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Exergetic and thermoeconomic analyses of a coal-fired power plant

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ABSTRACT

Exergetic and thermoeconomic analyses of a coal-fired power plant with 160 MW capacity where located in Turkey were performed. Specific Exergy Costing (SPECO) and Modified Productive Structure Analysis (MOPSA) methods were separately applied to the system to determine the unit exergy cost of electricity generated by the coal-fired plant. The differences of these methods were discussed. As a result, the exergy efficiency of coal-fired power plant is found to be 39.89%. The equipment having the highest improvement potential is determined as boiler. The unit specific exergy cost of electricity generated by the system obtained for SPECO and MOPSA thermoeconomic analysis methods are 12.14 US$/GJ and 14.06 US$/GJ, respectively. The unit specific exergy cost of electricity obtained by using MOPSA thermoeconomic method is the same as the one obtained by the overall cost-balance equation for the coal-fired power plant.

1. Introduction

Although global climate change leads to doubts on fossil fuel usage, it is estimated that fossil fuels will remain the dominant energy source until 2030 [1]. According to the annual report of the British Petroleum, the lifetimes of coal, natural gas and oil are 114, 52.8 and 50.7 years for the data at the end of 2015, respectively [2]. Also, coal fuels cover 40.8% of global electricity production [3]. Therefore, coal has a critical importance for power generation compared to other fossil fuels.

In last decade, Turkey is in the second rank after China in point of natural gas and electricity demand growth and this demand growth trend will continue. In 2015, Turkey's electricity production was supplied by natural gas (37.8%), coal (28.4%), hydraulic (25.8%), wind (4.4%), liquid fuels (1.6%), geothermal (1.3%) and biogas (0.6%). In 2015, Turkey imported 99% of natural gas supplied, 89% of oil supplied and 75% of total energy supplied. Turkey utilizes the 37% of existing coal sources. Turkey's 2023 targets for electricity sector include the usage of known lignite and anthracite coal sources in electricity production and the increase of the share of coal in electricity production up to 30% [3,4]. Therefore, it is seen that coal-fired power plants will be favor in electricity production at long term in Turkey and globally as well.

Performance assessment and improvement of coal-fired power plants has a great importance in prolonging the lifetime of coal reserves and resources, reducing the emissions of carbon dioxide (CO_2) and conventional pollutants, increasing the power output from a given size of unit and reducing operating cost potentially.

Exergy analysis is an effective tool in performance assessment of thermal systems. It plays an important role to determine the locations and magnitudes of irreversibilities in the system. In this sense, exergy analysis helps to define the critical equipment in the system for some possible adjustment and modification in the performance improvement studies of thermal systems. Therefore, exergy analysis provides more detailed and comprehensive information than energy analysis. Also, it is required to realize thermoeconomic analysis.

Thermoeconomic analysis is a method that combines exergy analysis and economic analysis. The method provides a technique to evaluate the cost of inefficiencies or the cost of individual process streams, including intermediate and final products [5]. The general aim of thermoeconomic analysis can be expressed as (i) revealing the cost formation process and (ii) calculating the cost per exergy unit of the product streams of the system [6].

There are several methods for thermoeconomic analysis in the literature. These methods can be mainly ordered as follows:

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- Engineering Functional Analysis (EFA) [7]
- Exergy-Cost-Energy-Mass Analysis (EXCEM) [8]
- Exergy Economic Approach (EEA) [9–11]
- Last-in-First-out Principle (LIFO) [12]
- Modified Productive Structure Analysis (MOPSA) [13]
- Specific Exergy Costing (SPECO) [6,14,15]
- Structural Theory of Thermoeconomics (STT) [16]
- Theory of Exergetic Cost (TEC) [17]
- Thermoeconomic Functional Analysis (TFA) [18]

There are several applications of these methods to different thermal systems. The specific unit exergy cost (SPECO) method was used to determine changes in the design parameters of a copper-chlorine (Cu-Cl) thermochemical cycle for hydrogen production and to improve the cost effectiveness of the Cu-Cl cycle. It was found that the cost rate of exergy destruction varies between 1$ and 15$ per kilogram of hydrogen [19]. The specific unit exergetic cost of the power produced by a diesel engine powered cogeneration was calculated to be 10.3 US$/GJ and the cost flows of the system were obtained by means of SPECO [20,21]. The exergetic cost allocations of a trigeneration system with gas-diesel engine having 6.5 MW capacity were performed by means of SPECO. The specific unit exergetic cost of the net electrical power, chilled water, heat energy which is separated two stream for different purposes were found to be 45.94 US$/GJ, 167.52 US$/GJ, 29.98 US$/GJ and 42.42 US$/GJ, respectively [22,23]. In the same manner, by using SPECO method, the product costs of a cement plant are allocated and the specific unit exergetic cost of the farine, clinker and cement produced by the cement plant were calculated to be 43.77 US$/GJ, 133.72 US$/GJ and 180.5 US$/GJ, respectively [24,25]. A geothermal district heating system was investigated to provide cost based information and to suggest possible locations/components in the system for improving the cost effectiveness. Also, the unit exergy cost of heat produced by the system was found as average 5624 US$/h [26]. SPECO were also applied to a building heating system with a low-exergy analysis [27].

The modified productive structure analysis (MOPSA) method were applied to a 1000 kW gas turbine cogeneration system to provide information on decisions about the design and operation of the cogeneration system for first time. In addition, the system was investigated for different load conditions and the values of unit exergy costs were obtained for these conditions [13]. MOPSA method was used to visualize the cost formation process and the productive interaction between components of a 500 MW combined cycle plant [28]. The unit exergy cost of electricity produced by a 200 kW phosphoric acid fuel cell plant was compared with that of 1000 kW gas turbine cogeneration plant by using MOPSA method. The calculated unit cost of electricity of fuel cell was found to be 125% higher than the cost obtained for the gas turbine cogeneration plant [29]. Also, MOPSA method was applied to a geothermal district heating system to show how exergy cost flow rates change with the reference state [30].

Each method mentioned above has different foundations and the assumptions made in their formulation of the cost-balance equations are different. Therefore, comparison of thermoeconomic methods is required to be able to determine the method that present more accurate estimation of the unit cost of products from the thermal power systems. To compare the advantages of these methods each other, a few studies were performed except CGAM problem which is predefined cogeneration system. Thermoeconomic functional analysis (TFA), theory of exergetic cost-disaggregating methodology (TECD), theory of the exergetic cost (TEC) and exergoeconomics (EE) were applied to a simple gas turbine cogeneration system [31]. Significant differences were obtained in the costs of power and heat which result from the application of the methods. SPECO and MOPSA methods are applied to CGAM problem for right decisions about the design and operation of thermal systems as well as the replacement of a particular component in the systems [32]. In a similar manner; the product cost obtained by separately application of SPECO, MOPSA and Moran methods to a gas turbine system was 8.55, 9.57 and 7.28 $/GJ, respectively [33]. Also, total revenue requirement and SPECO methods were applied to an ultra-supercritical coal-fired power plant to determine the unit cost of product [34].

In this study, the exergetic and thermoeconomic analyses of a coal-fired power plant having 160 MW electricity production capacity are performed by using actual operational data. The exergetic performance of overall system is evaluated and the components which are most responsible for system irreversibilities are defined by means of exergetic performance parameters. Moreover, SPECO and MOPSA thermoeconomic analysis methods are separately applied to determine the unit exergy cost of electricity produced by the system. The advantages and disadvantages of these methods in the estimation of the unit cost of product from the power plant are discussed.

2. System description

A schematic diagram of the power plant analyzed in this study is illustrated in Fig. 1. The plant has 25 components whose functions are as follows. There is a coal-fired steam boiler (SB) in the system. Air required for combustion is supplied from atmosphere by primary air fan (FAN1) and secondary air fan (FAN2) and it is preheated in air preheater (AP) before being sent to SB. Steam generated is superheated firstly in cyclone (CYC) and then in heat exchanger unit (SH1, SH2 and SH3). Flue gas is used as hot stream in cyclone and heat exchanger unit. Steam superheated is supplied to high-pressure turbine (HPT). Steam leaving HPT is reheated via a heat exchanger (RH) and enters low-pressure turbine (LPT). The shaft power obtained by HPT and LPT is transferred to generator (G) to produce electricity. Some amount of steam leaving turbines is used for preheating of water supplied to SB, while remaining portion is sent to condenser (COND). Steam phase is converted to water phase in condenser and then it enters to condenser tank (CT). Water stored in CT is pumped to low-pressure heat exchanger unit (LPH1 and LPH2) by condenser pump (CP). Water leaving low-pressure heater unit as preheated enters to feed-water tank (FWT). All water streams are stored in FWT and then pumped by primary pump (PUMP1) and secondary pump (PUMP2). Water pressurized is preheated before entering SB in order of high-pressure heat exchanger unit (HPH1 and HPH2), deaerator (DPH) and economizer (ECO1 and ECO2) and then supplied to SB. In this way, the system completes a cycle. Generally, flue gas is used as hot stream to superheat the steam from SB to turbine group, while some amount of steam leaving turbine group is used as hot stream to preheat water from FWT to SB. A portion of electricity generated by system is used as feedback to operate the pumps and fans. Remaining portion is supplied to electrical network.

In the analysis, the temperature and pressure values of reference environment are taken as 288.15 K and 101.325 kPa, respectively. The mass flow rates of coal and air supplied to steam boiler for combustion process are 14.78 kg/s and 163.1 kg/s, respectively.

The ultimate analysis was performed to determine the chemical formula of coal used in the system. The chemical and physical analysis results of coal used in the system are presented in Table 1.

The molar distribution of atoms in coal can be found by using $n = m/M$ relation, where n is mole number and M is molar mass, in the light of molar mass of related atoms and physical analysis data given in Table 1. By this way, the molar distribution of carbon, hydrogen, nitrogen, oxygen and sulphur in coal are found to be