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Spatially smoothed fuel cell models: Variability of dependent variables underneath flow fields

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ABSTRACT

Spatial smoothing can be applied to reduce a three-dimensional (3D) fuel cell model to a computationally cost-efficient two-dimensional (2D) counterpart. In this study, the averaged dependent variables in the streamwise direction are augmented with a statistical measure of their distribution in the spanwise direction in the form of standard deviations. A functional form of the latter is postulated and justified *a posteriori* by comparing the predictions from the 2D spatially-smoothed model with the original 3D counterpart: good agreement is found. This measure of the variability thus complements the average predictions of existing spatially smoothed models.

1. Introduction

The performance of a solid oxide fuel cell (SOFC) depends on factors such as material parameters, design of bipolar plates and other functional layers, as well as operating conditions [1–6]. In order to design efficient SOFCs and operate them at optimal or near-to optimal conditions, one can employ detailed three-dimensional (3D) mathematical modeling and simulations. For instance, Pasaogullari and Wang [7] proposed a 3D model to predict the distributions of reactant species and current density in a planar SOFC (P-SOFC), and showed that depletion of reactants resulted in the decrease of current density along the channel. Magar and Manglik [8] investigated the effects of the anode backing layer thickness and the cross-sectional aspect ratio of rectangular flow channels on the distributions of reactant species and temperature within a P-SOFC. Their study demonstrated the relation between the geometry of cell components and the depletion of reactants along the cell width under the ribs of the bipolar plates. However, detailed 3D models are computationally expensive to solve – both in terms of computational time and memory requirements [9].

In order to reduce the computational cost of a three-dimensional (3D) fuel cell model without sacrificing the leading-order physics and geometrical features, we have earlier derived spatially smoothed fuel cell models based on volume averaging over a flow field comprising parallel channels separated by ribs for a P-SOFC [10] and a proton exchange membrane fuel cell (PEMFC) [11]. Doing so allowed for the reduction of a 3D detailed, mechanistic fuel cell model to a two-dimensional (2D) counterpart in the streamwise, $\mathbf{e}_x$, and normal, $\mathbf{e}_y$, directions for a P-SOFC with computational savings of around *two to three orders of magnitude* (see Fig. 1(a)–(b)).

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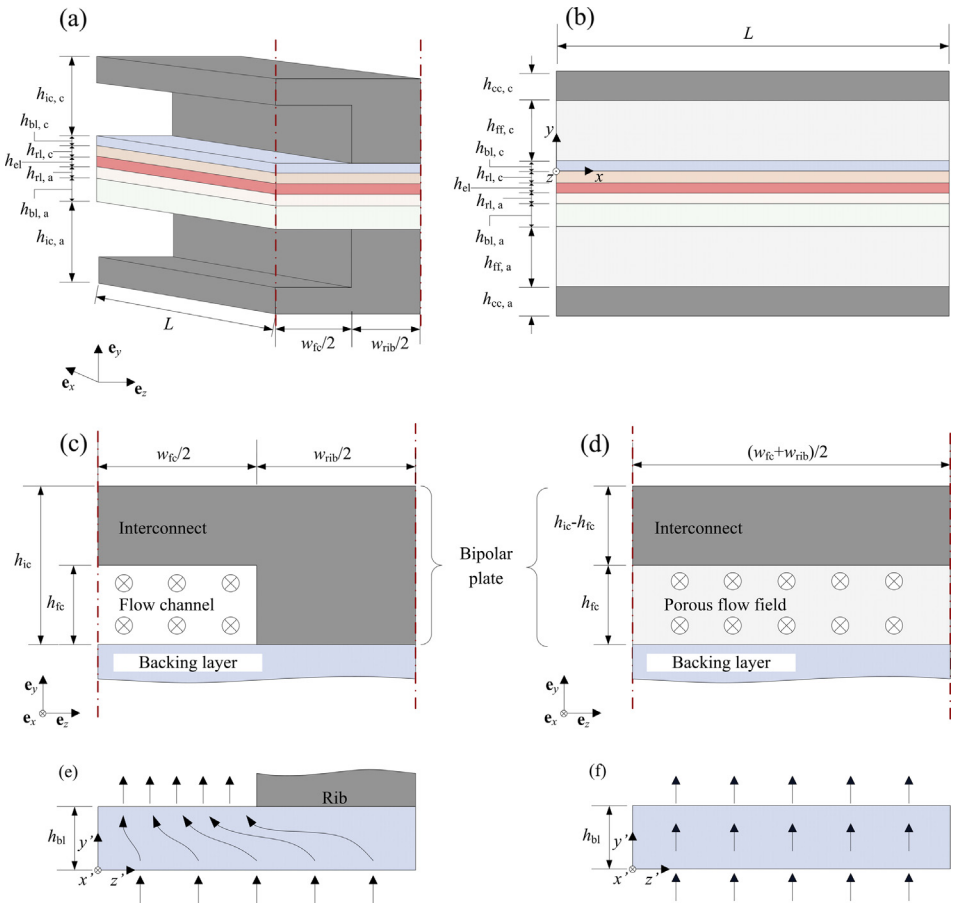

Fig. 1 – Schematics of (a) the repeating unit of a 3D P-SOFC with a pair of channels and (b) its 2D spatially-smoothed counterpart, (c, e) a backing layer and a flow field comprising a flow channel enclosed by a rib in a bipolar plate, and (d, f) the spatially-smoothed flow-field counterpart. The pathways for diffusive mass transports (→) in the backing layer (e) without and (f) with spatial smoothing.

Moreover, the 2D spatially-smoothed model took the influence of ribs on the pathways of transport processes into account, and quantified the loss of information due to model reduction from 3D to 2D, which were not captured by the other 2D fuel cell models such as [12–15] for the P-SOFC. When performing spatial smoothing for model reduction, there is no loss in physical information except that the local pointwise information is replaced with spanwise averaged counterparts. The benefits of the reduction will be greater for modeling of a stack that comprises tens or even hundreds of cells at a computational cost that is not prohibitive. Based on the reduced single-cell model, which can serve as a repeating element, a reduced stack model can be built up with automated code generation [16]. However, in our previous studies [10,11], only average properties for the dependent variables in the streamwise direction were derived without any information regarding their distribution in the spanwise direction, $\mathbf{e}_z$. From a design point of view, information pertaining to the distributions of variables is necessary in order to avoid designing flow fields that cause a significant depletion under ribs.

In this study, we seek to quantify the said distribution of the spanwise variability of dependent variables – demonstrated for mass fractions in a P-SOFC – underneath ribs in terms of their standard deviations, which are captured with polynomial expressions for ease of use. The functional form of the standard deviation is justified *a posteriori* by comparing with simulations of the original 3D P-SOFC model. Finally, other statistical measures are discussed.

2. Analysis

In our earlier analysis and derivation of a spatially smoothed model for fuel cells, we employed volume averaging over a representative elementary volume together with effective transport properties and accounted for the ribs of the flow field through correlation factors [11]. This strategy resulted in average properties of dependent variables in the streamwise direction that agreed well with the solutions from the 3D model. The correlation factors were derived in view of differences in *pathway* in the backing layer that occur depending on the relative width of a flow channel, w_{fc}, compared to the adjacent rib, w_{rib}, as well as height of the backing layer, h_{bl}, as shown schematically in Fig. 1(c)–(f). Based on a generic Laplace equation solving for a variable Ψ that applies for all