Energy Conversion and Management 152 (2017) 88–98

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Control structure design of a solid oxide fuel cell and a molten carbonate fuel cell integrated system: Top-down analysis

Prathak Jienkulsawad[a], Sigurd Skogestad[b], Amornchai Arpornwichanop[a,*]

[a] Computational Process Engineering Research Unit, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand
[b] Department of Chemical Engineering, Norwegian University of Science and Technology, N-7491 Trondheim, Norway

ARTICLE INFO

Keywords:
SOFC
MCFC
Integrated system
Control structure design
Top-down analysis

ABSTRACT

The integrated system of a solid oxide fuel cell and molten carbonate fuel cell theoretically has very good potential for power generation with carbon dioxide utilization. However, the control strategy of such a system needs to be considered for efficient operation. In this paper, a control structure design for an integrated fuel cell system is performed based on economic optimization to select manipulated variables, controlled variables and control configurations. The objective (cost) function includes a carbon tax to get an optimal trade-off between power generation and carbon dioxide emission, and constraints include safe operation. This study focuses on the top-down economic analysis which is the first part of the design procedure. Three actively constrained regions as a function of the main disturbances, namely, the fuel and steam feed rates, are identified; each region represents different sets of active constraints. Under nominal operating conditions, the system operates in region I. However, operating the fuel cell system in region I and II can use the same structure, but in region III, a different control structure is required.

1. Introduction

Most power plants are generally based on fossil fuels and are the largest source of CO_2 emissions [1]. High-temperature fuel cells, such as SOFCs (solid oxide fuel cells) and MCFCs (molten carbonate fuel cells), have been considered as alternative reliable power sources for decades because they have higher electrical efficiency and thus a lower environmental impact. Moreover, high-temperature fuel cells have been reported by both theoretical and experimental studies to have a great fuel flexibility, even to the extent of a fuel consisting of tar, as reported by Baldinelli et al. [2]. However, methane is selected as the fuel feed because it is easily obtained from many petrochemical and biochemical processes [3].

In general, a stand-alone SOFC cannot completely use all the fuel within itself, as NiO forms and corrosion occurs at the anode of the SOFC [4]. The study by Parhizkar et al. [5] showed that under the optimum operating conditions, the SOFC should be operated at a moderate fuel utilization to avoid a long-term cell degradation, resulting in a remaining fuel in the anode off-gas. Many researches have been carried out to enhance the SOFC system performance. Zhang et al. [6] proposed the hybrid SOFC system with a thermoelectric generator and thermoelectric cooler to recover the waste heat from SOFC. However, the proposed SOFC system did not deal with the remaining fuel in the exhaust gas. Hosseinpour et al. [7] studied a cogeneration system based on an SOFC integrated with a Stirling engine. The remaining fuel in the SOFC outlet was combusted to increase the temperature of the exhaust gas before it was fed to the Stirling engine. Sarmah and Gogoi [8] designed the combined SOFC power system with gas turbine and steam turbine cycles by using the remaining fuel for a gas turbine cycle. Zhang et al. [9] used a recycling strategy to enhance the SOFC system efficiency; an anode off gas was recirculated to the reformer providing steam and heat for the reforming process. Alternatively, the integration of SOFC with other fuel cell types to use the remaining fuel in the SOFC outlet for additional power generation has been explored. A combined SOFC and proton exchange membrane fuel cell (SOFC-PEFC) system was proposed by Obara [10]; however, several purifying units were required to treat the exhaust gas from SOFC before it can be fed to the PEFC. Two-staged SOFCs, low and high-temperature SOFCs, with a serial connection were studied by Araki et al. [11]. Patcharavorachot et al. [12] investigated the performance of the oxygen-ion and proton-conducting electrolyte SOFC hybrid system. Regarding the operation of MCFCs, syngas can be used as a fuel. Moreover, MCFCs need CO_2 and O_2 to promote CO_3^{2-} as an electron carrier. In other words, CO_2 is useful for power generation in an MCFC [13], and the remaining fuel and CO_2 exhaust from the SOFC can be used directly in an MCFC to generate more power [14]. Thus, the SOFC and MCFC integrated system can be a

---

[*] Corresponding author.
E-mail address: amornchai.a@chula.ac.th (A. Arpornwichanop).

http://dx.doi.org/10.1016/j.enconman.2017.09.033
Received 1 May 2017; Received in revised form 7 September 2017; Accepted 11 September 2017

Nomenclature

Symbols

A	area of reaction (m^2)
C_P	heat capacity ($J\ mol^{-1}\ K^{-1}$, $kJ\ kg^{-1}\ K^{-1}$)
CEC	carbon emission coefficient ($kg\ CO_2\ MWh^{-1}$)
D_h	hydraulic diameter (m)
E	operating voltage (V)
E_{OCV}	open-circuit voltage (OCV) (V)
E^0	OCV at standard temperature and pressure (V)
F_i	mole flow rate ($mol\ s^{-1}$)
F	Faraday's constant ($C\ mol^{-1}$)
H	enthalpy flow (kW)
j	current density ($A\ m^{-2}$)
j_0	exchange-current density ($A\ m^{-2}$)
k	thermal conductivity ($kW\ m^{-1}\ K^{-1}$)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
N_i	mole of component i (mol)
Nu	Nusselt number (–)
P_i	pressure (atm)
P_W	power (W)
Q	heat (kW)
$\widehat{R}$	rate of reaction per area ($mol\ m^{-2}\ s^{-1}$)
R	rate of reaction ($mol\ s^{-1}$)
T	temperature (K)
U_f	fuel utilization (%)
V	volume (m^3)
y_i	molar fraction (–)

Greek symbols

$\in$	emissivity (–)
η	voltage loss (V)
$\mathfrak{R}$	gas constant ($kJ\ mol^{-1}\ K^{-1}$)
σ	Stefan-Boltzmann constant ($W\ m^{-2}\ K^{-4}$)
σ_i	electronical conductivity ($ohm^{-1}\ m^{-1}$)
τ_i	thickness of layer i (m)

Subscripts

a	air channel
an	anode
B	combustion chamber
ca	cathode
f	fuel channel
I	interconnect
i	gas species
M	MCFC
P	PEN
R	reformer
S	SOFC
TPB	three-phase boundaries
0	inlet

Superscript

SP	setpoint

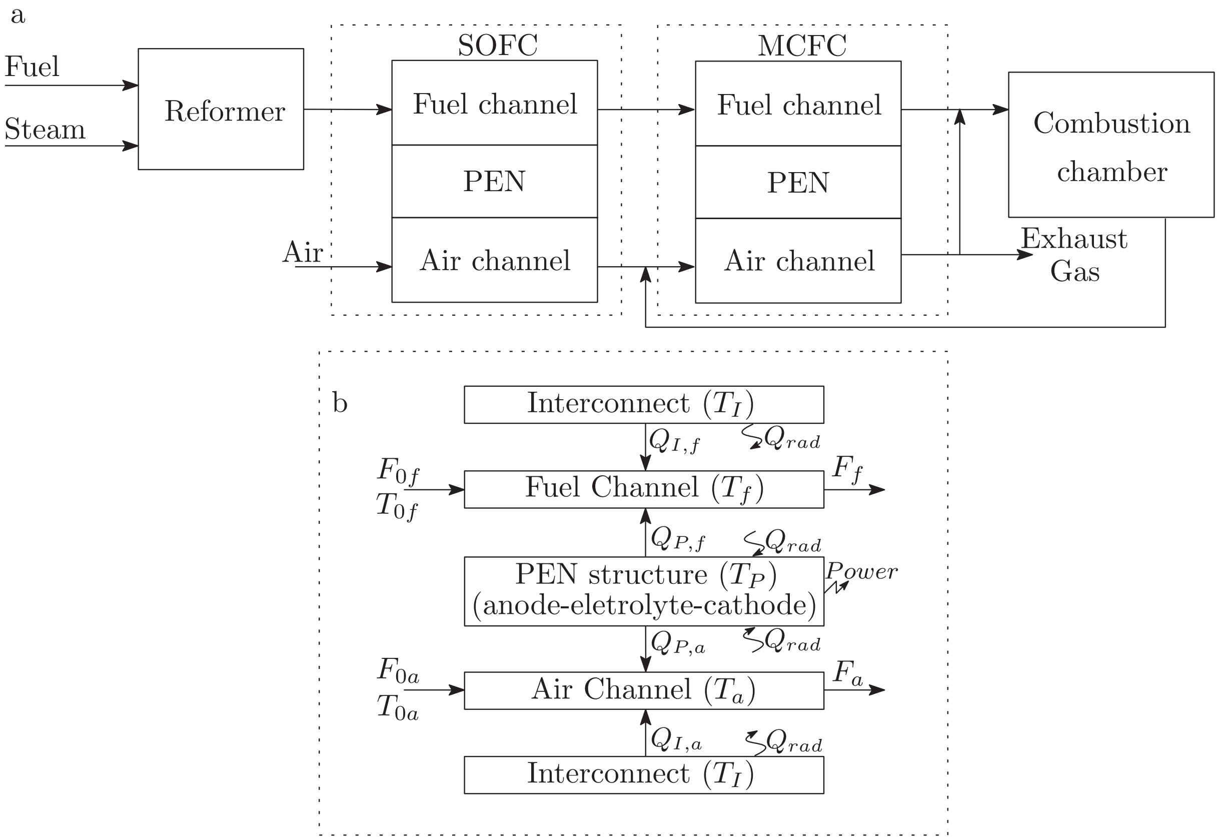

Fig. 1. (a) SOFC and MCFC integrated system and (b) the mass and heat balances in fuel cell components.