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Control-orientated thermal model for proton-exchange membrane fuel cell systems

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ABSTRACT

A lumped parameter dynamic model is developed for predicting the stack temperature, temperatures of the exit reactant gases and coolant water outlet in a proton-exchange membrane fuel cell (PEMFC) system. A dynamic model for a water pump is also developed and can be used along with the thermal model to control the stack temperature. The thermal and water pump models are integrated with the air flow compressor and PEMFC stack current–voltage models developed by Pukrushpan et al. to study the fuel cell system under open and closed-loop conditions. The results obtained for the aforementioned variables from open-loop simulation studies are found to be similar to the experimental values reported in the literature. Closed-loop simulations using the model are carried out to study the effect of stack temperature on settling times of other variables such as stack voltage, air flow rate, oxygen excess ratio and net power of the stack. Further, interaction studies are performed for selecting appropriate input–output pairs for control purpose. Finally, the developed thermal model can assist the designer in choosing the required number of cooling plates to minimize the difference between the cooling water outlet temperature and stack temperature.

1. Introduction

Fuel cells are electrochemical reactors which directly convert chemical energy to electrical energy. Fuel cells are typically classified based on the type of electrolyte used in the cell. The proton-exchange membrane fuel cell (PEMFC) is widely studied and attains its name from the use of a polymer membrane as the electrolyte. Most of the current research and development activity focuses on the PEMFC due to its versatile features such as high power density, relatively fast start-up, and short response times to changes in the power demand.

In automobile applications, an important requirement is that the stack should meet the load demands of a varying profile with short transient times. In this regard, knowledge of the stack in terms of steady state and transient behaviour is of critical importance. The dynamic behaviour of a PEMFC system is strongly dependent on the reactant flows and the water and thermal management. One of the several challenges that arise in the control of a PEMFC system is the level of interaction among these various factors such that an interaction study is necessary [1] to understand the relative importance of these parameters. In fact, water and thermal management have become the key technical challenges for fuel cell technology to be feasible for transportation applications. Proper thermal and water management is in fact, also essential to achieve optimum performance from PEMFC stacks [2,3].

Mathematical models play an important role in supporting the design and enhancing the understanding of the effect of parameters on the performance of the stack and fuel cell auxiliary systems. Studies based on these models are useful for the optimum design and control of a real-time stack. Two modeling approaches can be found in the literature. The first gives rise to what are known as *mechanistic* models [4–6] which use an in-depth knowledge of the electrochemistry, heat transfer and mass transfer that are involved in the fuel cells. Such models explain the fundamental processes occurring in fuel cell systems, and are developed as 1D, 2D and 3D models depending on the assumptions involved therein. These dimensional models for thermal and water management, which are summarized in [7,8], require iterative methods to solve the underlying differential and partial differential equations, thereby making them computationally intensive. In essence, the mechanistic models are suited for *design and optimization* of the individual cell components, rather than for control and monitoring of the stack. The second approach includes models that are based on *empirical* or *semi-empirical* equations which are applied to predict the effect of different input parameters on the *voltage–current* characteristics of the fuel cell [9–11]. When compared with the *mechanistic*

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Nomenclature

A	area (m^2)
C_p	specific heat capacity ($J\,mol^{-1}\,K^{-1}$)
g	gravity constant ($m\,s^{-2}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
ΔH	heat of reaction ($J\,mol^{-1}$)
I	current (A)
J	moment of inertia ($kg\,m^2$)
k	thermal conductivity of air ($W\,m^{-1}\,K^{-1}$)
L	length of stack (m)
m	mass (kg)
M	molar mass ($mol\,g^{-1}$)
n	number of cells in stack
N	molar flow rate ($mol\,s^{-1}$)
N_{pr}	Prandtl number
PEM	proton-electrolyte membrane
Q	water flow rate ($L\,s^{-1}$)
$\dot{Q}$	energy (W)
Ra	Rayleigh number
T	temperature (K)
V	stack voltage (V)
W	mass flow rate ($kg\,s^{-1}$)

Greek letters

ν	kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
ω_r	motor speed (rps)

Subscripts

a	anode
c	cathode
cell	proton-exchange membrane cell
com	combined
con	consumed
elec	electrical energy
H_2	hydrogen
H_2O	Water
in	inlet
l	liquid
latent	latent heat
LMTD	Logarithmic mean temperature difference
max	maximum
mot	motor-pump
N_2	nitrogen
out	outlet
O_2	oxygen
sens	sensible heat
stack	proton-exchange membrane fuel cell stack
theo	theoretical chemical energy
trans	net transfer of water
v	vapour
W	water
0	standard condition

models the physical and electrochemical phenomena are modelled at coarser levels. The semi-empirical models for thermal management of a stack cannot be used directly for control studies due to the implicit forms of the expressions that are used to calculate the stack temperature. From a control perspective, therefore, it is important to develop a model that describes the thermal behaviour of a PEMFC stack with good approximation of the dynamics of stack temperature under various load conditions.

The total thermal energy evolved during operation of a fuel cell is the difference between the chemical energy of H_2–O_2(input) and the electrical energy of the stack (output). This thermal energy is distributed as sensible heat of the coolant and reactants, latent heat during phase change of water and heat loss to the surroundings by convection. Most of the lumped parameter models that have been developed for predicting the stack temperature have considered the sensible heat of cooling water as a sole transport factor of the thermal energy [12,13]. One such simple thermal model of the PEMFC stack was embedded into the ADVISOR vehicle simulation package by group of researchers at NREL [14]. The required inputs and parameters for simulating that model were taken from the ADVISOR package of automotive fuel cell stack driving cycles [15].

A paradigm shift is observed in the work by Yu et al. [16] where the latent heat of water during the phase change of water in the fuel cell, the heat loss to the surroundings, the sensible heat of coolant water and reactants are taken into account to predict the temperatures of the stack, the exit reactant gases and the coolant outlet [16]. In this model, the heat loss to the surroundings by convection is not considered explicitly but rather is modelled in an implicit way. This implicit form again limits the utility of the model for control application.

In the present work, control-orientated system-level dynamic models are developed for (i) stack temperature dynamics by explicitly taking into account the heat loss to the surroundings in addition to the latent heat of vapourization, the sensible heat of coolant water and reactants, and (ii) the centrifugal water pump that is used to control the stack temperature. These models are integrated with first-principle based models of an air flow compressor and the *semi-empirical* voltage–current model of Pukrushpan et al. [17].

The results of the present work offer design ideas to (i) achieve the exit coolant water temperature and near stack temperature and (ii) decrease the settling time of the stack temperature. To the best of the authors' knowledge there has been no work reported in the literature that addresses the development of a control-orientated thermal model. Besides, the water pump sub-system model provides a realistic setting for studying the temperature control problem. The goals of the present work are to

- develop a control-orientated lumped parametric system level model for the stack temperature;
- develop a lumped parametric model for the water pump subsystem;
- design the number of cooling plates required to achieve the cooling water exit temperature close to the stack temperature;
- study the interaction between inputs (compressor motor voltage, motor-pump current) and outputs (air flow rate, stack temperature) using developed thermal and water pump models in conjunction with stack and air flow sub-system models;
- study the effect of stack temperature on the settling times of air flow rate, stack voltage and net power.

This paper is organized as follows. First, the development of a dynamic model of the centrifugal water pump is explained in Section 2. The proposed control-orientated thermal management model is then elucidated in Section 3. A brief review of the air flow compressor and the PEMFC stack models, which are used in building the integrated model, is provided in Appendix A. Subsequently, in Section 4, the results from simulation studies are presented with insights into the number of cooling plates, the knowledge of which is required during the design of the stack. Concluding remarks and directions for future work are given in Section 5.