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# A study of operation strategy of cooling module with dynamic fuel cell system model for transportation application

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ABSTRACT

A fuel cell system model with detailed cooling module model was developed to evaluate the control algorithms of cooling module which is used for the thermal management of a proton exchange membrane fuel cell (PEMFC) system. The system model is composed of a dynamic fuel cell stack model and a detailed dynamic cooling module model. To extend modeling flexibility, the fuel cell stack model utilizes analytic approach to capture the transient behavior of the stack temperature corresponding to the change of the coolant temperature and the flow rate during load follow-up. The cooling module model integrated model of fan, water pump, coolant passage, and electric motors so that the model is capable of investigation of operating strategy of pump and fan.

The fuel cell system model is applied to the investigation of the control logics of the cooling module. Since, it is necessary for the control of cooling module to define the reference conditions such as coolant temperature and fuel cell stack temperature, this study presents such thermal management criteria. Finally, two control algorithms were compared, a conventional control algorithm and a feedback control algorithm. As a consequence, the feedback control algorithm was found to be more suitable for the cooling module of the PEMFC stack, as they consume less parasitic power while producing more stack power compared to a conventionally controlled cooling module.



## 1. Introduction

The fuel cell vehicle has emerged as a solution stringent exhaust emission regulation such as zero-emission. A proton exchange membrane fuel cell (PEMFC) is the most attractive candidate in many types of fuel cells due to competitive power density, compactness, silent operation, low operating temperature and relatively simple design. To be viable the PEMFC in the market, substantial progress remains to be accomplished in water and management.

Different from micro-scale analysis, system level analysis is to design and control the fuel cell away from very harmful water and thermal management conditions. Jay conducted the system level study to determine proper control algorithm of turbo-blower for automotive fuel cells [1] but his system model is an isothermal model. Fuel cell system developers [2,3] recognized the technical challenges of thermal management systems such that the cooling capacity requirements of a fuel cell vehicle are significantly greater than that of a conventional. Recently, system modelers consider design of thermal management of fuel cell stack [4–7]. Earlier research of unit PEMFC has been limited mainly to isothermal models without thermal management [8–11]. Some models [12,13] have shown exceptionally valuable results as they pertain to water/thermal management. Amphlett *et al.* [14] developed a lumped transient thermal model with an empirical correlation and Francesco *et al.* [15] developed a lumped transient thermal model with an analytic water transport model.

This study is to conduct evaluation of control algorithms for the thermal management of a vehicular fuel cell. To extend range of system analysis, this study selects analytic fuel cell stack model so that the output of stack can describe thermal, electrochemical behavior during load changes. The comprehensive cooling module model is composed of water pump with the electric motor model, two-dimensional radiator model, fan with electric motor model and model for pressure drops through coolant passage and through compartment. Finally, the control strategies of cooling module were evaluated with the fuel cell system model.

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**Nomenclature**

| | |
|---|---|
| $A$ | area ($cm^2$) |
| $c$ | concentration ($mole/cm^3$) or specific heat (kJ/kg/K) |
| $F$ | Faraday's constant ($C/mole$) |
| $\Delta g_f^0$ | Gibb's free energy at STP ($J/mole$) |
| $h$ | convective heat transfer coefficient ($W/m^2s$) |
| $\Delta H$ | difference of Enthalpy (kJ/kg) |
| $J$ | current density ($A/cm^2$) |
| $m$ | mass flow rate($kg/s$) |
| n | number of cells |
| N | rotational speed (rpm) |
| $p$ | perimeter ($m$) or total pressure ($atm$) |
| $P$ | power ($W$) |
| $\Delta p$ | pressure difference ($kPa$) |
| Pr | pressure ration |
| Q | volumetric coolant flow rate ($m^3/s$) |
| $R$ | universal gas constant ($J/mol\ K$) |
| $R_{mem}$ | local membrane resistance, ($\Omega\ cm^2$) |
| $T$ | temperature ($K$) |
| $V$ | electric potential ($V$) |
| U | Velocity ($m/s$) |
| $\eta$ | Overpotential (V) |
| $\rho$ | density ($g/cm^2$) |

*Subscripts and superscripts*

| | |
|---|---|
| $a$ | amature |
| $act$ | active area |
| $air$ | air side |
| $amb$ | ambient condition |
| $avg$ | average |
| $A$ | anode side |
| $c$ | coolant |
| $condenser$ | condenser of air conditions |
| $C$ | cathode side |
| $cp$ | compressor |
| $fan$ | cooling fan |
| $frict$ | frictional pressure drop |
| $FC$ | fuel cell |
| $g$ | gas |
| $grill$ | radiator grill |
| $gross$ | gross power |
| $H_2$ | hydrogen |
| $in$ | inlet |
| $mem$ | membrane |
| $net$ | net power |
| $N_2$ | nitrogen |
| $o$ | outlet |
| $O_2$ | oxygen |
| $pump$ | cooling pump |
| $ram$ | ram air |
| $sat$ | saturation |
| $th$ | thermal management system |
| $w$ | water vapor |
| $\infty$ | free stream |

## 2. Modeling approach

### 2.1. Modeling of a PEMFC stack

The temperature distribution inside the fuel cell and through the stack can affect on the potential change of the fuel cell. However, when the system level simulation is considered, it is very difficult to simulate the cell to cell variation of temperature and mass flow rate due to computational load. Accordingly, a stack is assumed to be a simple extension of unit fuel cells without any mass and temperature among cells. Table 1 shows the specifications of the PEMFC stack. Electrochemistry of our previous model [16] is applied to the development of system model without any modification and the transient thermal response of stack is only presented. The maximum potential of the electrochemical reaction is formulated by the Nernst potential ($V_{Nern}$):

$$V_{Nern} = -\frac{\Delta g_f^o}{2F} + \frac{RT}{2F}\ln\left(\frac{p_{H_2} p_{O_2}^{1/2}}{p_{H_2O}}\right) \quad (1)$$

the electrical resistance ($R_{mem}$) in the membrane electrolyte is determined by water transport model, and the cathode overpotential ($\eta$) is determined by the electrochemical reaction model [16]. The electric potential of a fuel cell is:

$$V_{FC} = V_{Nern} - J\cdot R_{mem} - \eta \quad (2)$$

thus, the electric work ($W_{el}$) of a PEMFC stack produced by a chemical reaction is:

$$W_{el} = V_{FC}\cdot J\cdot n_{FC} \quad (3)$$

. a control volume analysis of the energy conservation of a lumped transient thermal PEMFC stack model was established with the PEMFC stack shown in Fig. 1.

$$\rho\cdot c_p\cdot V\frac{dT_{FC}}{dt} = \Delta H - W_{el} - Q_c - Q_g \quad (4)$$

here, $\Delta H = \sum_{in}\dot{m}h_i - \sum_{out}\dot{m}h_i$.

The energy conservation of the transient thermal model, Eq. (4), has three unknowns the temperature of the fuel cell system ($T_{FC}$), the heat rejection to bulk gases ($Q_g$), and the heat rejection to coolant ($Q_c$). The heat transfer to the bulk gas is derived from the energy conservation of gases.

$$T_{g,out} = T_{FC} + (T_{g,in} - T_{FC})\exp\left(-\frac{h_g A_g}{\sum \dot{m}_{g,i} c_{p,g}}\right) \quad (5)$$

**Table 1**
The Parameters of a FC stack.

| Parameters | Value |
|---|---|
| Fuel cell length ($l$) | 0.196 ($m$) |
| Fuel cell width ($w$) | 0.196 ($m$) |
| Catalyst layer thickness ($z_{act}$) | $1.29\times10^{-5}$ ($m$) |
| Membrane thickness ($t_{mem}$) | $1.08\times10^{-4}$ ($m$) |
| Characteristic length ($L$) | 1 ($\mu m$) |
| Ratio of specific area of solid electrolyte to char. thickness of electrolyte ($\delta/a$) | $6.5\times10^{-10}$ ($m$) |
| Electrode porosity ($\varepsilon$) | 0.5 |
| Fuel cell temperature ($T_{FC}$) | 75 ($^\circ C$) |
| Total pressure ($P_C$, $P_A$) | 3 ($atm$) |
| Number of cells in FC stack | 400 |
| $\nu_{H_2}$,$\nu_{O_2}$ | 1.05, 2.0 |
| Equivalent weight ($M_m$) | 1100 ($kg/kmol$) |
| Dry density of membrane ($\rho_{dry}$) | 2.0 ($kg/m^3$) |
| Charge transfer coefficient ($\beta$) | 1.24 |
| Exchange current density ($j_0$) | $2.5\times10^{-4}$ ($A/cm^2$) |