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Thermodynamic evaluation of a geothermal power plant for advanced exergy analysis

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ABSTRACT

As a result of decreasing fossil fuel resources and their adverse impacts on the environment, interest in renewable energy resources, particularly geothermal energy, has been revived. Finding approaches that are more accurate and systematic to the energy system development is of great importance for the exploitation of geothermal energy. The aim of this study was to carry out both conventional and advanced exergy analyses of an existing geothermal binary power system. In this way, in-depth information was collected about the exergy destroyed in the system and its parts. Through advanced analysis, it became possible to investigate the interactions between the system components and the actual performance of the reasonable improvements. The results show that the order of the primary improved components is CON 1, TURB 1 and VAP 2 for the conventional analysis and CON 1, CON 2 and PRE-HE 1 for the advanced analysis. The results of the advanced analysis were found to be more qualified than the results of the conventional one. The improvements made to the system, increased the modified exergy efficiency to 18.26%, while the total system efficiency was found to be 9.60% in the real conditions.

1. Introduction

There are many resources from which energy can be generated, including the conventional resources of coal, petroleum, and nuclear and renewable resources such as wind, geothermal, and solar energy. Recently, there has been a great deal of interest in sources of renewable energy because of their positive characteristics such as being limitless and cost-efficient. Among the renewable energy resources, geothermal energy seems to be the most promising one as it has been proven to be clean, reliable and secure and the amount of research on the exploitation of it for power generation, heating and cooling is increasing [1]. Geothermal energy can be used for various purposes depending on the temperature range. The areas in which low temperature geothermal energy is usually preferred are aquaculture, greenhouses and absorption chillers to refrigerate, while air conditioning and generation of power are among the high temperature applications [2].

The first exploitation of geothermal energy for the generation of electricity occurred in Lardrello, Italy in 1904, where light bulbs were powered by a small turbine driven by geothermal steam. This program led to the establishment of a power plant in 1913 that added 250 kW of capacity to the Italian grid system [3]. GPPs (Geothermal power plants) have continued their development up to the present through the use of various technologies such as dry stream and flash and binary cycles. Among these, the binary cycle, particularly the ORC (organic Rankine cycle), is a cutting edge technology that can generate power using low temperature/enthalpy geothermal heat at temperatures lower than 150 °C. A large amount of research deals with the performance, characteristics, design criteria and types of GPPs with ORC for power generation systems [4–8]. The critical challenges to be dealt with by this research are (i) the working fluid selection and (ii) the cycle design. An ideal GPP (geothermal power plant) with ORC is expected to provide good thermodynamic performance and high heat source utilization.

Moreover, GPPs can be developed in two different ways: (i) new power plants can be constructed in new fields, and (ii) the thermal efficiency of existing power plants can be enhanced. The thermal efficiency can be enhanced through the use of energy (First Law) and exergy (Second Law) analyses. Some researchers have used these analyses as efficient instruments to define and quantify the processes to lower energy because they enable the assessment of

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what types of energy losses occur, where they occur and how large they are [9]. In regard to the thermodynamic evaluation of GPPs, exergy analysis (called conventional exergy analysis in this study) in particular has been shown to be a powerful tool. A great deal of research in the literature explores the conventional exergy analysis and assessment of GPPs [2,10–20]. Here, when the temperature of the geothermal fluid is relatively low, low exergy efficiencies of GPPs are observed. Therefore, the difference between the exergy efficiency of a GPP with good performance and that of a GPP with poor performance is small. As a result, making a comparison based on only energy/exergy efficiencies can be very difficult. This particularly holds true in binary GPPs (with ORC) because the resource temperature is lower than the resource temperature of single and double flash systems [13].

A new direction called advanced exergy analysis emerged in which the exergy destruction is split into endogenous/exogenous and unavoidable/avoidable parts. Through such a splitting, the accuracy of conventional exergy analysis can be enhanced and thus the thermodynamic inefficiencies can be better understood [21]. In relation to advanced energy analysis and the assessment of power plants other than GPPs, Cziesla et al. [22] conducted a study to explore all of the components of a combined power plant fired externally according to both avoidable and unavoidable exergy destruction. Razmara and Saray [23] used the engineering method for a simple gas turbine cycle operating using different fuels to investigate the destruction of exogenous and endogenous exergy. The irreversibilities observed in the components were described and compared for these fuels. In Morosuk and Tsatsaronis' study [24], advanced exergy analysis was administered to a simple gas turbine cycle to evaluate its performance, and the details of their calculation methods were discussed. Tsatsaronis and Morosuk [25] conducted an advanced exergy analysis of a cogeneration system combining LNG (liquefied natural gas) regasification with power generation. In this way, they were able to define the improvement potentials and interactions between the components. Morosuk and Tsatsaronis [26] aimed to identify the improvement potential and what the interactions between the components in LNG-based cogeneration systems are. These researchers proved that this analysis is more advantageous than conventional exergy analysis; namely, it can yield more results with a higher rate of reliability and detail and help to better understand the interactions taking place among components and the potential for the improvement of energy systems. As a result of the analysis of a natural gas degasification plant that produced electricity using advanced exergy and advanced exergoenvironmental methods, Morosuk et al. [27] reported that the expander, the heat exchanger and the pump are the components that deserve the most attention for thermodynamic efficiency improvement and reducing the environmental impact of the plant. Wang et al. [28] conducted research on a power plant operating under supercritical conditions by means of advanced exergy analysis and proposed suitable optimization strategies. According to their proposal, the first component to be improved is the generator, followed by the turbines. Petrakopoulou et al. [29] capitalized on both conventional and advanced exergy analysis methods to analyse a combined cycle power plant. In their exergy analysis, the variables used demonstrated the components having the highest exergy. Most of the exergy destruction in the plant components was also reported to be unavoidable, apart from the expander that is a part of the gas turbine system and the high pressure steam turbine. The combustion chamber caused the highest exergy destruction. The operation of the component itself accounts for nearly 87% of the total exergy destruction taking place within this component, and it was not possible to avoid 68% of the total exergy destruction. Soltani et al. [30] applied advanced exergy analysis to an externally fired combined-cycle power plant that has been developed recently and was integrated with biomass gasification. The heat exchanger needs to be focused on to improve the cycle performance, not the combustion chamber of the gasifier. As a result of the study, they reported that the unavoidable part of exergy destruction in almost all components was higher than the avoidable value. Acikkalp et al. [31] utilized advanced exergy analysis to explore the trigeneration system located in the Eskisehir Industry Estate Zone in Turkey. They found the exergy efficiency of the system as 40.2% and the total exergy destruction of the system was calculated to be 78.242 MW. Weak relations were detected among the components as the ratio of the endogenous exergy rates was 70%. The potential for the improvement of the system was calculated to be 38%. Vuckovic et al. [32] analysed a complex industrial energy supply plant through advanced exergy analysis to identify the components that are critical for the performance and the potential for the improvement of exergy efficiency. This plant is a part of a rubbery factory and provides steam, compressed air and cooling water for the production facilities, and it also provides hot water for space heating and for sanitary purposes.

The reviewed literature makes it clear that no research is focusing on advanced exergy analysis and assessment of GPPs, to the best of the authors' knowledge. The present study aims to fill in this gap in the literature. For this purpose, the target system is analysed using both conventional and advanced exergy analysis methods. The target system was the Bereket geothermal power plant located in Denizli, Turkey. The performance of the plant was analysed to assess the extent to which the system components are interdependent on each other and the real potential for improving the components by applying conventional and advanced exergy analyses. The outcomes obtained from the analysis can be used to improve this power plant by optimizing the system components and thus achieving higher output power. The Engineering Equation Solver and GateCycle software packages are used to simulate the Bereket GPP based on a plant model that uses actual and designed data.

2. Description of the Bereket geothermal power plant

The Bereket GPP (geothermal power plant) is a two-level and binary power plant that uses water for cooling and has a net electricity production capacity of 6.35 MW in the city of Denizli, Turkey. The geothermal fluid is transported through a pipeline that is 2 km long. The plant was designed to operate using 145 °C geothermal fluid separated at the flash plant, and the temperature of the fluid at the outlet of the binary plant is approximately 75 °C. In the present study, a schematic diagram of the Bereket GPP is presented in Fig. 1. The plant gets its fluid from the Kızıldere geothermal field. The fluid is sent to the plant with a pressure of approximately 5 bar, a temperature of 145 °C at a rate of approximately 400 ton/h in total. The temperature of the fluid is reduced to approximately 70–75 °C. Then, all of the geothermal fluid is released via natural direct discharge. In the current study, the actual operational data related to the temperature, pressure and flow rate of the system for the analysis were recorded on April 14, 2013, by the SCADA (Supervisory Control System) program based on the state numbers specified in Fig. 1.

3. Thermodynamic analysis

The conventional exergy balance for the overall system and the exergy balance of the kth component together with the exergy destruction rate can be written, respectively, as [33].

$$\dot{E}x_{F,tot} = \dot{E}x_{P,tot} + \sum_k \dot{E}x_{D,k} + \dot{E}x_{L,tot} \quad (1)$$

$$\dot{E}x_{D,k} = \dot{E}x_{F,k} - \dot{E}x_{P,k} \quad (2)$$