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Effect of dynamic load on the temperature profiles and cooling response time of a proton exchange membrane fuel cell

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A B S T R A C T

Polymer Electrolyte Membrane Fuel Cells (PEMFC) is an electrochemical device that generates electrical energy from the reactions between hydrogen and oxygen. An effective thermal management is needed to preserve the fuel cell performance and durability. Cooling by water is a conventional approach for PEMFC. Balance between optimal operating temperature, temperature uniformity and fast cooling response is a continuous issue in the thermal management of PEMFC. Various cooling strategies have been proposed for water-cooled PEMFC and an approach to obtain a fast cooling response was tested by feeding the coolant at a high temperature. In this paper, the operating behaviour was characterized from the perspectives of temperature profiles, mean temperature difference, and cooling response time. A 2.4 kW water-cooled PEMFC was used and the electrical load ranged from 40 A–90 A. The operating coolant temperature was set to 50 °C where the maximum stack operating temperature is 60 °C. The stack temperature profiles, cooling response time, mean temperature difference and cooling rates to the load variation was analysed. The analysis showed that the strategy allowed a fast cooling response especially at high current densities, but it also promotes a large temperature gradient across the stack.

1. Introduction

One of the power generation technologies rapidly developed towards the agenda for greater energy sustainability is the PEMFC. It is a hydrogen based system capable of generating electricity with suitable features for a wide range of application. It has seen tremendous technology growth over the past 30 years and has the potential to become a central system in future power generation networks.

PEMFC uses hydrogen as fuel that reacts with oxygen to convert hydrogen-bound chemical energy into electricity. The normal operating energy conversion efficiency can reach up to 60% but the heat generated via the exothermic reactions requires an equally effective thermal management. Low temperature PEMFC operates between 60 °C and 80 °C while high temperature PEMFC operates between 100 °C and 200 °C [1] mainly depending on the membrane design and capability.

Thermal management of a PEMFC is an area where intensive research has been carried out to characterize and further improve the cooling performance of specific cooling tools and operating strategies. Coupled with water management, it is an essential aspect in PEMFC operation for these major reasons [2,3]:

(1) to maintain the membrane hydration levels as this factor influences the overall fuel cell performance in terms of charge transport,
(2) to prohibit excessive flooding due to liquid water formation at the anode,
(3) to promote temperature uniformity across the PEMFC for power output stability and long-term performance durability.

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The performance of a fuel cell decreases especially at higher current density as membrane dehydration rate increases with higher heat generation [1,4]. The maximum stack temperature and temperature distribution of a PEMFC are the physical parameter that contributes greatly to the membrane performance and durability [5]. Characterising the thermal characteristics and energy balance of PEMFC stacks has been conducted in various perspectives. The first order thermal analysis focuses on identifying the temperature profile of the stacks under variable operating conditions as well as relating the temperature to incurring phenomena within the stack. Meanwhile, the second order analysis covers the details of heat transfer behaviour of the cooling system or the stack such as the heat transfer coefficient, Nusselt number and cooling effectiveness [6].

Practical control of fuel cells merely requires the correct interpretation of real-time stack temperatures. Due to dynamic load demands, the thermal power of the stack will change in accordance to the load current generated and the efficiency of the stack. To maintain the stack at the optimal temperature region, the cooling system should be able to response effectively to the changes in the generated thermal power. The importance of temperature control strategies based on real-time parametric monitoring and effective response is highly necessary for PEMFC stacks operating with dynamic loadings [7].

A related important issue in temperature profiling of a PEMFC is the response time of the cooling system. The cooling response time is defined as the time needed by the stack to reach a steady-state operating temperature when the stack loads changes. The main factors affecting the response time are the coolant type, stack thermal load, stack size, effective cooling rate and coolant conditions. Current liquid-cooled PEMFC stacks still applies distilled water as the coolant where a shift towards superior coolants is expected in the future such as using nanofluid coolants for a more compact stack design [8,9]. Air cooling is also applied but limited for stacks generating less than 1.5 kW of electrical power.

The profiling of temperature distribution for water-cooled PEMFC is essential as large temperature gradients would lead to intensified thermal stresses to internal parts [10]. Generally, the temperature distribution of a stack follows the pattern of the most active reaction sites within the cells [11] and improving the temperature uniformity leads to improved cell performance [12].

Large water-cooled PEMFC stacks normally operates by introducing near-to-ambient coolant temperatures at the stack inlet, in the range of 30°–40 °C, to create a consistently large temperature difference between the cooling fluid and the stack for the best possible cooling rate across the cooling plates. This would impose a large cooling demand on the heat exchanger to bring back the coolant temperature to its base value, leading to larger parasitic loads for the heat exchanger cooling fans. For smaller water-cooled stacks, an alternative cooling strategy regarding the inlet temperature of the coolant was proposed. This proposal was based on two assumptions;

(1) The coolant temperature will not rise too drastically as it flows across the stack as the heat generated is smaller than large stacks; thus, maintaining a suitable temperature difference for heat dissipation across the stack.
(2) To allow the stack to operate as close as possible to the recommended operating temperature of 55 °C–60 °C.

In this work, the water coolant temperature at the stack inlet was set at 50 °C where the temperature difference between the average stack temperature and coolant supply at the inlet is limited to approximately 10 °C. The operating behaviour was characterized from the perspectives of temperature profiles, mean temperature difference, cooling effectiveness and cooling response time. It is hypothesized that the proposed cooling strategy using a higher coolant inlet temperature would lead to advantages in reducing the response time with low cooling rate requirement.

2. Heat generation and thermal analysis model

The electrical power of a fuel cell is calculated from the stack voltage and the electrical load applied.

$$P_{el} = V_{stack} I \tag{1}$$

The thermal power generated by the fuel cell stack is highly dependant on the load current,

$$P_{th} = (1.254 n_{cell} - V_{stack}) I \tag{2}$$

The stack cooling rate can be calculated by

$$\dot{Q}_c = \dot{m} C_p (T_{exit} - T_{in})_c \tag{3}$$

The cooling effectiveness of the system can be evaluated using the ratio of the actual cooling rate of the stacks and the thermal power generated at a particular load.

$$\varepsilon_c = \frac{\dot{Q}_c}{P_{th}} \tag{4}$$

The temperature uniformity index is a normalized value based on the deviations of local temperatures and the average stack temperature,

$$U_T = \frac{\int |T_i - T_{avg}| dA}{\int dA} \tag{5}$$

The Log Mean Temperature Difference (LMTD) is calculated by referencing the temperature differences between the stack surface and the coolant along the cooling line. The stack surface temperature is represented by its maximum value.

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