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Prediction of capillary pressure for resin flow between fibers

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The flow of resin into fiber tows is driven by an applied pressure gradient and the capillary pressure, which is dependent on the contact angle between the fibers and the resin as well as the fiber diameter and its arrangement with respect to neighboring fibers. Previous work has reported on methods to calculate the average capillary pressure between two fibers which does not take into account the effect of neighboring fibers in a closely packed tow. This paper introduces a novel method to calculate the average capillary pressure of resin moving through a unit cell containing five fibers in a commonly found fiber arrangement within a fiber tow. Both numerical and analytical solutions are presented, validated, and compared. The role of selected parameters on average capillary pressure is investigated. The influence of packing a unit cell with fibers with different surface treatments is also examined. This work should prove useful in predicting the average capillary pressure of resin moving between fibers and the results can be used to address filling of fiber tows during composites manufacturing and addressing void formation within fiber tows.

1. Introduction

Composite materials are comprised of fibers embedded in a resin matrix. The resin is usually introduced into the fibrous preform in the liquid form. During liquid composite molding (LCM), a pressure gradient drives the flow of resin into the preform. These preforms are a dual scale porous medium in which the resin will usually fill the macroscopic pores between fiber tows much faster than it saturates the microscopic pores inside the fiber tows for most composite applications (although it is possible to fill the tows first depending on the capillary number and flow front velocity) [1,2]. In addition to the applied pressure gradient, the microscopic flow of resin into fiber tows, especially in regions far from the inlet, is driven by the capillary pressure. The influence of capillary pressure on composites processing is an active area of research [3–7]. Increasing capillary pressure will result in less microscopic voids inside of fiber tows [8,9]. This will increase the fiber-matrix interfacial area and improve the mechanical properties of the resulting composite because it will eliminate many stress concentrations. On the other hand, presence of microscopic voids can increase energy absorption of the composites by dissipating the impact energy through friction between fibers within the tows devoid of resin [10]. Hence by understanding the role of capillary action within fiber tows at the microscopic level, one can tailor the composite properties for the desired application.

The capillary pressure is the pressure differential across the interface of immiscible fluids. It is dependent on the shape of the interface and can be found by examination of the radii of curvature of the surface and the surface tension, using the Young-Laplace equation [11]:

$$\Delta P = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \quad (1)$$

The radii of curvature of the interface between the immiscible fluids are given by R_1 and R_2 and γ is the surface tension. The radii are measured in orthogonal planes and considered positive if the circle's center is inside the liquid [11]. Bayram and Powell used Eq. (1) along with geometric quantities and the contact angle between the fibers and resin to derive an equation to describe the capillary pressure [12]:

$$P_c = \frac{\gamma \cos(\theta + \alpha)}{r(1 - \cos\alpha) + d} \quad (2)$$

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Here, γ is the surface tension, θ is the contact angle between the fiber surface and resin, r is the fiber radius, d is half of the gap between fibers, and α is the directional body angle (which is described later in Fig. 6). An average value of the capillary pressure is used for a practical way to simulate mesoscopic flow within a fiber tow because using the exact capillary pressure values between fibers would require the use of numerical methods and would not be solvable in a reasonable time due to the extremely large number of elements that would be necessary to determine the microscopic motion of the fluid between three to twelve thousand fibers in a single tow [13,14].

With the assumption that the fibers are either packed in a square or hexagonal packing arrangement, the only parameter describing capillary pressure that changes during resin flow between fibers is the directional body angle. Foley integrated this capillary pressure as a function of directional body angle to obtain an average capillary pressure term [13]. The approximation for the maximum and minimum directional body angles were found by setting the capillary pressure equal to zero and taking the first positive and negative value respectively. An alternative approach was formulated by Neacsu et al., which uses a more complicated weighting function [14,15]. Ahn et al. used an equivalent pore diameter as the input radius for Eq. (1) and calculated the average capillary pressure for transverse flow between hexagonally packed fibers using [16]:

$$\Delta P = \frac{\gamma}{r}\frac{v_f}{1-v_f}cos\theta \tag{3}$$

This approximation does not take the microflow details into account. The approaches by Neacsu et al. [14] and Foley [13] only examine flow between two fibers, without taking into account the influence of other neighboring fibers. The capillary pressure contributions have also been determined utilizing experimental methods, but these only find the average capillary pressure, and do not allow for the capillary pressure to be a function of location within a tow [17].

It is desirable to develop a methodology to calculate the average capillary pressure of resin moving through a unit cell representing the common hexagonal packing within the fiber tow. This calculated average capillary pressure could then serve as input at the resin flow front for a mesoscale model of tow filling. This paper introduces a method to numerically calculate the average capillary pressure for a resin as it fills a unit cell. In addition, a faster method, using the analytical expression for capillary pressure in Eq. (2), is also developed and compared with the numerical method. The average capillary pressure for both of these is found using the same concepts that Foley et al. has shown to be acceptable [13]. The influence of fiber packing as well as utilizing different sizings on the fibers within the unit cell will also be investigated in this paper.

2. Model setup

2.1. Numerical capillary pressure model

A multiphase flow model was developed to describe the flow of resin between two fibers and through a unit cell containing five fibers which is a more common arrangement of fibers within a fiber tow, as shown in Fig. 1. The geometry is simplified to two dimensions and resin flow is only considered across the fibers because the resin flow between two fibers is assumed to be uniform in the axial direction. The slight curvature in the axial direction will be orders of magnitude less than the curvature of the flow front across the fibers. Thus ΔP in Eq. (1) is decided by the very small in-plane radius of curvature across the fibers compared to the axial radius of curvature R_2 which will be very large. The flow is assumed to be Stokes flow due to its small scale and the low Reynolds number, allowing the effect of inertia to be neglected. The walls are periodic because the unit cell is geometrically repetitive and hence the flow pattern will be repeating. The wetting walls describe the partial wetting of the fiber surfaces by the resin. To avoid singularities at the contact line, where there is a triple point, the model uses a slip boundary condition at the fiber surface [18]. This is done through use of the slip length, β. The slip velocity on the fiber surface is expressed as the product of the slip-length and the local velocity gradient normal to the surface (the Navier-slip). The no-slip condition, instead of being applied at the fiber surface, is assumed at a distance β below the fiber surface and simple shear flow is assumed over the depth β: $\boldsymbol{u}=\beta(\boldsymbol{n_w}\cdot\nabla\boldsymbol{u})$, with $\boldsymbol{n_w}$ being the normal vector on the fiber surface [19].

The interface between the resin and air is described using the level set function [20]. The level set function creates an interface with a finite thickness, defined by the signed distance function, ϕ. The smeared-out delta function is then defined by the level-set function [21]:

$$\delta(\phi(\boldsymbol{x})) = -6|\nabla\phi|\phi(1-\phi) \tag{4}$$

The delta function is later integrated to introduce a smeared Heaviside function to change from 0 to 1 across the interface, as is done similarly with the volume-of-fluid method to differentiate the resin and air [21]. The equations governing the resin flow, implemented using COMSOL Multiphysics, are [21,22]:

$$\rho\boldsymbol{u}_t + \rho\boldsymbol{u}\cdot\nabla\boldsymbol{u} = -\nabla\cdot P + \mu^*\nabla^2\boldsymbol{u} + \rho^*\boldsymbol{g} + \boldsymbol{F}_{st} \tag{5}$$

$$\nabla\cdot\boldsymbol{u} = 0 \tag{6}$$

$$\phi_t + \boldsymbol{u}\cdot\nabla\phi = \lambda\nabla\cdot\left(\varepsilon\nabla\phi - \phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right) \tag{7}$$

Here, $\mathbf{u}$ is the velocity vector, μ^* is the viscosity, ρ^* is the density, P is the fluid pressure, $\mathbf{g}$ is the gravity vector, and $\mathbf{F}_{st}$ is the distributed body force over the interface, which is represented by the divergence of the interfacial stress tensor $\boldsymbol{T}$ due to interfacial tension (i.e., $\boldsymbol{F}_{st}=\nabla\cdot\boldsymbol{T}$). The re-initialization parameter for the interface, λ, is set to the approximate maximum interface speed. The interface thickness is given by ε. A value of 0.077 μm, one half of the largest element's height, was selected for ε. The capillary pressure solution was unchanged upon further refinement of the mesh, thus this is an acceptable value of ε. Eqs. (5) and (6) are the Stokes and mass conservation equations respectively. Eq. (7) describes the level set function, which is utilized to define the resin-air interfacial movement. There are multiple ways to formulate the level set method, this form was available in COMSOL and is effective in solving this problem as we are dealing with creeping flow at low Reynolds number also evidenced by the validation of our method. The viscosity and density are interpolated by the Heaviside function according to the regime where the fluid material is present: i.e., resin or air. The reinitialization has been introduced to normalize the distance function property of the level-set function.

We remark that the force from capillary pressure, acting on the resin interface, is assumed to be equal in magnitude as the traction force on the surface of the fibers, shown in Fig. 2, since the interfacial tensions that act in the tangential direction will be cancelled along the interface, except for the contact point. The continuous surface stress tensor of the resin acting on the fiber surface is [23]:

$$\boldsymbol{T} = -\gamma(\boldsymbol{I}-\boldsymbol{nn})\delta(\boldsymbol{x}) \tag{8}$$

The traction force within 0.5 ε from the solid surface, denoted by