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Longitudinal permeability determination of dual-scale fibrous materials

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ABSTRACT

In this work, the longitudinal permeability of squarely packed dual-scale fiber preforms is studied theoretically. These fiber preforms are composed of aligned porous tows and the tows are tightly packed. The effective permeability is calculated as a parallel-like network of intra-tow permeability and inter-tow permeability, which are quantified by Darcy's law and the inscribed radius between tows, respectively. The jump velocity at the interface between inter-tow fluids and porous tows is considered, as derived by substituting Beavers and Joseph's correlation into Brinkman's equation. We further examine the effects of intra-tow permeability on the effective permeability of the fibrous system with three interface conditions: (1) interface velocity = 0, (2) interface velocity = mean intra-tow velocity, and (3) interface velocity = jump velocity. The jump-velocity-based model is found to be closest to numerical data. The influence of the fiber volume fraction of tows on the effective permeability is also analyzed.

1. Introduction

Liquid composite molding (LCM) is an efficient process for shaping and manufacturing fiber reinforced polymer composites. A dense group of filaments are bundled as tows, which are much easier to handle in comparison to individual fibers. During LCM, the liquid resin is injected into the mold cavity along the pre-placed tow bundles [1]. Liquid impregnation is always driven by external pressures and capillary forces [2]. This technique offers cost-effective production of a large amount of composite materials of complex shapes. Much effort has been spent to design and optimize the molding parameters for LCM, reducing the possibility of structure deformation and void formation. However, the currently popular way of determining a set of proper parameters is based mainly on expensive molding experiments.

In efforts to avoid the high cost of trial and error, many predictive models have been proposed for characterizing molding flow. In actual fiber composites, fluid flows not only around but also within the tows [3]. The challenge in modeling is to quantify the inter-tow flow coupled with the intra-tow flow in the complex dual-scale structure. Early models of the permeability of a single-scale fibrous medium consisting of regularly aligned fibers approximated the intra-tow flow as negligible [4–6]. The prediction of the permeability has been conducted using the Stokes equation under different boundary conditions of the unit cell [7–9]. However, discrepancies were often found between these models and experiments [10]. The local flow motions at different length scales in multifilament composites determine the macroscopic flow behavior, so the neglect of considering microscale flows within tows lacks real scientific justification. To accurately realize local flows, researchers have applied the Stokes equation to quantify flow behavior in the inter-tow region and have used Darcy's law to determine intra-tow flow [11,12]. Flow velocity was assumed to be continuous at the sharp interface between the inter-tow and intra-tow areas. Nevertheless, the Stokes equation contains the shear term whereas Darcy's law does not. As such, the incompatible differential operators make it difficult to match the shear stress at the interface between the open and porous regions [13].

Later, the Brinkman equation was widely employed in preference to Darcy's law to describe intra-tow flow [14–18]. The Brinkman equation is a combination of the Stokes equation and Darcy's law, and has the same order of differential operator as the Stokes equation used for the inter-tow flow. Both continuity and discontinuity of shear stress at the fluid-porous interface are explored comprehensively for the Brinkman equation and the difference in effective permeability based on the two conditions is very small [17]. However, simultaneous calculation of the Brinkman equation and the Stokes equation is quite difficult for theoretical modeling. As an alternative, transverse and longitudinal permeabilities of tow assembly have often been calculated based on computational fluid dynamic simulations [14–19]. Yet this simulation involves the simultaneous resolution of flow fields in the complex dual-scale structure, and thus it is still computationally expensive. Following

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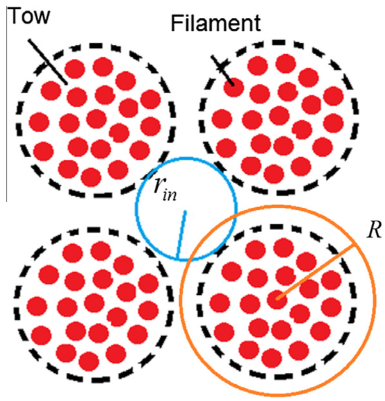

Fig. 1. Schematic of squarely packed porous tows consisting of aligned filaments. The radius of a representative cell is R and the inscribed radius between tows is r_{in}. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the previous studies [14–19], we recently investigated transverse flow in dual-scale fibrous materials based on a jump velocity at the porous-fluid interface, where the interface velocity was considered to differ or jump from the mean velocity of the intra-tow area [20]. The complexity of calculation is much reduced and the proposed model agrees closely with numerical and experimental results from circular to elliptical tows [20].

To the best of our knowledge, there are few theoretical models of longitudinal flow in dual-scale fibrous materials. In this paper we theoretically explore the longitudinal permeability of squarely, tightly packed dual-scale fiber preforms (Fig. 1). Jump velocity is considered at the interface between the inter-tow fluid and the porous tow. Effective permeability is calculated as a parallel-like network of intra-tow permeability and inter-tow permeability, which are characterized by Darcy's law and the inscribed radius between tows, respectively. This compact model of longitudinal permeability is expressed as a function of the filament volume fraction (VF) within a representative tow (υ_f), the tow VF of a fiber preform (υ_{tow}), tow radius (r_{tow}), and filament radius (r_f). No empirical constants are used and each parameter has clear physical meaning. Furthermore, we examine the effect of intra-tow permeability (K_{tow}) on effective permeability (K), with three interface conditions: (1) interface velocity = 0, (2) interface velocity = mean intra-tow velocity, and (3) interface velocity = jump velocity (Fig. 2). We also investigate the effect of the total fiber VF of the fibrous system (υ_t) on the effective permeability under different values of υ_f.

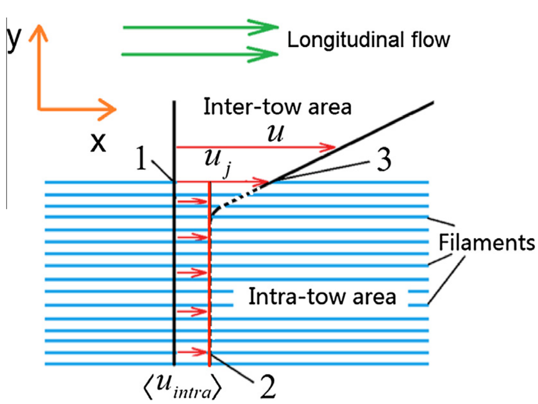

Fig. 2. Velocity profile for longitudinal flow along a porous tow adjacent to an open channel (Case 1: $u_i = 0$; Case 2: $u_i = \langle u_{\text{intra}} \rangle$; Case 3: $u_i = u_j$). Here, u_i is the velocity at the interface between the porous tow and the open channel, $\langle u_{\text{intra}} \rangle$ is the mean velocity of the porous tow, and u_j is the jump velocity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Model generation

In this work, dual-scale fiber arrays are assumed to consist of representative cells in a periodical fashion (Fig. 1). The dual-scale fibrous materials are characterized by two length scales, and the two associated fiber VFs are defined as: filament VF υ_f, the ratio of the solid filament volume to the total volume of a tow; and tow VF υ_{tow}, the ratio of the tow volume to the total volume of the weave when all the tows are impermeable solid. Fig. 2 demonstrates the flow profiles passing simultaneously through both intra-tow and inter-tow (open channels) areas. Additional assumptions are as follows:

1. The liquid is Newtonian and the viscous flow dominates, with the Reynolds number much smaller than one.
2. All filaments are impermeable and fluid flows exist in the void pores between both filaments and tows.
3. The fiber preforms are made up of straight tows, and the tow is made up of tightly packed straight filaments.

The Brinkman equation, which has been used to successfully describe intra-tow flow [14–16], is given by

$$-\frac{dp}{dx} + \mu_e \frac{d^2 u_{\text{intra}}}{dy^2} - \frac{\mu}{K_{\text{tow}}} u_{\text{intra}} = 0. \tag{1}$$

where u_{intra} and K_{tow} are the effective velocity and the permeability of the porous tow, respectively, $\frac{dp}{dx}$ is the pressure gradient, μ is the flow viscosity, and μ_e is the effective viscosity in the porous tow.

Beavers and Joseph [21] observed a phenomenological jump in flow velocity at the interface between inter-tow and intra-tow areas. The flow velocity at the interface u_i differs from the mean velocity in the intra-tow area $\langle u_{\text{intra}} \rangle$, based on the measurement of flow behaviors in a hollow channel bounded by a porous medium. Here, the mean velocity is referred to the superficial velocity in the porous medium. They found the jump velocity u_j or interface velocity u_i to be proportional to the shear rate of the flow at the interface using a scale analysis [21]:

$$\left.\frac{du_{\text{inter}}}{dy}\right|_{y=0} = \frac{\alpha}{\sqrt{K_{\text{tow}}}} (u_i - \langle u_{\text{intra}} \rangle), \tag{2}$$

where α is a dimensionless coefficient to be determined. The fluids in the open channels between tows (or inter-tow areas) are parallel with the intra-tow flows, so the pressure gradients in the porous tows is equal to that in the open channels, as described by Darcy's law,

$$\frac{dp}{dx} = -\frac{\mu}{K_{\text{tow}}} \langle u_{\text{intra}} \rangle. \tag{3}$$

Substituting Eq. (3) into Eq. (1) we have:

$$\frac{\mu}{K_{\text{tow}}} \langle u_{\text{intra}} \rangle + \mu_e \frac{d^2 u_{\text{intra}}}{dy^2} - \frac{\mu}{K_{\text{tow}}} u_{\text{intra}} = 0. \tag{4}$$

The porous tows of interest in LCM are always composed of tightly packed filaments [15]. In comparison to inter-tow permeability, the permeability of the porous tows is small. It has been found that there is very little penetration of inter-tow flow into the compact porous media [22]. As such, we assume the mean velocity of the tow equal to $\langle u_{\text{intra}} \rangle$ in Darcy's law of Eq. (3) (see the solid red line in Fig. 2). And then we calculate the velocity profile near the interface as driven by the inter-tow flow (see the dotted black line in Fig. 2). In most cases of LCM, μ_e in the porous