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Thermodynamic and economic evaluations of a geothermal district heating system using advanced exergy-based methods

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ABSTRACT

In this paper, a geothermal district heating system (GDHS) is comparatively evaluated in terms of thermodynamic and economic aspects using advanced exergy-based methods to identify the potential for improvement, the interactions among system components, and the direction and potential for energy savings. The actual operational data are taken from the Sarayköy GDHS, Turkey. In the advanced exergetic and exergoeconomic analyses, the exergy destruction and the total operating cost within each component of the system are split into endogenous/exogenous and unavoidable/avoidable parts. The advantages of these analyses over conventional ones are demonstrated. The results indicate that the advanced exergy-based method is a more meaningful and effective tool than the conventional one for system performance evaluation. The exergetic efficiency and the exergoeconomic factor of the overall system for the Sarayköy GDHS were determined to be 43.72% and 5.25% according to the conventional tools and 45.06% and 12.98% according to the advanced tools. The improvement potential and the total cost-savings potential of the overall system were also determined to be 2.98% and 14.05%, respectively. All of the pumps have the highest improvement potential and total cost-savings potential because the pumps were selected to have high power during installation at the Sarayköy GDHS.

1. Introduction

Geothermal energy is a form of renewable energy derived from heat deep in the earth's crust. The utilisation of this energy has recently been the focus of increasing attention because of its minimum negative environmental impact, low operating cost, decentralised production advantages, and simplicity of required technologies. The utilisation of geothermal energy can be categorised into two groups with regard to the temperature of the geothermal resources: (i) electricity generation and (ii) direct use [1]. Direct utilisation can use both high and low temperature geothermal resources, and it is therefore much more widespread in the world than electricity production [2].

The total installed capacity reported at the end of 2009 for the geothermal direct utilisation is 48,483 MW_t globally, representing almost a twofold increase over the data in 2005 and growing at a compound rate of 12.3% annually. Thus, it appears that the growth rate has increased slightly in recent years, despite the low cost of fossil fuels, economic downturns and other factors [3]. In addition, the countries with the largest installed capacity are the USA, China, Sweden, Germany and Japan, accounting for 63% of the world capacity, and the five countries with the largest annual energy use are China, USA, Sweden, Turkey and Japan, accounting for 55% of the world use. Space heating accounts for 5394 MW_t of the world's total installed capacity.

With geothermal direct utilisation in thermal systems, controlling the thermodynamic efficiency, the energy consumption and the product costs are an unavoidable topic. To achieve sustainable development, the focus on thermal system efficiency is moving from thermal analysis to economic analysis studies that assess both thermodynamic inefficiencies and economic benefits.

A geothermal district heating system (GDHS) also utilises geothermal energy when heating individual and commercial buildings and in industry through a distribution pipeline for direct utilisation. Today, Turkey has 20 geothermal district heating systems installed [4]. In recent years, exergy, which is a way to sustainability, has been a useful tool to analyse and assess the performance of GDHSs. To date, according to a comprehensive review on GDHSs conducted by Hepbasli [5], many studies have been conducted on energy and exergy analyses of some Turkish GDHSs (i.e., the Afyon, Balcova, Gonen, Edremit, Salihli and Simav GDHSs).

Similarly, conventional exergy-based methods have been extensively studied during the past several decades to improve the energy efficiency or to reduce the energy consumption in process industries, especially in combined heat and power plants [5–8]. A new direction in exergy-based methods to improve the so-called

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Nomenclature

c	cost per exergy unit (\$/GJ)
$\dot{C}$	cost rate associated with exergy (\$/h)
$\dot{E}$	exergy rate (kJ/s or kW)
f	exergoeconomic factor (%)
IP	improvement potential (%)
$\dot{m}$	mass flow rate (kg/s)
p	total cost-savings potential (%)
P	pressure (kPa)
T	temperature (°C or K)
$\dot{Z}$	cost rate associated with capital investment (\$/h)

Greek symbols

ε	exergy/exergetic or second law efficiency (%)
η	energy/energetic or first law efficiency (%)

Subscripts

D	destruction
F	fuel
is	isentropic
k	component
L	loss
mech	mechanical
P	product
tot	total/overall
0	reference state

Superscripts

AV	avoidable
CI	capital investment
EN	endogenous
EX	exogenous
OM	operating-maintenance
UN	unavoidable

Abbreviations

ECC	energy consumption cycle
EDC	energy distribution cycle
EPC	energy production cycle
GDHS	geothermal district heating system
HEX	heat exchanger
MTA	Mineral Research and Exploration Institute in Turkey
PEC	purchased equipment cost
PM	pump
SPECO	specific exergy costing
TW	thermal water
W	Water

conventional exergy-based methods is known as advanced exergy-based methods, which were proposed by Tsatsaronis et al. [9,10].

An advanced exergy-based method that involves the endogenous and exogenous concepts was recently proposed for further splitting of the proposed avoidable and unavoidable exergy destruction and the total operating cost (the sum of both the exergy destruction cost and the investment cost) into four parts [9–12]. Such splitting seems helpful to improve the accuracy of the conventional exergy-based methods. It was emphasised that the efforts to improve the energy efficiency should be focused on the avoidable endogenous part and the avoidable exogenous part. The method has already been demonstrated to be reliable and useful in related studies [13–18].

The main objective of the present work is to apply the advanced exergy-based methods (exergetic and exergoeconomic analyses) to a GDHS to identify the potential for improvement, the interactions among system components and the direction and potential for energy savings. The Sarayköy GDHS in Turkey is presented as a comprehensive case study, and its actual thermal data were collected. The corresponding procedure to calculate the endogenous/exogenous and avoidable/unavoidable parts of the exergy destruction and the total operating cost for the Sarayköy GDHS and its components was employed and later evaluated in terms of the thermodynamic and economic aspects along with the new performance parameters.

2. Description of the GDHS studied

The heat source of the Sarayköy geothermal district heating system (GDHS) is the Kızıldere geothermal field located next to the Büyük Menderes River 40 km west of the city of Denizli, Turkey. This geothermal field is the first area discovered for the purpose of energy production of Turkey and is also the first known high-temperature geothermal field in Turkey. This field is characterised by normal fault structures. The first geological and geophysical studies in this geothermal field were started in the year 1965 by the Mineral Research and Exploration Institute (MTA in Turkish). The first well had a depth of 540 meters and was opened in the year 1968, and the reservoir temperature reached 198 °C [19]. Seventeen wells were drilled during the following decade to develop and assess the capacity of the system. The field is liquid-dominated with temperatures of 195–212 °C at 300–800 m in depth [20]. No comprehensive reinjection strategy has been devised yet for the Kızıldere geothermal field that considers all of these operating conditions.

The installation of a bottoming binary power plant (the Bereket geothermal plant of the Bereket Inc.) fed from this geothermal field was completed at the end of 2007. The water-cooled, two-level, binary power plant has a net capacity of 6.35 MW_e. The plant was designed to operate using 145 °C water separated at the flash plant and transported through a 2-km-long pipeline. The temperature of the fluid at the outlet of the binary plant is 75 °C. Initially, Bereket Inc. had planned to operate the binary plant in conjunction with a GDHS in Sarayköy County (8 km away) using the waste geothermal fluid in an integrated manner. Because that GDHS is designed to operate at a temperature differential of 90–75 °C, the overlapping temperature ranges caused heat shortage problems in the GDHS, and it was not possible to run the binary plant in the winter of 2008 [4].

The Sarayköy GDHS was installed in 2002 to provide residential heating and hot water for buildings using geothermal water. The system was initially designed for 5000 residences with a potential of 27.2 MW_t. There are only 2350 residences at present that are heated. In this study, only the Sarayköy GDHS was investigated, and a schematic of the Sarayköy GDHS, which mainly consists of three cycles, namely, (i) the energy production circuit, (ii) the energy distribution circuit and (iii) the energy consumption circuit, is illustrated in Fig. 1. In the energy production circuit, the geothermal fluid from Kızıldere geothermal field is sent to the Bereket geothermal plant with a pressure of approximately 5 bar, a temperature of 145 °C and 700 ton/h in total. However; the geothermal fluid is sent at a rate of 200 tons/h to the Sarayköy GDHS at approximately 3.2 bar pressure and temperature of 125 °C. Here, this geothermal fluid is sent to the three heat plate exchangers with a total capacity of approximately 36 million kcal/h for the