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Fan selection and stack design for open-cathode polymer electrolyte fuel cell stacks

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ABSTRACT

The design of open-cathode polymer electrolyte fuel cell (PEFC) stacks with forced-air convection from one or several fans requires careful consideration of the characteristic curves of the stack and the fan(s). Ideally, the intersection – the operating point – between the stack and the fan characteristic curves should be located in the optimal operating region of the fan; and be sufficiently far away from any unstable region. In this paper, the effect of various fan and stack configurations, operating conditions and their impact on the fan and system characteristic curves as well as stack performance are investigated with a model considering two-phase flow and conservation of mass, momentum, species, charge, and energy in the PEFC stack and ambient; the fans are treated as interface conditions. The results indicate that the fan power rating, fan type, single fan or fans in series, fuel cell length, and separate air-coolant channels have a significant impact on the operating point and resulting stack performance – these factors therefore have to be accounted for when designing the PEFC stack and selecting fans. Furthermore, the results suggest that the stack characteristic curve can be secured by straight-forward air-flow simulations instead of solving a detailed, mechanistic fuel-cell model, allowing for more efficient model-based design studies of fans interacting with a PEFC stack.

1. Introduction

In a polymer electrolyte fuel cell (PEFC) stack, efficient thermal and gas management is vital in order to ensure optimal or near-to-optimal operation. Typically, PEFC stacks between around 100–1000 W do not require liquid cooling but can be operated in an open-cathode mode with air supplied by one or several fans [1,2] – thus reducing the overall complexity of the PEFC system since liquid coolant loops, plates and radiators are not necessary. Such an open-cathode design, however, requires careful selection of the type of fan – axial, centrifugal, or compressor – or blower, as the air flow through the PEFC stack not only has to provide sufficient cooling (thermal management) but also sufficient reactant air (gas management).

Generally, the selection of the type of fan is based on the system characteristic curve (SCC) that gives the pressure drop over the system at various flow rates and the fan characteristic curve (FCC), which in turn describes the static pressure increase that the fan can provide at a given air flow rate. The FCC is usually available from the manufacturer whereas the SCC has to be either measured experimentally or estimated from various engineering correlations or computational fluid dynamics (CFD). Once both characteristic curves are known, one can determine the operating point of a given fan for the system from the intersection of the FCC and the SCC; the operating point should ideally be chosen so that the fan is able to provide a stable air flow at low noise levels and low cost whilst ensuring a high fan lifespan [3–5].

In a PEFC stack the SCC can be expected to depend on a range of design and operating parameters: e.g., overall stack geometry, cathode opening area (channel height and width), cathode flow field type (mesh, parallel, serpentine and so forth) and overall length, stack voltage, and additional coolant channels for separate cooling air. Similarly, the FCC of a given fan typically depends on several factors: e.g., power rating, type, size, and blade design. Overall, the interaction between the fan(s) and the fuel cell stack is thus more intricate compared to other typical applications with fans, such as cooling of electronics [6,7], ventilation [5,8] and steam boilers [9,10].

Several experimental [11–15] and computational [16–23] studies have been conducted for open-cathode PEFC stacks with

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forced-air-convection cooling in order to study the overall stack performance and thermal management. Out of these computational studies, only Sasmito et al. [16] included the fan as an integral part of the model in the form of a polynomial interface condition. In short, Sasmito et al. [16] studied a PEFC stack equipped with porous flow fields on the cathode and anode and an axial fan, which allowed for a reduction in dimensionality of the computational domain from three to two dimensions; with this model, they studied the impact of fan power rating, height of the cathode flow field and fan placement on the stack and fan performance; and demonstrated a strong correlation between the first two factors and the overall performance.

To continue the work on mathematical modeling and computation of open-cathode PEFC stacks with one or several fans, the mechanistic model by Sasmito et al. [16] is extended to account for three-dimensional effects associated with flow fields comprising channels; in this particular case parallel flow channels, which are common for open-cathode PEFC stacks [11–15]. Within this framework, a study is then carried out to evaluate how key factors – fan power rating, series placement of fans, type of fan/blower, channel length, operating voltage, and addition of separate coolant flow channels – affect the FCC and the SCC, their interaction and the resulting PEFC stack performance. In essence, the mechanistic model considers two-phase (liquid and gas) conservation of mass, momentum, energy, charge and species together with the relevant electrochemistry. From a model-based design point of view, the computational cost of solving such a highly detailed mechanistic model does not lend itself well to wide-ranging parameter studies, design and optimization of a PEFC stack – which raises the question whether such a highly detailed model is required to determine the SCC of a PEFC stack. If not, then it would entail a significant reduction in computational cost and complexity, and allow for standard CFD simulations (i.e. only conservation of mass and momentum) of laminar and/or turbulent flow in the PEFC stack to predict the SCC during the design and optimization of a given open-cathode PEFC stack.

The layout of the paper is as follows. First, the mathematical formulation is summarized, followed by a brief discussion of its implementation with a one-domain approach. A parameter study for the characteristic curves of the fan and system is then carried out, after which the question whether the SCC of a PEFC stack can be predicted with standard air flow simulations is addressed. Finally, conclusions are drawn with emphasis on how the herein presented mathematical framework can aid in the design and optimization of open-cathode PEFC stacks as well as selection of one or more fans.

2. Mathematical formulation

A repetitive unit of a PEFC stack, ambient and fan(s) is considered for one fan (see Fig. 1a), two fans in series (see Fig. 1b), and for one fan with one additional separate coolant flow field for air (see Fig. 1c); the fans are of a tube-axial design, except for the study of fan types, for which centrifugal-backward curved and blower fans are also considered. These fans are common for open-cathode fuel cell applications and readily available commercially. The flow fields in the cathode and anode comprise parallel channels operating in co-flow mode. Symmetry is invoked to the left and right (x -direction) and periodicity for the lower and upper parts (y -direction) to reduce the computational cost and complexity.

The mathematical formulation is based on the work by Sasmito et al. [16]: conservation of mass, momentum, species, and energy for two-phase flow (liquid and gas flow) are solved in the PEFC stack and its ambient, with two additional conservation equations for electrons and ions in the PEFC stack; the fan is reduced to an interface condition and a polynomial expression that describes the pressure increase over the fan as a function of the fluid velocity (flow rate) that is generated; see [16] and [24] for more details on the mathematical formulation and experimental validation respectively. The polynomial expression allows for adaptation of various types of fans, which can then easily be studied within the numerical framework.

In this study, the height and width of the stack are taken to be the same as those of the fan, whence the number of cells, n_{cell}, in the stack is given by $n_{\mathrm{cell}} = h_{\mathrm{stack}}/h_{\mathrm{cell}}$ (rounded up), where h_{stack} and h_{cell} are the stack and single-cell height respectively. With this constraint and the design parameters given in Table 1, the modeled PEFC stack thus comprises 32 cells for the base case and 23 cells when additional coolant channels are introduced in the bipolar plate. Note that this constraint can easily be relaxed within the mathematical framework presented here.

For comparison purposes later, the stack net power is given by $P_{\mathrm{net}} = P_{\mathrm{stack}} - P_{\mathrm{fan}}$, where P_{fan} is given by the fan manufacturer and the stack power, $P_{\mathrm{stack}} = E_{\mathrm{cell}}\ n_{\mathrm{cell}}\ I_{\mathrm{tot}}$; here, the total current, $I_{\mathrm{tot}} = i_{\mathrm{ave}}\,A_{\mathrm{cl}}$ where i_{ave} is the average current density of the unit cell, A_{cl} is the area of the catalyst layer (x and z -direction), and E_{cell} is the cell voltage of the repetitive unit.

3. Numerics

The computational domains, illustrated in Fig. 1, were created and meshed with around 10^5 elements in the commercial preprocessor software Gambit 2.3 after a mesh-independence study. The mathematical formulation was implemented with a one-domain approach in the commercial CFD software Fluent 6.3 and its fuel-cell module, user-defined functions and scalars. A typical simulation required around 500 MB of random access memory and 200 to 500 iterations with a convergence criterion for all relative residuals of 10^{-6}; overall, a simulation took around 1–2 h on a workstation with a quad-core processor of 2.68 GHz.

4. Results and discussion

Simulations were carried out for typical conditions found in an open-cathode PEFC with forced-air convection cooling; the geometry, operating parameters, and polynomial constants, $\mathfrak{C}_i$, for a centrifugal-backward curved fan [25] and a centrifugal blower [26] are summarized in Table 1; the remaining physical parameters and polynomial constants for tube-axial fans [27] can be found in [16]. In the following, key parameters, design features, and conditions that affect the characteristic curves and the stack performance will be studied, after which the level of mathematical detail that is required to predict the SCC of a PEFC stack will be discussed.

4.1. Fan power rating

One of the key factors that determines the performance of a fan is its power rating; i.e. the power required to generate the static pressure increase over the fan. Intuitively, one would expect that an increase in power consumption of the fan is mirrored by an increase in performance for the same fan architecture and size, provided that the fan can sustain the higher flow rates. This is indeed the case, as can be inferred from Fig. 2, which depicts several FCCs for tube-axial fans with increasing power rating [27] and the SCC for the unit cell of the fuel cell stack at 0.7 V (*N.B.* 0.7 V for the unit cell corresponds to 0.7 × n_{cell} V for the entire stack). Here, several features are apparent. Foremost is that the shape of the FCCs is similar for all power ratings due to the shared fan architecture. Furthermore, each FCC exhibits three typical regions for axial fans [3–5]: a stalling, an unstable, and an optimal operating region. The