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A micro tri-generation system based on direct flame fuel cells for residential applications

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ARTICLE INFO

Article history:
Received 4 December 2013
Received in revised form
21 January 2014
Accepted 27 January 2014
Available online 18 February 2014

Keywords:
Direct flame fuel cell
System model
Cogeneration
Tri-generation
Residential applications

ABSTRACT

A novel micro tri-generation system which combines a direct flame fuel cell, a boiler and a double-effect absorption chiller is proposed and analyzed for residential applications. Parametric analyses are conducted to investigate the effects of operating parameters (i.e. the equivalence ratio and the fuel utilization factor of the fuel cell) on the system efficiency and the thermal-to-electric ratio. Then optimum operating parameters are determined based on the typical energy demand of Hong Kong in the summer and the typical energy demand of Beijing in the winter, respectively. It is found that very high efficiency (over 90%) can be achieved by this novel tri-generation system for both Hong Kong and Beijing. Besides, the system is modified for combined heat and power cogeneration, combined cooling and power cogeneration and their efficiencies are compared with the tri-generation system to evaluate the effect of each single unit on the whole system.

1. Introduction

High efficiency micro cogeneration (combined heat and power, CHP) and tri-generation (combined cooling, heating and power, CCHP) systems using solid oxide fuel cells (SOFCs) are promising technologies to meet the energy demand of a single-family [1–4]. In convectional SOFCs, the fuel and oxidizer are separated in two chambers by a sealant [5]. Although SOFC can achieve high performance with this dual-chamber configuration, it may not be ideally suited for certain applications, especially small-scale applications subject to temperature change or other variations that may cause seal failures [6]. Recently, a novel SOFC configuration which is called direct flame fuel cells (DFFCs) has been proposed and studied by several researchers [7–11]. In this system, the anode is directly exposed to a fuel-rich flame while the cathode is open to the ambient air, thus completely eliminating the problems with the sealant. The flame is the partial oxidation of the fuel by air and serves as a quick-starting and simple fuel reformer for the SOFC. This feature simplifies the fuel cell system but causes a relatively lower electrical efficiency of DFFC than traditional SOFCs as part of the fuel is used for heat generation by combustion and only the remaining un-combusted fuel can be used for power generation in DFFC. However, the energy efficiency of DFFC system can be enhanced by integrating DFFC with other components or cycles to effectively utilize the thermal energy from the combustion for simultaneous generation of power, heat and cooling.

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0360-3199/$ – see front matter
http://dx.doi.org/10.1016/j.ijhydene.2014.01.183

Currently, DFFC is still in its early development stage and planar SOFCs were usually used in the previous experimental studies. In recent years, due to the fast start-up and higher volume power density, the microtubular SOFC has been rapidly developed [12–14]. Several cogeneration systems have been built based on microtubular SOFCs [15,16]. In the study of Alston [15], a cogeneration system was built using 1000 microtubular SOFCs with the intention of supplying 30 kW of hot water and 500 W of power for domestic cogeneration. Tompsett [16] built a CHP system in which the microtubular SOFCs were combined with a catalytic gas burner and a pre-reformer to generate heat and power from propane/butane fuels. Although the SOFC-based multi-generation systems are still expensive, the high efficiency achieved in the previous studies demonstrated their potential for future applications. Of course, before their wide application, extensive research efforts are needed to further reduce the system cost, which can be done by developing novel SOFC materials or by system optimization. In this paper, a micro tri-generation system based on the DFFC is proposed and evaluated. The flame and a microtubular SOFC stack were directly combined in the DFFC model. The system model was implemented in the commercial simulation platform of gPROMS to analyze the system performances at various operating conditions including the equivalence ratio and the fuel utilization factor of the SOFC stack. Optimum operational parameters were determined accounting for the typical energy demand of Hong Kong in the summer and the typical energy demand of Beijing in the winter, respectively. Moreover, the performance of each main system component was analyzed by comparing the system performance with different cogeneration configurations.

2. System description

2.1. System configuration

The configuration of the proposed tri-generation system is shown in Fig. 1. It consists of a DFFC generating DC electric power and heat; a boiler producing hot water for a residential dwelling; and a double-effect LiBr–water absorption chiller generating chilled water for air conditioning. In the system, fuel and air are converted to a mixture of H_2O, CO_2, O_2 and N_2 in the DFFC and the exhaust gas of the DFFC acts as the heat source of the boiler and the absorption chiller.

2.2. DFFC model

The DFFC system consists of the burner and a microtubular SOFC stack, as shown in the dash box of Fig. 1. The configuration of the DFFC is based on our previous paper [17], which is shown in Fig. 2. In the system, methane is considered as fuel and is converted to a mixture of H_2, H_2O, CO, CO_2 and N_2 by fuel-rich combustion. The microtubular SOFC stack is directly combined with the burner with its anode facing the combustion exhaust gas and the cathode supplied with air. The SOFC stack and the air in the cathode are both heated by the anode gas; and excess air is fed into the SOFC cathode to maintain the temperature of the SOFC stack at 1173 K. The fuel fed into the SOFC stack is partially reacted through electrochemical reaction and the unreacted fuel is then fully combusted with the ambient air.

The fuel-rich combustion of CH_4 is shown as follows:

$$CH_4+\frac{2}{\phi}(O_2+3.76N_2)\rightarrow aCO_2+bCO+cH_2O+dH_2+\frac{2\times 3.76}{\phi}N_2 \quad (1)$$

where ϕ is the equivalence ratio which is defined as the ratio of the actual air–fuel ratio to the stoichiometric air–fuel ratio.

The gas composition of the fuel-rich combustion is calculated by the species mass balance and the water gas shift equilibrium is introduced as an additional condition [18]:

$$\text{Conservation of Elements}: \begin{cases} C: a+b=1 \\ H: 2c+2d=4 \\ O: 2a+b+c=\frac{4}{\phi} \end{cases} \quad (2)$$

$$\text{The water gas shift equilibrium}: \quad K_{eq,WGS}=(P_{CO_2}/P^0)\times(P_{H_2}/P^0) \quad (3)$$

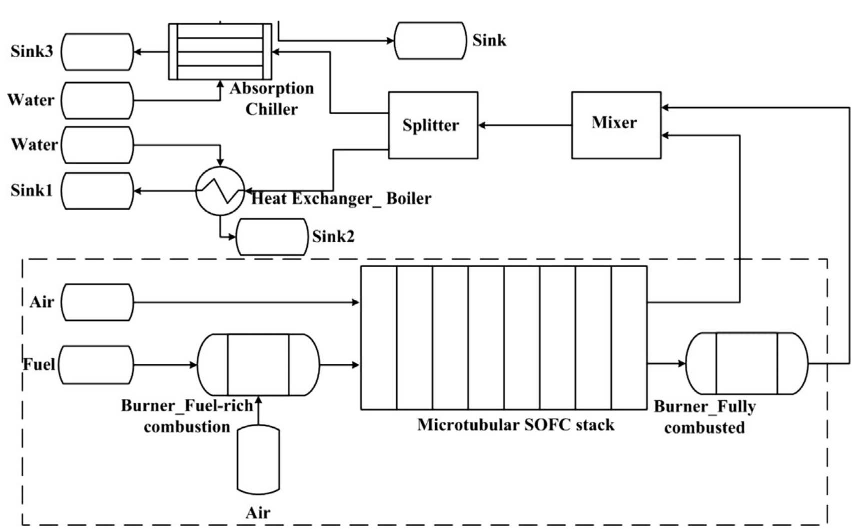

Fig. 1 – Configuration of the tri-generation system.