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A comparative advanced exergy analysis for a solid oxide fuel cell using the engineering and modified hybrid methods

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ABSTRACT

A modified form of hybrid method for advanced exergy analysis is introduced and applied to an anode gas recirculation solid oxide fuel cell system. The results are compared with the corresponding values achieved from applying the well-known engineering method of advanced exergy analysis to the system. The modified hybrid method proved to be accurate and less time consuming and also, in contrast with the hybrid method introduced in literature, doesn't require the violation of the conservation of mass or exergy balance. In addition the modified hybrid method is more appropriate for parametric studies and optimization of energy conversion systems. The results obtained from both the advanced exergy methods are found to agree with one another and differ from those obtained from conventional exergy analysis. The values of endogenous and unavoidable endogenous exergy destruction rates for modified hybrid method are approximately 4% higher than the corresponding values obtained by the engineering method. The unavoidable conditions required for the analyses in both methods are obtained by a micro-structure analysis showing that the energy and exergy efficiencies of the system, under unavoidable conditions can be higher by up to 26%, 24.8%, respectively, compared to the corresponding values under the real conditions.

As the highest avoidable endogenous exergy destruction rates occur in the inverter, 6.6 kW, and the stack, 3.7 kW, more attention should be paid to these components when the system performance is to be optimized. A different order, however, is achieved by applying the conventional exergy analysis.

1. Introduction

One of the main goals for researchers in the field of energy is to design and develop modern energy converting systems with high efficiency and low environmental impact. In this regard, fuel cells are considered as a promising technology for power production as they convert gaseous fuels into electrical power and thermal energy directly by an electrochemical process. An excellent feature of these systems is their high efficiency which is not restricted to the Carnot cycle efficiency. Another aspect of fuel cell systems is their lower emissions including NOx or CO_2 compared to even the cleanest combustion processes [1]. The wide range of power production capacity is another characteristics of fuel cells making them look even more attractive [2]. Several types of fuel cells have attracted the attention of researches. Among these, the proton exchange membrane fuel cells [3] can be named. For this type of fuel cell experimental works [4] and also theoretical and simulation studies [5] have been carried out. In this regard, Kahraman and Orhan reported that an improvement on the micro-structural membrane electrode assembly (MEA) and gas diffusion layer (GDL) brings about a better performance for the PEMFCs [6]. Performance improvement is also reported by Zehtabiyan-Rezaie et al. investigate the effects of converging and diverging channels on the performance of proton exchange membrane fuel cells and reported that the net electrical output power can increase by 16% [7]. The solid oxide fuel cells (SOFCs), however, are well-known systems, which can be described as a solid-state device working on the basis of a solid oxide electrolyte [8]. The SOFCs are becoming prominent systems in energy sector, as in addition to the advantages mentioned before, they can use various fuels and have high-temperature exhaust gases so that they can be combined with different bottoming cycles [9]. Khani et al. [10] investigated the exergoeconomic evaluation of a new power/cooling cogeneration system, based on a solid oxide fuel cell.

Using conventional exergy analysis a lot of research works have been conducted on the SOFC systems. These works provide information about how much of input exergy is converted into useful form and how much of it is destructed or lost in the system component [11]. Gholamian and Zare [12] carried out a comparative energy and exergy analyses, employing organic Rankine and Kalina cycles for waste heat

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Nomenclature

B	diameter ratio of ions to electrons
$\bar{h}$	specific enthalpy
$\dot{E}$	exergy
$\bar{R}$	universal gas constant
$\dot{z}$	molar flow rate of reacted hydrogen
A_a	active surface area
d_c	neck diameter of the TPB
e	specific exergy
E_{act}	activation energy
F	Faraday's constant
G	Gibbs free energy
i	current density
K	equilibrium constant
L_{TPB}	three phase boundary length
n	number fraction
Nc	number of cells
N_t	number density of all particles
P	pressure/percolation probability
P_{ref}	ambient pressure
U_f	fuel utilization factor
U_a	air utilization factor
V_{act}	activation overvoltage
Vc	produced cell voltage
V_{cons}	concentration overvoltage
V_{loss}	voltage loss
V_N	Nernst cell voltage
V_{ohm}	ohmic overvoltage
$\dot{W}_{FC}$	fuel cell output power
$\dot{W}_{net}$	net output power
x	molar fraction
y	exergy destruction ratio
y^*	exergy destruction ratio
Z	coordination number
γ	pre-exponential coefficient
θ	contact angle,
ε	*porosity*
ε_k	*kth* exergy efficiency
η_{ex}	exergy efficiency
$\dot{n}$	mole flow rate
η_{th}	energy efficiency
τ	*tortuosity*

Subscripts

a	*anode*
c	*cathode*
ch	chemical
D	destruction
el	electronic
ex	exergy
F	fuel
io	ion
L	loss
P	product
ph	physical
ref	reference

Superscripts

AV	avoidable
EN	endogenous
EX	exogenous
UN	unavoidable
AV,EN	avoidable endogenous
AV,EX	avoidable exogenous
UN,EN	*u*navoidable endogenous
UN,EX	*u*navoidable exogenous

recovery from the hybrid SOFC/GT system. Acikkalp [13] investigated an irreversible hybrid solid oxide fuel cell (SOFC)/Brayton heat engine system and Taner [14] performed energy and exergy analyses of PEM fuel cells. The conventional exergy analysis, however, is not capable of determining the real contribution of each system component in the overall exergy destruction rate and the actual improvement potential for each system component. In this regard, the advanced exergy analysis described by Morosuk et al. [15] can be helpful. The technique is based on splitting the exergy destruction rate in a component into avoidable/unavoidable and also endogenous/exogenous parts. This type of analysis provides a more detailed information about the exergy destruction rate in each system component, so that the designer will know how to reduce the exergy destruction rate in the component [16]. Several methods have been introduced for advanced exergy analysis, each of which is more convenient for some particular energy converting systems. Kelly et al. [17] proposed several methods for systems in which a combustion process takes place. These methods include: engineering method, hybrid method consisting of mass and exergy balance methods, equivalent component method and structural theory method (algebraic approach) [17]. It has been reported that the engineering method, among the others, is more accurate [18]. In this method, in order to analyze an irreversible component such as combustion chamber, a hypothetical component i.e., a reversible adiabatic heater is considered as some part of the combustion chamber. Having applied this method, Kelly et al. [17] determined the exergy destruction rate sub-divisions for system components in a compression refrigeration, gas turbine and combined cycles. They also, compared the results obtained from the engineering method with those calculated by thermodynamic cycle method.

The engineering method was also applied by Soltani et al. [19], for an externally fired combined cycle power plant, using biofuel as an energy source. Fallah et al. [20] used this method for performing advanced exergy analysis on a steam injection gas turbine coupled with an evaporative inlet air cooler. The engineering method was also used by Fallah et al. [21] for the advanced exergy analysis of a solid oxide fuel cell.

The engineering method, however, is tedious and time-consuming. In addition, the results obtained from this method are highly dependent on the ranges of different variables selected by the designer. The hybrid method (thermodynamic cycle method), on the other hand, is simple and quick to accomplish but has its own problems, such as selecting some appropriate ideal conditions for combustion chamber. In this method the ideal conditions are estimated approximately, as under these conditions, the conservation of mass or energy is not satisfied for the combustion chamber. To overcome these shortcomings, in the present work, the hybrid method as reported in literature [15], is modified and used for advanced exergy analysis of an anode gas recirculation SOFC system combined with an afterburner. In the modified hybrid method, a hypothetical reversible heat exchanger, similar to that used in the engineering method, is utilized to eliminate the exergy destruction rate in the afterburner. The temperature at the exit of this heat exchanger is assumed in such a way that the exergy destruction rate in the afterburner is reduced to a possible lowest value. The results obtained from the proposed modified hybrid method are compared with those achieved by the engineering method. The comparison indicates the superiority of the proposed method over the engineering