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An experimental and simulation study of novel channel designs for open-cathode high-temperature polymer electrolyte membrane fuel cells

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HIGHLIGHTS

- A novel open cathode configuration with uniform temperature and flow distribution.
- Guidelines to select channel design in terms of power, weight and web thickness.
- Two different cathode design configurations without pin and with pin structure.
- Simulation and experiment validation of flow, pressure and temperature distribution.

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ABSTRACT

A minimum balance of plant (BOP) is desired for an open-cathode high temperature polymer electrolyte membrane (HTPEM) fuel cell to ensure low parasitic losses and a compact design. The advantage of an open-cathode system is the elimination of the coolant plate and incorporation of a blower for oxidant and coolant supply, which reduces the overall size of the stack, power losses, and results in a lower system volume. In the present study, we present unique designs for an open-cathode system which offers uniform temperature distribution with a minimum temperature gradient and a uniform flow distribution through each cell. Design studies were carried out to increase power density. An experimental and simulation approach was carried out to design the novel open-cathode system. Two unique parallel serpentine flow designs were developed to yield a low pressure drop and uniform flow distribution, one without pins and another with pins. A five-cell stack was fabricated in the lab based on the new design. Performance and flow distribution studies revealed better performance, uniform flow distribution, and a reduced temperature gradient across the stack; improving overall system efficiency.

1. Introduction

The increasing need for energy devices with high efficiency and low emission has fostered research and the development of renewable energy sources. Fuel cells are a well-known technology that has the potential to meet the requirement for an efficient and low emissions energy device. Fuel cells (FCs) based on proton exchange membranes (PEM) have become a favored green energy technology because of their high power density, high efficiency, and modular nature [1,2]. In spite of the growing popularity of fuel cells, they still need to overcome some challenges of cost, size, and durability if they are to serve as a promising and reliable power source.

The automobile industry is a major energy consumer as well as one of the chief emitters of toxic emissions. The Intergovernmental Panel on Climate Change (IPCC) report of 2007 identified the transport sector as one of the largest contributors of CO_2 emissions and toxic particles [3,4]. As a result of the increasing number of motor

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Nomenclature

ρ	density, kg m^{-3}	$\mathbf{F}$	force vector, N
$\mathbf{u}$	velocity field, m s^{-1}	Q_{br}	source term, kg m^{-3} s^{-1}
p	pressure, Pa	ϵ_p	porosity
$\mathbf{l}$	entrance length, m	K_{br}	permeability, m^2
μ	dynamic viscosity, Pa s	β_F	Forchheimer drag, kg m^{-4}
T	temperature, °C		

vehicles and recent concerns about greenhouse gas emissions, a great deal of emphasis has been placed on the development of fuel cell systems as an alternative to internal combustion engines (ICEs) in automobiles [3,4]. PEM fuel cells specifically are considered a potential alternative to internal combustion engines in automotive applications because they give off no harmful emissions, are modular, exhibit high efficiency, and have a good response to varying load. Of the various PEM fuel cells, low-temperature polymer electrolyte membrane (LTPEM) fuel cells are particularly suitable for automotive applications because of their quick start-up; however, they have an inadequate heat and water management system [5]. An alternative to a LTPEM fuel cell is a high-temperature polymer electrolyte membrane (HTPEM) fuel cell. In a HTPEM, the Nafion membrane is replaced by a polybenzimidazole (PBI) membrane doped with phosphoric acid, which operates optimally at 160–180 °C [6].

A higher operating temperature offers substantial improvements to PEM fuel cells in the form of system design and operational advantages. A PEM fuel cell tolerance toward carbon monoxide (CO) improves at higher temperatures. Li et al. [7] reported a CO tolerance of 3% CO in hydrogen operating at 0.8 A cm^{-2} and 200 °C compared with 0.1% CO in hydrogen at 398 K and current densities lower than 0.3 A cm^{-2}. The CO tolerance is defined by a voltage loss of less than 10 mV. Furthermore, water management is made simpler by the existence of single phase water at high temperatures [8]. Bezmalinovic et al. performed a water transport study within an HTPEM fuel cell stack experimentally and was confirmed using a computational fluid dynamics model [9]. Similarly, Siegel et al. studied the thermal behavior of an HTPEM fuel cell at high temperatures and operated with pure hydrogen and hydrogen with carbon monoxide resulting in an improved fuel cell [10]. Zuliani et al. performed an energy analysis on a HTPEM fuel cell and modeled the balance of plant using simulation software [11]. They then validated the software experimentally and showed that HTPEMs could achieve electrical efficiencies similar to LTPEMs. The operation of the HTPEM results in high-quality waste heat that may be employed for useful work such as fuel processing. As a result of thermal energy available in HTPEM fuel cells, combined electrical and thermal efficiencies of 90% are achievable making for a highly efficient system [12,13]. Schmidt et al. demonstrated the durability of high-temperature MEAs that operated continuously for more than 6000 h with a degradation rate of approximately 5 mW h^{-1} [14]. Ossiander et al. showed the durability and longevity of a PBI based membrane in an HTPEM after thermal post-curing [15]. Due to the absence of liquid water, HTPEMs demonstrate a more stable operation, especially at a high current density. Because the PBI based membrane for HTPEM conducts protons with the help of phosphoric acid, it is possible to supply an HTPEM fuel cell with non-humidified air. This allows for the integration of a blower without a humidifier to supply the coolant and oxidant for the HTPEM fuel cell; this arrangement is called an open-cathode fuel cell stack [16].

Bandlamudi et al. reported an experiment carried out on a 12-cell HTPEM stack assembled with commercial PBI MEAs with an active area of 50 cm^2 [17]. Andreasen et al. developed a model of a compact open-cathode system based on an HTPEM fuel cell [18]. The stack was fed with three reformates that simulated the composition obtained by three different types of reformers operating with methanol, propane, and natural gas. The reported stack power with pure hydrogen at approximately 165 °C was 166 W at a cell voltage of 0.55 V. Radu et al. demonstrated that, with reformate containing 75% H_2 and 1% CO, the stack power for the same operating point decreased by a maximum of 10 W [19]. HTPEMs are also a potential candidate for combined heat and power (CHP) operation. Romero et al. modeled an HTPEM based fuel cell system that showed a CHP efficiency of 87% [20]. Korsgaard et al. carried out simulation studies with results showing power density much higher than that of an LTPEM [21]. Rabiu et al. developed a novel heat integration method for an HTPEM fuel cell based CHP system [22]. They considered the effects of a heat recovery system on the efficiency of an HTPEM. In an open-cathode HTPEM fuel cell system, the flow rates need to be high to meet the oxidant and coolant requirement, both of which are handled by a single stream of air in an open-cathode system. Hence, a blower is required for the system, but the pressure drop that a blower can bring about at high flow rates is much lower than a pump, which is usually the mechanism incorporated in an LTPEM fuel cell.

In an open-cathode HTPEM fuel cell system, the airflow rate stoichiometry may be 8–10 or more to cool the stack at a high current density. A lower air flow in the channel will result in degradation of the membrane because of the exposure to a prolonged high temperature [13]. It is imperative to have a proper cathode channel design to obtain a uniform flow distribution. An optimal flow field design is also necessary to enable a blower, which consumes less power than a pump, to be used for the air supply. Another important factor in an open-cathode system is the channel size. An optimal channel size is required for high performance with low parasitic losses. An important issue related to flow field design is scale-up; flow distribution and non-uniform compression become prominent with higher active areas.

An important factor to consider in the flow channel design for a fuel cell is the channel-to-rib ratio, which plays an important role in pressure drop in the channel. Guo et al. developed a bio-inspired flow field design for LTPEM [23]. They carried out numerical and experimental studies to determine the velocity, pressure drop, and performance. A review of nature inspired flow field designs for low temperature fuel cell using CFD simulations was presented [24]. They discussed various designs and the constraints in terms of development and performance. Studies done by Roshandel et al. focused on improving the flow design in fuel cells to improve the overall system efficiency [25]. They developed a three-dimensional simulation model to verify various nature inspired designs. An improvement of 56% and 26% compared to parallel and serpentine designs, respectively, was reported.

To harness the advantages of both parallel and interdigitated designs, a design strategy was developed to switch between the two designs using valves [26]. The results show higher power at low current density with a parallel design, while lower overvoltage at high current density with an interdigitated design. A switching