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Dynamic investigation of a novel SOFC-MHR-Engine hybrid energy conversion system

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ABSTRACT

A novel SOFC-MHR(metal hydride reactor)-Engine hybrid energy conversion system fueled with alternative fuels is proposed and modelled in this present study. The MHR is introduced into the hybrid system for H_2 addition by waste heat recovery. The dynamic modelling is performed to investigate the transient response of the proposed hybrid energy conversion system. The results show that the SOFC has a relatively slow dynamic behavior while the engine has the fast dynamic behavior. Besides, the SOFC dominates the transient responses of the hybrid system because that the engine fuel directly comes from the FC off-gas. Therefore, it is found that the addition of H_2 by MHR not only extends the system power output, but also improves the dynamics of the hybrid system due to the enhanced autonomy of the engine with fast transient response. When the H_2 addition is χ=2.0, the hybrid system can quickly reach the stable power output within 5 s, indicating that the hybrid system presents superior dynamic behaviors and is promising for mobile applications.

Keywords: SOFC, metal hydride reactor, engine, dynamic modelling

Nomenclature

Abbreviations	
DIR	Direct internal reforming
HCCI	Homogeneous charge compression ignition
MHR	Metal hydride reactor
SOFC	Solid oxide fuel cell
WGS	Water gas shift
Symbols	
h	Specific enthalpy (J mol^{-1})
K	Reaction equilibrium constant
P	Power (kW)
p	Pressure (kPa)
T	Temperature (K)
t	Time (s)
Subscripts	
comb	Combustion
comp	Compression
ex	Expansion
ign	Ignition

1. INTRODUCTION

Solid oxide fuel cell (SOFC) usually operates at high temperatures more than 873 K, which enables SOFC running in various fuels, such as NG, biogas, petroleum gas and methane through high-temperature reforming and water gas shift (WGS) reactions [1-3]. Accordingly, a mass of heat is released along with the exhaust gas at such high temperatures so that it can be re-utilized by waste heat recovery to drive bottomed thermodynamic cycles such as Rankine, Brayton, and Otto cycles, for additional power generation. Therefore, the combination of SOFC and IC engine into hybrid system for power generation not only improves the overall energy conversion efficiency, but also extends the power range to facilitate practical applications.

Actually, more and more researches [4, 5] focus on the novel SOFC-IC engine hybrid system. Park et al. [6] reported that the SOFC-IC engine hybrid system can achieve the efficiency of 59.5% and exhibits the levelized cost of electricity (LCOE) of $0.23/kWh, both of which are better than the standalone SOFC and SOFC-GT hybrid system. However, an additional heater instead of waste heat recovery is installed to heat the external reformer in this case. Besides, the output power and energy conversion efficiency of IC engine were found to be a little small due to the lean combustion in the engine. In

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order to further improve the power and overall efficiency, coupling metal hydride reactor (MHR) for H_2 addition by waste heat recovery was introduced into the SOFC-IC engine hybrid system in our previous study [7]. It was found that the overall efficiency can be improved up to 79.54% by H_2 addition from MHR for IC engine and H_2 recirculation for SOFC anode off-gas. The high efficiency suggests that the SOFC-Engine hybrid system coupled with MHR for H_2 addition is a promising energy conversion system. The fuel flexibility and extended output power show potential possibility in the practical application of vehicles, especially the heavy bus, truck and marine ship. As is known to all that the dynamic behaviors of the power generation system are important in the mobile application. However, no research work on dynamic modelling the SOFC-MHR-Engine hybrid energy conversion system was reported before.

In the present study, we performed the dynamic modelling of the novel SOFC-MHR-Engine hybrid energy conversion system fueled by methane. Then, the dynamic behaviors of the hybrid system is further investigated for obtaining the optimal operation strategy.

2. SYSTEM MODELLING

2.1 Working principle and system configuration

The SOFC-MHR-Engine hybrid energy conversion system consists of two main subsystems, which are Exreforming-SOFC and MHR-Engine subsystems, as shown in Fig. 1. The reason for choosing HCCI-engine is that the fuel of engine, which is in fact lean, directly comes from SOFC anode off-gas. As for the lean burning, the best method to make the fuel completely burn in the engine is using the technology of HCCI which synergistically combines spark ignition (for gasoline) and compression ignition (for diesel) [6]. In the Exreforming-SOFC subsystem, the reformer first converts the preheated methane partly into CO and H_2 as anode fuel of SOFC. The SOFC consumes the anode fuel and oxygen by electrochemical reaction to generate electricity. Then, the SOFC anode off-gas (main compositions: CO, CO_2, H_2, N_2, and H_2O) and cathode off-gas (air) after preheating pristine fuel enter into the downstream HCCI-engine subsystem as the fuel of the engine. In the MHR-Engine subsystem, the SOFC anode and cathode off-gas sequentially go through the processes of compression, combustion, and expansion stroke for additional power generation. The engine off-gas, which generally has a high temperature, is used to sequentially provide the thermal source for driving the ex-reforming reaction and heat the water into steam as the reactant of the ex-reforming reaction.

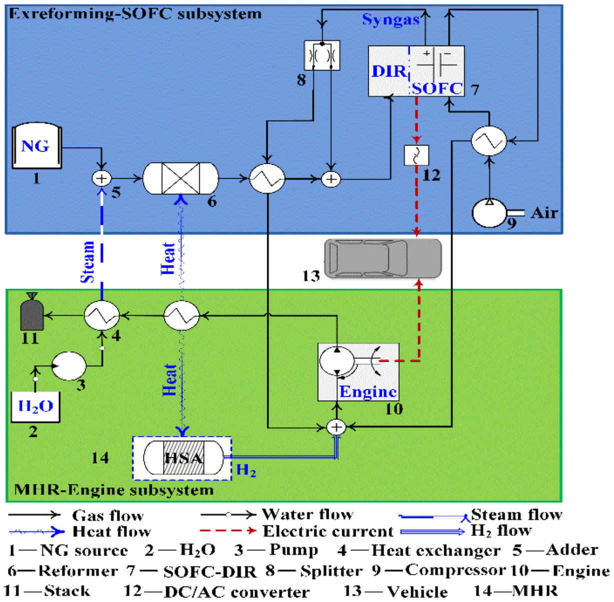

Fig. 1. The layout of the proposed SOFC-MHR-Engine hybrid energy conservation system

2.2 Modelling details

The models of the reforming and WGS reactions are described as follows.

$$\begin{aligned} K_{reform} &= \frac{p_{CO}\cdot p_{H_2}^3}{p_{CH_4}\cdot p_{H_2O}} = f\left(T_{reform}\right) \\ &= -2.63121\times10^{-11}\cdot T^4 + 1.24065\times10^{-7}\cdot T^3 - 2.25232\times10^{-4}\cdot T^2 + 0.195028\cdot T - 66.1395 \qquad \text{for reforming reaction} \\ K_{WGS} &= \frac{p_{CO_2}\cdot p_{H_2}}{p_{CO}\cdot p_{H_2O}} = f\left(T_{WGS}\right) \\ &= 5.47301\times10^{-12}\cdot T^4 - 2.57479\times10^{-8}\cdot T^3 + 4.63742\times10^{-5}\cdot T^2 - 0.03915\cdot T + 13.2097 \qquad \text{for WGS reaction} \end{aligned} \tag{1}$$

Equations. (2-6) shows the SOFC electrochemical model describing the relationship between cell voltage and irreversible overvoltage.

$$V_{cell} = E_N - V_{act} - V_{ohm} - V_{conc} \tag{2}$$

$$E_N = 1.253 - 2.4516\times10^{-4}\cdot T_{SOFC} - \frac{R\cdot T_{SOFC}}{4F}\cdot\ln\left(\frac{p_{H_2O}^2}{p_{H_2}^2\cdot p_{O_2}}\right) \tag{3}$$

$$\begin{aligned} V_{act} &= V_{act,a} + V_{act,c} \\ &= \frac{R_g\cdot T_{SOFC}}{F}\cdot\ln\left[\frac{J}{2J_{0,a}} + \sqrt{\left(\frac{J}{2J_{0,a}}\right)^2 + 1}\right] + \frac{R_g\cdot T_{SOFC}}{F}\cdot\ln\left[\frac{J}{2J_{0,c}} + \sqrt{\left(\frac{J}{2J_{0,c}}\right)^2 + 1}\right] \end{aligned} \tag{4}$$

$$\begin{aligned} V_{conc} &= V_{conc,a} + V_{conc,c} \\ &= \frac{R\cdot T_{SOFC}}{2F}\cdot\ln\left(\frac{1 + \frac{R\cdot T_{SOFC}\cdot l_a\cdot J}{2F\cdot D_a^{eff}\cdot p_{H_2O}}}{1 - \frac{R\cdot T_{SOFC}\cdot l_a\cdot J}{2F\cdot D_a^{eff}\cdot p_{H_2}}}\right) + \frac{R\cdot T_{SOFC}}{4F}\cdot\ln\left(\frac{p_{O_2}}{\frac{p_c}{\delta_{O_2}} - \left(\frac{p_c}{\delta_{O_2}} - p_{O_2}\right)\cdot e^{\frac{R\cdot T_{SOFC}\cdot l_c\cdot J\cdot\delta_{O_2}}{4F\cdot D_c^{eff}\cdot p_c}}}\right) \end{aligned} \tag{5}$$

$$V_{ohm} = 2.99\times10^{-11}\cdot J\cdot l_e\cdot e^{\frac{10300}{T_{SOFC}}} \tag{6}$$

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The transient responses of electrochemistry and fuel processor are modelled to predict the SOFC dynamic behaviors, which are shown in Eq. (7) and Fig. 2.

$$V_{CDL} = V_{act} + V_{conc} = I_{FC} \cdot \left(R_{act} + R_{conc}\right) \cdot \left(1 - e^{-\frac{t}{\tau_c}}\right) \tag{7}$$

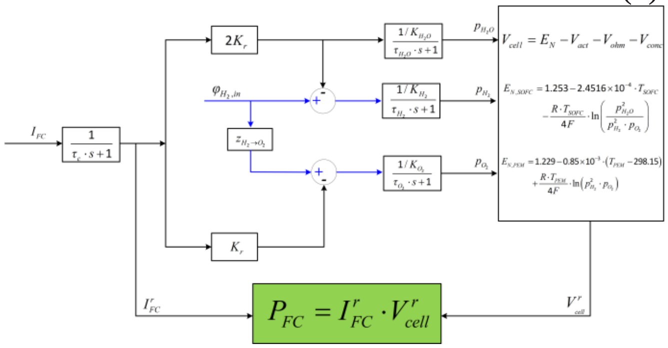

Fig. 2. Block diagram of fuel processor dynamic model

Through the Otto-cycle, the HCCI engine generates a certain amount of power. The net power output P_{Engine} can be calculated as the work subtraction between expansion and compression strokes, as listed in Eq. (8).

$$P_{Engine} = \phi \cdot \left[\left(h_{comb} - h_{ex}\right) - \left(h_{comp} - h_{in}\right)\right] \tag{8}$$

The auto-ignition modelling of the engine is predicted in the Eq. (9).

$$\tau_{ign} = 3.7 \times 10^{-6} \cdot P^{-0.5} \cdot \phi^{-0.4} \cdot \chi_{O_2}^{-5.4} \cdot \exp(52325/RT) \tag{9}$$

In the present study, MATLAB/SIMULINK is used to perform the dynamic modelling of the hybrid system. The acceptable relative tolerance is set as 0.001. Besides, some important parameters used for modelling the hybrid system are summarized and listed in Table 1.

Table 1. Some important parameters in the models

Parameter	Value
DC/AC conversion efficiency, $\eta_{DC/AC}$	0.96
Isentropic efficiency of compressor, η_{ISC}	0.8
Compressor mechanical efficiency η_{MEC}	0.90
Isentropic efficiency of turbine, η_{IST}	0.80
Mechanical efficiency of turbine, η_{MET}	0.90
Generator efficiency, η_{GEN}	0.90

3. RESULTS AND DISCUSSION

3.1 Dynamic behaviors

Fig. 3 and Fig. 4 show the dynamic behaviors of individual SOFC and HCCI engine components. It can be seen that SOFC exhibits the inertia effect response with the time constant of 1.31 s, while the engine shows the delay effect response with the delay time of approximately 0.192 s. By comparison, it can be concluded that the engine has a relatively faster dynamics than the SOFC in the hybrid energy conversion system.

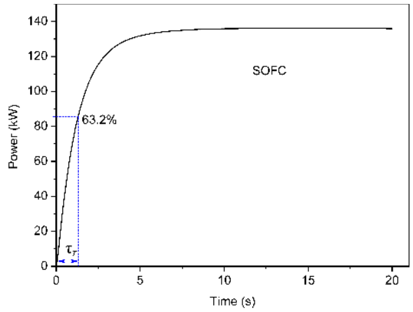

Fig. 3. Inertia effect response of the SOFC

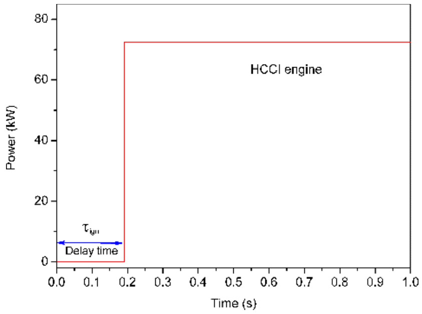

Fig. 4. Delay effect response of the engine

Since the engine fuel is directly from the SOFC off-gas, the dynamics of the engine depends on the SOFC performance. Fig. 5 displays the variations of the engine and total power with the time. The engine in the hybrid system has different dynamic behaviors to the individual one. The engine in the hybrid system also has a delay effect response with the delay time of about 0.05 s. Besides the delay effect, the engine exhibits an overshoot of 66.3% and then reaches the stable power output in ~5 s.

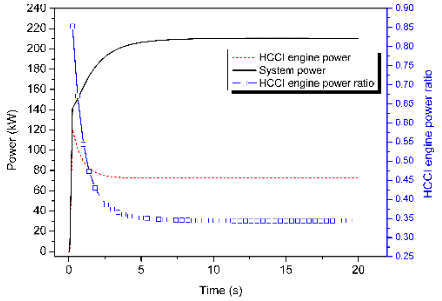

Fig. 5. Dynamic behaviors of the hybrid system

3.2 Effects of reforming dynamics

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This paper also discussed the effects of reforming dynamics on the hybrid system. Fig. 6 shows the effects of ignoring the reforming dynamics on the SOFC power and H_2 production variations under the conditions of 823 K temperature, 101.3 kPa pressure and 1 g catalyst. It can be clearly seen that no big effect appears in the SOFC power due to slow FC response time (>1 s time scale) even though H_2 production changes in the beginning few seconds. This is because that the reforming and WGS reactions generally finish in very fast rates, which are ~3500 mol/s/kg_{cat} at 823 K and ~$1.8X10^7$ mol/s/kg_{cat} at 1073 K for the H_2 production rates. Therefore, the dynamics of the reforming and WGS reactions can be ignored in the hybrid system.

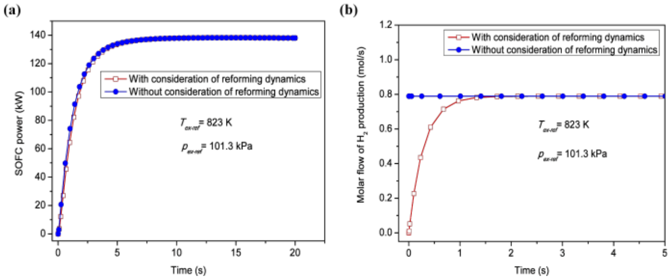

Fig. 6. The effects of ignoring reforming reactions dynamics on SOFC power and H_2 production variations

3.3 Effects of H_2 addition

The effects of H_2 addition by MHR on the SOFC-engine hybrid system was further investigated to achieve the optimal dynamic properties. Fig. 7 shows the hybrid system performance at different H_2 additions. It can be seen that the addition of H_2 helps to enhance the total power output due to the increased engine power. The engine power ratio increases from 37% to 55% when the H_2 addition is increased to χ=2.0. Besides, the dynamics of the hybrid system is improved due to enhanced autonomy of the engine with fast transient response. The system can quickly reach the stable power 300 kW output within 5 s and has an overall efficiency up to 75.7% at χ=2.0, indicating that the hybrid system is a promising energy conversion device for mobile applications

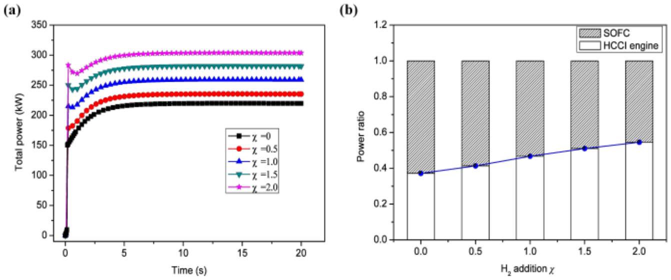

Fig. 7. Effects of different H_2 additions on the hybrid system performance

4. CONCLUSIONS

The novel SOFC-MHR-Engine hybrid energy conversion system fueled with alternative fuels is proposed and modelled in this paper. The dynamic modelling results show that the SOFC component with a relatively slow transient response dominates the dynamic behaviors of the whole hybrid system, causing the poor dynamics of the hybrid system. Besides, the fast transient response of the engine is replaced by the combination of delay and overshoot effects due to the fuel directly from the SOFC off-gas. The H_2 addition by MHR to the engine is found to enhance the dynamics of the hybrid system because of the enhanced autonomy of the engine. The hybrid system can stably output the power within 5 s with an overall efficiency up to 75.7%, indicating the proposed hybrid system is promising energy conversion device for mobile applications.

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REFERENCE

[1] Sulaiman N, Hannan MA, Mohamed A, Ker PJ, Majlan EH, Wan Daud WR. Optimization of energy management system for fuel-cell hybrid electric vehicles: Issues and recommendations. Appl Energy 2018;228:2061–2079.

[2] Xu HR, Chen B, Tan P, Cai WZ, He W, Farrusseng D, et al. Modeling of all porous solid oxide fuel cells. Appl Energy 2018;219:105–113.

[3] Song K, Chen H, Wen P, Zhang T, Zhang B, Zhang T. A comprehensive evaluation framework to evaluate energy management strategies of fuel cell electric vehicles. Electrochemica Acta 2018;292:960–973.

[4] Kang S, Ahn KY. Dynamic modeling of solid oxide fuel cell and engine hybrid system for distributed power generation. Appl Energy 2017;195:1086–1099.

[5] Lee YD, Ahn KY, Morosuk T, Tsatsaronis G. Exergetic and exergoeconomic evaluation of an SOFC-Engine hybrid power generation system. Energy 2018;145:810–822.

[6] Park SH, Lee YD, Ahn KY. Performance analysis of an SOFC/HCCI engine hybrid system: system simulation and thermo-economic comparison. Int J Hydrogen Energy 2014;39:1799–1810.

[7] Wu Z, Tan P, Zhu PF, Cai WZ, Chen B, Yang FS, et al., Performance analysis of a novel SOFC-HCCI engine hybrid system coupled with metal hydride reactor for H2 addition by waste heat recovery. Energy Convers Manage 2019;191:119–131.

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