.12	0.15	0.13	65–80
16	Narlıdere circ. pump	5.98	15	30	9.02	15	60.13	0.40	0.07	0.08	0.17	65–80
17	Pressurized water tank (Narlıdere)	0	—	4	0	—	—	—	—	—	—	65–80
18	Caglayan booster pump	14.13	22	22	7.87	22	35.7	0.93	0.16	0.20	0.25	65–80
19	Heat exchangers and pumps	1512.29	40690.63	96643	7155.42	8667.46	—	—	—	—	—	—
20	Overall plant[a]	7998.43	7155.42	96643	7155.42	8667.46	46.00	—	—	—	100.00	41.90

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

Using the values given in Table 3 and Eqs. (25) and (27), the energy and exergy efficiencies of the BGDHS are determined to be 41.9% and 46%, respectively. The energy balance diagram is illustrated in Fig. 2. The thermal reinjection accounts for 26.89% of the total energy input, while the natural direct discharge of the system cover its 31.21%, respectively.

The study of the exergy flow diagram given in Fig. 3 shows that 54% (corresponding to about 7998.43 kW) of the total exergy entering the system is lost, while the remaining 46% is utilized. The highest exergy loss (accounting for 28.96%) occurs from the natural direct discharge of the system due to a significant amount of water leaks and includes some part of the exergy destructions through the primary and secondary fluid networks, which were not determined in this study. The second largest exergy destruction occurs from the thermal reinjection with 14.84% (corresponding to about 2197.46 kW) of the total exergy input. This is followed by the total exergy destruction associated with the pumps and heat exchangers amounts to some 1512.29 kW, which accounts for 10.21% of the total exergy input to the system.

Using Eq. (14), the exergetic IP is determined from van Gool's expression [43] for the 13 plate-type heat exchangers installed in the BGDHS, as shown in Fig. 4. As can be seen from this figure, the first heat exchanger has the largest exergetic IP rate as 96.93 kW, followed by the fifth, tenth, fourth and second heat exchangers at 89.44, 45.2, 14.47 and 9 kW capacities, respectively, with the remaining ones under 4.7 kW, which does not present much potential for improvement. On the other hand, in order to improve the system efficiency, water leakages in the distribution network should be prevented.

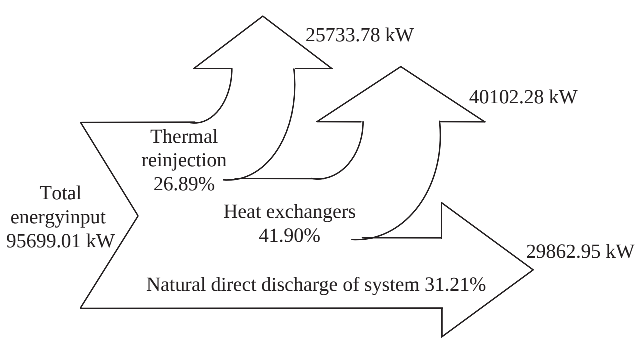

Fig. 2. Energy flow diagram (given as the percentages of brine energy input).

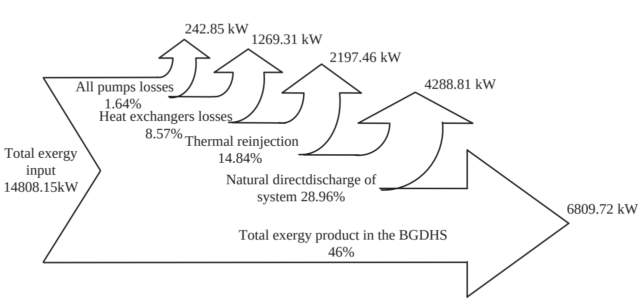

Fig. 3. Exergy flow diagram (given as the percentages of brine exergy input).

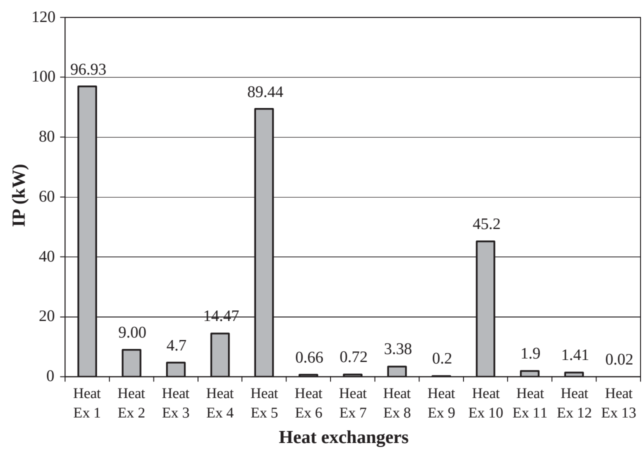

Fig. 4. Exergetic improvement potential of heat exchanger.

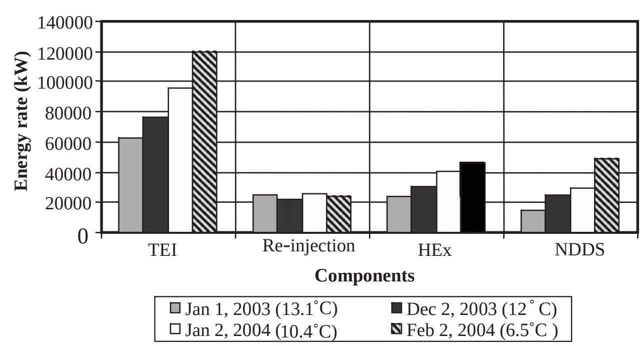

Fig. 5. Energy flow chart in the graph of brine energy input for different dead state temperatures.

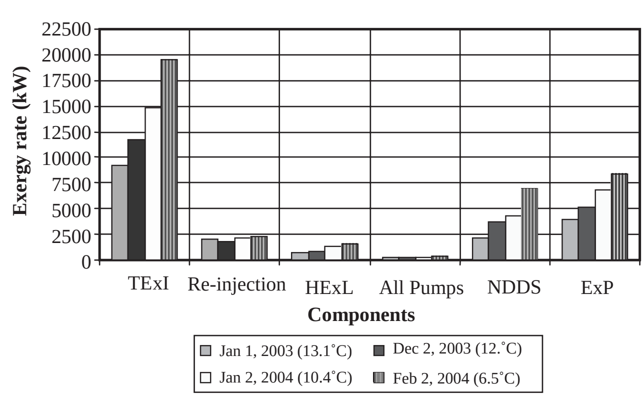

Fig. 6. Exergy flow chart in the graph of brine exergy input for different dead state temperatures.

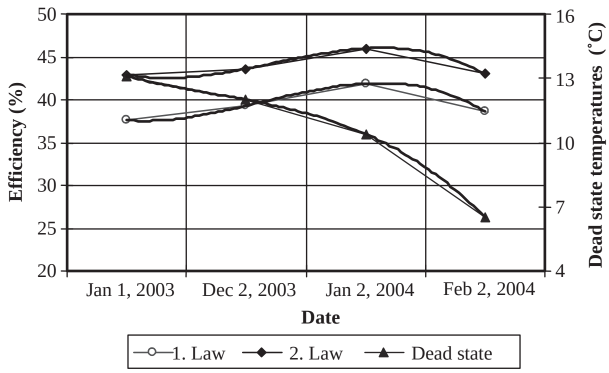

Fig. 7. Overall system efficiencies for different dead state temperatures.

Figs. 5 and 6 show the distributions of energy and exergy rates, respectively. Besides this, energy and exergy efficiency values are illustrated in Fig. 7 where energy and exergy rates increase with decreasing dead state values. However, energy and exergy efficiencies of the BGDHS vary between 35% and 42% and between 42% and 46%, respectively. As indicated earlier, an uncertainty analysis is needed to prove the accuracy of the experiments and was performed using the method described by Holman [41]. When the errors and uncertainties are evaluated according to Table 2, the values of energy and exergy efficiencies for the BGDHS are found to be 41.9% and 46%, respectively.

The total energy input values are obtained for a range from 62,665.11 to 119,917.2 kW for four different days on 1 January 2003, 2 December 2003, 2 January 2004 and 2 February 2004 for a better coverage and presentation. The corresponding reference state (dead state) temperatures were measured to be 13.1, 12, 10.4 and 6.5 °C, respectively, as the environment temperatures. In conjunction with this, the total exergy input values are obtained to be from 9164.29 to 19,488.02 kW for the same days. As expected, the largest energy and exergy losses occur on 2 February 2004, which was the coldest day among the dead state values considered. As can be seen in Figs. 5 and 6, energy, exergy reinjection and pump losses generally fluctuate between 1 January 2003 and 2 February 2004. Energy and exergy reinjection values decrease to about 21,684 and 1788 kW, respectively, while the values for pump losses decrease to 229.38 kW. However, energy and exergy rates of natural direct discharge of the system, heat exchangers, and useful exergy increase dramatically. The reason for this rapid rise in energy and exergy rates is due to gradually decreasing the ambient temperature, as clearly seen in Fig. 7.

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 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. For example, taking into account the heat exchanger 1 as illustrated in Fig. 1 and assuming that the supply temperature of the district heating network increased from 89.4 to 95 °C (with a difference of 35 °C between supply and return temperatures), the exergy efficiency of this heat exchanger increases from 84.3% to 88.8% while the overall system exergy efficiency increase from 45.99% to 47.18%. In the design and performance improvement, there are also some crucial points to consider, such as the return temperature of the district heating network affected by the outdoor conditions, type of connected users and characteristics of the heating apparatus. In addition, in the design and operating condition of the primary heat exchangers, a temperature approach of about 5.6 °C is desired. On the other hand, by dropping the district heating supply temperature increases the amount of building heating equipment to be oversized. Oversizing does not mean only cost, but also more exergy production due to unnecessarily inflated pumping, pipe frictions, etc. In this regard, there is an optimum district flow rate and the minimum possible exergy loss (mainly due to pumping), of which determination is planned as a future work.

The results presented here show that exergy analysis is a potential tool in determining locations, types and true magnitudes of wastes and losses, furthering the objective of more efficient energy use, and revealing whether or not and how much it is possible to design more efficient geothermal district heating systems by reducing the inefficiencies in the system and its components. In addition, exergy analysis can further help optimize the systems, when combined with assessments of other factors, such as resource-use reductions, environmental impact and emissions decreases, and economics.

5. Conclusions

In this study, we present an energy and exergy analysis of geothermal district heating systems in general and apply to Balcova geothermal district heating system in Izmir, Turkey as a case study. We also utilize actual thermal data taken from the technical staff to perform a system performance evaluation through energy and exergy efficiencies, specific exergy index, exergetic improvement potential, as well as some other thermodynamic parameters. We can extract some concluding remarks from this study as follows:

- Exergy analysis is more meaningful and useful tool than energy analysis for system performance assessment and evaluation since it allows true magnitudes of the losses to be determined.
- Exergy destructions (representing the losses) in the overall system are quantified and illustrated using an exergy flow diagram along with an energy flow diagram.
- Based upon the SExI parameter, the current geothermal field falls into the category of medium-quality geothermal resources.
- Actual thermal data taken from geothermal district heating system present a valuable database and source for future studies, such as exergoeconomic analysis which will include cost accounting.
- The district heating supply temperature should be higher in order to increase the exergy efficiency of the heat exchangers and hence the whole system.
- The energy recovery should be implemented and can be improved with more effective reinjection wells and will result in less energy consumption.
- Exergy analysis is more significant tool, than energy analysis, for system performance assessment and improvement since it allows true magnitudes of the losses to be determined. The results of the paper, particularly on locations and types of the losses, will help the researchers, government administration, and engineers and operators working in the area of geothermal district heating systems develop and adapt appropriate measures and policies.

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