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Exergoeconomic analysis of a district heating system for geothermal energy using specific exergy cost method

Mehmet Ali Alkan [a], Ali Keçebaş [b,*], Nurettin Yamankaradeniz [c]

[a] Department of Electricity and Energy, Ula Ali Koçman Vocational High School, Muğla Sıtkı Koçman University, 48640 Muğla, Turkey
[b] Department of Energy Systems Engineering, Technology Faculty, Muğla Sıtkı Koçman University, 48000 Muğla, Turkey
[c] Department of Air Conditioning and Cooling Technology, Vocational School of Technical Science, Uludağ University, 16059 Bursa, Turkey

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ABSTRACT

This study presents the exergoeconomic analysis and evaluation in order to provide cost based information and suggests possible locations/components in a GDHS (geothermal district heating system) for improving the cost effectiveness. The analysis is based on the SPECO (specific exergy costing) method, and used to calculate exergy-related parameters and display cost flows for all streams and components. As a real case study, the Afyon GDHS in Turkey is considered based on actual operational data. The obtained results show that the unit exergy cost of heat produced by the Afyon GDHS is calculated as average 5624 $/h. The HEX (heat exchanger)-III among all components should be improved quickly due to the high total operating cost rate and relative cost difference. The HEX-I and PM (pump)-V have the highest exergoeconomic factors among all other system components due to the high owning and operating costs of these components. The heat production costs per exergy unit for all the HEXs decrease due to the high exergy destruction cost rate of the system, while the well head temperature and ambient temperature increase. The SPECO method may be used to improve the cost effectiveness according to exergy rates in GDHSs as a thermal system.

1. Introduction

GDHS (geothermal district heating system) has recently been given increasing attention in many countries. These systems are simple, safe and adaptable systems, minimum negative environmental impact, low operating cost, decentralized production advantages, and simplicity of their technologies. Numerous successful GDHS projects have been reported. Experience by researchers and engineers still plays an important role in the system analysis, design and control [1,2]. Especially the heat economic losses in GDHSs cause the fast energy consumption, eventually environmental problems. Therefore, an optimization analysis is vital in terms of exergetic and economic aspects.

Exergy is a way to sustainability while exergy analysis has been recently widely used as a very useful tool for performance assessment of energy-related systems as well as sustainable buildings [3]. Exergy analysis helps to identify the inefficiencies caused by the irreversibilities within the system being. Therefore, exergy based methods reveal the location, the magnitude and the sources of inefficiencies and costs. Exergoeconomic (or thermoeconomic) analysis also combines both exergy and economic analyses [4]. It is based on the exergy costing principle, which assigns monetary values to energy streams and to the thermodynamic inefficiencies within the system [5]. It also provides the designer or operator of an energy conversion system with information crucial to the design of a cost-effective system [6].

Two main groups of thermoeconomic methods have been developed [7] as (i) cost accounting methods and (ii) optimization methods. The exergy cost theory [8], the average cost approach [9], the Last-in-First-out method [10] or the specific exergy costing [11–13] method have been used for the first method, while the thermoeconomic functional analysis [14] or engineering functional analysis [15] have been used for the other method.

One of the best developed and comprehensive methods is the SPECO (specific exergy costing) method presented by Lazzaretto and Tsatsaronis [13]. This tool provides simple and unambiguous procedures for evaluating energy conversion systems and uses a matrix formulation which facilitates fast problem solving. Several studies have discussed the SPECO method, e.g. Refs. [4,13,16–20]. Bejan et al. [4] and Tsatsaronis [16] discussed in detail the SPECO

* Corresponding author. Tel.: +90 252 2115471; fax: +90 232 2113150.
E-mail addresses: alikecebas@mu.edu.tr, alikecebas@gmail.com (A. Keçebaş).

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method technique. Lazzaretto and Tsatsaronis [13] proposed a methodology to calculate exergetic efficiencies and exergy related costs in thermal system to be used for SPECO method.

The different studies have been conducted on this topic. For example; Abusoglu and Kanoglu [17] presented the thermoeconomic formulations using the SPECO method of an actual diesel engine powered cogeneration system installed in Gaziantep, Turkey. They then evaluated this analysis in Ref. [18]. Balli et al. [19] studied on the thermodynamic and thermoeconomic analyses of an actual trigeneration system with a rated output of 6.5 MW gas–diesel engine installed in the Eskisehir Industry Estate Zone, Turkey. Kanoglu et al. [20] developed exergoeconomic formulations and procedure including exergy flows and cost formation and allocation for a high temperature steam electrolysis system at three environmental temperatures. Kalinci et al. [21] calculated exergy-related parameters of hydrogen production from plasma gasification of sewage sludge and display cost flows for all streams and components. Yildirim and Gungor [22] conducted the exergoeconomic analysis that combines exergy analysis with economic analysis of a CHP (combined heat and power) system for the system improvement. Bagdanavicius et al. [7] conducted a thermoeconomic analysis of four different thermal systems operated by biomass. They are biomass steam turbine combined heat and power CHP, gas turbine CHP, biomass integrated gasification gas turbine CHP and biomass integrated gasification combined cycle CHP systems. In a different study, Kalinci et al. [23] investigated three different gasifiers, namely, downdraft gasifier, circulating fluidized bed gasifier and plasma gasifier in cogeneration of hydrogen and power for hydrogen production. Abusoglu et al. [24] presented the thermoeconomic analysis and assessment of a municipal wastewater treatment system. Cay et al. [25] developed the cost balances and auxiliary thermoeconomic relations for direct gas heated and hot oil heated stenters in textile dryers and evaluated the exergoeconomic aspect. Gungor et al. [26] analysed and evaluated the performance of the drying system components and the drying process in a gas engine-driven heat pump drying system based on the experimental data from an exergoeconomic point of view.

As can be seen from the previously conducted studies reviewed, no studies on exergoeconomic analysis and assessment of GDHSs according to the SPECO method have appeared in the open literature to the best of the authors' knowledge. This study deals with the exergoeconomic analysis and evaluation for improving the cost effectiveness of the Afyon GDHS, based on an SPECO method. The SPECO method is used in this analysis which is based on specific exergies, and costs per exergy unit, exergetic efficiencies, and the auxiliary costing equations for the system and its components. In this regard, the main objectives of this study are to (i) derive exergoeconomic relations, (ii) evaluate the exergoeconomic performance of each component of the Afyon GDHS by using actual cost data, and (iii) conduct a parametric study on the effect of well head and ambient temperatures for the GDHS.

2. Description of the selected system

The Afyon geothermal district heating system (GDHS) was installed in 1994 in the city of Afyonkarahisar/Turkey to provide residential heating for buildings through geothermal water. Its heat source originates from the Ömer-Gecek geothermal field, 15 km north-west of the city of Afyonkarahisar. It was initially designed for 10,000 residences. Nowadays, there are only 4613 residences that have been heated with a potential of 48.333 MW_t. The average reservoir temperature of wells is 105 °C. As can be seen in Fig. 1, modified from Refs. [27,28], the Afyon GDHS consists of three cycles: (i) the EPC (energy production cycle), (ii) the EDC (energy distribution cycle), and (iii) the ECC (energy consumption cycle). For the EPC, the geothermal fluid collected from the production wells is sent to the inlet of the mixing pool. The fluid at an average temperature of about 95 °C is then pumped through the main pipeline to the Afyon GDHS, located in the centre of the Afyonkarahisar province. The geothermal fluid is sent to the six heat plate exchangers in the geo-heat mechanical room of the Afyon GDHS and is cooled to about 45–50 °C. For the EDC, the hot water is pumped to the six heat exchangers and then the supply (flow) water is sent to the heat exchangers installed under all the buildings in the zones. The mean supply/return water temperatures of the building cycle are 60/45 °C. In this study, the ECC for the Afyon GDHS was not considered. The actual operational data on temperature, pressure and flow rate of the system have been hourly recorded since 2006 by the technical staff based on the state numbers specified in Fig. 1. The pressure and temperature data on the fluids (including hot water and geothermal fluid) have been measured with Bourdon-tube pressure gauges and fluid-expansion thermometers, respectively. The volumetric flow rates of fluids have also been measured by an ultrasonic flow meter.

3. The specific exergy cost (SPECO) method and its evaluation

The exergoeconomic is a unique combination of exergy analysis and cost analysis conducted at the component level, to provide the designer or operator of an energy conversion system with information crucial to the design of a cost-effective system [29]. There have been numerous published papers all around the world on exergoeconomic cost analysis, and its application and optimization in thermal systems since the 1990s. Most of them have been published due to the improved structural formalism of the exergoeconomic methodologies [30]. Among these methodologies, the specific exergy costing (SPECO) method introduced by Lazzaretto and Tsatsaronis [13] has been largely and successfully used and applied to energy intensive systems by the researchers in the field of thermoeconomics [30]. It is a systematic methodology for calculating exergy related costs in thermal systems [13]. The SPECO method was also applied in this study.

In a conventional economic analysis, a cost balance is usually formulated for the overall system operating at steady state [21], as following

$$\dot{C}_{\rm P,tot} = \dot{C}_{\rm F,tot} + \dot{Z} \tag{1}$$

where $\dot{C}$ is the cost rate and $\dot{Z}$ denotes sum of the capital investment and operating–maintenance costs in this study.

For $\dot{Z}$ value in the economic analysis of thermal systems, the annual values of carrying charges, fuel costs, raw water costs, and OM (operating–maintenance) expenses supplied to the overall system are the necessary input data. However, these cost components may vary significantly within the economic life. Therefore, the levelized annual values must be used in the economic analysis of the overall system. The levelized cost is given by Abusoglu [18]

$$C\dot{A}_{\rm sys} = P\dot{W}_{\rm sys}{\rm CRF} \tag{2}$$

where CRF is capital recovery factor which depends on the interest rate as well as estimated equipment lifetime. CRF is determined using the following relation

$${\rm CRF} = \left({\rm i}(1+i)^n/(1+i)^n - 1\right) \tag{3}$$

$$1 + i = (1 + i_n)/1 + r \tag{4}$$

where i_n, r, i and n mean nominal interest, inflation, real interest rates and lifetime of processes as year, respectively.