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Metal foam heat exchangers for thermal management of fuel cell systems – An experimental study

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ABSTRACT

The present study explores the possibility of using metal foams for thermal management of fuel cells so that air-cooled fuel cell stacks can be commercialized as replacements for currently-available water-cooled counterparts. Experimental studies have been conducted to examine the heat transfer enhancement from a thin metal foam layer sandwiched between two bipolar plates of a cell. To do this, effects of the key parameters including the free stream velocity and characteristics of metal foam such as porosity, permeability, and form drag coefficient on temperature distribution, heat and fluid flow are investigated. The improvements as a result of the application of metal foam layers on fuel cell systems efficiency have been analyzed and discussed. Empirical results were in an agreement with previous numerical studies and have shown that to remove the same amount of generated heat, the air-cooled fuel cell systems using aluminum foams require half of the pumping power compared to water-cooled fuel cell systems. The critical coolant temperature difference for Proton Exchange Membrane (PEM) fuel cell systems was considered in which the applied foam layer created a uniform temperature distribution across the graphite plates.

1. Introduction

Fuel cell systems, converting fuels directly into electrical energy, are promising energy conversion systems for future mobile and stationary applications [1,2] such as computers, fuel cell power plants, fuel cell vehicles, and residential power generators. They can be commercialized when significant technical challenges are addressed; among them, the proper thermal management is one of the critical issues which needs to be resolved [3–12]. A fuel cell stack is composed of a number of cells where the same temperature must be maintained uniform throughout the cell in order to prevent destruction of the cell through thermal loading. This is particularly challenging as the $2H_2 + O_2 \rightarrow 2H_2O$ reaction is highly exothermic, so a large quantity of heat is generated within the cell. Characteristics of bipolar plates and sealing system (both material and thickness) impose difficulties on heat removal from the bipolar plate [2].

The goal is to enhance the thermal management in fuel cell systems where three aspects of that should be considered: size/weight, thermal resistance and electrical resistance of the system. Following that, two key design factors of heat exchangers, pressure drop and heat transfer, should be also noticed as they significantly affect the performance of different types of fuel cell stacks, including proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC). Consequently, there are noteworthy parameters depended on other aspects of a fuel cell stack which should be simultaneously considered when we design a heat exchanger. Having a complicated structure of fuel cell systems [2], those factors cannot be separated and dramatically affect the efficiency of fuel cell stacks.

Fuel cell system can be commercialized when significant technical challenges are addressed; among them, the proper thermal management is the most critical issue which needs to be resolved. As an example, PEM fuel cells work in a temperature range of 60–80 °C, dictated by the material properties of the PEM and a low or high operating temperature are objectionable with a resultant voltage loss [11]. Eventually, fuel cell stack cooling is always facing two critical factors, being a constant normal operating temperature and a supplementary cooling system to remove the entire waste heat load [10,11,13]. Moreover, in the case of SOFC stack, thermal stress distribution can be significantly affected by sealing design and studies have been done to improve the sealant material and design [14]. Although the existing technologies such as cooling with cathode air flow, cooling with separate air flow, cooling with heat spreaders, water cooling and cooling with antifreeze coolant have been challenging with thermal management issues [6].

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In a PEMFC, the heat generated is generally removed by a cooling system or transferred by conduction–convection across the faces of the stack. Thus, the thermal properties of individual components, i.e. polymer electrolyte, catalyst layer, gas diffusion layer (GDL) and bipolar plate (BPP) dictate the total heat removal rate [15]. Use of either water or air as the coolant through a multi-channel heat exchanger is the current practice in fuel cell industry to remove the heat, released by each single cell, and provide a constant operational temperature [3,9,16,17].

Water-cooled heat exchangers, requiring an extra cooling loop for water (radiator), use water as the coolant and remove heat from graphite plates (Fig. 1). Such stacks need a complicated system to form fluid passages between the cells, on the back of bipolar plates [4,18]. This asks for a complicated control system to monitor the water-bipolar interaction, corrosion, and possible vaporization and freezing (depending on the ambient condition) [6,19–24].

Air-cooled fuel cell systems, on the other hand, use the ambient air as the coolant. Fig. 2 shows a common design of an air-cooled fuel cell system with vertical air flow channels [4,7,9,25,26]. For instance, the Nexa™ fuel cell stack operates with a cooling fan located at the base of the unit, blowing air through vertical cooling channels in the stack [27,28]. The fuel cell operating temperature is maintained at 65 °C by varying the speed of the cooling fan. Air-cooled fuel cell systems do not have the aforementioned drawbacks associated with the wet cooling systems. Nevertheless, air cooling is not as efficient as liquid cooling is. As the specific heat for water is almost 4 times higher than that of air, it is anticipated that the size of a water-cooled heat exchanger for a fuel cell stack be almost a quarter of that of an air-cooled counterpart.

Considering both water and air cooled systems, thicker bipolar plates are needed for water or air channels (either straight or serpentine), formed on the back of the bipolar plates. This dramatically increases the cost as bipolar plates are expensive so is the manufacturing of the cooling channels [29]. Finally, as the whole stack is pressurized to minimize the contact resistance, the performance of the bipolar plates, in conducting electricity and providing coolant channels, depends on the applied compression force. This is limited by other constrains such as material characteristics and properties (of the fuel cell stack) [11].

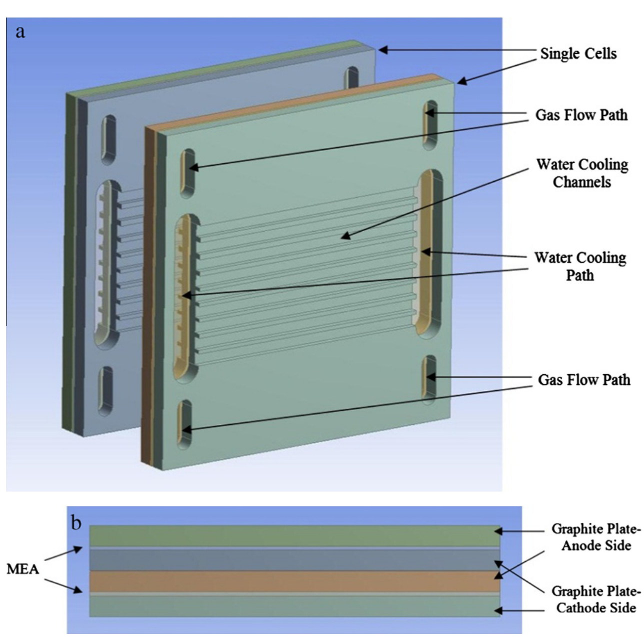

Fig. 1. (a) Isometric view of two separated single cells with water-cooled system and (b) top view of two single cells.

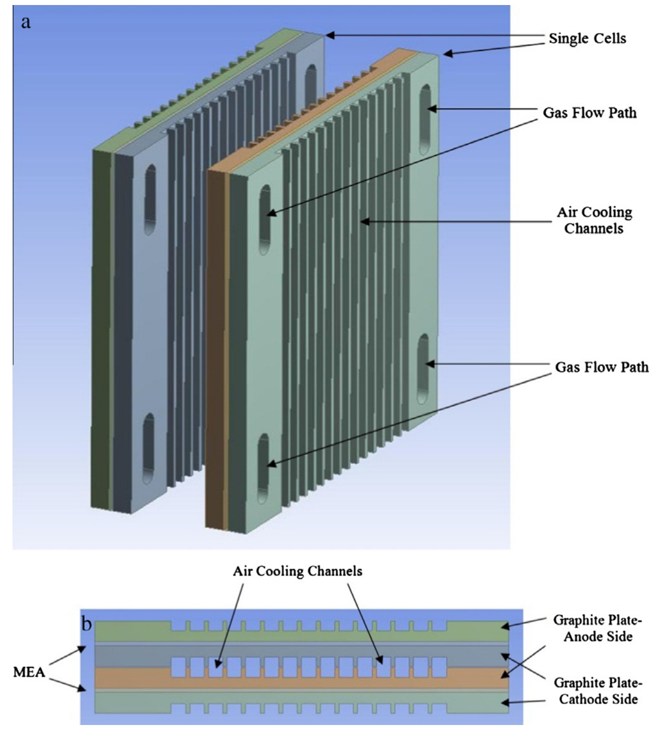

Fig. 2. (a) Isometric view of two separated single cells with air-cooled system and (b) top view of two single cells.

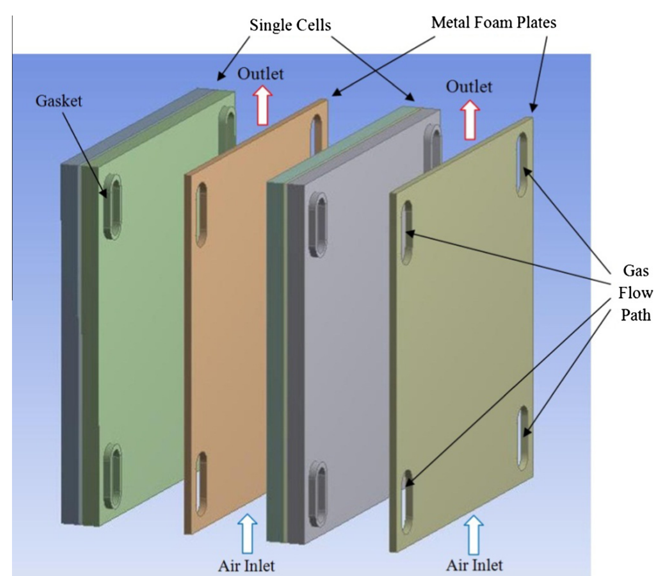

Fig. 3. Isometric view of two separated single cells with metal foam air-cooling system.

The novelty of the present design [30] lies in the use of an efficient air-cooled heat exchanger that at the same time reduces the contact and electrical resistance, leads to lower cost, and downsizes the fuel cell stack. Fig. 3 shows a thin layer of aluminum metal foam inserted between two cells with a thermal conductivity of about 200 times higher than that of air and 20 times higher than that of water [31–36]. Studies of metal foam heat exchangers quote significantly higher heat transfer rates from the hot plate, here graphite plate, compared to the existing technologies