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Numerical study of an internal-reforming solid oxide fuel cell and adsorption chiller co-generation system

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Abstract

A study is conducted on a cogeneration system that incorporates a natural gas fed internal-reforming solid oxide fuel cell (IRSOFC) and a zeolite/water adsorption chiller (AC). The main aim is to investigate the performance of this combined system under different operating conditions and design parameters. A mathematical model is developed to simulate the combined system under steady-state conditions. The effects of fuel flow rate, fuel utilization factor, circulation ratio, mass of adsorbent and inlet air temperature on the performance are considered. The results show that the proposed IRSOFC-AC cogeneration system can achieve a total efficiency (combined electrical power and cooling power) of more than 77%. The electrical efficiency is found to decrease as the fuel flow rate increases, while the cooling power increases to a constant value. The total efficiency reaches a maximum value with variation of the fuel utilization factor. Both the circulation ratio and the inlet air temperature exert positive impacts on system efficiency.

Keywords: Solid oxide fuel cell; Adsorption cooling; Modelling; Cogeneration system; Internal reforming; Efficiency

1. Introduction

Solid oxide fuel cells (SOFCs) have been considered to be promising energy conversion technologies because they can provide a highly efficient rate of energy conversion with low pollutant emissions. The chemical energy of the fuel gas is converted directly to electricity in a SOFC, and hence it is expected that high electrical efficiencies can be achieved. The high operating temperature of SOFCs allows the use of cogeneration and hybrid systems. Gas–solid adsorption cooling systems are environmental-friendly compared with traditional CFC systems based on the vapour compression cycle as they employ safe and non-polluting refrigerants. Another advantage of adsorption cooling systems is that they can be driven by waste heat or solar energy. As a result, both SOFCs and adsorption cooling systems have attracted much research attention in the recent years.

Fuel cell cogeneration systems (FCCS) have been applied successfully in some developed countries. There have been increased interests in such systems because they can achieve higher efficiency in electricity production and a higher overall efficiency with a low level of adverse environmental impact. One type of fuel cell and absorption cogeneration system has been investigated by several researchers [1,2] to produce electrical power and cooling simultaneously. Because the gas–solid adsorption cooling system is more flexible in operation compared with the absorption cooling cycle [3], a combined fuel cell and adsorption cooling cogeneration system can be a promising alternative.

In this paper, an internal-reforming solid oxide fuel cell (IRSOC) and a zeolite/water adsorption chiller (AC) cogeneration system is proposed. A numerical model based on the first law of thermodynamics is developed to simulate this combined system under steady-state operating conditions. The main aim is to investigate the performance of the combined system under different operating conditions and parameters.

2. System description

A schematic of the proposed SOFC and adsorption chiller cogeneration system is shown in Fig. 1. The system incorporates

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Nomenclature

a	flow rate (kmol h^{-1})
E	cell voltage (V)
E_{re}	reversible cell voltage (V)
F	Faraday constant (96,487 C mol^{-1})
i	current density (mA cm^{-2})
i_0	exchange current density (mA cm^{-2})
I	current (A)
K_p	equilibrium constant
n	number of electrons participating in the reactions
p	pressure (bar)
Q	heat transfer rate (kJ h^{-1})
r_a	circulation ratio
R	universal gas constant (8.314 J mol^{-1} K^{-1})
T	temperature (K)
U_f	fuel utilization factor

Greek letters

β	transfer coefficient
δ	thickness (cm)
ΔH	enthalpy of formation (kJ mol^{-1})
η_{act}	activation over-potential (V)
η_{conc}	concentration over-potential (V)
η_{ohmic}	ohmic over-potential (V)
η_t	total efficiency

Subscripts

a	anode
c	cathode
r	reforming reaction
s	shifting reaction

Superscripts

f	fuel
i	inlet
o	outlet

a natural gas feed, an IRSOFC, an AC, a dc–ac inverter, and two heat exchangers. The system can produce electricity, cooling and heating simultaneously. Air is preheated at the heat exchanger before it enters the IRSOFC generator. Part of the exhaust fuel gas is recirculated and mixed with fresh fuel gas and the mixture re-enters the IRSOFC. Fuel gas and air flow through the anode and cathode, respectively. Fuel gas is internally reformed at the anode and hydrogen is produced. The electrochemical reaction occurs in the SOFC and electricity is generated together with heat. Subsequently, the non-recirculated portion of the effluent fuel gas and depleted air flow into a combustor. After reacting in the combustor, the fuel–air mixture enters heat exchanger 1 where the air is preheated. The combustion gases exiting from heat exchanger 1 then flows through the adsorption chiller to drive this cooling system during the heating process. Zeolite/water is used as the working pair for the adsorption chiller. Zeolite has satisfactory adsorption ability and its adsorption properties are also stable under high temperature. Finally, the gases from the adsorption chiller are passed through heat exchanger 2 for heat generation and then exhausted to the environment.

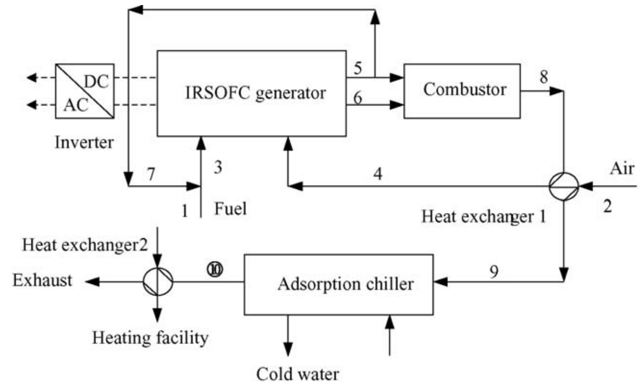

Fig. 1. Schematic of SOFC and adsorption chiller cogeneration system.

3. Numerical modelling

The numerical model consists of three parts: (i) internal reforming and electrochemical reaction model; (ii) SOFC model; (iii) adsorption cooling cycle model. The following assumptions are made: (i) equilibrium reforming and shifting reactions; (ii) the exit temperature of the cathode is equal to that of the anode; (iii) the SOFC and heat exchangers are in thermal balance; (iv) the burner efficiency is assumed to be 100%; (v) the mass of the adsorbent is proportional to the surface area of the adsorber; (vi) there is no heat loss in the cogeneration system.

3.1. Internal reforming and electrochemical reaction model

The recirculated anode exhaust fuel gas and the high-temperature conditions greatly assist the internal reforming and shifting reactions in a SOFC. The mechanisms for internal reforming and electrochemical reactions for the SOFC are commonly reported in the literature [4–7]. The reactions are:

reforming reaction:

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

shifting reaction:

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

electrochemical reaction:

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

where the reforming and shifting reactions are assumed to reach thermodynamic equilibrium with the respective equilibrium constants represented by:

$$K_{p,r} = \frac{p_{H_2}^3 \cdot p_{CO}}{p_{CH_4} \cdot p_{H_2O}}; \qquad K_{p,s} = \frac{p_{CO_2} \cdot p_{H_2}}{p_{CO} \cdot p_{H_2O}} \tag{4}$$