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Simulation and thermodynamic analysis of a combined heat and power cycle based on solid oxide fuel cell in the building sector

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Abstract

In this research, thermodynamic modeling of a combined production cycle of heat and power is performed based on a solid oxide fuel cell for building sector applications. Initially, the thermodynamic assessment is explained by introducing the mentioned cycle and its respected modeling technique. Then, cycle simulation is performed using Cycle Tempo analytical software by simultaneously solving the mass, energy, and electrochemical equilibrium equations. Parametric analysis of the main characteristics influencing the performance of the cycle is assessed, and the appropriate operating conditions are determined after presenting the performance results. The results show that using this model, electric power of 14.00 kW, thermal power of 4.56 kW, heat to power ratio of 32% at net electrical efficiency of 58.5%, and total efficiency of 77.3% is achievable. These results also confirm the attractiveness of the proposed systems over other electricity and heat cogeneration technologies, which are based on gas engines or gas micro turbines. The system is highly recommended in administrative buildings and warm and warm/moderate climates considering the functionality of the proposed system in different heat to power ratios.

Keywords: Solid oxide fuel cell, Combined heat and power, Thermodynamic modeling, Building sector

1. INTRODUCTION

The centralized or distributed electricity generation is one of the strategic decisions of the electricity industry in many countries [1]. Rapid demand growth, limited fossil energy resources, and related environmental pollutants have led to a focus on energy sustainable technologies [2]. Fuel cells with high efficiency, reliable and stable production are suitable technologies for distributed electricity generation globally. This technology will reduce fuel consumption and environmental pollutants. It also shifts consumption from pollutant fuels such as coal to green fuels such as natural gas or hydrogen.

The studies of many companies focus on the market development of polymer fuel cells. This type of fuel cell is the most commercial, especially in the automotive industry [3]. Solid oxide fuel cell technology has high energy efficiency and a completely solid structure [4]. This cell has higher efficiency, higher operating temperature, and a longer lifetime than polymer cell. The high operating temperature of this cell (between 650 to 1000 ºC) [5] can produce hydrogen by fuel reforming and therefore can use a wide range of fuels, especially natural gas [6]. Also, the operating temperature of the solid oxide fuel cell has led to the possibility of using it in the cogeneration of heat and power systems [7]. The new type of solid oxide fuel cells produced has an operating temperature of 650 to 700 ºC, which leads to a sharp reduction in production costs and makes this technology more economical [8].

In this research, a tubular solid oxide fuel cell stack with an internal reformer of Solid Power Company has been used and considering a 15 kW solid oxide fuel cell system based on the arrangement of 10 stacks of 1.5 kW commercial products introduced by this company. Simulation and thermodynamic analysis (energy and exergy) are performed using Tempo cycle [9]. The capabilities of this system in the heat and power supply of a building in Iran are analyzed.

2. Thermodynamic simulation

2.1. Cycle description

A schematic of the cogeneration system is presented in Figure 1. The fuel enters the system from point 1. Then it is sent to the reformer by a blower to be mixed with a part of the re-circulated stream from the output of the fuel cell anode (stream 5) and enters the fuel cell anode as stream 3. The output current from the fuel cell anode contains hydrogen, fuel, and water and is capable of chemical reaction or combustion. Air enters in the cycle from stream 7 and after passing through a blower, and a preheating step through stream 9 enters the cathode of the cell. At the cathode, some of the oxygen contributes to the electrochemical reaction.

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The dilute anode and cathode streams are burned in the combustion chamber, and the hot gases provide the energy required for the air pre-heater and hot water boiler. The exhaust gases are sent out of the engine room through the chimney.

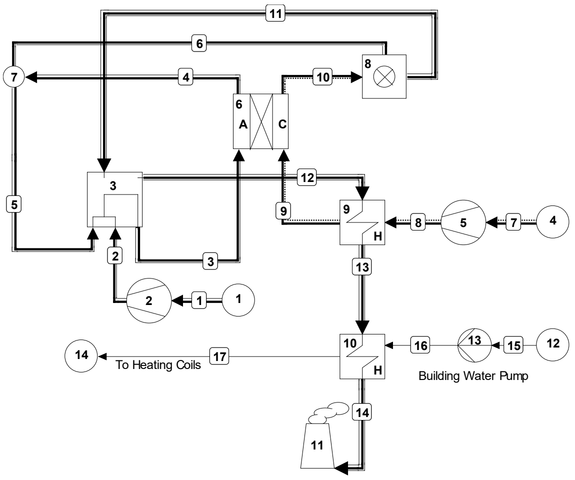

Figure 1. Schematic of cogeneration heat and power system based on solid oxide fuel cell for building applications

2.2. Simulation

In a solid oxide fuel cell, the chemical energy of the fuel is converted directly into electrical energy. A steady-state thermodynamic model has been developed to simulate the system, and the mass, energy, and electrochemical relations have been solved simultaneously. In the reformer and the fuel cell with the internal reformer, the two reactions of fuel reforming and water-gas shifting are performed simultaneously, and the required hydrogen of the fuel cell is supplied. The heat required for these reactions is provided by the fuel cell. The reaction rate is based on the equilibrium constant. The electrochemical reaction is performed in the fuel cell according to Equation (1), and direct current electricity is generated, which can be converted to alternating current electricity by an inverter. The fuel cell voltage is obtained using Equation (2), where E_{re} is the reversible voltage of the fuel cell and is obtained according to the Nernst equation [10]. The system's electrical efficiency is calculated based on the ratio of electrical power generated by the fuel cell to the energy of the input fuel. The system's overall efficiency is calculated according to Equation (3), and heat to power ratio (Equation 4) in cogeneration cycles indicates the ability to use these systems in different climates or a guide to selecting the size of the facility in different climates. The exergy destruction in the equipments and the exergetic efficiency are also obtained using equations (5) and (6).

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{1}$$

$$V_{cell} = E_{re} - R_{cell} * I \tag{2}$$

$$\eta_{total} = \frac{\dot{W}_{ele} + \dot{Q}}{\dot{E}_{fuel,in}} \tag{3}$$

$$HPR = \frac{\dot{Q}}{\dot{W}_{ele}} \tag{4}$$

$$\dot{Ex}_D = \sum_j \dot{Q}_j\left(1 - \frac{T_0}{T_j}\right) - \dot{W} + \sum_i (\dot{Ex}_i)_{in} - \sum_i (\dot{Ex}_i)_{out} \tag{5}$$

$$EPC_{cycle} = \left(1 - \frac{\dot{E}_{X_{D,total}}}{\dot{E}_{X_{fuel,in}}}\right) * 100 \tag{6}$$

3. Results and discussion

3.1. Simulation results

The most important performance characteristics of the cycle are presented in Table 1, and the results show 58.5% electrical efficiency and 77.3% overall efficiency at the design point. Due to the high electrical efficiency of this system, the advantages of this system for electricity generation are quite clear. The system's overall efficiency reaches more than 77% with heat production, which shows many advantages in the simultaneous production of heat and electricity power. Considering the higher proportion of electrical power and mentioning that the leading refrigeration equipment and facilities in Iran are consumers of electricity, so it can be recommended to use this system for warm and warm/moderate climates of the country and combine it with the current building air conditioning system. Due to the climatic conditions of Iran, many parts of the country can use this system. It is necessary to use an auxiliary system to provide heat shortage to use this system in cold regions.

Table 1. Cycle operational results (design condition)

Parameter	Simulation result
Cell voltage (V)	0.8
DC electric power (kW)	15.03
Net AC electric power (kW)	14.00
Thermal power (kW)	4.52
Electrical efficiency (%)	58.5
Total efficiency (%)	77.3
Anode recirculation fraction (%)	65.50
Heat to Power ratio (HPR) (%)	32.29
Annual electricity production (kWh)	93820
Specific CO2 production (gr.kWh-1)	346.1

The generated electricity is assumed to be a capacity factor of 85% and a function factor of 90%. This comparison shows the priority of this system in generating electric power compared to other commercial technologies in areas that need a lower heat to power ratio. Gas engine systems or micro turbines have a high potential for heat supply due to lower electrical efficiency and compensate poor electrical efficiency with heat supply. The emission production rate of this power plant is 346.1 g.kWh^{-1} that in comparing with the emission rate of coal-fired power plants (915 g.kWh^{-1}), natural gas power plants (549 g.kWh^{-1}), and combined cycle power plants (436 g.kWh^{-1}) [11] shows 62%, 37%, and 21% emission reduction respectively. These results show the high capability of this system in complying with environmental requirements and laws.

The results of exergy analysis are reported in Table 2. The fuel cell has the most exergy losses due to electrochemical reactions, followed by the heat exchanger (due to temperature difference and heat transfer irreversibility) and the combustion chamber. The cycle exergetic efficiency is 56.5%, which is less than the cycle energy efficiency but still shows high efficiency.

Table 2. Exergy analysis results

Parameter	Value (kWh)	Share (%)
SOFC exergy loss	16.77	72.7
Heat exchanger exergy loss	2.45	10.6
Combustion chamber exergy loss	1.73	7.5
Reformer exergy loss	1.39	6.0
Stack stream exergy loss	0.72	3.1
Exergetic cycle efficiency (%)	56.5	

3.2. Parametric study

Operating conditions are different from design conditions. Therefore, the following parametric analysis has been considered to find suitable operating points. The input energy, cycle net power, thermal power, and heat to power ratio trends are presented based on fuel utilization factor and current density variation in figures 2 and 3.

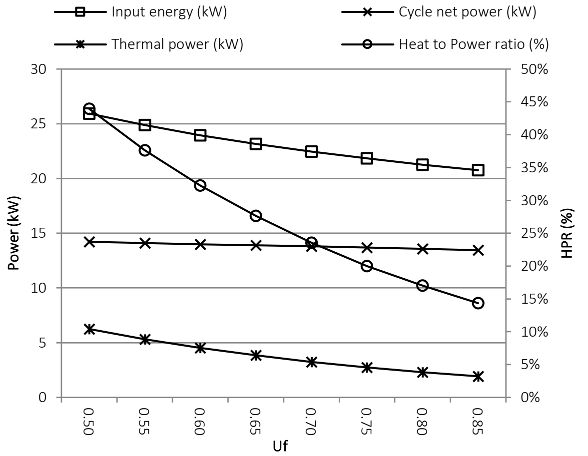

Figure 2. The cycle characteristic trends based on fuel utilization factor variation

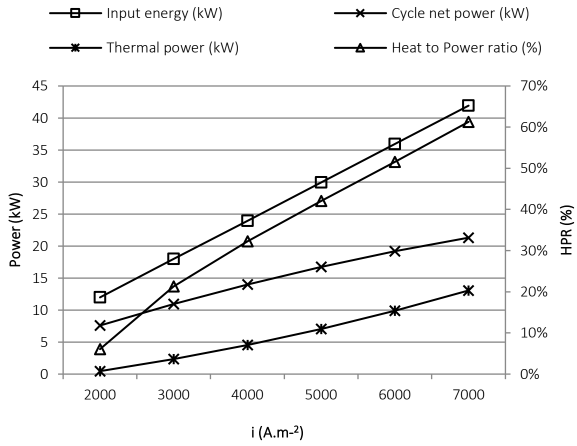

Figure 3. The cycle characteristic trends based on current density variation

The parametric analysis shows the adaptation of this system for electricity and heat demand in climates with heat to power ratio of 6 to 61%. Due to their higher electrical and lower thermal requirements, these climates will be warm, warm/moderate climates.

4. Conclusion

Thermodynamic simulation of cogeneration heat and power cycle based on solid oxide fuel cell shows that this system has a high capability to supply heat and electrical power to the building. With a net output power of 14.00 kW, this cycle can generate 93820 kWh of electricity per year. At a thermal power to electrical power ratio of 32%, this cycle can deliver 2,073 liters of hot water from 25 ° C to 70 ° C daily. The amount of hot water produced in the heat to power ratio equal 61%, reaches 6000 liters per day. Achieving electrical efficiency of 58.5% and overall efficiency of 77.3%, along with environmental benefits and the ability to use natural gas as fuel, are the main advantages of this system compared to other cogeneration systems. Due to the different geographical climates of Iran, the changes in buildings electrical and thermal energy demand can be adjusted with the cycle, and using this system in warm, warm/ moderate climates is recommended.

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