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Control-oriented dynamic model optimization of steam reformer with an improved optimization algorithm

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ABSTRACT

An effective temperature controller for steam reformers is critical to ensure a high performance reforming process in the connection of Solid Oxide Fuel Cell (SOFC). The establishment of a control-oriented dynamic model plays an important role in the development of a control system. In this work, a high-fidelity lumped parameter model for a steam reformer is constructed based on physical and chemical laws. In order to fit simulated data to experimental data, such as flow rate and temperature characteristics, a new identification method based on a breed particle swarm optimization (Breed PSO) algorithm is introduced for parameter identification. The results show that the identified model can achieve an accurate description of the actual plant and can be used to replace it for the development of a control system.

1. Introduction

The solid oxide fuel cell (SOFC) acts as a promising green generator by converting chemical energy into electrical power directly via electrochemical reactions. This provides many advantages, including high efficiency, minimal emission of pollutants, fuel flexibility and zero noise [1–3]. To apply this technology, methane steam reformer is a critical part of the fuel supply for SOFC systems due to hydrogen supply limitations and the global abundance of methane [4].

However, the performances of SOFC systems are significantly influenced by the reforming process because it determines the hydrogen flow rate contained in the product gas of steam reformer. Moreover, the reforming process is primarily affected by reforming temperature. Thus, the reforming temperature should be regulated within a specific range to

Abbreviation: GA, Genetic Algorithm; ODE, Ordinary Differential Equation; PEMFC, Proton Exchange Membrane Fuel Cell; PLC, Programmable Logic Controller; PSO, Particle Swarm Optimization; RMSE, Root Mean Square Error; SLM, Standard Liter per Minute; SOFC, Solid Oxide Fuel Cell; SPSO, Simple-PSO; SR, Steam Reform reaction; WGS, Water Gas Shift reaction.

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Nomenclature

C	Heat capacity ($c \cdot m$)
c	Specific heat capacity
c_1, c_2	Accelerate coefficient
G	Gibbs enthalpy
g	Specific Gibbs enthalpy or global best position[1]
Δh	Heat of reaction
k	Heat transfer coefficient
m	Mass
$\dot{n}$	Molar flow rate
Δn	Extent of reaction
p	Pressure or particle's best position
$\overline{p}$	Parameter vector
Q	Heat flow
r	Reforming ratio[2]
S	Seed index
S/C	Steam to carbon ratio
T	Temperature
$\overline{u}$	Parameter vector
x	Particle position
v	Particle velocity
w	Inertial weight
BCH_4	Burner methane flow rate
RCH_4	Reforming methane flow rate

Greek letters

α	Parameter decided by reforming temperature
β	Parameter decided by steam to carbon ratio
λ	Excess air ratio

Subscripts

B	Burner
E	Evaporator
F	Flame
G	Ground plate
ind	Index
R	Reactor
W	Wall
i	Component i or particle index
j	Solution space dimension index
0	Standard state
1	Associated with reaction SR
2	Associated with reaction WGS
EXP	Experimental

[1] "best position": The model parameters to be identified can be written as a vector, which is the coordinates of particle in a multi-dimension space, representing the position in the solution space. In order to evaluate the "fitness degree" of each particle, the

[2] "Reforming ratio": the percentage of the methane consumed in reforming reactions.

maintain the reforming process stable, resulting in a stable hydrogen production. An effective thermal management controller of steam reformer is demanded for the high performances of SOFC system.

It is a truth that the steam reformer can be generally controlled by PID controller, especially for a steady-state operation. But in this work, the steam reformer is designed for a solid oxide fuel cell (SOFC) system, which usually imposes large changes of reforming methane flow rate on steam reformer during tracing external load power demand. The reforming process can be significantly affected by the fluctuations of reforming methane flow rate, and large changes of the temperature and composition of product gas happen, and the SOFC is degraded or even damaged due to thermal stress and fuel starvation. For this reason, a high performance controller with disturbance rejection capability is required to maintain the reformer operating temperature and avoid the destructive perturbations.

Meanwhile, the reforming process may have lots of environmental and economic constraints requiring multivariate advanced controller to maintain the optimal performance of the system. If using advanced control strategy, a control-oriented dynamic model is required to generate simulation data and get reduced models such as state-space model and other identified models. Furthermore, the effectiveness of these controllers highly depends on the accuracy of the dynamic model. Therefore, an accurate description of the input–output relationships of the actual plant is the key to the implementation of the dynamic model. In a word, a high-fidelity control-oriented dynamic model is critical for the regulation of reforming process achieving high performances of SOFC system.

Recently, various models for a reformer have been proposed [5–12], but most of them have focused on thermal behavior and searched into the reforming process itself. Halabi [5,6] presented a 1-D dynamic model for a methane auto-thermal reformer to simulate the reforming process. In particular, the performance of the reformer using different operating parameters was analyzed (such as pressure, steam to carbon ratio and gas velocity). Using a 1-D heterogeneous reactor model and a 3-D zonal furnace model, Zamaniyan [7] investigated the thermal behavior of the top fired methane steam reforming process and Farhadi [8] studied the bottom fired process. In order to improve the primary steam reformer performance, Pedernera [9] constructed a heterogeneous 2-D model containing a burner and a reactor.

Few reports have presented steam reformer models for fuel cell systems. Jahn et al. [4] constructed a lumped element dynamic model of the steam reformer for a residential proton exchange membrane fuel cell (PEMFC) system. Moreover, the parameters of the model were identified from the measured data by the identification algorithm known as "fmincon" [13], but large errors can be detected between the simulated data and experimental data. In the research conducted by Peksen et al. [14], a 3-D computational model of the reformer containing some typical sub-components for SOFC was presented.