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Characterization of bubble mobility in channel flow with fibrous porous media walls

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ABSTRACT

In composites processing, resin is introduced into a fibrous domain to cover all the empty spaces between the fibers. It is important to extract air bubbles from the domain before the resin solidifies. Failure to do so will entrap these voids in the final part, which is detrimental to its performance. Hence, there is a need to understand bubble motion in a fibrous porous domain in which the bubbles move with the resin in channels surrounded by fibrous walls. A rising bubble model is presented that consists of a single spherical void in a cylindrical axisymmetric two-phase domain of resin and air surrounded by porous media boundaries. The motion of a bubble in a channel flow with porous boundaries is modeled by replacing the walls with a slip velocity. Focus is on how the porous media permeability influences the bubble motion. A parameter called bubble mobility is defined as the ratio of bubble rise velocity to the resin free surface velocity. Results suggest that fabric permeability and fluid properties can be optimized to increase bubble mobility and ultimately lead to reduction in void content during composites processing.

1. Introduction

One of the methods to fabricate composites is from prepregs. A partially impregnated prepreg is like a tape with unidirectional or woven continuous fibers partially covered with a polymeric resin. The prepregs are stacked in the desired sequence on top of a tool using a pressure roller. The pressure roller redistributes the resin and partially consolidates the stacked layers. The composite at this stage will have some void regions that have no resin or fibers. The stacked sequence is subjected to a vacuum to remove the air and water vapor from these prepregs so it is important that there are pathways to extract these voids before the prepregs are fully consolidated in an oven to fabricate a void free composite. Voids in polymer matrix composite materials can deteriorate structural performance and reliability. The following is a study of voids or bubbles in uncured viscous polymer resin as it is being processed to form composites. The goal is to determine if voids can successfully migrate around fibrous porous media towards vacuum pathways, coalesce with the pathways, and escape during processing. Precursor to the coalescence and detrainment process is the drainage and rupture of the resin thin film formed between voids within the resin in the proximity of the resin free surface. Fig. 1 describes a simplified model schematically. The goal is to explore the role of process and material parameters that will help the bubble to catch up and merge with the resin surface in contact with the vacuum so that it can be swept away in the vacuum pathways. This can be estimated by comparing the average resin velocity to a bubble velocity to determine if the conditions are favorable for the void to arrive at the moving resin surface, coalesce, and be extracted by the vacuum.

For this work, the scope is focused on modeling how the presence of porous media affects through-thickness void migration. Resin saturation of porous media during composites processing was studied by (Pillai, 2002; Foley and Gillespie, 2005; Park and Woo, 2011). We seek to model through-thickness void migration through inter-ply channels as a resin column with an air interface as depicted in Fig. 1. This simplified approach permits development of a model describing void migration in a channel surrounded by porous media. The void migration is induced by applied pressure (i.e. vacuum + roller) during processing. The goal is to explore (i) if the pressure gradient is sufficient to move the voids to the resin free surface so they can be removed by the sustained vacuum and (ii) the role of the permeability of fibrous porous media walls on void dynamics. It is hypothesized that the influence of porous walls is a key to the void dynamics. The presence of the porous walls creates an effective interfacial slip on the porous wall boundary as discussed by (Beavers and Joseph, 1967; Neale and Nader, 1974). An objective of this work is to explore an approach to model void and resin motion with porous media boundaries. First, the void and resin migration is studied using a framework governed by the Stokes–Brinkman equations. These equations solve for the flow in

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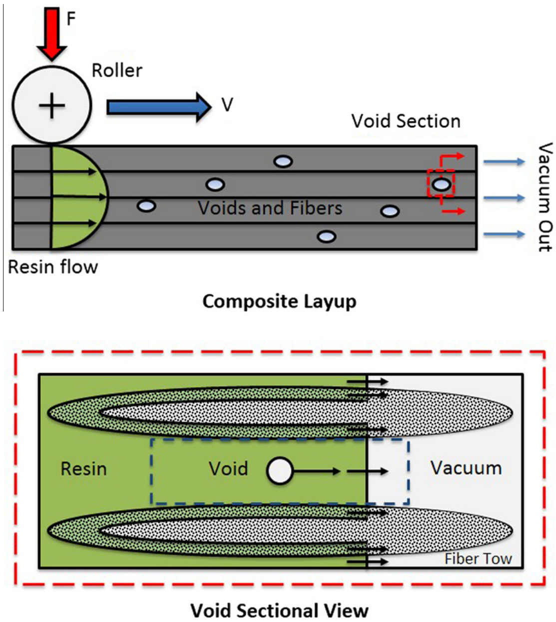

Fig. 1. Void migration during vacuum application in composites processing. External pressure is applied to enhance void migration through resin surrounded by fiber tow porous media.

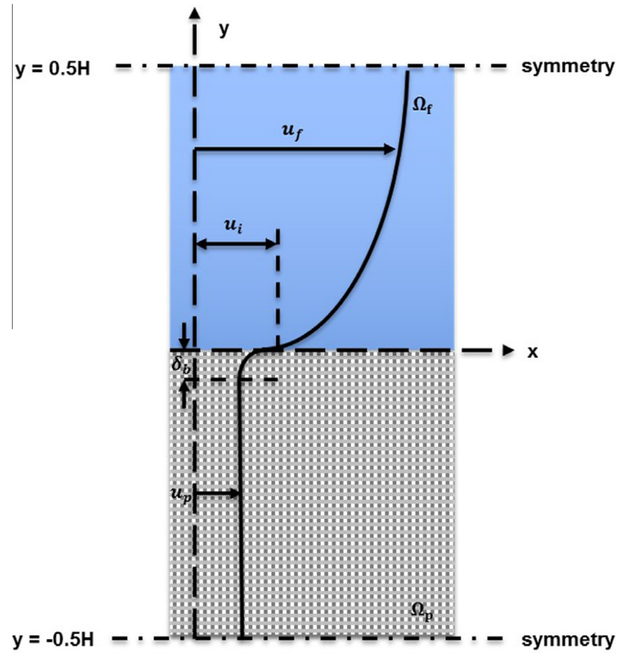

Fig. 2. The parallel channel flow schematic. A free channel domain (Ω_f) and a porous media domain (Ω_p) are filled with a viscous fluid driven by a pressure gradient (dP/dx).

both an empty channel domain and porous media domain. Next, we explore if the channel flow–porous boundary condition from the Stokes–Brinkman equations can be replaced entirely with a suitable slip velocity boundary condition. The slip velocity model from theory is compared with the Stokes–Brinkman results. Since we are interested only in void migration around fiber tows rather than into the fiber tow, we can simplify the problem by considering porous media effects on the channel flow via the introduction of a slip velocity boundary condition and not solve for detailed flow in porous media domains directly. In addition, the validity of introducing the slip velocity rather than the actual porous interface has been discussed, which provides a simplified framework to conduct flow simulations of complex fluids in dual-scale porous media. An implication of this framework could be much reduced computational effort for multiphase 3D flow simulation in a complex 3D porous media structures.

2. Theory

2.1. Parallel channel flow

To understand the influence of porous media on void movement in resin flow, consider a steady one-dimensional pressure-driven parallel channel flow problem as shown in Fig. 2. Here an empty channel domain (Ω_f) is surrounded by a porous media domain (Ω_p). The empty channel flow domain is defined from $y \in [0, 0.5H]$, with H being the channel height. The porous media domain is from $y \in [-0.5H, 0]$. Both domains are filled by a viscous fluid driven by the pressure gradient, dP/dx. Symmetry boundary conditions are shown to define the channel geometry. The fluid velocity in the empty channel domain is denoted u_f and the volume averaged velocity (or "superficial" velocity) of the porous media domain is denoted u_p. Of particular interest is the empty channel/porous media interface at $y = 0$. Here the treatment of the boundary condition will influence a so called porous media boundary layer of thickness δ_b. With the presence of the porous media boundary, a slip velocity is created in the empty channel domain denoted as u_i. Detail will be placed on how the presence of porous media influences this slip velocity and thus voids that are migrating in the pure fluid channel domain.

The analytical solution to the parallel channel flow problem as described by Hwang and Advani (2010) is summarized here. The mass conservation is solved in both the channel domain and the porous media domain in terms of the incompressible fluid velocity u,

$$\nabla \cdot \boldsymbol{u} = 0. \tag{1}$$

For the channel, momentum conservation is written in the form of Stokes equation due to the viscous nature of the fluid,

$$\nabla \cdot [-p\boldsymbol{I} + \eta_f(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T)] = 0 \quad \text{in } \Omega_f. \tag{2}$$

Here, p is the fluid pressure and η_f is the fluid viscosity. For the porous media domain, momentum conservation is written in the form of the Stokes–Brinkman equation as follows,

$$\nabla \cdot [-p\boldsymbol{I} + \eta'(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T)] - \frac{\eta_f}{K_p}\boldsymbol{u} = 0 \quad \text{in } \Omega_p. \tag{3}$$

Here, K_p is the permeability of the porous media and η' is the effective viscosity in the Brinkman equation.

As presented in Hwang and Advani (2010), the governing equations can be simplified from their tensorial forms into a 2D formulation for the channel and the porous media domains as shown below,

$$\frac{dp}{dx} = \eta_f \frac{d^2 u_f}{dy^2}, \quad 0 < y \leqslant 0.5H, \tag{4}$$

$$\frac{dp}{dx} = \eta' \frac{d^2 u_p}{dy^2} - \frac{\eta_f}{K_p} u_p, \quad -0.5H \leqslant y < 0. \tag{5}$$

For the boundary conditions in Fig. 2, the symmetry condition is applied in the fluid channel as,

$$\frac{du_f}{dy} = 0, \quad y = 0.5H. \tag{6}$$

In the porous domain, we introduce the Darcy velocity as an approximation of the symmetry boundary condition,