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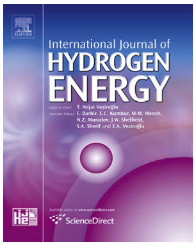

A unified model of high-temperature fuel-cell heat-engine hybrid systems and analyses of its optimum performances

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ABSTRACT

On the basis of the models of various developed high-temperature fuel-cell heat-engine hybrid systems, a unified model of hybrid systems is proposed. General expressions for the power output and efficiency of hybrid systems, high-temperature fuel cells such as solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs), and heat engines including the Brayton, Otto, Diesel, Atkinson, Braysson, and Carnot engines are, respectively, derived by using the theories of electrochemistry and non-equilibrium thermodynamics. The effects of main irreversible losses existing in real fuel cells and heat engines on the performance of hybrid systems are investigated. The general performance characteristics and optimal operating regions of some of the key parameters of hybrid systems are discussed in detail. A variety of special typical cases are discussed. The important results in the literature can be readily reproduced, and the interesting findings of our study are presented.

1. Introduction

In general, fuel cells can yield the highest efficiency and lowest emission for any known fossil-fueled power generation technology [1]. Consequently, they have received considerable attention in the world. Especially for high-temperature fuel cells, such as solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) [2,3], they boast advantages of coal and biomass gasification [1,4,5], fuel internal reforming [6,7], fuel flexibility [8,9], CO_2 capturing [10], high-quality heat coproduction [11], etc. However, high-temperature fuel cells face some market entry challenges, ranging from the cost to the durability [12–14]. Researchers are making an effort in the development of suitable materials and fabrication of SOFCs [15–17], so that SOFCs could be suitable for small-scale residential market applications at sufficiently low cost of $1000/kW [18]. A 3.5-kW SOFC cogeneration system for residential and commercial applications with an electrical efficiency of about 50% and overall efficiency of approximately 80% has been developed by Hydrovolt [19]. The cost of MCFCs is generally low in comparison with that of SOFCs when cheaper materials and inexpensive fabrication techniques are used.

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The power density of MCFC systems operating at 650 °C, however, is relatively low, and is approximately 1.5 kW m^{-2} [20]. It follows that MCFC will likely be commercialized at sizes greater than 100 kW, and such commercialization will certainly increase the cost. Hence a more appropriate strategy is to develop smaller MCFC systems for distributed combined heat and power (CHP) applications with a typical electrical power output between 250 kW and 1 MW [20]. The cost of fuel cell systems can be reduced not only by better-quality materials [21–23] but also by further-advanced technologies [24] that include the integration of high-temperature fuel cells with heat engines.

For purposes of low pollutant emission and high fuel economy, a hybrid system including fuel cells and Diesel or Otto engines was proposed in 1999 [25]. Since up to a half of the fuel energy of high-temperature fuel cells is waste heat, numerous investigators have carried out the research on high-temperature fuel-cell based hybrid systems in order to increase the overall efficiencies of fuel cells. Research activities are exemplified by (a) using high-temperature fuel cells as topping units within gas turbine cycles [26,27], (b) overcoming lower performances of high-temperature fuel cells than those of low-temperature ones by constructing fuel cell-Carnot heat engine hybrid systems [28], (c) recovering waste heat from the cell by the design of SOFC-Stirling or MCFC-Stirling hybrid systems [29], and (d) proposing a Brayton-cycle thermal-management system to reduce the hydrogen fuel flow for cooling [30]. High-temperature fuel-cell based hybrid systems also include CHP systems, combined cooling, heat, and power (CCHP) systems [31,32], SOFC-proton exchanger membrane fuel cell (PEMFC) systems [33], and fuel-cell and Rankine or Kalina cycle hybrid systems [34–36].

The integration of heat engines and fuel cells are capable of not only recovering energy from fuel-cell exhaust gases, but also generating extra power. The efficiencies of SOFC- or MCFC-based hybrid systems can attain up to 70%–90% [37]. By comparing the technologies of fuel cells and internal combustion engines in vehicles, the former enjoys simpler designs, higher reliabilities, noiseless operations, higher efficiencies, less environmental impact, and lower energy consumption [38–40]. However, fuel cells may not supply sufficient energy during peak power demand periods and transient events, and cannot save power and recycle braking energy, either. The optimal combination of the fuel cell, internal combustion engine, and electric energy storage and conversion devices is proposed. It is more flexible with its efficiency being less load-dependent than individual units un-combined [25,41,42].

In the present paper, the general performance characteristics of high-temperature fuel cells, heat engines, and their hybrid systems are described. The advantages of hybrid systems are demonstrated in numerical results, with contents organized as follows. In Section 2, a unified model of high-temperature fuel-cell heat-engine hybrid systems is established. The power output and efficiency of hybrid systems are derived. In Section 3, some general performance characteristics of hybrid systems are revealed and their parametric optimal criteria are determined. Many interesting cases are discussed in detail in Section 4. The performance characteristics of several developed hybrid systems are presented. Finally, some important conclusions are drawn.

2. A unified model of high-temperature fuel-cell heat-engine hybrid systems

A generic hybrid system primarily consists of a high-temperature fuel cell and a heat engine, as shown in Fig. 1 [28,29], where the high-temperature waste heat generated in the fuel cell is utilized as the heat input of the heat engine, the waste gases produced in the fuel cell are used to preheat the fuel and the oxidant through a heat exchanger, P_e and P_h are the power outputs of the fuel cell and the heat engine, respectively, q_1 and q_2 are the rates of heat flow from the fuel cell at temperature T to the working substance of the heat engine and from the working substance of the heat engine to the environment at temperature T_O, respectively, and q_l is the heat leak rate from the fuel cell to the environment. Below, we first introduce the developed models of high-temperature fuel cells and heat engines, and then establish a unified model of high-temperature fuel-cell heat-engine hybrid systems.

2.1. *Power output and efficiency of high-temperature fuel cells*

When studying the performance of high-temperature fuel cells, one has to consider the thermodynamic and electrochemical irreversibilities which result from the activation overpotential (η_{act}), ohm overpotential (η_{ohm}), and concentration overpotential (η_{con}) [43,44]. A general equation

$$\eta_{act} + \eta_{ohm} + \eta_{con} = f\left(\frac{i}{i_0}\right) + i\sum^{j}\rho_j\delta_j - \frac{RT}{n_eF}\ln\left(\frac{p_{H_2}p_{H_2O,b}p^{an}_{CO_2,b}p^{ca}_{CO_2}}{p_{H_2,b}p_{H_2O}p^{an}_{CO_2}p^{ca}_{CO_2,b}}\sqrt{\frac{p_{O_2}}{p_{O_2,b}}}\right) \tag{1}$$

can summarize the three overpotentials of high-temperature fuel cells based on the theoretical and experimental results, where i and i_0 are, respectively, the current density and the exchange current density, ρ_j and δ_j are the specific resistivity and the flowing length in layer j, respectively, R is the universal gas constant, n_e is the number of electrons transferred in reaction, F is Faraday's constant, $p_i(i = H_2, H_2O, O_2,\ldots)$ is the partial pressure of component i, and $p_{i,b}$ is the partial pressure of component i in bulk phase on the surface of electrodes.

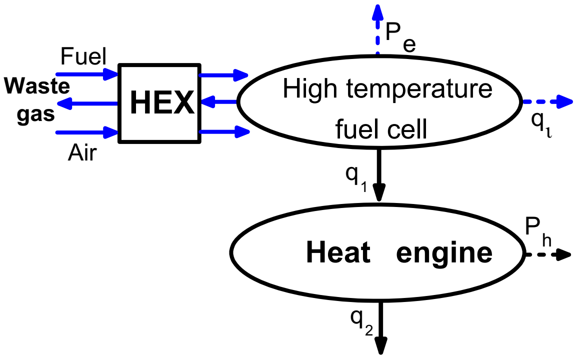

Fig. 1 – A schematic diagram of the unified model of high-temperature fuel-cell heat-enigne hybrid systems.