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A novel flow reversal concept for improved thermal management in polymer electrolyte fuel cell stacks

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ABSTRACT

In a polymer electrolyte fuel cell (PEFC) stack equipped with a forced-convection open-cathode manifold, significant temperature gradients can develop from the inlet to the outlet due to the incoming cool air heating up as it passes through the cathode flow fields. In this study, we propose a new conceptual design for effective cooling of a PEFC stack by periodically reversing the flow direction of the air used for convective cooling. The impact of the flow reversal scheme is studied via mathematical model of the three-dimensional two-phase flow and associated conservation equations of mass, species, momentum, charge, and energy. The model includes both the stack and the fans used for cooling air supply. The model results indicate that the temperature, water and current density distributions become more uniform and produce reduction in the highest temperature reached in the stack which also enhances stack performance relative to the unidirectional coolant flow case.

1. Introduction

Forced-air convection in open-cathode PEFC stacks with external fans is a promising strategy for thermal management of stacks with power ratings of around 100–1000 W to ensure good stack performance and efficiency [1,2]. The fans or blowers deliver air to the cathode for electrochemical reaction and also effect heat transfer between the stack and the ambient for thermal management. The advantage of such a setup is the significant reduction in complexity of the design and cost of fuel cell operation, as additional cooling loops and plates in the stack are not required.

Several studies have reported on studies of the behavior of PEFC with open-cathode manifold. Li et al. [3] studied free-convection heat and mass transfer in PEFC based on non-dimensional analysis. Mennola et al. [4] developed a two-dimensional isothermal, cathode-side model to identify the limiting processes of mass transport due to free-convection. Schimtz et al. [5] developed a 2D, isothermal, steady-state model; they investigated three different cathode opening ratios with regard to the cell performance. Wang et al. [6–9] simulated 3D non-isothermal PEFC with natural convection including its immediate ambient; they also validated the model with experimental data. Tabe et al. [10] showed with 3D modeling and experimental data that the mass transport limitation due to oxygen depletion depends strongly on the cathode channel design. Lister et al. [11] simulated micro-structured PEFC with natural convection where the ambient is also resolved in the model; the model considers two-dimensional, non-isothermal and steady-state condition. Hwang et al. [12,13] developed a three-dimensional cathode model of a free-breathing PEFC to investigate mass transport limitations. O'Hayre et al. [14] developed and validated a one-dimensional, non-isothermal engineering model for a planar air-breathing PEFC.

Rajani and Kolar [15] derived a two-dimensional planar air-breathing model with ambient included in the model; three different fuel cell lengths and ambient conditions were simulated. It was shown that mass transport limitation in the limiting current density region can be reduced by shortening the fuel cell channel in an air-breathing PEFC. Zhang and Pitchumani also simulated two-dimensional non-isothermal air-breathing PEFC model for a single cell [16] and a stack [17]. Both gravitational orientation and fuel cell length were included in the model. Matamoros and

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Bruggemann [18] investigated mass transport limitations and effect of fuel cell length on cell performance with a three-dimensional model of a free-breathing PEFC. Paquin and Frechette [19] analyzed water management including cathode flooding and membrane dry-out in air-breathing PEFC with a one-dimensional model. Xing et al. [20] optimized the geometry of air-breathing PEFC with sequential programming method. Al-Baghdadi [21] developed a three-dimensional non-isothermal two-phase model; performance of air-breathing and air-flow channel PEFC was compared. Kumar and Kolar [22,23] developed a three-dimensional non-isothermal model for air-breathing PEFC; various cathode channel design and operating parameters were investigated. None of these studies, however, examined forced-air cooling in an open-cathode PEFC stack, where the fan is an integral part of the model. We have developed an open-cathode PEFC stack model [24–26] where the fan and its immediate ambients are included in the model, which allows interaction between the stack, the surroundings and the fan.

Although the open-cathode PEFC design has several advantages due to its simplicity, one of its drawbacks is that significant temperature gradients develop along the stack due to ineffective cooling. Temperature differences between the stack inlet and outlet can reach values up to 50 °C [24,25,27,28]. To reduce the temperature rise and thus also improve thermal management and stack performance, periodic reversal of the cooling air is proposed for the cathode open manifold. In this case, two fans placed in ahead of and behind the stack are considered. They are operated such that the flow direction can be alternated (see Fig. 1a). One could also consider other designs within the computational framework presented here; e.g. designs that employ only a single fan or a blower, manifold and utilize valves to control the flow direction.

This operating concept is studied with a computational model utilizing a validated PEFC stack model (see our previous work [29] for details of the model validation) that is extended to account for two fans, the ambient and transient operating conditions. In short, the model solves for transient two-phase flow and the equations of conservation of mass, momentum, species, energy, and charge. They are coupled with a phenomenological membrane model and an agglomerate model for the cathode catalyst layer. The model is solved using the CFD software FLUENT and its fuel cell module [30–32]. User-defined functions are employed to implement the various governing equations and closure relations for the electrokinetics, membrane properties, agglomerate catalyst layer model, heat generation and associated boundary conditions.

2. Mathematical formulation

The mathematical model comprises three components: the fuel cell stack, the ambient and the fan. In this study an open-cathode PEFC stack with a capacity of ∼400 W was simulated, similar to previous work [25]. The flow fields in the anode and cathode comprise parallel channels operating in co-flow mode; the oxygen is supplied from the ambient air using fans (see Fig. 1a) while the hydrogen is supplied from a hydrogen tank/canister (not shown in the figure) The computational cost is kept to a minimum by introducing a representative computational domain with symmetry boundary conditions to the left and right and periodic

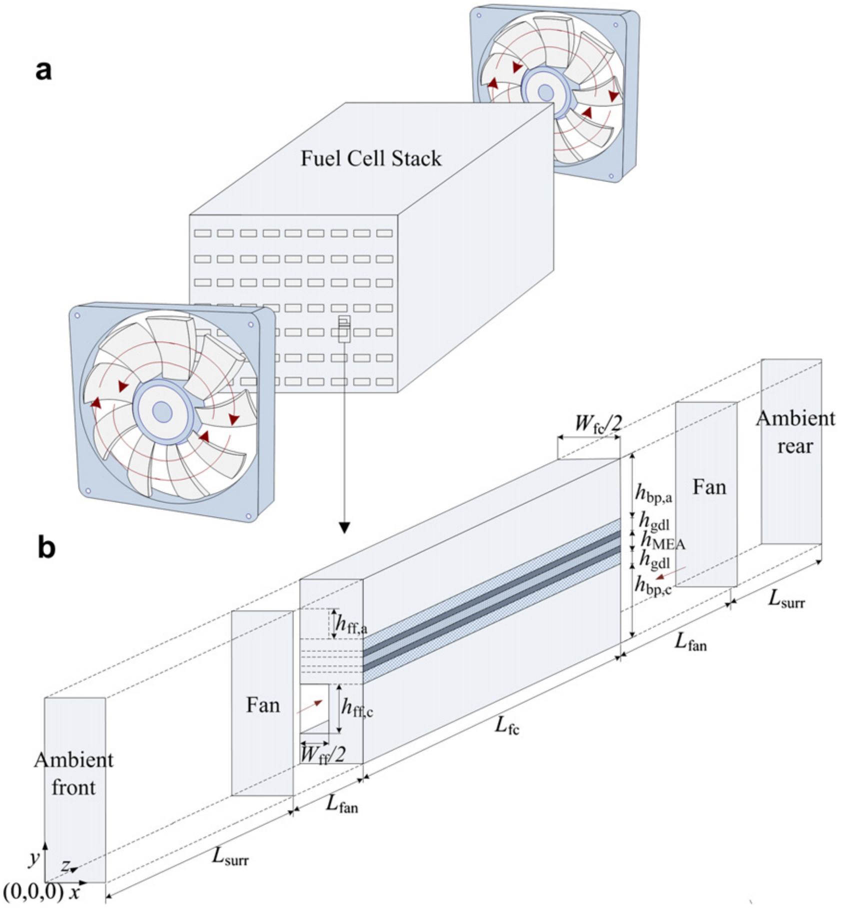

Fig. 1. Schematic of (a) the reversing flow concept with forced-air convection cooling at the cathodes of a PEFC stack and (b) computational domain with ambient, stack and two fans. The arrows indicate the reversal of the flow.