Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 49(1) (2017) 75-77
DOI: 10.22060/mej.2016.740

A New Electrical Power and Cooling Cogeneration Cycle Based on a Solid Oxide Fuel Cell

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ABSTRACT: A new electrical power and cooling cogeneration system is proposed and analyzed. The proposed system is a combination of a Solid Oxide Fuel Cell (SOFC)-gas turbine for generating electrical power and a Generator-Absorber-heat eXchange (GAX) absorption refrigeration cycle for cooling. Using the Engineering Equations Solver (EES) software, the system is modeled by means of solving mass and energy balance equations for each system component and electrochemical equations for the SOFC. The obtained results show that the combined system thermal efficiency is 37.26% higher than that of the stand-alone SOFC-gas turbine system. It is also concluded that an increase in the current density leads to an increase in the net electrical output power, produced cooling and inlet fuel flow rate so that the thermal efficiency increases. The thermal efficiency however, is minimized at a special value of fuel cell operating temperature.

Review History:

Received: 30 July 2015
Revised: 25 November 2015
Accepted: 24 January 2016
Available Online: 8 November 2016

Keywords:

Solid oxide fuel cell
Absorption refrigeration cycle
Combined cooling and power production

1- Introduction

Fuel cell technology has attracted interest of researchers due to its many advantages, such as capability of off-grid energy generation and having high efficiency as well as low environmental pollution [1]. SOFC operating temperature, among different types of fuel cells, is the highest so that this fuel cell can be used in large power plants and various combined cycles. Several studies show that the combined SOFC-gas turbine cogeneration systems achieve an overall efficiency of 70% or even higher [1-3].

Considering previous studies, there is a lack of information on the SOFC-absorption refrigeration systems. In the present work, a SOFC-gas turbine cycle is combined with a GAX absorption refrigeration system to cogenerate electrical power and cooling.

2- Methodology

The proposed combined system is shown in Fig. 1. The main part of this system is the solid oxide fuel cell in which the electrochemical reaction $H_2+0.5O_2 \rightarrow H_2O$ takes place. Following assumptions are considered for the system modeling [2, 4]:

- The system operates under steady state condition.
- Kinetic and potential energy changes are neglected.
- SOFC-gas turbine cycle components are adiabatic.
- All gases in the SOFC-gas turbine cycle are ideal gases.
- Anode and cathode outlet temperatures are the same.
- There is no frictional pressure drop in the GAX cycle.

Mass and energy balance equations are applied to each system component as a control volume.

$$\sum_{i,k} \dot{m}_i - \sum_{e,k} \dot{m}_e = 0 \quad (1)$$

$$\dot{Q}_k - \dot{W}_k + \sum_{i,k} \dot{m}_i h_i - \sum_{e,k} \dot{m}_e h_e = 0 \quad (2)$$

The fuel cell ideal voltage is calculated using the Nernst equation [1]:

$$V_{Nernst} = \frac{-\Delta \bar{g}_f^0}{2F} + \frac{\bar{R} T_{cell}}{2F} \ln\left(\frac{P_{H_2}\sqrt{P_{O_2}}}{P_{H_2O}}\right) \quad (3)$$

The SOFC voltage however, is lower than the Nernst voltage due to irreversibilities occurring in the stack.

Ohmic overvoltage occurs because of the resistances of electrodes and electrolyte in ion and electrons flows and is calculated by the Ohm law [1, 3]:

$$\begin{aligned} V_{Ohm} = i[&1.7842\times10^{-7} exp(600/T_{cell}) + \\ &2.98\times10^{-9} exp(-1392/T_{cell}) + \\ &1.176\times10^{-9} exp(10350/T_{cell}) + \\ &1.02\times10^{-7} exp(4690/T_{cell})] \end{aligned} \quad (4)$$

All reactions, even exothermic ones, need some energy named as activation energy to initiate. A part of the produced voltage is consumed to overcome the electrochemical reaction activation energy barrier. This voltage loss which is named as activation overvoltage is calculated using the Butler-Volmer equation [2]:

$$V_{act} = \frac{\bar{R} T_{cell}}{F}\left[\sinh^{-1}\left(\frac{i}{2i_0^a}\right) + \sinh^{-1}\left(\frac{i}{2i_0^c}\right)\right] \quad (5)$$

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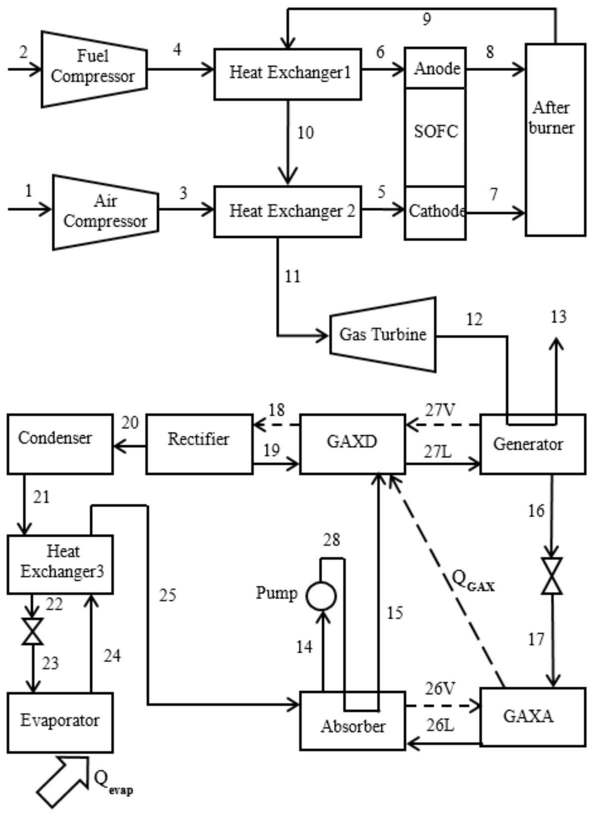

Figure 1. Schematic figure of the power/cooling cogeneration system

$$i_0^a = 7\times10^9\left(\frac{P_{H_2}}{P_0}\right)\left(\frac{P_{H_2O}}{P_0}\right)\exp\left(\frac{-110000}{\bar{R}T_{cell}}\right) \quad (6)$$

$$i_0^c = 7\times10^9\left(\frac{P_{O_2}}{P_0}\right)^{0.25}\exp\left(\frac{-155000}{\bar{R}T_{cell}}\right) \quad (7)$$

Concentration overvoltage is [2, 3]:

$$V_{con} = \frac{\bar{R}T_{cell}}{2F}\left[\ln\left(\frac{1-{i}/{i_{L,H_2}}}{1+{i}/{i_{L,H_2O}}}\right)+\ln\left(\frac{1}{1-{i}/{i_{L,O_2}}}\right)\right] \quad (8)$$

$$i_{L,k} = \frac{2FD_{eff,k}}{\bar{R}T_{cell}\delta_k}P_k \quad (9)$$

Real output voltage is calculated by subtracting the overvoltages from the Nernst voltage:

$$V_{cell} = V_{Nernst} - \left(V_{ohm} + V_{act} + V_{con}\right) \quad (10)$$

The amount of hydrogen consumed in the reaction depends on the current density and can be calculated using the Faraday's law:

$$\dot{z} = \frac{i\,A\,N}{2F} \quad (11)$$

The entering hydrogen and oxygen molar flow rates are calculated using fuel and air utilization factors, respectively:

$$\dot{n}_{i,H_2} = \frac{i\,A\,N}{2u_f\,F} \quad (12)$$

$$\dot{n}_{i,O_2} = \frac{i\,A\,N}{4u_a\,F} \quad (13)$$

The fuel cell electrical power is the density multiplied by the output voltage:

$$\dot{W}_{SOFC} = i\,A\,NV_{cell} \quad (14)$$

The net electrical output power, the amount of produced cooling and thermal efficiency are used to assess the cogeneration cycle performance:

$$\dot{W}_{net} = \dot{W}_{SOFC} + \dot{W}_{GT} - \dot{W}_{AC} - \dot{W}_{FC} - \dot{W}_{P} \quad (15)$$

$$\dot{Q}_{evap} = \dot{m}_{23}\left(h_{24} - h_{23}\right) \quad (16)$$

$$\eta_{th} = \frac{\dot{W}_{net} + \dot{Q}_{evap}}{\dot{n}_f\,LHV} \quad (17)$$

3- Results

The results obtained for the cogeneration system are compared with those of the stand-alone SOFC-gas turbine system in Table 1. Referring to Table 1, the thermal efficiency of combined system is 37.26% higher than that of the stand-alone SOFC-gas turbine system, due to the considerable cooling produced in the evaporator.

Table 1. Thermodynamic simulation results

Parameter	SOFC-gas turbine	SOFC-gas turbine-GAX
η_{th}	47.33 %	84.59 %
$\dot{W}_{net}$(kW)	110.3	109.9
$\dot{Q}_{evap}$(kW)	-	87.19
V_{cell}(V)	0.78	0.78

i=1000 A/m^2, T_{cell}=1073 K, r_p=4, u_a=0.15, u_f=0.8

Fig. 2 shows the variation in thermal efficiency of the proposed system as the fuel cell operating temperature changes. As indicated in this figure, the thermal efficiency is minimized at a special value of Tcell. It is also observed that a higher thermal efficiency is obtained for a higher value of current density. The rate of increase is higher for lower values of fuel cell temperature.

4- Conclusions

In this paper, based on a solid oxide fuel cell, a new electrical power and cooling cogeneration system is proposed and analyzed. Simultaneous solution to the equations of mass and energy balance for system components and of the electrochemical equations for the SOFC reveals that the efficiency of combined solid oxide fuel cell- gas turbine-GAX system is 37.26% higher than that of the stand-alone fuel cell system. It is also observed that an increase in the current density makes the thermal efficiency to increase. A change in fuel cell operating temperature however, causes the thermal efficiency to minimize at a special value of the fuel cell operating temperature.

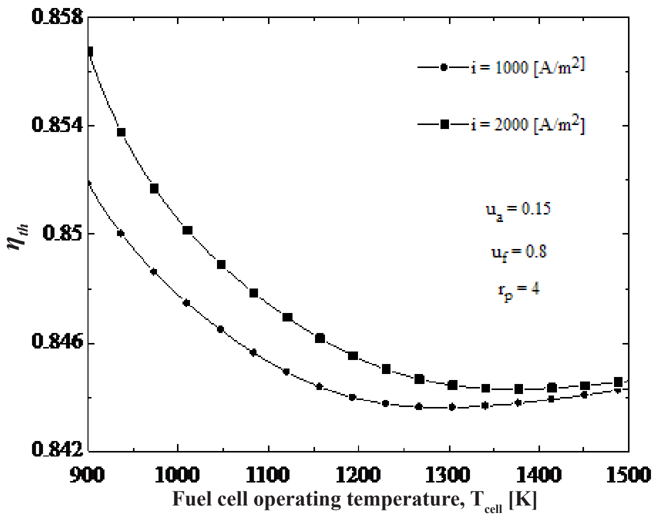

Figure 2. Variation of thermal efficiency with fuel cell operating temperature at two current densities

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Please cite this article using:

L. Khani and S. M. S. Mahmoudi, "A New Electrical Power and Cooling Cogeneration Cycle Based on a Solid Oxide Fuel Cell", *Amirkabir J. Mech. Eng.*, 49(1) (2017) 231-237.

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