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The investigation of bubble mobility in channel flow with wavy porous media walls

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ABSTRACT

During composites processing, thermoset polymer resin is injected into network of densely packed continuous fibers with the goal of complete saturation. The formation and entrapment of gas bubbles, due to the presence of air or volatiles during processing, will create voids in the cured composite. Voids can degrade the mechanical properties and increase design risks and costs. Thus, there is a need to understand the two phase flow of resin and bubbles through channels within fibrous porous media. A two-phase flow model of a channel containing resin and gas bubbles is presented. The boundaries of the channel are porous media with sinusoidal wavy or corrugated walls, which represents the wavy nature of the porous media. This causes the change in bubble movement dynamics, due to the non-uniform pressure gradient induced by non-rectilinear walls. Parameters such as porous media permeability, channel waviness, and channel width are studied to investigate the influence of wavy porous wall effects on the two-phase flow and how these parameters may influence the likelihood of bubble entrapment. By maximizing the bubble mobility, which is the ratio of average bubble velocity to average resin velocity, one can remove the bubbles from the system before the resin cures.

Introduction

The primary goal during composites processing is the complete saturation of fibrous porous media reinforcement with polymeric matrix. Successful resin impregnation into fibers yields high fiber volume fraction composites and improved mechanical performance. One of the methods to fabricate composites is from partially pre-impregnated composite fibers or "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, typically using a pressure roller. The pressure roller redistributes the resin and partially consolidates the stacked layers. The composite at this stage will have some empty spaces that have no resin or fibers, but is filled with air. The stacked sequence is subjected to a vacuum to remove the air, water vapor, or other volatiles from these prepregs. 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.

The following is a study of voids or bubbles in uncured viscous polymer resin during composites processing. The goal is to determine if voids can successfully migrate within the fibrous porous media towards flow pathways, coalesce with the pathways, and escape. Fig. 1 describes the simplified model schematically. The goal is to explore the role of material and process parameters that will help the bubble to catch up and merge with the resin surface, such that it can be removed in the flow pathways. This can be estimated by tracking the bubble mobility, which is the ratio of the average bubble velocity to the average resin velocity, to determine if the conditions are favorable for bubble removal.

For this work, the scope is focused on modeling how the presence of wavy porous walls affects void motion. The goal is to model bubble movement through inter-ply channels as a single resin channel with an air interface as depicted in Fig. 1(b). Previous work by Gangloff et al. (2013) considered a problem where a channel with rectilinear porous media walls was saturated with resin and the movement of the single bubble was modeled. The bubble velocity was compared to the average resin velocity, and was shown to be a function of various material and process parameters. In this work, the domain from Gangloff et al. (2013) is perturbed to form a sinusoidal wavy or corrugated porous wall as depicted in Fig. 1. The wavy porous wall creates a non-uniform pressure gradient along the wall compared to the rectilinear porous wall. It is of interest to study the effect of waviness on bubble mobility. Waviness in the flow domain is present due to the wavy nature of the fibers or within a prepreg or between two adjacent prepreg layers.

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Others have considered the study of single phase flow through wavy pores or porous media such as Ng and Wang (2010), Malevich et al. (2006), and Kitanidis and Dykaar (1997), to address the influence of wavy porous walls and permeability on the flow. The void migration is induced by applied pressure (i.e. roller) during processing. The goal is to explore (i) if the pressure gradient is sufficient to move the bubbles to the resin flow front so they can be removed and (ii) the role of wavy porous walls on the bubble dynamics. It is hypothesized that the wavy porous walls may play a significant role on the dynamics of bubble movement.

The presence of the porous walls creates an effective interfacial slip on the porous wall boundary as discussed by Neale and Nader (1974). The movement of the bubble in a channel with porous walls is studied using a framework established in Gangloff et al. (2013) governed by the Stokes–Brinkman equations. These equations solve for the flow in both a rectilinear empty channel domain and rectilinear porous media domain. Next, a framework is presented where the rectilinear domain is perturbed with a sinusoidal wave to define the wavy porous wall. Similar equations to the rectilinear case are developed for the wavy case.

It was shown in Gangloff et al. (2013) that the rectilinear porous media boundary could be reasonably approximated by a suitable slip velocity. A goal of this work is to explore if this can be extended to the wavy porous wall case. In addition, the validity of introducing the slip velocity rather than the actual porous interface is discussed for the wavy porous wall case, which provides a simplified framework to conduct flow simulations within complex flow domains. Substitution of slip velocity to represent the porous domain will reduce computational effort significantly, allowing one to easily address large scale two phase flow in a complex 3D porous media structures (i.e. undulated, woven, or wavy fiber tow networks).

Theory

Parallel channel flow with rectilinear porous walls

To investigate the influence of wavy porous media on bubble movement and dynamics in resin flow, the theoretical framework

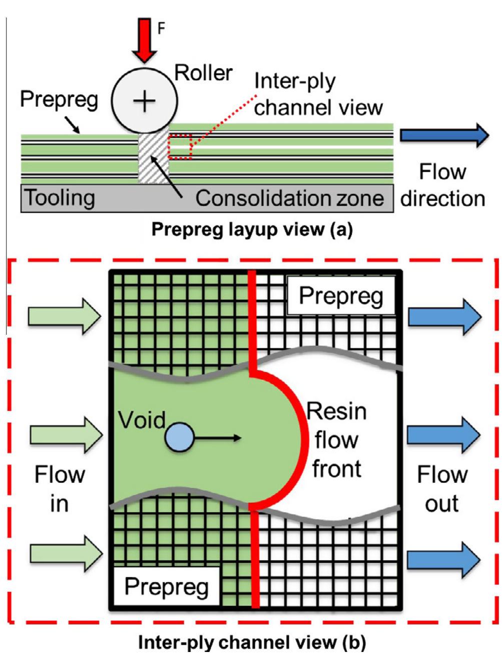

Fig. 1. A schematic of a partially impregnated prepreg process with an applied pressure from a roller. Microvoids are mobilized with the resin in between wavy prepreg layers as they are consolidated.

for the rectilinear wall is summarized from Gangloff et al. (2013). Consider a steady one-dimensional rectilinear pressure-driven parallel channel flow as shown in Fig. 2(a). Here an empty channel domain (Ω_f) is surrounded by a rectilinear porous media domain (Ω_p). The empty rectilinear channel flow domain is defined from $y \in [0, 0.5H]$, with H being the channel height. The porous media domain is defined 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 rectilinear 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 the 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. The details of how the porous media influences this slip velocity was investigated.

The analytical solution to the single-phase rectilinear parallel channel flow was presented by Hwang and Advani (2010). The mass conservation is solved in both the rectilinear channel domain and the porous media domain in terms of the incompressible fluid velocity $\boldsymbol{u}$,

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

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

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

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

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

Here, K_p is the permeability of the porous media and η' is the effective viscosity in the Brinkman equation. Note, $\eta' = \eta_f$ for this work, assuming a continuous stress porous media boundary condition as discussed in Gangloff et al. (2013) and Hwang and Advani (2010). Note, a primary goal of this work is to explore the effects on the changing wavy porous channel geometry on the flow, rather than the influence of parameters that drive the flow (i.e. dP/dx). Corresponding non-dimensional parameters related to the inlet resin flow velocity, such as the Reynolds number ($Re = \rho_f u_f H/\eta_f$) and the Capillary number ($Ca = \eta_f u_f R_b/\gamma_f H$), were unchanged and only the channel geometry and permeability were varied. This work assumes Stokes flow conditions, with the $Re \ll 1$ to match typical flow conditions during composites processing with relatively viscous resin (i.e. $\eta_f = 0.1$–10 Pa s).

As presented in Gangloff et al. (2013) and 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. One can write the result for the analytical slip velocity for the continuous rectilinear porous media interface as the sum of the slip and Darcy velocities as the following,

$$u_s = u_i = \left[-\frac{H}{2\eta_f}\cdot\frac{dP}{dx}\right]\sqrt{K_p} - \frac{K_p}{\eta_f}\frac{dp}{dx}. \tag{4}$$

The volume flow rate per unit depth of the rectilinear channel can also be found analytically. Numerical results are compared to the analytical results for flow out of the rectilinear channel domain. The relative error can be calculated from this comparison. The volume flow rate per unit depth is defined as $Q_f = \int_0^{0.5H} u_f dy$,