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Thermal management system modeling of a water-cooled proton exchange membrane fuel cell

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In water-cooled proton exchange membrane fuel cell (PEMFC) system, a thermal management system which involves coordinating thermal management components such as the coolant circulation pump and radiator fan plays the important role for keeping the output performance of PEMFC in safe and steady condition. In order to avoid coolant temperature fluctuations and prevent thermal runaway, a control-oriented water-cooled system model based on electrochemical reactions and thermodynamic for the thermal management control is established and an experimental system is also developed for model validation. The comparisons between the model results and the experimental data under three different operating conditions (increasing the coolant temperature difference between outlet and inlet, reducing the coolant inlet temperatures, increasing the output current) demonstrate that the proposed model can efficiently simulate the dynamic behaviors with a high accuracy for the changing of the output voltage, the coolant temperature, the coolant flow rate and the controlling voltage of radiator. Therefore, the proposed model will be used as guidance for the design and optimization of the water-cooled PEMFC control system.

Introduction

A proton exchange membrane fuel cell (PEMFC) is an electrochemical power generator with the advantages of high power density, low operating temperature, quick response and no pollution etc. It is widely regarded as an ideal power source for transportation in the future [1]. When electricity is generated by a PEMFC, equivalent heat will be produced and must be released out of the PEMFC system, otherwise temperature of the fuel cell system will be runaway. For a water-cooled PEMFC system, the coolant temperature is one of the most important control parameters, which will affect the gases transfer, water balance, electrochemical reaction activities and influence the fuel cell output performance. A higher operating temperature will benefit the electro catalytic activity and result in better output performance, while it is more difficult to keep the water balance in PEMFC [2–4]. Therefore, effective thermal management is very important to ensure a better performance and longer working life of the PEMFC system.

The PEMFC system contains complex electrochemical reactions and thermal management system with time-varying,

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Nomenclature

A	cell active area, cm^2
C_i	the specific heat of the species i, J/mol/K
c_{O_2}	the gas–liquid interface concentration of oxygen, mol/L
C_e	electromotive force constant
C_T	torque constant
E_{nernst}	the Nernst open circuit voltage, V
F	Faraday's constant
ΔH	the enthalpy of combustion for Hydrogen, kJ/mol
I_{den}	actual current density, A/cm^2
I_{max}	the maximum current density, A/cm^2
I_{st}	stack current, A
l	the thickness of the membrane, cm
M_{st}	PEMFC stack mass, kg
n	number of cells in the stack
N_i	the amount of the species i produced or consumed per unit of time(mol/s)
P	pressure, kPa
P_{st}	the power of the stack, kW
Q	heat, kw
R	the cell membrane impedance, Ω
R_a	the armature resistance, Ω
R_t	thermal radiation, kW/K
T	the load torque, N·m
T_i	the temperature of the species i, K
T_o	the temperature on standard pressure, K
V	voltage, V
W_{cl}	coolant flow rate, kg/s

Greek letter

ρ	membrane resistivity
λ	stoichiometry

Subscripts

act	activation
an	anode
amb	ambient
ca	cathode
cl	coolant
con	concentration
dis	dissipation
gen	generated
ohmic	ohmic
st	stack
tot	total

Superscripts

cre	created
g	gas
in	inlet
l	liquid
out	outlet

non-linear, strong coupling and characteristics of large delay and uncertainty [4–6]. Most of the thermal management models were proposed to analyze the thermal management system and its influences on the PEMFC system. Zhang [7] proposed a 60 kW PEMFC generation system model developed to set the operation conditions of current, temperature, and cathode and anode gas flows and pressures, which had major impacts on system performance. However, some models are more complex. Dumercy [8,9] proposed a 3D thermal modeling by a nodes network model for two PEMFC of 150 and 500 W to describe the temperature and the heat flux distribution in the fell cell stack. Tiss [10], basing on the theory of heat and mass transfer, proposed a dynamic model for the thermal system of a PEMFC, which showed that the fuel cell temperature is a significant function for manipulative the fuel cell output voltage and gas flow. Hosseinzadeh [11]developed a general zero dimensional PEMFC model to analyze the effects of inlet temperature, outlet temperature and temperature gradient on system performance. These proposed models were developed to analyze the influence of the thermal management on the performance of a PEMFC system, but they were not suitable for heat control of a fuel cell system.

Some thermal management models were also developed for system heat control. Some black box models based on experiments were established. Li [12] described a method using Artificial Neural Net-work (ANN) to control the temperature of the PEMFC. The model did not contain the internal mechanism of the thermal management system, which was very useful to understand the heat gain and loss. So it was applicable for specific systems and needed to be trained again for other systems. Some authors proposed models based on the mechanism of thermal management system. According to the conservation equations of mass and energy, Li [13,14] proposed a control-oriented thermal model of PEMFC stack, which can be used to reflect actual temperature response of PEMFC stack. However, the expressions of this model were too complicated to be used in the design of control. Yu [15] proposed a water and thermal management model for a Ballard PEMFC stack to predict the dynamic information regarding to stack temperature, cell voltages, and power as functions of time. Zhang [16] represented the fuel cell stack by a lumped thermal mass model, which shows an assessment of the effect of operating parameters and parameter interactions on the system thermal performance. Hu [17] presented a coolant circuit modeling method and a temperature fuzzy control strategy to keep the PEMFC within the ideal operation temperature range. Ahn [18] proposed a new temperature control strategy based on a thermal circuit, and classic proportional and integral (PI) controllers and a state feedback control for the thermal circuit were used in the design. Most of the proposed models were built to verify their thermal management control method in theory, but the study on verifying the accuracy and validity of the models with experimental results were very limited.

Aim at developing a control-oriented model for the thermal management control of a water-cooled PEMFC system, a semi-mechanical semi-empirical thermal management model is proposed in this paper and the modeling results are compared with experimental data for three different working conditions. Results show that the model has very good accuracy to reveal the transit changes with the same control parameters set for both the model and experiments. The model developed in this paper could be used as guidance for design and optimization of the water-cooled PEMFC control system.

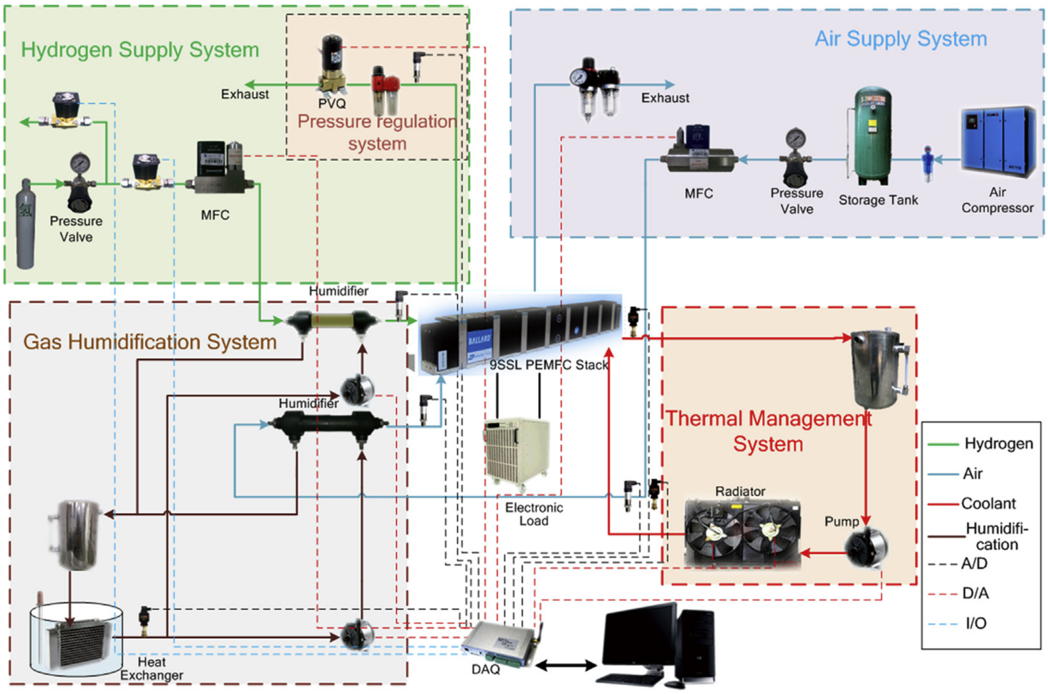

Fig. 1 – System structure of the experimental platform.

Experimental

Water-cooled PEMFC system

In this paper, a PEMFC test system based on a water-cooled PEMFC stack with 75 cells (Ballard, FCvelocity®-9SSL) has been built. The test system structure is shown in Fig. 1.

The water-cooled PEMFC test platform consists of the PEMFC stack, air supply system, hydrogen supply system, thermal management system, gas humidification system and control system. Power generated by the fuel cell is consumed away by an electronic load (ITECH, IT8816B) and the experimental data are collected and recorded with a data acquisition card (ZTYC, USB7635BD) and two paperless recorders (Hangzhou Pangu, KT800). The PEMFC's operating temperatures, reactants pressures, flow rates, the output currents and voltages are sampled by different sensors, which are converted to voltage signals for the data acquisition card. And then these signals are transmitted to the control system via USB interface and are displayed in real time on the control system screen. The PEMFC multifunction test platform is shown in Fig. 2.

Heat management system

The schematic diagram of the PEMFC thermal control system is shown in Fig. 3. The primary control objective is the operating temperature of the PEMFC, by adjusting the rotation speeds of the radiator fans and the circulating water pump. Both the fans and the pump are driven by DC motors in the practical system.

Coolant is driven by the circulating water pump to flow through the heat radiator and the PEMFC stack. It removes the heat generated by the PEMFC stack. Then the heat is released to the environment by the radiator. The control voltage of the water pump motor is adjusted to control the temperature difference between the coolant inlet and outlet of the PEMFC stack, and the control voltages of the fans are adjusted to control the coolant inlet temperature.

Experimental methods

In order to verify the accuracy of the heat management model, three experiments are carried out and the fuel cell output

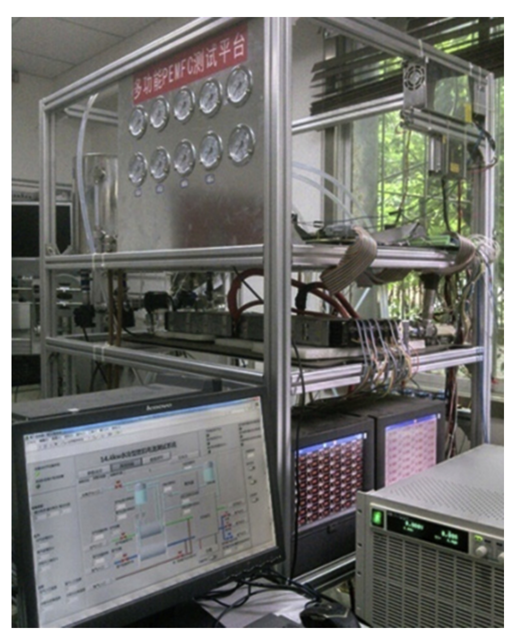

Fig. 2 – The water-cooled PEMFC experimental platform.

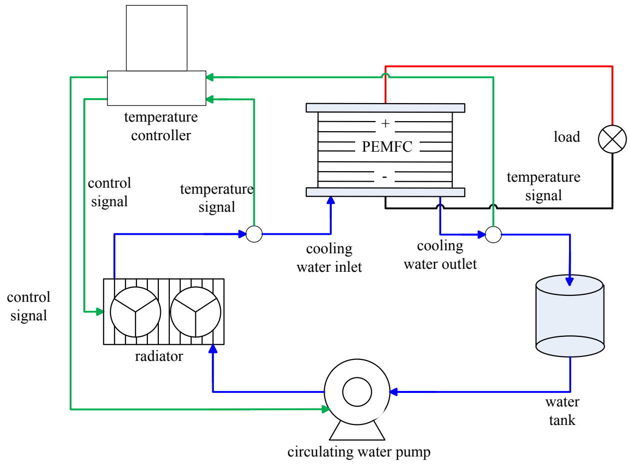

Fig. 3 – Schematic diagram of the PEMFC's heat management system.

voltages, coolant flow rates, temperatures are recorded and compared with the model results during transit changes:

Case 1. Increasing the coolant temperature difference between outlet and inlet: keep the fuel cell output currentat70A, the coolant inlet temperature at50 °C and the temperature difference between coolant inlet and outletat5 °C, then increase the coolant temperature difference from 5 °C to 6 °C. Record the data from the beginning of the change to steady state.
Case 2. Reducing the coolant inlet temperatures: keep the fuel cell output current at 70A, the coolant temperature difference between outlet and inlet at6 °C, then increase the coolant inlet temperature from 52 °Cto 50 °C.
Case 3. Increasing the output current: keep the coolant inlet temperature at 50 °C, the coolant temperature difference between outlet and inletat5 °C, then increase the fuel cell output current from 60 A to 70 A.

Dynamic model of PEMFC thermal management system

Based on the specific heat equation $Q = CM\Delta T$, the relation between the gain and loss of heat and the temperature of the PEMFC per unit of time is [15]:

$$C_{st}M_{st}\frac{dT_{st}}{dt} = Q_{gen} - Q_{dis} = (Q_{tot} - P_{st}) - \left(Q_{gas} + Q_{cl} + Q_{abm}\right) \qquad (1)$$

where Q represents the produced or lost heat flux.

In order to simplify the thermal management model, some assumptions are set:

1. The temperature of the PEMFC stack equals to the coolant outlet temperature [16];
2. The reactants are assumed to be ideal gases;
3. The reactants are fully humidified;
4. The membranes of the PEMFC stack are fully saturated;
5. The pressure difference inside the PEMFC stack is neglected.

Heat production

For the reaction of hydrogen and oxygen, the chemical energy Q_{tot} is converted to electrical power P_{st} and heat, so the heat generated Q_{gen} is:

$$Q_{gen} = Q_{tot} - P_{st} \qquad (2)$$

The chemical energy
According to the chemical equation

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad \Delta H = 285.8\text{kJ/mol} \qquad (3)$$

The gas consumption and the water production per unit of time [19]

$$N^{rec}_{ca.O_2} = \frac{nI_{st}}{4F} \qquad (4)$$

$$N^{rec}_{an,H_2} = \frac{nI_{st}}{2F} \qquad (5)$$

$$N^{gen}_{ca,H_2O} = \frac{nI_{st}}{2F} \qquad (6)$$

Chemical energy of hydrogen fuel per unit of time

$$Q_{tot} = \Delta H \times N^{rec}_{an,H_2} \qquad (7)$$

The output power of the PEMFC
According to the power formula $P_{st} = nV_{cell}I_{st}$, a single voltage model of the PEMFC is needed to build. The output voltage consists primarily of the Nernst open circuit voltage E_{nernst}, the activation polarization voltage V_{act}, the concentration polarization voltage V_{con} and ohmic polarization voltage V_{ohmic} [20,21].

$$V_{cell} = E_{nernst} - V_{act} - V_{ohmic} - V_{con} \qquad (8)$$

The Nernst open circuit voltage is related to the operating temperature and the oxygen partial pressure in the cathode and the hydrogen partial pressure in the anode:

$$E_{nernst} = 1.229 - 8.5 \times 10^4(T_{st} - 298.15) + 4.308 \times 10^{-5} \times T_{st} \times \left[\ln P_{H_2} + 0.5 \times \ln P_{O_2}\right] \qquad (9)$$

The oxygen partial pressure and the hydrogen partial pressure are related to the operating temperature and the pressure of cathode and anode [22]. For simplicity, they are approximately treated as follow.

$$P_{H_2} = 0.99P_{an} \qquad (10)$$

$$P_{O_2} = 0.21P_{ca} \qquad (11)$$

In the PEMFC test system, the air flow controlled by the mass flow meter is different under different output currents. Therefore, the cathode pressure will vary with different air flows without back-pressure valve. This is very similar to an actual fuel cell system with an air compressor for oxidant supply. In order to reflect more accurately the PEMFC's pressure, the cathode pressure is measured under different output currents with experiments. The relationship between the cathode pressure and output current is polynomial fitted, as shown in Fig. 4.

The fitting formula is:

$$P_{ca} = 1000 \times \left(-6.085e - 006 I_{st}^3 + 0.002767 I_{st}^2 + 0.1527 I_{st} + 12.1\right) \quad (12)$$

For the anode, a proportional valve is added to the outlet of hydrogen exhaust hose to control the anode inlet pressure a little greater than the cathode by 0.2 bar, so the anode pressure is set 0.2 bar higher than the cathode pressure in the simulation model.

$$P_{an} = P_{ca} + 20 \quad (13)$$

Concentration of oxygen c_{O_2} is the gas–liquid interface concentration of O_2. According to the Henry theorem [5,23]:

$$c_{O_2} = 1.97 \times 10^{-7} \times P_{ca,O_2} \times \exp(498/T_{st}) \quad (14)$$

According to Tafel equations, the activation polarization voltage is:

$$V_{act} = -\left[\xi_1 + \xi_2 T + \xi_3 T \ln(c_{O_2}) + \xi_4 T \ln(I_{st})\right] \quad (15)$$

where, ξ_1, ξ_2, ξ_3, ξ_4 are the system experience parameters of the Ballard's PEMFC stack.

The ohmic loss can be expressed as [24–26]:

$$V_{ohmic} = I_{st} R \quad (16)$$

The cell membrane impedance R can be expressed as:

$$R = \frac{\rho \times l}{A} \quad (17)$$

The membrane resistivity ρ is a function with the current, the active area, the water content of the membrane. l is the thickness of the membrane.

The concentration polarization loss can be expressed as:

$$V_{con} = -B \times \ln\left(1 - \frac{I_{den}}{I_{\max}}\right) \quad (18)$$

where, B is the coefficient, I_{den} is the actual current density, $I_{\max}$ is the maximum current density.

The ideal electrode potential for oxygen reduction reaction is1.229 V, but due to the impurities, it is a mixed potential on 1.0~1.1 V [27]. In this paper, the experimental open circuit voltage is used instead of the ideal potential. So the Nernst open circuit voltage is:

$$E_{nernst} = 1.009 - 8.5 \times 10^4 (T_{st} - 298.15) + 4.308 \times 10^{-5} \times T_{st} \times \left[\ln P_{H_2} + 0.5 \times \ln P_{O_2}\right] \quad (19)$$

Based on the above voltage model of the PEMFC, the simulation polarization curve of the PEMFC stack consisting of 75 single cells is shown in Fig. 5, which matches the experimental results very well.

Heat dissipation model

Heat dissipated from the fuel cell system includes heat carried out by reactants exhausts Q_{gas}, heat removed by coolant Q_{cl} and thermal radiation heat Q_{amb}:

$$Q_{dis} = Q_{gas} + Q_{cl} + Q_{amb} \quad (20)$$

The heat carried out by reactants exhausts

The heat carried out by reactants exhausts equals to the difference between heat in the inlet gases and the outlet gases [15].

$$Q_{gas} = Q^{out} - Q^{in} \quad (21)$$

The hydrogen and air inlet flow rates are:

$$N^{in}_{an,H_2} = \lambda_{H_2} N^{rec}_{an,H_2} \quad (22)$$

$$N^{in}_{ca.air} = \lambda_{O_2} N^{rec}_{ca,O_2} \big/ 0.21 \quad (23)$$

According to Antoine equation, the saturated vapor pressure can be expressed as [17,23]:

$$P_{sat} = 1000 \times \exp(9.3876 - 3826.36/(T_{st} - 45.47)) \quad (24)$$

The water vapor in the reactants can be calculated:

$$N^{in}_{an,H_2O} = \frac{P_{sat}\left(T^{in}_{an}\right)}{P_{an} - P_{sat}\left(T^{in}_{an}\right)} N^{in}_{an,H_2} \quad (25)$$

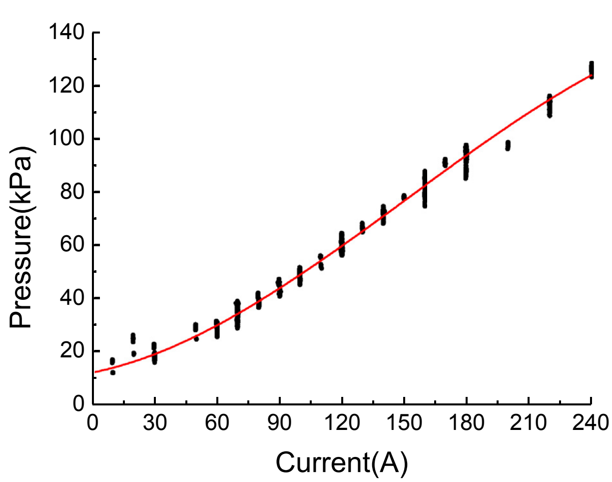

Fig. 4 – Fitted curves of the cathode pressure.

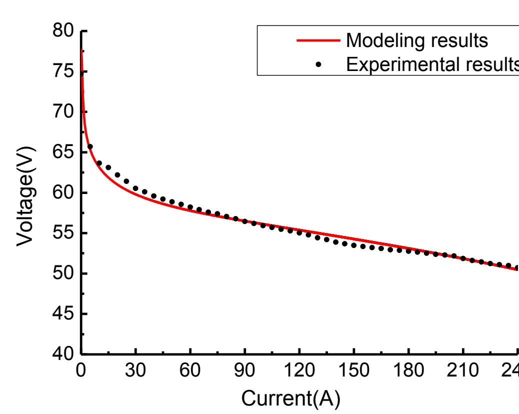

Fig. 5 – The simulation and experimental polarization curves of the fuel cell stack.

$$N^{in}_{ca,H_2O} = \frac{P_{sat}\left(T^{in}_{ca}\right)}{P_{ca} - P_{sat}\left(T^{in}_{ca}\right)} N^{in}_{an,air} \tag{26}$$

The heat in the inlet reactants is:

$$Q^{in} = \left(N^{in}_{an,H_2} C_{H_2} - N^{in}_{an,H_2O} C^g_{H_2O}\right)\left(T^{in}_{an} - T_o\right) + \left(N^{in}_{ca,air} C_{air} - N^{in}_{ca,H_2O} C^g_{H_2O}\right) \times \left(T^{in}_{ca} - T_o\right) \tag{27}$$

Since the oxygen in the air is consumed and the nitrogen does not react, the outlet gas composition changes. The heat of the oxygen and nitrogen are considered separately in this paper [15].

$$N^{out}_{an,H_2} = N^{in}_{an,H_2} - N^{rec}_{an,H_2} \tag{28}$$

$$N^{out}_{ca,N_2} = 0.79 N^{in}_{ca,air} \tag{29}$$

$$N^{out}_{ca,O_2} = 0.21 N^{in}_{ca,air} - N^{rec}_{ca,O_2} \tag{30}$$

The water vapor contained in the outlet gas is:

$$N^{out}_{an,H_2O} = \frac{P_{sat}\left(T^{out}_{an}\right)}{P_{an} - P_{sat}\left(T^{out}_{an}\right)} N^{out}_{an,H_2} \tag{31}$$

$$N^{out}_{ca,H_2O} = \frac{P_{sat}\left(T^{out}_{ca}\right)}{P_{ca} - P_{sat}\left(T^{out}_{ca}\right)} \left(N^{out}_{ca,N_2} + N^{out}_{ca,O_2}\right) \tag{32}$$

Assuming that water is only drained from cathode exhaust and according to conservation of substances, the flow rate of water is:

$$N^{out}_{ca,H_2O,l} = N^{in}_{an,H_2O} + N^{in}_{ca,H_2O} + N^{gen}_{ca,H_2O} - N^{out}_{an,H_2O} + N^{out}_{ca,H_2O} \tag{33}$$

The heat in the outlet reactants is:

$$Q^{out} = N^{out}_{an,H_2} C_{H_2}\left(T^{out}_{an} - T_o\right) + \left(N^{out}_{an,H_2O} C^g_{H_2O} + N^{out}_{ca,O_2} C_{p,O_2} + N^{out}_{ca,N_2} C^g_{N_2} + N^{out}_{ca,H_2O} C^g_{H_2O} + N^{out}_{ca,H_2O,l} C^l_{H_2O}\right)\left(T^{out}_{ca} - T_o\right) \tag{34}$$

In the PEMFC test system, hydrogen and air will be heated to get a temperature equaling to the coolant inlet temperature and humidified in humidifiers before entering the fuel cell stack. Therefore, in the model, ignoring the response time of the gas heating subsystem, we assume that the gas inlet temperatures of the cathode and anode are equal to the coolant inlet temperature, and the gas outlet temperatures are equal to the coolant outlet temperature.

$$T^{in}_{ca} = T^{in}_{an} = T^{in}_{st} \tag{35}$$

$$T^{out}_{ca} = T^{out}_{an} = T_{st} \tag{36}$$

The heat dissipated by coolant

According to the heat balance equation, the heat brought out from the PEMFC by the coolant is:

$$Q_{cl} = W_{cl} C_{H_2O}\left(T_{st} - T^{in}_{st}\right) \tag{37}$$

From the above equation, two affecting factors of the heat dissipated by coolant are the coolant flow rate W_{cl} and the coolant inlet temperature T^{in}_{st}.Namely, the control objects are the circulating water pump and the radiator fan. Since both are driven by DC motor, the models are similar. The example of DC pump is described as follows.

The relationship between the number of revolutions of the DC motor and the motor voltage is as follows [28].

$$n_m = \frac{\sqrt{C_T} V}{C_e \sqrt{C_\varphi T}} - \frac{R_a}{C_e C_\varphi} \tag{38}$$

where, C_e, C_e and C_e are the motor constants. R_a is the armature resistance. T is the load torque, and its square is approximately proportional to the number of revolutions. The scale factor is set as K_1. The scale factor between the motor voltage (V) and motor controller output voltage (V_c) is set as K_2. According to the equation (38), the number of revolutions of the motor can be described as:

$$n_m = \left(-\frac{R_a}{C_e C_\varphi} + \sqrt{\frac{R_a}{C_e C_\varphi}^2 + 4\frac{K_2\sqrt{C_T}}{C_e\sqrt{C_\varphi K_1}} V_c}\right) \Big/ 2 \tag{39}$$

Assuming the number of revolutions of the pump is proportional to coolant flow rate and the scale factor is K_3, the coolant flow rate is:

$$W_{cl} = K_3\left(-\frac{R_a}{C_e C_\varphi} + \sqrt{\frac{R_a}{C_e C_\varphi}^2 + 4\frac{K_2\sqrt{C_T}}{C_e\sqrt{C_\varphi T}} V_c}\right) \Big/ 2 \tag{40}$$

By fitting the experimental data, the equation (40) can be described as:

$$W_{cl} = \left(-b + \sqrt{b^2 + 4aV_c}\right) \Big/ 2 \tag{41}$$

where, a, b are the fitting parameters based on the experimental data.

The model of the radiator fan is similar to the pump. But for the radiator fan, it is assumed that the air temperature downstream $T^{out}_{rad,air}$ equals to arithmetic average temperature of coolant inlet and outlet ($T^{in}_{rad,cl}$ and $T^{out}_{rad,cl}$). So, after passing through the radiator, the coolant outlet temperature is as follow.

$$T^{out}_{rad} = T^{in}_{st} = T^{in}_{rad} - \frac{Q_{rad}}{W_{cl} C_{cl}} \tag{42}$$

$$Q_{rad} = C_{air} W_{air}\left(T^{out}_{rad,air} - T_{atm}\right) \tag{43}$$

Thermal radiation

The heat dissipated by the thermal radiation is the ratio of the temperature difference between the PEMFC stack and the environment to the thermal radiation [17].

$$Q_{atm} = (T_{st} - T_{atm})/R_t \tag{44}$$

Based on the above equations, the thermal management system modeling of the water-cooled PEMFC is built with the Matlab/Simulink.

Results and analysis

As a PID controller is used in the PEMFC test system, the control strategies and parameters used in the simulation model are identical to the actual parameters.

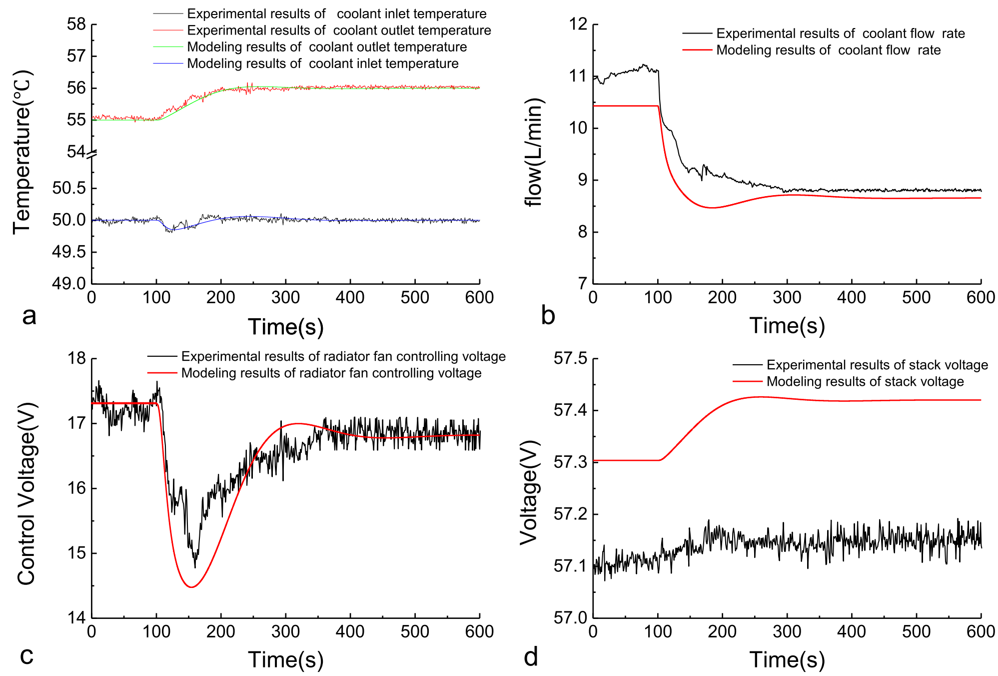

Fig. 6 – Results for case one.

In each case, five different data were compared between the experimental and modeling results. In the results for each case, Fig. 6a is the coolant inlet and outlet temperatures; Fig. 6b is the coolant flow rate; Fig. 6c is the radiator fan controlling voltage; Fig. 6d is the stack voltage. Experimental and modeling results are shown as follow.

Results for case1

From Fig. 6a, the coolant outlet temperature starts to increase slowly at 100 s. After approximately 100 s, the outlet temperature reaches the set value. The experimental results match the simulation results with a very small error margin.

As shown in Fig. 6a, the inlet temperature decreases at approximate 100 s, thereafter returned to the set value (50 °C). Because the coolant inlet temperature is affected by the coolant pump and the radiator fan, when the difference between the coolant outlet water temperature and inlet temperature is changed from 5 °C to 6 °C, the radiator fan controlling voltage decreases (Fig. 6c) and the wind speed decreases, but the coolant flow rate decreased sharply (Fig. 6b). As a result, coolant will spend more time through the

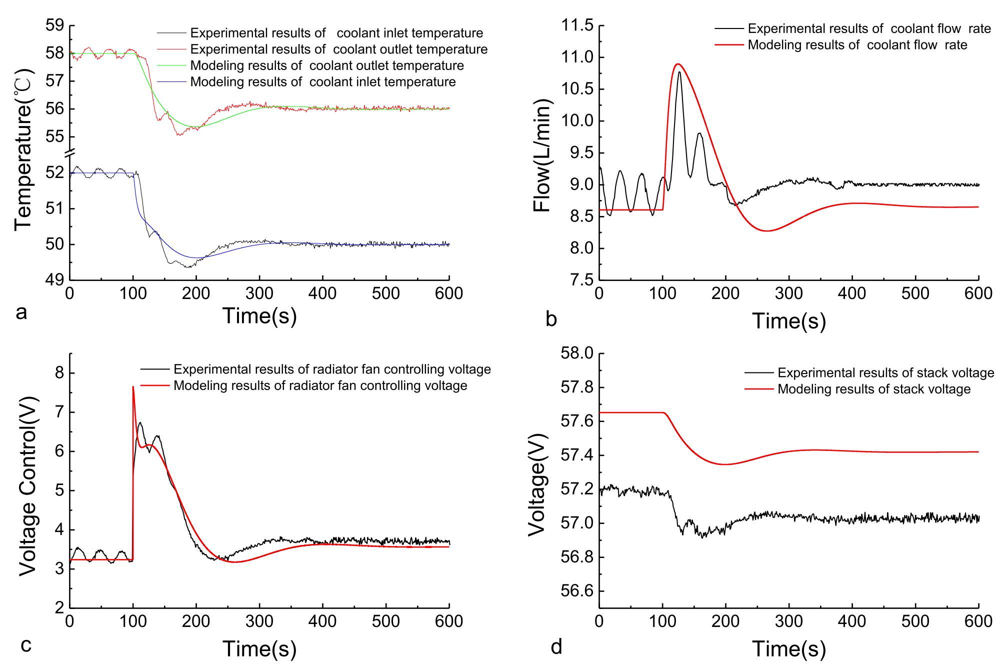

Fig. 7 – Results for case two.

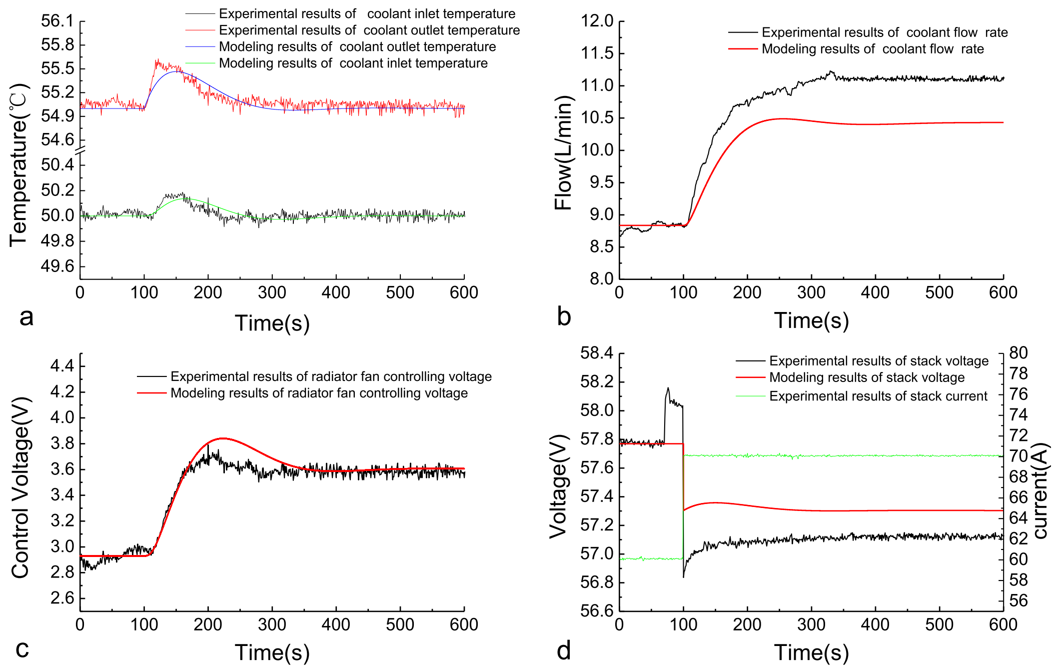

Fig. 8 – Results for case three.

radiator and the radiator fan will bring out more heat. So the coolant temperature drops when it leaves the radiator outlet.

In Fig. 6d, after 100 s, it shows that the stack voltage has a slight rise in the both modeling and experimental results. Because the coolant outlet temperature is set as the fuel cell operating temperature in the model and the outlet temperature rises causing the fuel cell electrochemical reaction activity to increase, the stack voltage has a slight rise in the modeling results. From the experimental results, it also shows that the coolant outlet temperature has an effect on the stack voltage.

Results for case2

From Fig. 7a, the curves of the coolant inlet and outlet temperatures show that the coolant outlet temperature decreased from 52 °C to 50 °Cat 100 s.After 150 s, the coolant inlet and outlet temperatures drop down to the set value. The temperature has a slight overshoot at 150 s, which is caused by the control method. In Fig. 7a, the inlet and outlet temperatures experience a shock before time is100 s. The reason is that the water pump and the radiator fan should be asked to work coordinately in the thermal management of the fuel cell. But in the actual experiment, due to the inconsistent coordination between water pump and fan, the radiator fan controlling voltage (Fig. 7c) and the coolant flow rate (Fig. 7b)experience a periodical shock, thus resulting the temperature shock at the inlet and outlet temperatures.

InFig. 7d, the stack voltage has arisen after the first drop. The season is the influence of the stack temperature on the stack voltage. From the Fig. 7a,b and d, it is shown that the Changing trends are similar between the stack voltage and the stack temperature. These validate the influence of the stack temperature on the stack voltage.

Results for case3

From Fig. 8a, the curve of the coolant inlet and outlet temperature shows that the stack output current increases from 60 A to 70 A at 100 s, and the coolant inlet and outlet temperatures have an increase, and then decrease gradually to the set value. The reason is when the stack output current increases, the heat generated by the entire system instantly increase, but the system has not enough responding time, causing the coolant inlet and outlet temperatures to increase slightly. Then in order to shed excess heat, the radiator fan controlling voltage increases (Fig. 8c), the number of revolutions increases; coolant flow rate increases (Fig. 8b), making the coolant inlet and outlet temperature to decrease gradually to the healthy set value.

Fig. 8d is the curve of the stack voltage. As seen from the figure, at 100 s, the current rises and the output voltage drops. The simulation and experimental results show the same trend. But at approximately 75 s, there is an upward step in the curve of the experimental results due to the experimental operation. To ensure that there will be a sufficient amount of fuel gas when the current changes, the Gas flow rate corresponding to 70 A is given in advance. So, there will be an increase in both the pressure inside the stack and the stoichiometry of the gas, which will result in an increase of the stack voltage.

From the modeling and experimental results of the three programs, it is shown there are some errors between the temperature model and the experiment system, but the model can well reflect the temperature dynamic change, and the modeling results are consistent with the change tendency of the actual system. And the model can well reflect the influence of the temperature of the stack on the output characteristic of the stack. The errors are controlled in an acceptable range, so the model is accurate and effective.

Conclusions

In this paper, semi-mechanical semi-empirical thermal management model of a water-cooled PEMFC system is proposed and validated with experimental data of three different working conditions (increasing the coolant temperature difference between outlet and inlet, reducing the coolant inlet temperatures, increasing the output current). Simulation results including coolant temperatures, stack voltages, coolant flow rates and radiator fan controlling voltages are compared with experimental data of all three cases. The results show that the model matches experiments very well under the same control parameters. The proposed thermal management model in this paper can be used as guidance for the design and optimization of the water-cooled PEMFC control system.

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