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A solid oxide fuel cell system for buildings

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Abstract

This paper examines an integrated solid oxide fuel cell (SOFC) absorption heating and cooling system used for buildings. The integrated system can provide heating/cooling and/or hot water for buildings while consuming natural gas. The aim of this study is to give an overall description of the system. The possibility of such an integrated system is discussed and the configuration of the system is described. A system model is presented, and a specific case study of the system, which consists of a pre-commercial SOFC system and a commercial LiBr absorption system, is performed. In the case study, the detailed configuration of an integrated system is given, and the heat and mass balance and system performance are obtained through numerical calculation. Based on the case study, some considerations with respect to system component selection, system configuration and design are discussed. Additionally, the economic and environmental issues of this specific system are evaluated briefly. The results show that the combined system demonstrates great advantages in both technical and environmental aspects. With the present development trends in solid oxide fuel cells and the commercial status of absorption heating and cooling systems, it is very likely that such a combined system will become increasingly feasible within the following decade.
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Keywords: Solid oxide fuel cell; Absorption heat pump; Heating; Cooling; Building

1. Introduction

Fuel cells are electrochemical devices that convert the chemical energy of a fuel directly into electrical energy. Fuel cells are a clean, quiet and efficient energy conversion technology and have been considered to be an advanced alternative to conventional combustion technologies for power generation. Fuel cells also may have high efficiencies even in small size units and are easy to site. Because of these features, fuel cells have recently been the focus of great interest as a distributed generation technology [1–4].

Solid oxide fuel cells (SOFCs) are one type of fuel cell and use ceramic materials as their electrodes and electrolyte. This allows SOFCs to work at high temperatures (up to 1300 K). Because of their high operating temperature, SOFCs are capable of incorporating internal fuel reformation, which allows multiple fuel options. Natural gas is one of the fuels that can be directly consumed by a SOFC system with an internal reformer [5,6]. SOFC systems also exhibit stable performance with a varying load [7–9]. The high temperature operation also makes SOFC systems less susceptible to fuel composition changes than low temperature systems. These features make SOFCs particularly suitable for distributed power generation and integration with other types of bottoming cycles such as gas turbine cycles and cogeneration [7,10–12].

A heat pump is an environmental energy technology that extracts heat from low temperature sources, upgrades it to a higher temperature and releases it for the required applications, such as space and water heating. Heat pumps can also be used in a reverse mode for cooling purposes, such as refrigeration and air conditioning. Heat pumps can be categorized into systems using vapor compression

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Nomenclature

$[CH_4]$	molar flow rate of methane ($mol\ s^{-1}$)
$[CO]$	molar flow rate of carbon monoxide ($mol\ s^{-1}$)
$[CO_2]$	molar flow rate of carbon dioxide ($mol\ s^{-1}$)
c_p	specific heat at constant pressure ($J\ mol^{-1}\ K^{-1}$)
COP	coefficient of performance
f	hydrogen flow rate at inlet of SOFC stack ($mol\ s^{-1}$)
h	enthalpy ($J\ mol^{-1}$)
Δh_e	combustion heat of hydrogen ($J\ mol^{-1}$)
Δh_{fuel}	combustion heat of natural gas fed into combined system ($J\ s^{-1}$)
Δh_{hc}	combustion heat of consumed hydrogen in SOFC bundle ($J\ s^{-1}$)
$[H_2]$	molar flow rate of hydrogen ($mol\ s^{-1}$)
$[H_2O]$	molar flow rate of steam ($mol\ s^{-1}$)
K	reaction equilibrium constant
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
n	total molar flow rate of gas mixture ($mol\ s^{-1}$)
P	partial pressure of a gas in anode gas mixture
P_{H_2O}	partial pressure of steam in anode gas mixture
P_{CH_4}	partial pressure of methane in anode gas mixture
P_{CO}	partial pressure of carbon monoxide in anode gas mixture
P_{CO_2}	partial pressure of carbon dioxide in anode gas mixture
Q	heat (J)
T	temperature (K)
x	molar flow rate of the reacted methane in reforming reaction ($mol\ s^{-1}$)
y	molar flow rate of reacted carbon monoxide in shifting reaction ($mol\ s^{-1}$)
z	molar flow rate of reacted hydrogen in electrochemical reaction ($mol\ s^{-1}$)
U_f	fuel utilization
w_{AC}	AC power generated from SOFC power generation unit (W)
w_{DC}	DC power generated from SOFC power generation unit (W)
w_{H_2S}	molar flow rate of hydrogen decomposed from H_2S ($mol\ s^{-1}$)

Greek symbols

η	efficiency
Δ	difference

Subscripts

AB	absorber
AC	alternating current
CH_4	methane
CO	condenser
CO	carbon monoxide
CO_2	carbon dioxide
c	cooling mode
DC	direct current
e	electrochemical reaction
el	electric
EV	evaporator
GE	generator
H_2	hydrogen
H_2O	water vapor
h	heating mode
r	reforming
f	fuel
s	shifting
stack	fuel cell stack

Superscripts

i	inlet
o	outlet

cycles and absorption cycles. Absorption heating and cooling systems are thermally driven, which means that heat rather than mechanical energy is supplied to drive the cycle. Thermally driven absorption heating and cooling systems are attractive for using waste heat from other processes. They only require a small amount of electric power to drive the system, and they can use natural substances, which do not cause ozone depletion, as a working fluid.

Fuel cell systems can be used as for combined heat and power (CHP) technology in buildings [13–16,42]. Proton exchange membrane fuel cells (PEMFC) and phosphoric acid fuel cells (PAFC) are widely used for CHP applications [15,16] but exhibit operation with electrical efficiencies only in the low 30% range. Furthermore, the lower operating temperature of a PEMFC requires the use of highly reformed fuels such as hydrogen and prohibits effective utilization of its waste heat for most absorption or water heating technologies. We will show that a higher temperature SOFC system has greater advantages for the combined supply of heating and electricity over these technologies.

As mentioned above, SOFC systems with internal reformation can be directly powered with natural gas, a fuel that already has an extensive supply infrastructure. It also emits flue gas at high temperatures, which allow it to be used as input for an absorption heating and cooling system. We propose a CHP design that combines a SOFC with an absorption heating and cooling system to produce power, heating/cooling and/or hot water for buildings while consuming natural gas. The high temperature exhaust and high efficiency (electrical and thermal) of our system render it superior to conventional low temperature CHP systems as described in Refs. [4,16,42]. For large residential or commercial buildings, such as office buildings, apartment

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