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Thermodynamic Modeling of the Multi-Generation Cycle of Power, Cooling and Fresh Water Using the Basic Cycle of Solid Oxide Fuel Cell

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Abstract

This study presents a multi-generation system with solid oxide fuel cell, Brayton modular helium, reverse osmosis desalination, Stirling engine and cascaded absorption-condensation refrigeration. In this way, the system performance was examined from the perspective of the first and second laws of thermodynamics. The proposed cycle was also subjected to exergoeconomic analysis. At the end, in order to understand the behavior of the performance criteria of the system with the design parameters, a comprehensive parametric study has been conducted. The results show that the proposed cogeneration system can produce 9.705 MW of net power, 8.45 kg/s of fresh water and 68.79kW of cooling. Also, the energy and exergy efficiency of the whole production system at the same time have been calculated as 55.02 and 49.82%, respectively. Also, the component's investment cost rate is 105.7 $/kWh.

Keywords:

Solid oxide fuel cell, Brayton modular helium, Stirling engine, Reverse osmosis desalination

1. Introduction

solid oxide fuel cells (SOFC) are vibration-free due to the absence of moving parts, which eliminates noise pollution caused by power generation. Ranjbar et al. [1] implemented waste heat recovery for a solid oxide fuel cell using a branch refrigeration cycle and a heat generation unit. They observed that the exergy efficiency decreased with current density, and the highest exergy efficiency was calculated to be 47%. The potential of using a SOFC coupled with a simultaneous cooling/heating unit for a famous building in China was investigated by Wang et al. [2]. Sadat et al. [3] recovered the waste heat of a SOFC using a heating unit and an ejector cooling cycle. They estimated the overall exergy efficiency to be 33.9%.

In recent years, among gas-cooled high-temperature nuclear reactors, the modular gas turbine helium reactor (GT-MHR) has attracted attention due to its promising features such as good safety, improved economics, and high durability. Van den Brambusche et al. [4] presented the aerodynamic design and performance constraints of a 600 MW multistage helium turbine for a high-temperature nuclear reactor closed-cycle gas turbine. Zhao and Peterson [5] predicted the performance of helium-Brayton cycles with multiple heating and cooling modes for SFRs with reactor outlet temperatures in the range of 510–650 °C. Recently, Dardora et al. [6] presented a sequence of steps that led to the development of physical and mathematical models that allowed the calculation of the costs of modular helium desalination in Brayton, which provided free thermal energy. Water is one of the most abundant resources on earth. Nowadays, freshwater supply has become an important issue in different regions of the world [7]. Among the widely used technologies, reverse osmosis is considered the most efficient system for desalination of brackish water with a much higher second-law efficiency than other desalination processes [8]. Delgado-Torres et al. [9] used a parabolic trough solar collector to capture solar energy as fuel to drive the organic Rankine cycle to provide the power required for a reverse osmosis desalination unit. Li et al. [10] used a supercritical organic Rankine cycle to drive a reverse osmosis desalination unit that can be used for various low-temperature heat sources (solar, geothermal, waste heat, etc.).

2. System description

In Figure 1, which is an outline of the proposed process, Methane fuel enters at stream 5 and H_2O enters at stream 8, and then these streams are pressurized at points 6 and 9, respectively. They are then heated and mixed, and the mixture is transferred to the SOFC anode (stream 11). stream 3 is transferred to the cathode of the SOFC. Then, CO_2, CO, H_2O, and H_2 are discharged from the anode (stream 12). This stream is used to the steam generator to drive the modular helium-Brayton cycle. In the modular helium-Brayton cycle, the cooling helium is heated in the reactor core before entering the power conversion unit as it flows downward through cooling channels in the graphite fuel elements. A Stirling engine is then used to power the reverse osmosis desalination plant. When heat is transferred to the engine's working fluid, helium, changes are made in the temperature, pressure, and volume of the fluid. Next, the power generated by the Stirling engine is applied to the reverse osmosis desalination unit. In the next step, a cascade absorption-condensation refrigeration cycle is used with lithium bromide-water working fluid in the absorption cycle and R134a fluid in the compression cycle.

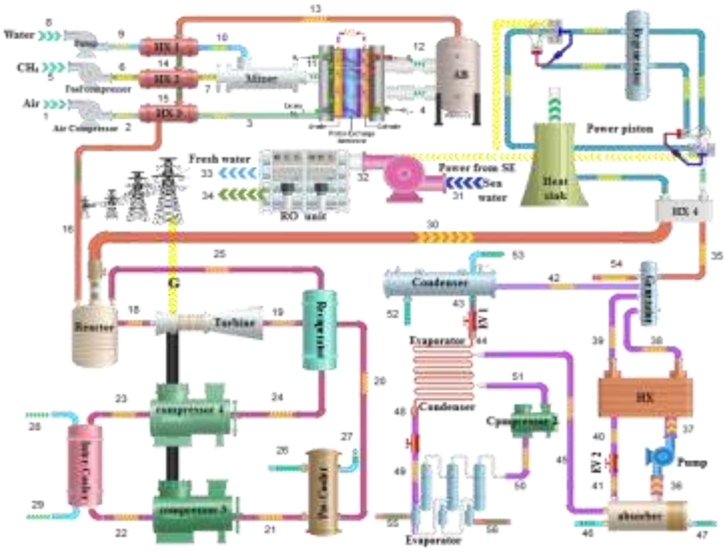


Figure 1- Schematic of the proposed multiple production system

3. Simulation of the proposed system

The following assumptions have been considered for the simulation of the proposed system:

-Analysis and investigation of all flows have been carried out in a steady state [11].

-In all assumptions, kinetic and potential energy have been neglected [11].

Table 1 shows the input parameters of the proposed system.

Table 1. Input parameters required for thermodynamic modeling [12-14]

	PARAMETERS	AMOUNT
2	Solid oxide fuel cell inlet temperature, (K)	973.15
3	Anode exchange current density fuel cell cycle, (A/m^2)	6500
4	Cathode current density exchange fuel cell cycle, (A/m^2)	3000
5	Heat capacity of hot and cold cylinder Stirling engine, (W/K)	1900
6	Hot and cold cylinder efficiency Stirling engine, (W/K)	75
8	Seawater salinity Reverse osmosis desalination, (ppm)	45000
9	Recovery ratio Reverse osmosis desalination, %	25
10	Element area Reverse osmosis desalination, (m^2)	34
11	Gas turbine inlet temperature Modular Helium Brayton, (K)	1023.15
12	Precooling and intercooling pressure difference Modular Helium Brayton, (kPa)	300

4. Energy and Exergy Analysis and performance parameters

In the steady state, the general form of the energy conservation equations is given below [11]:

$$\dot{Q}_k - \dot{W}_k = \sum \dot{m}_{out,k}\,(h_{out,k}) - \sum \dot{m}_{in,k}\,(h_{in,k}) \qquad (1)$$

In the above equation, $\dot{Q}_k$ and $\dot{W}_k$ represent the work produced and the heat transferred. The exergy conservation equation for the kth component of the system is shown as follows [11]:

$$\dot{E}x_{D,k} = \sum_{j}(1 - \frac{T_0}{T_{j,k}})\,\dot{Q}_{j,k} - \dot{W}_{cw,k} + \sum_{i}\dot{E}x_{inlet,k} - \sum_{e}\dot{E}x_{outlet,k} \tag{2}$$

In the above equation, $\dot{E}x_{D,k}$ is the destruction exergy, and $\dot{E}x_{inlet,k}$ and $\dot{E}x_{outlet,k}$ are the input and output exergy. The important parameter is the net power generated:

$$\dot{W}_{net} = \dot{W}_{Brayton\ modular\ helium} + \dot{W}_{Stirling\ engine} + \dot{W}_{SOFC} \tag{3}$$

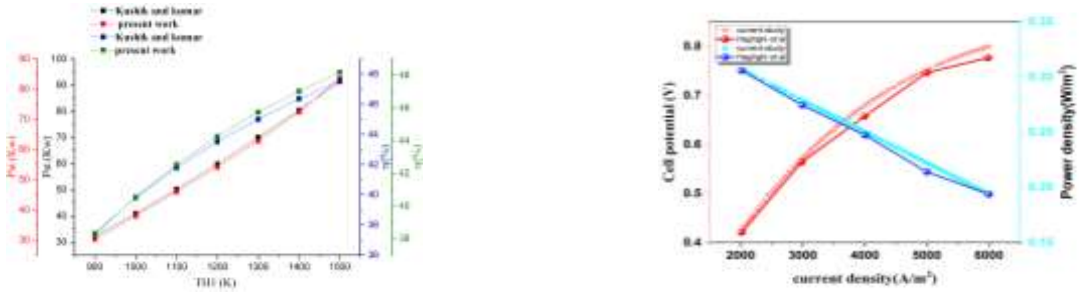
The first and second law efficiencies for the proposed system can be defined in terms of the following relationships:

$$\eta_{energetic} = \frac{\dot{W}_{net} + \dot{Q}_{Cooling} + \dot{m}_{freshwater} \times h_{fg,fw}}{\dot{m}_{CH_4,5} LHV_{CH_4}} \times 100 \tag{4}$$

$$\eta_{exergetic} = \frac{\dot{W}_{net} + \dot{E}_{33} + \dot{E}_{pr,evaporator\ 2}}{\dot{m}_{CH_4,5}\ \overline{ex}_{CH_4}^{ch,o}} \times 100 \tag{5}$$

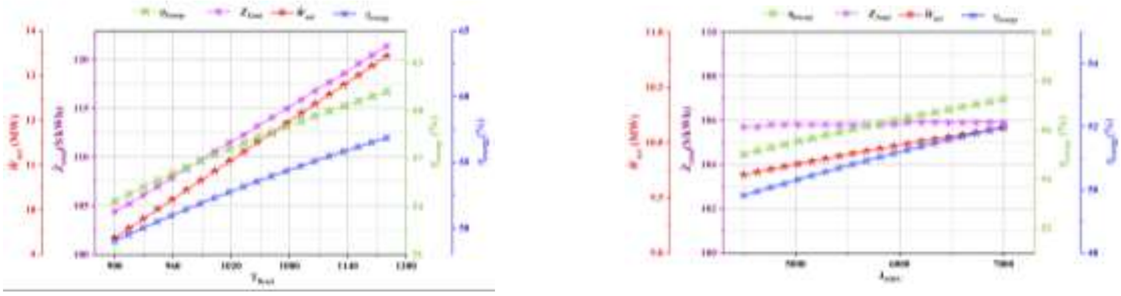
5. Results and Discussion

In order to evaluate the feasibility of the proposed system, the SOFC based on [15] and the Stirling engine based on [16] are validated as shown in Figures 3(a) and 3(b).



a b

Figure 2 - Validation of the Stirling engine cycle (a) and the SOFC cycle (b)



a b

Figure 3 - The effect of increasing the inlet temperature of the modular helium Brayton cycle (a) and J_{SOFC} on the system performance parameters (b)

5.1. Parametric study

According to Figure 3(a), increasing the turbine inlet temperature in the Brayton helium modular cycle has caused the turbine work and consequently the total net power produced by the proposed cycle to increase. The increase in power has a direct impact on the energy efficiency as well as the exergy efficiency of the system and both have increased in an upward direction. From an economic point of view, the value of Z_{total} has increased due to the increase in the net output power. In Figure 3(b), the impact of J_{SOFC} on the performance criteria under study is evaluated. This parameter affects the molar flow rate of the fuel (CH_4) input and the output voltage of each solid oxide fuel cell. In addition, the output enthalpy rate of the fuel cell increases. Accordingly, according to Figure 3, the amounts of products increase. According to the figure, the amount of work produced has increased from 9.705 to 10.13 MW.

According to the figure, due to the growth of the output products, the energy and exergy efficiency have increased. From an economic point of view, the value of $\dot{Z}_{total}$ has increased due to the increase in the net output power.

Conclusions

In this study, a novel hybrid system including SOFC, modular helium Brayton, Stirling engine, cascade absorption-condensation refrigeration and reverse osmosis desalination was investigated for the simultaneous production of power, cooling and fresh water. The summary of the important results obtained from the simulation is as follows:

- Increasing the inlet temperature to the turbine in the modular helium Brayton cycle has increased the total net power produced by the proposed cycle.
- By increasing the J_{SOFC} effect, the amount of work produced has increased.

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