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Thermo-economic performance analysis of a gas turbine generator equipped with a pressurized and an atmospheric solid oxide fuel cell

Jamasb Pirkandi *, Mostafa Mahmoodi, Mohammad Ommian

Department of Aerospace Engineering, Malek Ashtar University of Technology, Tehran, Iran

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ABSTRACT

The main objective of this research is to introduce and present two different configurations for hybrid gas turbine-fuel cell systems of direct type and to analyze these systems based on the thermodynamic and thermo-economic models. In the first proposed design, two fuel cells are situated at the upstream of turbine and operate at a specific pressure; while in the second design, one of the cells is transferred to the downstream of turbine, and it works under atmospheric pressure. Also, in the economic analyses performed in this research, a simple economic model and the Total Revenue Requirement model are employed to compute the electricity generation price and the other relevant expenses. The examination of the two proposed systems shows that the hybrid system with one pressurized and one atmospheric fuel cell (the second design) enjoys a higher efficiency and power generation capacity, but at the same time, it has greater exergy destruction and irreversibility rates. The results also indicate that this design generates more pollution compared to the first design. From an economical point of view, the generated electricity price and the purchase, installation and startup costs of both systems are almost the same, and have no significant difference.

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1. Introduction

A solid oxide fuel cell is a type of cell with a high working temperature, and it can be used more fittingly in hybrid power generation systems. This cell always produces a substantial quantity of high-quality heat and energy. Many researchers have recently become interested in using this heat in the most effective way. A more common application for solid oxide fuel cells is to combine these cells with various types of turbines and micro gas turbines [1]. In this type of hybrid systems, the gas turbine cycle can be combined with the fuel cell directly (under pressure or at atmospheric pressure) or indirectly [2]. Replacing the gas turbine cycle's combustion chamber by a high-temperature fuel cell (or a set of fuel cell and afterburner) or placing a fuel cell at the downstream or upstream of the combustions chamber forms a type of pressurized direct hybrid system; and placing a fuel cell at the downstream of a gas turbine forms a direct hybrid system operating under atmospheric pressure. In direct hybrid systems under pressure, the fuel cell is often subjected to a specific pressure; which increases its output power but, accordingly, creates more challenges in the design and control of the resulting hybrid system. Because of the high pressures produced in the fuel cell, its casing has to be properly and securely sealed. In this system, the fuel and the oxidizer that have not reacted in the cell, exit the cell at a high temperature, burn in an afterburner or a secondary combustion chamber, and provide the needed heat energy for the lower cycle. Another example of this type of direct hybrid system includes the direct combination of an atmospheric fuel cell with a gas turbine cycle. In this system, the air flowing into the fuel cell is extracted from the gas turbine's exhaust gasses. Due to low pressure of the turbine's exhaust gasses, medium-temperature solid oxide fuel cells or molten carbonate fuel cells are used in this type of hybrid systems. The gasses exiting the fuel cell then enter a combustion chamber and, after reacting, are used in the cycle's heat exchangers. In this type of hybrid systems, the output power of the gas turbine is about 1/3 of the hybrid system's total power. The indirect combination of the gas turbine cycle with fuel cell forms another type of hybrid systems. In this type of hybrid system, the fuel cell and the gas turbine cycle use separate systems for providing their needed air. In this type of systems, the fuel cell mostly operates under atmospheric pressure. Although in this case, the insulation requirement for the fuel cell becomes less, the major issue in these systems is the proper design of the heat exchanger. Because of the large differences between the temperatures and pressures of the hot and cold sections of the heat exchanger, these

* Corresponding author.
E-mail address: j_pirkandi@dena.kntu.ac.ir (J. Pirkandi).

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Nomenclature

A	cell area, m^2
C	electricity price, \$/kW h
$\dot{C}$	cost rate, \$/h
$\dot{C}_{P,tot}$	rate of total power generation cost, \$/h
$\dot{C}_{F,tot}$	rate of total fuel cost, \$/h
c_P	electricity generation cost, \$/kW h
CC_L	investment cost, \$
c_{fuel}	cost of fuel in the first operating year of the system
$\dot{E}$	cell voltage at standard conditions, V
$\dot{E}_D$	rate of exergy destruction, kW
$\dot{E}_L$	rate of exergy losses, kW
FC_0	annual cost of fuel in the first year of system operation, \$
i	interest rate
$\dot{m}_{fuel}$	flow rate of consumed fuel, kmol/h
n	number of years the equipment have been in operation
N	total annual operating hours
PEC_k	initial purchase cost of equipment, \$
r_{FC}	yearly escalation rate of fuel cost
$\dot{Z}^{CI}_{tot}$	initial capital investment cost, \$/h
$\dot{Z}^{OM}_{tot}$	operating and maintenance cost, \$/h

Greek letters

h	efficiency
Φ_r	operating and maintenance cost

Acronyms

BL	book life of the system
CRF	capital recovery factor
LHV	lower heating value of consumed fuel, kj/mol
OMC	operating and maintenance cost, \$
SOFC	Solid Oxide Fuel Cell
TRR	total revenue requirement cost, \$

Subscripts

ab	afterburner
is	isentropic
p	polytropic

sections must be made of special metals; which probably amounts to high costs. Because of the existing heat transfer and pressure losses inside the heat exchanger of indirect hybrid systems, they are expected to have a lower efficiency than the direct hybrid systems [2].

A review of the literature indicates that, in recent years, numerous research works have been conducted on hybrid power generation systems. In 2006, Araki et al. [3] explored a hybrid power generation system consisting of two high-temperature and low-temperature solid oxide fuel cell stacks. In this analysis, a comparison was made between the efficiencies of a high-temperature and a low-temperature fuel cell, and the efficiency of these two cells connected in series. Their findings indicated the increased efficiency of the hybrid system consisting of two fuel cells connected in series. In 2008, Musa and Paepe [4] investigated the performances of hybrid cycles with two high-temperature and medium-temperature solid oxide fuel cells. They concluded that the efficiency of a hybrid cycle with two medium-temperature fuel cells is higher than that of a hybrid cycle with two high-temperature and medium-temperature cells and also a cycle consisting of a single fuel cell. In 2010, Cheddie [5] analyzed a 10 MW hybrid system of gas turbine and fuel cell. In this system, four heat exchangers had been used to recover the output heat of the turbine and fuel cell. In this investigation, he employed a thermo-economic model to optimize his hybrid system. In this study, the output power of the hybrid system including the heat exchangers, with 66.2% efficiency, was close to 4 times that of the initial hybrid system. Also, based on the presented model in this research, the capital investment return period was estimated to be less than 4 years. In 2010, Tarroja et al. [6] studied a hybrid system of gas turbine and solid oxide fuel cell, investigated the different methods of preheating the cathode's inflowing air (e.g., using a blower or ejector), and compared the results with those of a system with a single heat exchanger. The effects of parameters such as pressure ratio, fuel utilization, oxygen consumption and current density were also analyzed in this research. The findings indicated that the hybrid system with a single heat exchanger has a better performance. In 2014, Facchinetti et al. [7] explored the design and optimization of a SOFC-GT hybrid cycle with a new configuration, which had been considered for use in residential buildings. The presented hybrid cycle included a 5 kW plate type solid oxide fuel cell unit and a micro gas turbine unit consisting of two turbines and a radial compressor, whose thermodynamic performance was analyzed. The optimization results of this research showed a first law efficiency of 64% and an exergy efficiency of nearly 66% for the new hybrid system. In this research, the temperature of the turbine's inflowing gasses was assumed to be 1573 K. Arsalis [8,9] investigated four different steam turbine cycles. The models have been developed to function both at design and off-design conditions. Cheddie and Murray [10–12] proposed direct, semi-direct and indirectly coupled of SOFC and a 10 MW power plant. Akikur et al. [13] presented performance assessment of a co-generation system to deliver electrical and thermal energy using the solar energy and the reversible solid oxide fuel cell. Lorenzo and Fragiacomo [14] formulated zero-dimensional and stationary simulation model of an SOFC system fed by syngas in cogenerate arrangement and implemented in the Matlab environment by which the SOFC system performances were evaluated. Ebrahimi and Moradpoor [15] proposed a novel cycle combining three technologies of solid oxide fuel cell, micro gas turbine, and organic Rankine cycle to produce power in micro scale. Zouhri and Lee [16] analyzed the effect of various materials parameters and environmental conditions on the performance of SOFC. These researchers have employed simple economic models in their investigations in order to determine the price of the generated electricity, and their considered hybrid systems have consisted of gas turbines and pressurized fuel cells.

The main goal of this research is to introduce and present two different configurations for direct hybrid systems of gas turbine and fuel cell and to analyze these two structures based on their thermodynamic and thermo-economic models. In the economic analyses performed in this research, a simple economic model and the total revenue requirements (TTR) model have been used to calculate the price of the generated electricity and the other associated expenses. The TRR model is an accurate and complete model for economic analyses and it can calculate all the capital investment and current costs of a system [17].

2. The proposed hybrid systems

In this section, the schematics of two types of gas turbine generators equipped with two fuel cells, which have been investigated in this research, are presented. The first proposed system consists

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