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Review article

Metal foams application to enhance cooling of open cathode polymer electrolyte membrane fuel cells

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HIGHLIGHTS

- Important parameters of air flow field of open cathode PEMFCs have been discussed.
- Air cooling challenges in open cathode PEMFCs have been identified.
- Metal foams are found sound for open cathode PEMFCs from air cooling perspective.
- Challenges in incorporating metal foam in PEMFCs have been discussed.

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ABSTRACT

Conventional channel flow fields of open cathode Polymer Electrolyte Membrane Fuel Cells (PEMFCs) introduce some challenges linked to humidity, temperature, pressure and oxygen concentration gradients along the conventional flow fields that reduce the cell performance. According to previous experimental reports, with conventional air flow fields, hotspot formation due to water accumulation in Gas Diffusion Layer (GDL) is common. Unlike continuous long flow passages in conventional channels, metal foams provide randomly interrupted flow passages. Re-circulation of fluid, due to randomly distributed tortuous ligaments, enhances temperature and humidity uniformity in the fluid. Moreover, the higher electrical conductivity of metal foams compared to non-metal current collectors and their very low mass density compared to solid metal materials are expected to increase the electrical performance of the cell while significantly reducing its weight. This article reviews the existing cooling systems and identifies the important parameters on the basis of reported literature in the air cooling systems of PEMFCs. This is followed by investigating metal foams as a possible option to be used within the structure of such PEMFCs as an option that can potentially address cooling and flow distribution challenges associated with using conventional flow channels, especially in air-cooled PEMFCs.

1. Introduction

1.1. Background

A fuel cell (FC) is an electrochemical engine that converts chemical energy of hydrogen or a hydrogen-rich fuel (e.g. methanol) into DC electricity [1,2]. The key advantages of fuel cells include high electrical energy efficiency (above 80% theoretically and usually up to 55% based on high heating value of hydrogen [3–9]), flexible scalability for various sizes of plants, low to zero in-operation emissions, and no primary moving parts (leading to less maintenance and parasitic energy [10]) except for fuel, oxidizer and coolant supply pumps, etc. However, the technology is still facing some techno-economic barriers such as high system cost, low durability (that include water and cooling, degradation of the membrane-electrolyte assembly (MEA), and lifetime effects), and fuel storage and generation [1,2,7,11–14]. Fuel cells are generally categorized in two groups based on their operating temperature, such as low temperature (operating within 50–220 °C) and high temperature (operating above 650 °C) stacks [15]. Polymer Electrolyte/Proton Exchange Membrane (PEM), alkaline and phosphoric acid fuel cells fall under low temperature category, whereas molten carbonate and solid oxide fuel cells are of high operating temperature [15]. Usually Hydrogen is used as the anode reactant in a PEMFC. However, on the basis of the fuel types, the PEMFC can be

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subcategorized into different groups, such as the Direct-Hydrogen (DHFC), Direct-Methanol (DMFC), Direct-Ethanol (DEFC), Direct-Borohydride (DBFC), formic acid, dimethyl ether and other aliphatic alcohols are also picked for this type of fuel cell [8,16,17]. All these fuel cells are dependent on the polymer electrolyte membrane (PEM); therefore, the concept of the term “PEMFC” represents all these fuel cells in general [18].

Proper thermal management of PEMFCs has been identified as one of the critical technical challenges associated with this technology [19–22]. Both the nullifying conditions such as, MEA drying and flooding could happen due to improper thermal management [19]. From the electrical performance and water management points of view, common operating temperature of low temperature PEMFCs is usually within the range of 60–85 °C [19–21,23–25]. Cooling is more difficult to meet the required performance of the PEMFCs due to their narrow optimum operating temperature range [26]. This low operating temperature (i.e. 60–85 °C) results in low temperature difference with surrounding atmosphere where the heat is usually releases to by the coolants from the fuel cell stacks and thus it results in a reduced cooling capacity [27,28]. Improper cooling effect/thermal management is responsible for an increase in temperature of the stacks that leads to dehydration of PEM and thus reduction in overall efficiency of the stacks [21].

Depending on the fuel cell stacks' sizes and operating conditions, air and/or water cooling techniques are employed for thermal management purposes. As a rule of thumb, PEMFC stacks of above 5 kW power mainly require liquid cooling, and those of below 2 kW are usually designed to be air cooled [22,29]. For example Ballard Mk1020 ACS fuel cell, an open cathode PEMFC, has been designed to be cooled using air within its wide operating range of 300 W to 4 kW [30]. Conventional way of air cooling is to allow air through channel passages that might be consisted in bipolar plates or in separate cooling plates. Essentially, air cooling method is simpler and needs fewer accessories but has some disadvantages as well. Difficulty in maintaining a uniform temperature distribution within the stack, which is exacerbated with an increase in power density, is one of the common problems associated with using conventional air-cooling methods [19]. Since the specific heat of air is low, much air is needed to remove the generated heat, which incorporates an additional parasitic loss due to increased power consumption by the cooling fan. In addition, the dimensions of air cooling channels should be larger than those of water cooling channels, which makes the stack larger [19].

Metal foams, a new kind of engineered porous metal structure, exhibit excellent thermo-electrical and structural properties. Their feasibility in customizing thermo-electrical properties for a given volume supports their possible use in thermal management systems and thermo-electric devices. Due to their porosity, metal foams are very light in weight in comparison with solid materials of same volume. Open pore open cell metal foams have high surface to volume ratio that makes them appropriate candidate for heat exchangers [31–33]. Being metal, they possess higher electrical conductivity than non-metal materials that makes them suitable electrode materials. Their outstanding structural behaviours (stiffness to weight ratio [34], even distribution of loads [35], high load bearing capacity [34], impact energy absorbing [36], etc.) have made them applicable in different fields like building [35], automobile [37–39] and clinical [40,41] applications. They are also reported to be used in fuel cell technologies by several researchers as electrodes [42,43], current collectors [44], gas flow fields [45–53] and bipolar plates [50]. Hence, metal foams are becoming versatile engineering materials [33].

Few articles have cited their use in thermal management of the fuel cells. Metal foams or porous metal materials (e.g. mesh, fibre, etc.) were previously used in flow fields of fuel cells. Odabaee, Mancin and Hooman [54] demonstrated the cooling behaviour of metal foam through a cooling plate of a PEMFC. In all the cases, metal foams were reported with positive feedbacks. Careful design of porous structure might make it possible for proper mixing of air due to circulation of air around randomly distributed metal ligaments that can surpassingly enhance the thermal performance of the PEMFCs. Again, due to random flow path, water accumulation and pressure drop due to water blockage might not be as much as that in conventional channel flow fields. At the best of the authors' knowledge, there is no research work reported on the investigation of air cooling system of open cathode PEMFCs in which metal foams are used as flow fields. Hence, there is an excellent research opportunity to continue further investigation on metal foams to be used in open cathode PEMFCs.

This article addresses the important parameters considered in the design of air cooling systems of open cathode PEMFCs followed by relevant metal foam properties. This review is then expected to shed light on the possibility of integrating metal foams within the structure of open cathode PEMFCs in order to address the thermal and water management related challenges of such type of fuel cells and enhance their performance.

2. Cooling of PEMFCs

Fuel cell operating temperature is a crucial design parameter since it is linked to key factors such as reaction kinetics, membrane stability, and water management. The fuel cell cooling system is responsible for maintaining this temperature at a desirable level.

The heat generated by a PEMFC is approximately equal or sometime can be even more than the maximum power generated by the fuel cell [5,22]. Four factors such as, entropic heat/reversible heat/Peltier effect of reactions (35% of total heat), irreversibility of electrochemical reactions (55% of total heat), ohmic resistances/joule heating (10% of total heat) and water condensation are responsible for the heat generation in a PEMFC [19,23,55–57]. Entropic heat is the difference between electrochemical reaction and maximum useful work according to the second law of thermodynamics [57], it must be supplied to or removed from the electrode compartment [19]. The irreversibility of the electrochemical reactions inside a fuel cell is a significant source of heat generation. The ohmic heat is resulted from both the protons current in the electrolyte and the electrons current in the electrodes and bipolar plates as well as current collectors [19]. The heat is continuously generated as long as the cell is in operation and need to be removed for the fuel cell to operate at a desired level of temperature [25]. Further information can be found in a detailed report on heat sources in a PEMFC published by Ramousse, Lottin, Didierjean and Maillet [55].

Cooling system for PEMFC has to be designed in such a way that (i) proper/optimized hydration of MEA, (ii) uniform temperature all over the stack and (iii) minimum pressure drop across the flow field of reactants and coolant are met. Besides, weight and size of the complete fuel cell stack should not be undermined for enhancing portability, usability and productivity. A comparative study on different cooling principles and strategies for PEMFCs has been carried out by Sasmito, Birgersson and Mujumdar [58]. Their results provided useful insights for fuel cell cooling system design. A lot of analytical, semi-empirical and theoretical studies have also been done by many researchers in the field of cooling of fuel cells. The list of previous works and reviews in the field can be obtained from Özden, Tolj and Barbir [59], Hosseinzadeh, Rokni, Rabbani and Mortensen [60], Hwang [20], Faghri and Guo [22] and Mench, Burford and Davis [61]. There are also some more related works that have been done in recent years – *e.g.* Refs. [19,21,25,27,60,62–65].

There are two critical factors that make the cooling of PEMFCs