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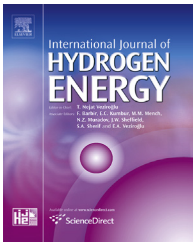

Comparative assessment and optimization of fuel cells

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ABSTRACT

In this study, a comprehensive exergoeconomic analysis and a multi-objective optimization study are performed for four different types of fuel cell systems, in order to determine their maximum power production capacities, exergy efficiencies, and minimum production costs, by use of a genetic algorithm method. The investigated fuel cell types are Polymer Electrolyte Membrane (PEMFC) and Direct Methanol (DMFC) for low temperature fuel cells, and Solid Oxide (SOFC) and Molten Carbonate (MCFC) for high temperature fuel cells. The selected fuel cell systems are modeled exergetically and exergoeconomically. After modeling, the cases are studied parametrically with various available operating conditions, such as temperature, pressure, surrounding temperature and pressure, current density, and relative humidity, using the developed computer program MULOP (Multi-Objective Optimizer). For the low temperature fuel cells it is observed that the efficiencies are in the range of 10–30% and the costs are around $3–4/kW. On the other hand, for the high temperature fuel cell systems, efficiencies are in the range of 15–45% and the costs seems to be $0.003–0.01/kW. The results show that high temperature fuel cells operate more effectively for large scale applications.

Introduction

The global energy need has rapidly increased since the 1990s. It has now reached the highest amount in history, and it is still expected to increase worldwide. For example, the global energy need in 2010 has increased by 40% compared to the 1990's [1,2]. On the other hand, from the sustainability and global warming point of view, the implications of fossil fuels cannot be underestimated and engineers are urged to find solutions to this problem, especially considering the fact that with today's consumption rates, the global fossil fuel sources may deplete within 50 years [3].

Fuel cells convert chemical energy to electrical energy and heat using electrochemical processes. Since Carnot's law is not applicable to electrochemical processes, fuel cell systems have relatively large efficiencies and low pollutant emissions, despite their low operating temperatures compared to traditional fossil-based energy sources. On the other hand, the efficiency of these systems greatly depend on the amount of

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power produced [4]. Because of the wide variety of fuel cell elements, reactions, system characteristics, and equipment related to the subject; the fuel cell phenomena is complicated. Therefore, achieving better efficiency, power output or cost optimization becomes even more crucial [5].

There are various studies in literature on the performance investigation of the fuel cell systems, including exergy analysis and exergoeconomic analysis [1,6–10]. The thermodynamic irreversibilities and modeling study has been performed by Ref. [11] for a PEM fuel cell. Also the implementation of fuel cell systems for stationary applications from an exergetic performance investigation has been accomplished by Ref. [12]. A hybrid MCFC and gas turbine system's exergy and energy analysis is performed and it is found that the efficiencies may reach up to 42.89% [13]. Performance assessment of an integrated tri-generation SOFC aided energy system for power, heating and cooling production is conducted through energy and exergy analyses including sustainability analysis that results 32.62% exergetic efficiency in the study of [14]. Moreover, the multi-objective [15] investigation is also taken into account in literature seeking the best working conditions from relevant objectives such as efficiency and cost [15–22]. In the study of [23] SQP method is applied to a PEM fuel cell system for determining exergetic multi-objective optimum points. Besides, an efficiency and size trade-off investigation for a PEM system is applied [20] to a PEM system in a multi-objective manner and it is seen that system must operate above 40% efficiency for best trade of. Multi-objective optimization of a solid oxide fuel cell (SOFC) reactor for oxidative coupling of methane has been studied with the elitist non-dominated sorting genetic algorithm by Ref. [24]. A review study [18] investigated the methods and strategies for optimizing fuel cell systems. Fuel cell systems are discussed when considering the potential usage areas such as portable applications, stationary power production and fuel cells in transportation. It is noted that, there are numerous studies about the single and multi-objective optimization investigations considering the fuel cell systems Another review study [25] evaluated the optimization studies about the fuel cell systems up to 2011 in literature. It is seen that there has been very little attention to the high temperature fuel cells like SOFC and MCFC. It is also seen that there are various solution algorithms presented, some of them rely on in-house programs, whereas, the others are based on packages like COMSOL and MATLAB. Multi-objective exergy-based optimization of a polygeneration energy system using an evolutionary algorithm is studied [21] for determining the Pareto solution set for environmental and thermodynamic objectives.

The present study differs from the literature works, as it investigates and compares the fuel cell systems simultaneously through electrochemical and exergoeconomic analysis, with a self-developed, hybrid genetic-solver oriented and multi-objective optimization technique. The aim of this optimization study is, in this regard, to reach an easy and unique solution to help fuel cell selection and reveal the performances of the various kinds of fuel cell systems. Also, the comparison of the performances of fuel cell systems, considering the exergoeconomic multi-objective optimization, brings a new perspective to literature.

Fuel cell systems considered

With the idea to create easy calculation, comparison and validation processes, four common types of fuel cells were selected for the present study; namely, PEMFC, DMFC, SOFC, and MCFC. This selection also enables a comparison between the operating temperatures of the systems. The SOFC and MCFC fuel cells are examples for high temperature cell systems, whereas the PEMFC and DMFC are examples for the low temperature fuel cell systems. In order to understand and investigate the properties of fuel cell systems, first, the behavior of the fuel cell should be comprehended. For this goal, electrochemical models of the cells were gathered from literature studies and the aforementioned multi-objective optimization was carried out on these models. The detailed models were studied in previously in the literature [15,16,26,27].

Polymer electrolyte fuel cell (PEMFC) system

As an example of the PEMFC system, Ballard's Xcellsis™ HY-80 Fuel Cell Engine [28] was selected (Fig. 1) in which 97 fuel cells form the fuel cell stack with an effective area of 900 cm^2 (Fig. 1). A cooling and humidification system is used in the fuel cell system in order to maintain temperature and humidity for the operating conditions. In addition, the cooling system's own heat is also lost to the environment due to the temperature difference [9,29–31].

Direct Methanol fuel cell (DMFC) system

The Direct Methanol Fuel Cell (DMFC) is used to directly produce electricity from methanol. DMFC is supposed to appear in the market within the next few years for portable electronic devices and other applications in the low power range. The system and the operation of the DMFC's are much simpler compared to the other systems. However the cascade structure of the reaction in the DMFC presents the main disadvantage of this system [32,33]. A flow chart of a DMFC system is shown in Fig. 2. The fuel cell stack, post combustor, and preheater are the main components of the system. The post-combustor converts the unreacted fuel to energy and the pre-heater sustains the operating temperature.

Solid oxide fuel cell (SOFC) system

The Solid Oxide Fuel Cell (SOFC) directly oxidizes fuel without irreversible oxidation using an electrochemical process. In general, SOFC systems are designed to produce a large amount of power and are used in central (stationary) power stations. But nowadays with improvements in technology, SOFC systems can also be designed to supply power and heat for single residential and auxiliary power needs. The system used for the investigation of the SOFC in this study is given in Fig. 3 [34].

Molten carbonate fuel cell (MCFC) system

The molten carbonate fuel cell (MCFC) is a promising member of fuel cell family with high operating temperatures. It uses a