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Comparative thermodynamic evaluation of a geothermal power plant by using the advanced exergy and artificial bee colony methods

Osman Özkaraca [a], Ali Keçebaş [b, *], Cihan Demircan [c]

[a] Department of Information Systems Engineering, Technology Faculty, Muğla Sıtkı Koçman University, 48000 Muğla, Turkey
[b] Department of Energy Systems Engineering, Technology Faculty, Muğla Sıtkı Koçman University, 48000 Muğla, Turkey
[c] Department of Energy Systems Engineering, Graduate School of Natural and Applied Sciences, Süleyman Demirel University, 32260 Isparta, Turkey

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ABSTRACT

In this study, the thermodynamic performance of a binary geothermal power plant (GPP) is comparatively evaluated using the exergy analysis and optimization method. Thus, in addition to routes to improve the thermodynamic performance of the system, the thermodynamic relationships between the system components and improvement performances of the components are determined. With this aim, the Sinem GPP located in Aydın province in Turkey as a real system is selected. All data from the system are collected and a numerical model simulating the real system is developed. On the developed model, the conventional and advanced exergy analyses for exergy analysis and the artificial bee colony (ABC) method for optimization process are performed. The results of the study show that total exergy efficiencies of the conventional exergy analysis, advanced exergy analysis and artificial bee colony are determined as 39.1%, 43.1% and 42.8%, respectively. The exergy efficiency obtained from advanced exergy analysis is higher compared to the other two methods. This is due to the fact that theoretical and unavoidable operation assumptions in advanced exergy analysis are arbitrary as a single value depending on the decision maker. However, decision variables in the ABC method are within certain constraints chosen by the decision maker. It is better to select constraint limits instead of an arbitrary single value selection. Therefore, its arbitrary values should be confirmed with any optimization method. Additionally, the highest exergy destruction identified in the three methods is occurred in heat exchangers as the condenser and vaporizer.

1. Introduction

Energy forms one of the most important and basic requirements for the economic and social life of humans and countries through the ages. As a result, energy needs to be clean, cheap, uninterrupted, reliable and diversified supply [1]. Currently energy is obtained both from fossil resources and renewable resources. The use of renewable energy resources has become mandatory as fossil based energies will run out within a certain period, production from new reserves is very expensive and it harms the environment. Therefore, in the 21st century energy production from renewable energy resources has focused on biomass, solar, wind energies and to a lesser extent on hydraulic energy [2]. However, the basic problem related to renewable energy resources is that they are not baseload power generation. Traditionally the most important responsibility of thus systems is baseload providers, which are power plants able to generate a fixed and predictable supply of electricity [3]. The primary energy source in the majority of electricity networks are baseload electricity power plants using fossil fuels [4]. The renewable energy resources such as geothermal and biomass energies are the only renewable energy resources that is not affected by external weather conditions. Thus, geothermal and biomass energies may be used as a basic energy source [1]. However, this article focuses on geothermal energy.

Geothermal energy is heat energy carried to the surface as hot water and steam formed due to heat accumulated at a variety of depths within the crust with temperatures continuously above the mean regional atmospheric temperature and containing higher amounts of dissolved minerals, a variety of salts and gases compared to normal underground and surface water in the environment [5]. Geothermal energy resources are therefore used linked to their temperature. Generally high temperature

* Corresponding author.
E-mail address: alikecebas@gmail.com (A. Keçebaş).

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(T > 150 °C) resources are used for electricity production, with moderate (90 °C < T < 150 °C) and low temperature (T < 90 °C) resources are used in direct use fields such as bathing, individual and district heating and cooling etc. [6]. In recent times, very low temperature (T < 35 °C) resources have been used in heat pump applications. Additionally the latest researches have stated that while the global geothermal installed power capacity was 1.3 GW in 1975, in 2010 this had risen to 10.9 GW and then to 12.7 GW in 2015. Since 2015, nearly 3.45 GW of the installed power of 12.7 GW was installed in the USA. There was a 17% increase in global geothermal installed power and a 10% increase in electricity production in 2015 compared to 2010. In 2020 it is estimated the installed power will be about 21 GW [6]. According to Bertani [6], the top 5 countries with highest geothermal installed power and electricity production globally may be listed as USA, Philippines, Indonesia, Mexico and New Zealand. In Turkey the installed power from geothermal energy was 19 MW in 2005, while this had risen to 624 MW in 2015. Currently this value has reached nearly 821 MW. According to Turkey's Energy Atlas, the 32 geothermal power plants in Turkey reached a total installed power of 921.5 MW and corresponded to 1.2% of the 78497.4 MW installed power in Turkey at the end of 2016 [7]. Thus while the development of geothermal power continues to meet the increasing electricity demands in the USA and globally, engineers and policy makers require data about feasibility and optimum design of geothermal energy power plants within a spectrum of geothermal resource conditions and climates. Therefore, there is a need for this type of scientifically robust design, analysis and optimization guidelines.

In spite of the disadvantages of geothermal power plants, due to the limitations of primary energy resources and rapid increase in energy costs, the importance of energy analyses to determine the energy losses of these and many thermal systems is increased. One of the important roles of energy analysis within development of energy systems is to ensure the energy system designers and operators have the necessary information. After the oil crisis occurring in the 1970s, it was understood that energy analysis alone did not reveal how effectively energy was used. Thus, exergy analyses began to gain great importance [8]. However, through the conventional exergy analysis, one cannot assess the mutual interdependencies among the system components neither the real potential for improving the components. This may be possible in an advanced exergetic analysis [9]. In recent times, very few researchers have used advanced exergy analysis for a variety of geothermal power plants [10–12]. In regard, this paper will comparatively evaluate the thermodynamic performance of a binary geothermal power plant using conventional and advanced exergy analyses and the artificial bee colony optimization method.

There are many studies about application of various optimization methods in thermodynamic cycles of any energy conversion system. Dai et al. [13] conducted the thermodynamic optimization of an organic Rankine cycle (ORC) with low grade waste heat recovery using different working fluids with exergy efficiency as the objective function by means of the genetic algorithm (GA). They reported that the ORC system with R236EA had higher exergy efficiency compared with other working fluids (e.g., ammonia, isobutene, R11, water). Sun et al. [14] proposed a ROSENB optimization algorithm combining with penalty function method to search the optimal set of operating variables to maximize either the net power generation or the thermal efficiency. They investigated the effects of working fluid mass flow rate, air cooled condenser fan air mass flow rate and expander inlet pressure on the system thermal efficiency and system net power generation. Rashidi et al. [15] conducted a parametric study and optimization of regenerative ORC with two feedwater heaters with thermal efficiency, exergy efficiency and specific work as the objective functions by means of artificial neural network (ANN) and artificial bee colony (ABC). They found that the maximum values of the specific network, the thermal efficiency and the exergy efficiency for R717 were greater than those for water. Arslan and Yetik [16] optimized a supercritical ORC-Binary geothermal power plant in the Simav region using ANN for economic costs. Arslan [17] completed a similar study in a geothermal-sourced Kalina power cycle. Wang et al. [18] used the non-dominated sorting genetic algorithm-II (NSGA-II) to increase the thermodynamic and economic performance of a low grade waste heat recovery organic Rankine cycle. Besides, the effects of turbine inlet pressure, turbine inlet temperature, pinch temperature difference, approach temperature difference and condenser temperature difference on the exergy efficiency and overall capital cost were investigated. They found that the optimum exergy efficiency and overall capital cost were 13.98% and 1292800 USD, respectively. Clarke et al. [19] compared the limited, non-linear simulation-based optimization of a double flash geothermal energy power plant using GA and particle swarm optimization (PSO) performance. Another study by Clarke and McLeskey Jr [20] used a multi-objective PSO method for the Pareto-optimal set used in the design of a power plant to determine the optimum use of the superheater and/or recuperator in a binary geothermal electricity power plant at environmental temperatures and brine temperatures. Karadas [21] used the true design parameters of the Dora 1 GPP located in Turkey to design an air-cooled, binary fluid geothermal power plant and investigated the effect of the design parameters on the theoretical power plant performance. Additionally, to be able to assess the power plant performance, they used real data from the Dora 1 GPP for regression analysis. Using three measurable independent variables such as ambient air temperature, flow rate and temperature of geofluid, they developed multiple annual linear regression models from 2006 to 2012. Saffari et al. [22] used the ABC method to optimize the thermal efficiency of a low temperature Kalina cycle with double turbine. Additionally, the study researched the effects of the entry pressure and temperature of the separator, basic ammonia mass fraction and basic mass flow rate of the working fluid on the net power output and thermal efficiency of the cycle. They reported that the proposed Kalina cycle had a thermal efficiency of 26.32%. Another study by Saffari et al. [23] assessed the thermodynamic performance of the Husaviv power plant with a Kalina cycle using the ABC optimization method. With the aim of identifying a more rapid and sensitive optimization of this system, they compared the ABC method with the GA, PSO and differential evolution (DE) methods. They researched the effects of parameters like entry temperature, pressure and mass flow rate of separator and basic ammonia mass fraction on the energy and exergy efficiencies of the system. They found the energy and exergy efficiencies of the system were 20.36% and 48.18%, respectively. They showed again in this study that the ABC method is more useable compared to the other methods. Proctor et al. [24] developed a dynamic model of a commercial scale geothermal ORC and confirmed this with power plant data. The standard deviation between the model and real power plant for output power and mean output power was between 1.4% and 0.24%, respectively. Li et al. [25] performed quantitative analysis of non-design performance for a low temperature geothermal resource using a Kalina cycle. In this study the non-design models including the turbines, pump and heat exchangers were previously created. To maximize the net output power and determine thermodynamic parameters in the design stage, they used the GA method. Wu et al. [26] presented and analysed the transcritical power cycles used for a CO_2-based binary zeotropic mixtures with temperatures of cooling water of 10–30 °C and low grade geothermal fluid of 100–150 °C. Under these conditions, 6 coolants were chosen to be added to CO_2. The transcritical power cycle