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Dynamic analysis of a micro CHP system based on flame fuel cells

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ABSTRACT

Micro combined heat and power (CHP) systems based on flame fuel cells (FFCs) are promising technologies for residential applications due to their simple setup and rapid startup. A dynamic model was developed in this paper for a micro FFC-based CHP system which consists of an FFC and a heat exchanger. At first, the operation conditions at the design point (system AC power output is 1.1 kW) and the part-load point (system AC power output is 0.7 kW) were determined respectively at steady state. An exergy assessment was conducted for each component and the whole system. It is found that at the design point, the heat exchanger accounts for the majority of the exergy losses. Then, the transient responses of the system components as well as the electrical and heat dynamics of the whole system were investigated when the operation conditions of the system ramped from the values at the design point to those at the part-load point. The electrical dynamic response of the CHP system, in terms of the output AC power shows a time delay of less than 50 s, while the thermal dynamic response, in terms of the generated heat shows a time delay of 300 s. The electrical dynamic response of the system is limited by the dynamics of the gas supply process of the fuel-rich burner. The thermal settling time of the system is governed by the thermal settling time of both the SOFC stack and the heat exchanger. The relatively slow thermal response under a transient electrical demand indicates that an additional heat storage is necessary in the FFC-CHP system.

1. Introduction

Currently, the residential applications consume approximately 27% of the electricity and 38% of the thermal energy around the world [1]. Most of the energy comes from the electricity produced from centralized power plants, with up to 70% available energy wasted [2]. Converting from centralized power generation systems to on-site high efficiency micro CHP (combined heat and power) systems is vital for reducing the energy consumption of residential sector. The micro CHP system based on fuel cells is a promising technology to meet the heat and electricity demand of a single family at the mean time [3–7].

Among the various types of fuel cells, the high-temperature solid oxide fuel cell (SOFC) is advantageous for its high efficiency and low cost. Currently, micro CHP systems based on SOFCs have been paid increasing attention for residential applications with several systems being commercially available. An SOFC-based micro CHP system called ENE-FARM-S has been commercialized in Japan with a power generation efficiency of 46.5% [8]. In conventional SOFC-based CHP systems, dual-chamber SOFCs were applied where the fuel and oxidizer are separated in two chambers with the help of a sealant [9]. However, in residential applications where the load and temperature variations are quite frequent, several problems may arise in dual-chamber SOFCs, such as sealing, complex thermal management and slow start-up [10].

Recently, a sealant-free SOFC configuration, which is the flame fuel cell (FFC), has been developed and investigated [11–16]. In the FFC, the SOFC anode is directly integrated with a fuel-rich flame. The flame acts as a partial oxidation reformer and a quick start-up heater for the SOFC. The FFC is featured with rapid start-up and simple set-up, which makes it a promising candidate in micro CHP systems [17–21]. A concept configuration of the FFC-based micro-CHP system is shown in Fig. 1. Air and fuel are converted to syngas through fuel-rich combustion. Then the SOFC stack utilizes the syngas for power generation. The unutilized syngas be will further utilized through complete combustion with the ambient air. Since a large amount of heat will be produced by the fuel-rich combustion before the SOFC stack as well as the complete combustion after the SOFC stack, integrating the FFC with a heat exchanger in a micro-CHP system can effectively utilize the thermal energy for simultaneous generation of heat and power. A steady-state model for a micro CHP system based on flame fuel cells has been developed for residential applications in a previous study [22]. The cogeneration energy efficiency of the FFC-based CHP system reached 90% and the system was demonstrated feasible to meet the typical energy

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Nomenclature

Abbreviation

AC	alternating current
BOP	balance of plant
CH	chemical
CHP	combined heat and power
DC	direct current
FFC	flame fuel cell
LHV	low heat value
NTU	number of transfer units
PEN	positive-electrolyte-negative
PH	physical
SOFC	solid oxide fuel cell
TER	thermal-to-electric ratio
WGS	water gas shift

English letters

A	effective area of mass transfer (m^2)
c	concentration (mol/m^3)
c_p	specific heat (J/(kg K))
ex	exergy per unit mass (J/kg) or molar exergy (J/mol)
g_f	molar Gibbs free energy of formation (J/mol)
G	transfer function
h	heat transfer coefficient ($W/m^2 K$) or enthalpy per unit mass (J/kg)
H	molar enthalpy (J/mol)
J	current (A)
k	kinetic constant
K_{eq}	reaction equilibrium constant
$\dot{m}$	mass flow rate (kg/s)
M	molar mass (kg/mol)
$\dot{n}$	molar flow rate (mol/s)
N	molar flux ($mol/(m^2 s)$)
P	power (W)
Q	heat (W)
r	radius (m)
R	reaction rate per unit area ($mol/(m^2 s)$) or universal gas constant (8.314 J/(mol K))
R_i	source term of species i in mass conservation equation ($mol/(m^2 s)$)
s	entropy per unit mass (J/(kg K))
t	time (s)
t_{gap}	distance between tubes (m)
T	temperature (K)
u	velocity (m/s)
V	volume (m^3) or voltage (V)
V_k	diffusion volume of species k (m^3)
x	molar fraction
y	mass fraction

Greek letters

η	efficiency
ρ	density (kg/m^3)
λ	thermal conductivity ($W/(m^3 K)$)
τ	time constant (s)
ϕ	equivalence ratio

Subscripts and superscripts

0	environmental state
an	anode
conv	convection
el	electricity
e-s	syngas energy conversion
E/C	electrode/channel
Ex	exergy
fu	fuel
g	gas
gs	gas supply
Hx	heat exchanger
in	inlet parameter
liq	liquid
m	average
out	outlet parameter
s	solid
S	stoichiometric
Sy	system
t	total
th	thermal
w	wall

demand in China. However, to completely evaluate the system thermodynamic performance at steady state, an exergy assessment should be further conducted.

In practical residential applications, the micro-CHP systems will experience frequent load dynamics. Consequently, the dynamic response of the system components and the whole system need to be investigated to study the load-following capability of the micro-CHP systems. Several studies have been carried out to study the dynamic characterizations and control strategies of micro-CHP systems based on conventional SOFCs [23,24]. However, the dynamic characterizations of the FFC-based micro-CHP systems have not been analyzed before.

To that end, a dynamic model for a micro-CHP system based on FFC was developed in this study. The operation conditions of the system at the design point and the part-load mode were determined by the model in steady state. An exergy assessment was further conducted for each component and the whole system at the design point. The dynamic characterization of the system components and the cogeneration dynamics of the FFC-CHP system were investigated by the model in transient state. This study will promote the practical application of the FFC-CHP system in the residential sector.

2. System description

2.1. System layout

The layout of the developed micro CHP system model is shown in Fig. 2(a). The system is based on the concept of the flame fuel cell. Air and methane are converted to syngas through partial oxidation in a fuel-rich burner. The produced syngas enters a micro-tubular SOFC stack and generates electricity through electrochemical reactions. The unutilized syngas is then fully combusted with the ambient air and produces hot exhausts. The hot exhaust gases of the flame fuel cell act as the heat source of the heat exchanger to heat the cool water to hot water. In this paper, the system is modelled on the platform of a commercial software gPROMS, as shown in Fig. 2(b).

2.2. Flame fuel cell model

The dynamic flame fuel cell model was developed based on the steady-state flame fuel cell model, which was described in detail in the previous paper [22]. Methane and air are supplied to a burner and converted to a mixture of H_2, CO, H_2O, CO_2 and N_2 through fuel-rich