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A comparative thermoeconomic cost accounting analysis and evaluation of biogas engine-powered cogeneration

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ABSTRACT

This study presents an analysis of a biogas engine-powered cogeneration system using four different thermoeconomic methods. The most important parameter is the thermoeconomic cost of work produced by the gas engine for each method. The aim is to compare the results obtained from each of those methods. The first method is the exergetic cost theory, which introduced the exergetic cost concept to the thermoeconomic field for the first time. An incidence matrix is defined to show the interaction of flows and components within the system. Exergetic cost theory defines the main rules and delivers a result of 110.065$/h for the work produced by the gas engine. A second method, modified productive structure analysis, is applied to the system and cost balance equations are formed for each component. Exergy destruction is clearly defined and tabulated. At the end of the analysis, the cost of gas engine work was found to be 85.536$/h. A third new method described in published literature, Wonergy, is used to determine both the cost of work and the heat utilized in the cogeneration system. Wonergy gives the same thermoeconomic cost for the components which help to produce work. The smallest value obtained was 72.5$/h. The fourth method, SPECO (specific exergy cost), was the final analytical method used on the system. It defines fuel and product rules to obtain auxiliary equations. The thermoeconomic cost of work produced from the gas engine was determined to be 141$/h which was the highest value obtained in comparison to the others.

1. Introduction

In the analysis of the production processes of complex energy systems, the economic profitability and the productivity displayed in resource consumption should both be considered. Performing this analysis, thermodynamics enables us to calculate the efficiencies of the subcomponents that make up the system and determine the locations and amounts of system irreversibilities that occur in the process. However, thermodynamic analysis cannot assess the overall production process in an economic context. Thermoeconomic analysis, by contrast, is a combined discipline that directly assesses the cost of consumed resources, i.e., money and system irreversibilities, within the total production process. While a thermoeconomic analysis shows a variety of ways to use resources more effectively, it also describes the concept of monetary irreversible cost as the economic impact of inefficiency, and it aims to increase the cost efficiency of production processes. Thus, in a detailed thermoeconomic analysis, it becomes possible to understand the flows in the subcomponents and the entire production process, from the perspective of cost, from the raw material sources entering the system to the final products.

Thermoeconomic methods are generally divided into two groups: cost accounting [1–5], and optimization techniques [6–12]. Cost accounting is the process of determining the total cost of the production per unit of each output of a thermal system, such as electricity, steam, hot water, chilled water, etc., while optimization methods are applied to finding the optimum design or optimum set of operation conditions. All initial investment and operating costs for establishing and operating a thermal system should be allocated to the final product. Principally, there are two costs that must be defined for each product: (i) Direct costs, which include the cost of resources and materials that are clearly attributable to the product cost throughout the production process, and (ii) Indirect costs.

In a comprehensive thermoeconomic analysis, the aim of cost accounting is to establish a logical framework for evaluating the profitability, starting from the determination of the rational costs of the products, to organizing and evaluating the decisions made in

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accordance with this framework. Valero et al., in their initial work on exergetic cost accounting, developed the basic ideas of their thermoeconomic approach and presented a strong theoretical background. That study, which consisted of two parts, has been accepted as one of the pioneering studies in the thermoeconomic field. In the first part, they identified exergetic and thermoeconomic costs for a relatively simple thermal system and presented the basic conditions for conducting the thermoeconomic analysis of a more complex system [13]. In the second part, they developed the mathematical background for three different applications of the thermoeconomic analysis method described in the first part [14].

Exergetic Cost Theory (ECT) is one of the earliest cost accounting methodologies applied to energy conversion systems. The theory was first developed by Lozano and Valero [5], and the methodology presented in this theory is based on a set of analytical propositions. Previously, Valero et al. [13] had defined an incidence matrix that represented a system and interconnected the subcomponents with flows in the system. According to this very early study, the two main routes for calculating costs had been identified, and they had been evaluated in terms of the cost hexagon method. Vieira and Velásquez [15] conducted a thermoeconomic analysis of a thermal power plant using the exergetic cost theory in order to understand the cost history of internal flows in the system and to rationally evaluate the costs in question. Deng et al. [16] applied the exergetic cost theory, based on the structural theory of thermoeconomics, to a gas-fired micro-trigeneration system, which used a small-scale generator set driven by a gas engine and a new small-scale absorption chiller. They also presented a comparison between the methods of conventional energy-based economic analysis and exergetic cost analysis.

The Modified Productive Structure Analysis (MOPSA) is another well-known cost accounting method, and it was first developed theoretically by Kwak et al. [17]. This theory was presented by applying its synthetic propositions to the famous CGAM problem in order to investigate the cost structure of a predefined cogeneration system. The reason that we describe the proposals as "synthetic" [18] in the MOPSA method (this description is valid for all other cost accounting methodologies) is that they employ analytical judgments using both universal and mandatory principles (conservation of energy, generation of entropy or destruction of exergy) as well as extending our cost knowledge of the processes. The MOPSA method was also applied to a combined gas and steam cycle plant in order to estimate the unit exergetic cost of the electricity produced [19]. Bandpy et al. [20] performed a comprehensive exergetic and thermoeconomic analysis of an existing gas turbine plant and compared three cost-accounting methodologies, arriving at the conclusion that MOPSA is the best method for estimating the unit cost of the electricity produced.

As a relatively new thermoeconomic methodology developed by Kim [21], Wonergy is not as widely practiced as other cost accounting methods in published literature to the best of the authors' knowledge. This published work is one of the few studies in which the Wonergy method is applied in detail to a cogeneration system.

In energy conversion systems, defining the inputs and outputs of a subcomponent with the "fuel" and "product" approach and then recording all exergy flows through subcomponents using this method in a systematic way to establish exergy-based cost flows was first proposed by Lazzaretto et al., and this methodology has become known as the specific exergy costing method, or SPECO. This approach has been one of the most preferred thermoeconomic methods in available published literature due to its ease of application [22–29].

In this study, a comparative thermoeconomic cost-accounting analysis and assessment, including the four methodologies mentioned above, is used for a biogas engine-powered cogeneration system in Gaziantep. The results from this study will be used in the thermoeconomic performance improvement and optimization of biogas-fueled cogeneration systems. This is the first study of its kind in Turkey since biogas engine-powered cogeneration became preferable in facilities where energy recovery from waste is possible as in the case of wastewater treatment systems. The results should provide a realistic and meaningful basis for thermoeconomic performance evaluation of these power systems, which may be useful in the analysis of similar systems.

2. System description

The biogas engine-powered cogeneration system presented in this work was established by Gaziantep Metropolitan Municipality Wastewater Works, and it started to produce electricity in 2006 using biogas produced from wastewater sludge. The total installed electricity generation and hot water capacity of the plant is 1.66 MWh and 135.11 tons/hr, respectively. Biogas produced through an anaerobic sludge digestion process is first transferred to a desulfurization unit for lowering its sulfur content to an acceptable legal value and then to a gas engine for electricity production. The total electricity produced by the biogas-powered gas engine is 1000 kWh, which is used within the wastewater treatment facility. A schematic diagram of the biogas engine-powered cogeneration unit in the wastewater treatment plant with all flow streams is shown in Fig. 1. The biogas engine in the cogeneration facility is a four stroke, spark ignition engine with 12 cylinders in a V configuration. It uses biogas that is produced by anaerobic digestion reactors. The annual electrical energy production is 8760 GWh, and the annual biogas consumption is nearly 3,400,000 m^3 at its intended operating conditions, which means 61% of the biogas produced through anaerobic digesters is consumed by the on-site cogeneration system in the plant. In the cogeneration process, the biogas is first mixed with air before flowing through the intake valves of the gas engine. When the engine is started, an air-biogas mixture is injected into the compressor of the turbocharger unit. The compressor of the turbocharger is powered by a turbine mounted in the exhaust flow of the engine. The advantage of this is that none of the engine shaft output is used to drive the compressor, and only waste energy in the exhaust is used. The turbocharger is equipped with an intercooler to lower the compressed air-biogas mixture temperature. The exhaust gases leaving the turbine of the turbocharger enter the exhaust gas heat exchanger to transfer heat to the water, which circulates in a closed loop through the primary anaerobic digester unit to supply the necessary heat for the digestion process. The exhaust gas leaving the exhaust gas heat exchanger is sent to an exhaust filter which captures and reduces the CO_2 and CO emissions. The high temperature water flowing through the engine jacket of the gas engine is first used to heat the water from the primary digester units. It then enters the lubrication oil heat exchanger to coo the lubrication oil from the engine. Finally, it returns back to the gas engine after cooling the water by circulating it through an intercooler in a closed loop. Oil is used for lubrication and cooling purposes in the engine components. The temperature, pressure and mass flow rate data, and the energy and exergy rates in the biogas engine-powered cogeneration system are presented in Table 1 that is labeled using the nomenclature shown in Fig. 1.

3. Cost accounting methodologies

3.1. Exergetic Cost Theory (ECT)

This methodology requires the division of the system into units