Applied Energy 161 (2016) 181–196

Contents lists available at ScienceDirect

Applied Energy

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

Dynamic simulation of a fuel cell hybrid vehicle during the federal test procedure-75 driving cycle

Sanggyu Kang [a,b], Kyoungdoug Min [b,*]

[a] Korea Institute of Machinery and Materials, Daejeon 305-343, Republic of Korea
[b] School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-742, Republic of Korea

HIGHLIGHTS

- Development of a FCHV dynamic model.
- Integration of a PEMFC system dynamic model with the electric vehicle model.
- Investigation of the dynamic behavior of the FCEV and PEMFC system during FTP-75.
- Capturing the dynamic correlation among components in PEMFC system during FTP-75.

ARTICLE INFO

Article history:
Received 17 July 2015
Received in revised form 11 September 2015
Accepted 27 September 2015
Available online 22 October 2015

Keywords:
Fuel cell hybrid vehicle (FCHV)
Proton exchange membrane fuel cell (PEMFC)
Dynamic modeling
System and control design
Federal test procedure (FTP)-75 driving cycle

ABSTRACT

The dynamic behavior of a proton exchange membrane fuel cell (PEMFC) system is a crucial factor to ensure the safe and effective operation of fuel cell hybrid vehicles (FCHVs). Specifically, water and thermal management are critical to stabilize the performance of the PEMFC during severe load changes. In the present study, the FCHV dynamic model is developed. The dynamic model of the PEMFC system developed by Matlab–Simulink® is integrated into the electric vehicle model embedded in the Amesim®. The dynamic model of the PEMFC system is composed of a PEMFC stack, an air feeding system, and a thermal management system (TMS).

The component models of PEMFC, a shell-and-tube gas-to-gas membrane humidifier, and a heat exchanger are validated via a comparison with the experimental data. The FCHV model is simulated during a federal test procedure (FTP)-75 driving cycle. One system configuration and control strategy is adopted to attain optimal water and thermal management in the PEMFC system. The vehicle speed obtained from the FCHV model aptly tracks the target velocity profile of the FTP-75 cycle within an error of ±0.5%. The dynamic behavior and correlation of each component in the PEMFC system is investigated. The mass and heat transfer in the PEMFC, a humidifier, and a heat exchanger are resolved to determine the species concentration and the temperature more accurately with discretization in the flow's perpendicular direction. Discretization in the flow parallel direction of humidifier and heat exchanger model makes it possible to capture the distribution of the characteristics. The present model can be used to attain the optimization of the system and control design for the PEMFC system in FCHVs.

1. Introduction

The conventional gasoline and diesel engine has revolutionized the lives of mankind. Although the efficiency and robustness of the conventional engine has increased, demand for alternative green power sources for automobiles is a major issue worldwide due to oil starvation and global warming [1]. A low-temperature proton exchange membrane fuel cell (PEMFC) system is regarded as a promising power source for automobiles due to its fast start-up, high-power density, and zero emissions [2]. Fuel cell hybrid vehicle (FCHV) is one type of vehicle powered by the PEMFC system. Because the dynamic response of the PEMFC stack is relatively low to fully meet the severe load change, PEMFC-powered vehicles could be unstable at the sudden load change [3]. To enhance the stability of a PEMFC-powered vehicle during instantaneous load change, a supplemental device such as a super-capacitor or a battery is installed to back up the relatively slow response of the PEMFC stack [4,5]. There have been many numerical and experimental studies on the estimation of the performance and

* Corresponding author. Tel.: +82 2 880 1661; fax: +82 2 874 2001.
E-mail address: kdmin@snu.ac.kr (K. Min).

http://dx.doi.org/10.1016/j.apenergy.2015.09.093
0306-2619/

Nomenclature

a	water activity (–)
$\underline{A}$	surface area (m^2)
B	species transport coefficient (ms^{-1})
C	solid specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)
C_P	constant pressure gas specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)
$\underline{C}_V$	constant volume gas specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)
C	species molar concentration ($kmol\,m^{-3}$)
D	diameter (m)
D_w	diffusion coefficient of water through electrolyte ($m^2\,s^{-1}$)
$\underline{D}_\lambda$	water diffusivity in Nafion ($m^2\,s^{-1}$)
$\underline{D}$	species diffusion coefficient through GDL ($m^2\,s^{-1}$)
E	total resistance for diffusion of species ($m^3\,s^{-1}$)
E	activation energy ($kJ\,kmol^{-1}$)
F	Faraday's constant (96,485 $C\,mol^{-1}$)
f	friction factor (–)
ΔG	gibbs energy ($kJ\,kmol^{-1}$)
h	enthalpy ($kJ\,kmol^{-1}$), or convection coefficient ($kW\,K^{-1}\,m^{-2}$)
hd	head loss (m)
ΔH	formation enthalpy ($kJ\,kmol^{-1}$)
i_o	exchange current density (Am^{-2})
i	current (A)
J	inertia ($kg\,m^2$)
$\underline{J}(s)$	Leverette function (–)
$\vec{j}$	liquid water flux ($kmol\,s^{-1}$)
j_L	limiting current density (Am^{-2})
k	thermal conductivity ($kW\,m^{-1}$)
L	length (m)
M	molecular weight ($kg\,kmol^{-1}$), or mass (kg)
N	molar capacity, or total number of moles (kmol), or cell number (–)
$\vec{N}$	species molar capacity (kmol)
$\dot{N}$	molar flow rate ($kmol\,s^{-1}$)
n	electron number (–)
n_d	electro-osmotic drag coefficient (–)
P	pressure (kPa), or power (kW), or perimeter (m)
$\underline{q}$	charge (C)
$\dot{Q}$	heat-transfer rate (kW)
R	external load resistance (ohm), or universal gas constant (8.3145 $kJ\,kmol^{-1}\,K^{-1}$)
s	liquid water saturation factor (–)
SOC	state of charge (%)
Sh	sherwood number (–)
T	temperature (K)
t	time (s), or thickness (m)
V	voltage (V), or velocity (ms^{-1})
$\underline{v}$	volume (m^3)
X	species mole fraction (–)

Greek letters

α	road slip (%), or activation overpotential tuning coefficient (–)
β	Ohmic overpotential tuning coefficient (–)
γ	specific heat ratio (–), or activation energy ($kJ\,kg^{-1}$)
ε	GDL mean porosity (–), or stiction coefficient (–)
Φ	species diffusion flux through GDL ($kmol\,s^{-1}$)
Ψ_{H_2O}	water diffusion flux through electrolyte ($kmol\,s^{-1}$)
Θ_{H_2O}	electro-osmotic flux ($kmol\,s^{-1}$)
τ	torque (Nm), or surface tension (Nm^{-1})
θ	contact angle (°)
ρ	density (kgm^{-3})
η	efficiency (–)
λ	membrane water content (–), or stoichiometric coefficient (–)
μ	grip coefficient between tire and ground (–)
ω	angular speed ($rev\,m^{-1}$)
K	permeability (m^2)

Subscripts

act	activation
aero	aerodynamic
B	battery
br	braking
c	capillary, or isentropic
cell	fuel cell
climb	climbing
con	concentration
d	electro-osmotic drag, or demand
distrib	distribution
drv	driving
dyn	Coulomb friction, or dynamic
e	electric
eff	effective
f	friction, or fin
FC	fuel cell system
H	hydraulic
H_2	hydrogen
H_2O	water
in	in-control volume
L	limiting
l	liquid phase, or longitudinal
local	local section
max	maximum
mea	membrane
o	standard condition, or overall
O_2	oxygen
ohm	ohmic
out	out-of-control volume
pore	pore
ref	reference condition
rel	relative
resist	resistive
roll	rolling
s	solid phase
sat	water saturation
t	total
wh	wheel

the establishment of the optimal control logic for PEMFC-powered vehicles. Ryu et al. proposed a novel fuzzy controller for optimum power management of FCHV and evaluated its performance by off-line simulation and hardware in a loop simulation during four driving cycles [6]. Tang et al. manufactured a small vehicle and analyzed the dynamic properties of the hybrid system with Pb-Acid batteries and PEMFC [7]. Fernandez et al. studied the hybrid system composed of PEMFC and the Ni–MH battery. They examined the regenerative braking characteristics of a city train with various driving conditions [8]. Hannan et al. studied the control strategy of the fuel cell-battery hybrid system for light vehicle [9]. The fuel economy of FCHV has been studied by capturing the variation of battery state of charge (SOC) during driving cycle by Zheng et al. [10]. Hwang et al. manufactured FCHV and