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Parametric analysis of the exergoeconomic variables of a solid oxide fuel cell (SOFC) coupled with a vapour-adsorption refrigeration system (VARS)



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ABSTRACT

This paper aims at performing a parametric analysis of the thermoeconomics costs associated with an integrated solid oxide fuel cell (SOFC) system with a vapour-adsorption refrigeration (VAR) system. Particular emphasis is put on the cost of the SOFC's product (i.e. the electrical energy) and on the cost of the VAR's product (i.e. the cooling effect). In order to do so, an hybrid system simulator was constructed to determine the influence of SOFC operating parameters: current density, inlet flow temperature, fuel utilization factor and steam to carbon ratio, on the exergy-based costs of the products as well as on the exergoeconomic factors. Results of the analysis show that an energy-based costing can lead to overvaluing the cost of an energy asset. Furthermore, the minimum exergy-based unit cost of electricity is 14 \$/GJ and of cooling is 16 \$/GJ. The exergoeconomic factor of the VAR systems is the most affected by the operating variables. From this study, it is concluded that production of cold is not highly cost-effective under the operating conditions studied herein.

1. Introduction

The overexploitation of fossil fuels and use of highly energy-inefficient systems has created global awareness on energy savings and use of other alternative technologies to generate energy assets. This growing awareness has guided researchers to new technologies to generate energy assets and use methods based on thermodynamic approaches, particularly on the exergy concept, for designing and improving energy consuming systems [1-3]. In this context, thermoeconomics is one of the most used and accepted methods to design and evaluate new power generation technologies based mainly on integrated systems [4–8], since it allows understanding the cost formation process within a power system and so reduce the cost of the power plant product. In this regard, the solid oxide fuel cell (SOFC) is a promising device to be used in power generation because of its fuel flexibility, high efficient energy conversion and high operating temperature [9] as well as it can be combined with other energy conversion technologies or power cycles such as gas turbines [10-12], refrigeration systems [13-15], gasification devices [16-18], rankine cycles [19-21], solar technologies [22-24] and even used in trigeneration systems [25-27].

As reported in the literature, several works show the results of

important findings on SOFC integrated systems. For example, Casas et al. [28] conducted a detailed exergoeconomic evaluation of an ethanol-fueled SOFC system. Their findings were that a reduction in the investment cost as well as in the exergy destruction within the SOFC stack may reduce the total production cost, the total investment costs and the exergy destruction cost by about 18%, 73% and 19%, respectively, whereas the electricity cost by about 21%. They concluded that the electricity cost using ethanol as feedstock can be roughly 0.04 US \$/kWh, which is comparable and competitive with natural gas using SOFC technology. Rokni [29], performed a thermoeconomic analysis considering a system integrated by a biomass gasification system, an SOFC and a stirling engine. He determined that the production price of electricity was about 0.1204 US\$/kWh and the cost of hot water as a by-product was 0.0214 US\$/kWh. Gandiglio et al. [30] applied a thermoeconomic analysis to a GT-SOFC integrated power plant. They concluded that a pressurized SOFC performed better than an atmospheric one based on an exergy destroyed reduction of about 20%. They reported a total cost of electricity at pressurized conditions of 47.71 US \$/MWh, whereas for atmospheric conditions the cost was as high as 64.19 US\$/MWh.

Likewise, a thermoeconomic comparison between a methanol and

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kerosene-fueled SOFC-GT power plant was proposed by Santin et al. [31]. In this case, the methanol fueled system showed lower efficiencies but was good from an economic standpoint, in comparison with a methane-fueled reference case. Whereas the kerosene fuel system turned out to be the worst with lower efficiencies and poor economic performance.

Chitsaz et al [32] performed an exergoeconomic analysis of trigeneration system focusing mainly on the effects of three SOFC parameters: current density, inlet flow temperature and fuel utilization factor on the unit cost of the electrical power, cooling and heating. The study determines that the maximum cost of the products is 34.2 \$/GJ and the minimum cost is 26.5 \$/GJ. Later. Chitsaz et al. [33] studied the effect of both anode and cathode recycling on the thermodynamic and thermoeconomic performance of 4 different configurations of trigeneration systems. Their findings show that the global energy efficiency with anode gas recycle is closely 82.5%, which turned out to be 6% larger than a simple base case configuration (no recycling). Most importantly, they reveal that the configuration with anode and cathode recycling is the most efficient from an exergy and economic point of view. Akbari et al [34] propose a novel cogeneration power and refrigeration system using carbon dioxide as working fluid. The system is optimized in order to have either maximum first law efficiency or maximum second law efficiency or minimum total product unit cost. In this regard, Sadeghi et al [35], implemented an evolutionary algorithm to optimize a trigeneration system from a thermoeconomic point of view. The investigation shows that the optimal exergy efficiency and total product unit cost are 48.24% and 25.94 \$/GJ, respectively.

The review of the literature allows us to find out that in spite of the several studies on thermoeconomics performed on SOFC integrated systems thus far, a parametric analysis to determine the effect of operating variables, apart from current density, inlet temperature and fuel utilization ratio, such as the steam-to-carbon ratio on the exergy-based unit product cost and the exergoeconomic factors of a hybrid system is not performed yet. Accordingly, the present work aims at performing a steady-state parametric analysis of a hybrid system composed of a solid oxide fuel cell and a vapor-absorption refrigeration system from an exergoeconomic point of view. Besides, a comparison of the unit cost of the solid oxide fuel cell's product is performed from an energy and exergy point of view in order to evoke the meaning of the exergy-based costing.

2. Model description

The schematic flow diagram of the SOFC-VARS coupled system considered herein is depicted in Fig. 1. The energy system is integrated by an SOFC stack with internal reforming of feed gas at the anode side, an afterburner, a mixer, three pre-heaters and a DC/AC inverter. Anode and cathode exit streams are fed into the afterburner, the exhaust gas is then used to preheat the supply of fuel and the air. The high-grade heat yielded in the SOFC reaction is used to perform the reforming process. In order to improve the overall efficiency of the SOFC, the exhaust gas from the stack enters a LiBr-H₂O based vapor absorption refrigeration system (VARS) coupled to it. Table 1 presents the physical characteristics of an intermediate temperature, anode-supported planar SOFC as reported in [36]. The operating conditions of the SOFC stack considered as baseline data are given in Table 2.

The simplifications considered for constructing the SOFC and VARS models are, respectively:

(A) For the solid oxide fuel cell (SOFC):

- (1) Air consists of 79% N_2 and 21% O_2 .
- (2) All gases are considered as ideal gases.
- (3) Gas mixture at the fuel channel exit is at chemical equilibrium.
- (4) Fuel cell is completely insulated, so there is no heat interaction with the environment.
- (5) Contact resistances are negligible.

- (6) Temperature at the channel inlets is the same. Also, the temperature at the channel exit is the same.
- (7) Radiation heat transfer between gas channels and solid structure is negligible.
- (B) For the vapor absorption refrigeration system (VARS), as proposed in [37]:
 - (1) Water is considered as a refrigerant at states 20 and 23.
 - (2) States 14, 17 and 21 are considered as saturated liquid.
 - (3) Water is considered as saturated vapor at state 23.
 - (4) Pressure in generator and condenser are equivalent.
 - (5) Pressure in the evaporator and absorber are equivalent.

3. Mathematical models description

All of the results obtained in this study are obtained from an integrated model created in Engineering Equation Solver (EES). The general model includes mathematical equations regarding electrochemical, thermodynamic and exergoeconomic equations which support the simulations performed herein.

3.1. SOFC's electrochemical model

Modelling of the electrochemical part can be complicated as the study requires it and most of the current literature provide basic models developed under the zero-dimensional assumption [16,25,38]. The main idea of such modelling is to have mathematical equations that mimic the connection between the chemical energy of the fuel and the electrical power. So, the mechanisms of reaction involved are:

For the steam reforming reaction:

$$CH_4 + H_2O \rightarrow 3H_2 + CO \tag{1}$$

For the shifting reaction:

$$CO + H_2O \rightarrow H_2 + CO_2 \tag{2}$$

Thus the net electrochemical reaction of the fuel cell is given as:

$$H_2 + 1/2O_2 \rightarrow H_2O \tag{3}$$

Reforming and shifting reactions are carried out within the fuel cell stack, so the energy required for the reaction is directly supplied by the fuel cell as heat. The real velocity at which both chemical and electrochemical reactions are carried out are based on the following equilibrium reactions:

For the real reforming reaction;

$$X_{r}[CH_{4} + H_{2}O \rightarrow 3H_{2} + CO]$$
(4)

For the real shifting reaction:

$$Y_r[CO + H_2O \rightarrow H_2 + CO_2]$$
(5)

For the real net electrochemical reaction:

$$Z_r[H_2 + 1/2 \ O2 \rightarrow H_2O]$$
 (6)

where X_r , Y_r and Z_r represent the conversion ratios during the reactions. The equilibrium constants for the reforming and shifting reactions can be formulated as a function of the operating temperature:

$$Log_{10}K_{r,s} = A_{r,s}T^4 + B_{r,s}T^3 + C_{r,s}T^2 + D_{r,s}T + E_{r,s}$$
(7)

whereas constants are provided in Table 3 as suggested in [39].

The equilibrium constants can also be determined as a function of the molar fraction of each species as now described. For the reforming reaction:

$$Ln(K_r) = \frac{(\mathbf{y}^{CO}_{11})(\mathbf{y}_{11}^{H_23})}{(\mathbf{y}^{H_2O}_{11})(\mathbf{y}^{CH_4}_{11})} * \left[\frac{\mathbf{P}}{\mathbf{P}_0}\right]^2$$
(8)

For the shifting reaction:

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