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Invited review

Modeling capillary pressure in dual-scale fibrous structures for resin transfer molding processing of composites: A brief review and perspective

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Abstract:
Resin transfer molding has garnered significant attention for the development of high performance and complex structural composites. Capillary forces, driven by surface tension and fibre wettability, play a crucial role in the impregnation of fibres by resin flow. Capillary pressure is identified as a key factor in void formation and transport during the molding process. The influence of geometrical parameters on the capillary pressure is also examined. This review delves into the mechanism of capillary pressure, considering the effects of fibre arrangement and dual-scale pore structures during the resin transfer molding filling stage. The models incorporate fluid dynamics, surface tension and fibre wettability, and is validated by the wicking experiments. The recent works suggest that better control over capillary pressure during resin transfer molding processing can lead to improved filling uniformity, reduced void content, and enhanced mechanical properties of composite materials. The development of artificial intelligence assisted methods for capillary pressure assessment and control shows great potential for improving high-performance composite manufacturing.

1. Introduction

The resin transfer molding (RTM) is a widely adopted process approach for manufacturing fibre-reinforced composites, renowned for its ability to produce high-strength, lightweight, and complex-shaped components with an excellent surface finish (Delgado et al., 2019; Wang et al., 2022; JEC, 2023). This process is highly efficient for producing large components with consistent quality, making it a popular choice in industries such as aerospace, automotive and wind energy (Fan et al., 2023; Chen et al., 2024; Xu et al., 2024). In RTM, liquid resin is injected into a closed mold containing dry fibre preforms, where it impregnates the fibres before curing. A significant challenge has remained in achieving defect-free components with high mechanical performance of composites, particularly in controlling the formation of voids during resin impregnation process (Mendikute et al., 2022; Chen et al., 2023a, 2023b). Given the standard of US aeronautics, parts containing more than 2% of void defects should be rejected (Park and Woo, 2011).

Capillary effects occur at resin flow front during impreg-

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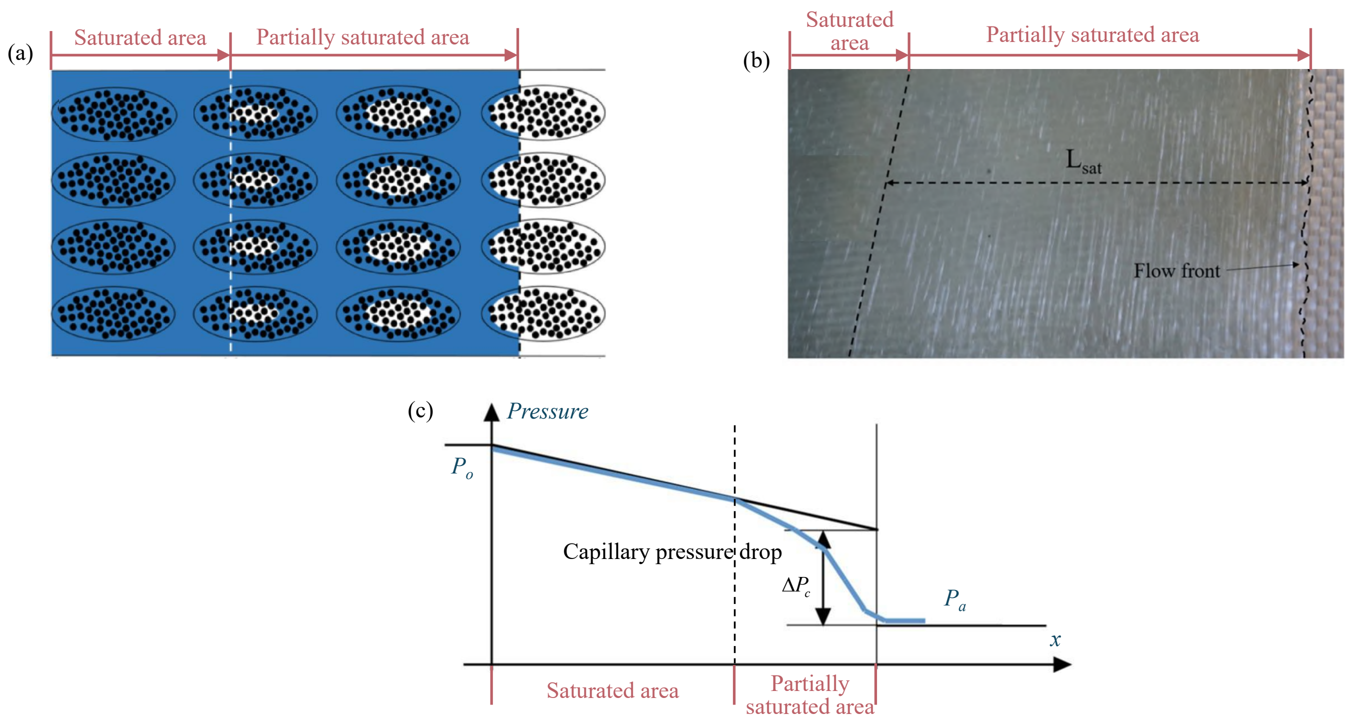

Fig. 1. Dual scale flow scheme showing saturated and partially saturated regions (Park and Woo, 2011; Facciotto et al., 2023). (a) Schematic representation of the dual-flow impregnation yarns, (b) dual scale flow in RTM and (c) pressure profiles.

nation processing, where capillary pressure plays a significant role in the formation of voids (Wang et al., 2017; He et al., 2021; Patiño and Nieto-Londoño, 2021; Zhou et al., 2024). The preforms commonly have dual-scale pores, which are micro-pore within the intra-tows and macro-pore between the inter-tows (Zhang et al., 2023; Hong et al., 2024; Zhai et al., 2024). The complex hydrodynamic mechanism in this process is influenced by several factors, including resin viscosity, fibre permeability, injection pressure, and capillary forces (Jo et al., 2024; Peng et al., 2024a, 2024b). Capillarity-related phenomena occur primarily at the infiltration front, where air entrapment can lead to void formation, reducing the performance of products (Lee et al., 2006; Wu et al., 2019; Shevtsov et al., 2022; Lu et al., 2024). At this front, capillary forces lower the pressure boundary condition, as schematically illustrated in Fig. 1. Dual-scale flow describes the infiltration process where liquid resin penetrates the intra-tow spaces between individual fibres at a distinct rate compared to the inter-tow gaps. This phenomenon is driven by capillary forces, which dominate the wicking process during impregnation in low capillary number regimes (Ruiz et al., 2006; Sharma et al., 2009; Yeager et al., 2016; He et al., 2019; Facciotto et al., 2024). However, the capillary pressure is difficult to directly monitor during RTM in dual-scale preforms. To accurately capture resin flow evolution during the impregnation process, wicking experiments is adopted to monitor the complex hydrodynamic interactions among the liquid, gas, and solid phases. To account for the dual-scale structural effects, these processes are typically described using averaged properties within a unit cell or representative volume element. Insights into capillary action within fibre bundles and preforms provide crucial theoretical support for optimizing the performance of composites.

This work aims to systematically describe the capillary pressure models of fibre composites. In RTM process, the modeling of capillary forces is essential for accurately predicting the resin flow through the porous preform. This work examines the models that address capillary pressure within fibre tows and dual-scale preforms under capillary-driven flow, and highlight their key differences. Recent developments in computational modeling of capillary effects within RTM processes have focused on integrating these forces into traditional Darcy's law-based resin flow models. By adapting these models to include capillary pressure, researchers aim to better simulate the resin infiltration into the fibre bundles and voids, which is critical for achieving full impregnation and minimizing void defects. By synthesizing these insights, this work seeks to offer valuable support for future research endeavors and practical advancements that can better simulate and control RTM processes, and reduce waste and ensure more consistent product performance across a range of applications. This review is tailored for an audience well-versed in composite materials and will be especially relevant to the academic community focused on mechanics of manufacturing processes.

2. Capillary pressure model for fibre bundles

Capillary pressure refers to the pressure difference across the gas-liquid interface caused by the surface tension at the liquid-solid interface, as described by Young's equation (Duprat et al., 2012; Alzahrani et al., 2024; Minakov et al., 2024), which relates with the contact angle, surface ten-

Table 1. Capillary pressure model of fibre bundles.

References	Average capillary pressure models	Fibre packing
Ahn et al. (1991) Pillai and Advani (1996)	$\overline{P_c} = \frac{F}{D_f}\frac{V_f}{1-V_f}\gamma\cos\theta$	Hexagonal packing
Bayramli and Powell (1990)	$\overline{P_c} = \frac{2\gamma\cos(\theta-\alpha)}{D_f(1-\cos\alpha)+d_t}$	Quadrilateral packing
Neacsu et al. (2006)	$\overline{P_c} = \frac{2\gamma}{D_f}\frac{\sin(\alpha_{\text{sup}}+\theta)-\sin(\alpha_{\text{inf}}+\theta)}{\frac{5\pi}{6}\left(1+\frac{d_t}{r_f}\right)-1-\frac{\sqrt{3}}{2}}$	Hexagonal packing
Yeager et al. (2016)	$\overline{P_c} = \frac{1}{S_{\max}-S_{\min}}\sum_{1}^{n-1}\frac{1}{2}(P_{c,i}+P_{c,i+1})\Delta s$	Compressed hexagonal packing

Notes: F is form factor depending on the fibre alignment and the flow direction, D_f is the fibre diameter, V_f is the fibre volume fraction. d_t is the half of the gap between fibres, and α is the directional body angle. s is the fibre surface area wetted. The maximum and minimum permissible surface area wetted in the unit cell is given by $S_{\max}$ and $S_{\min}$ respectively. The number of data points in P_c versus s dataset is represented by n. α_{sup} and α_{inf} is the specific values of limits, $\alpha_{\text{sup}} \cong (\pi/2-\theta)$ and $\alpha_{\text{inf}} \cong (\theta-\pi/2)$. r_f is the fiber radius.

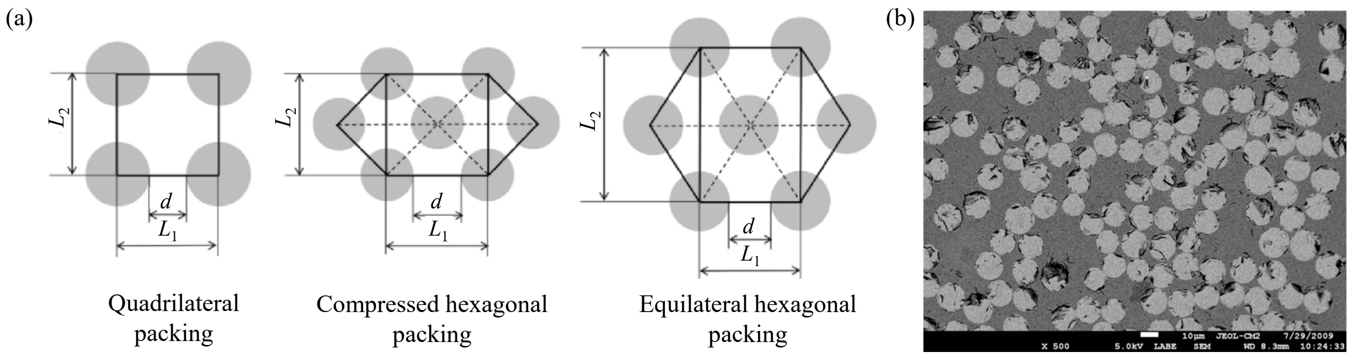

Fig. 2. Fibre structures in tows. (a) Assumption (Lu et al., 2017) and (b) microscopic (SEM) image of fibre glass tow (Lebel et al., 2012).

sion, and interfacial forces acting on the solid surface:

$$P_c = \frac{2\gamma\cos\theta}{r} \tag{1}$$

where P_c is the capillary pressure, γ is the surface tension, θ is the contact angle, and r is the radius of the tube.

The capillary-driven flow is characterized by the Lucas-Washburn (LW) equation (Washburn, 1921) in capillary tube:

$$H = \sqrt{\frac{r\gamma\cos\theta}{2\mu}t} \tag{2}$$

where H is the distance travelled by the liquid front, t is the time of flow, and μ is the viscosity of the liquid. The mass gain over time can be expressed:

$$m = \sqrt{\frac{\pi^2 r^5}{2}\frac{\rho^2\gamma\cos\theta}{\mu}t} \tag{3}$$

where ρ is density of the liquid, m is mass of the liquid.

The average capillary pressure models were established for flow within fibre bundles at the micro-scale level with assumption of ideal fibre arrangement. Table 1 presents the average capillary pressure models of intra-tows. Fig. 2 displays the representative fibre packing structures and a microscopic (SEM) image of a fibre glass tow. Ahn et al. (1991) and Pillai and Advani (1996) employed volume fraction ratio of the bundle to proposed an analytical expression of the capillary pressure, considering the effect of the tow structure on the capillary pressure. Bayramli and Powell (1990) investigated the influence of the unique structures of fibres to develop a capillary pressure model, assuming that a quadrilateral packing arrangement of the fibres. This model characterizes the variation of capillary pressure as a function of the directional body angle. Foley (2003) and Neacsu et al. (2006, 2009) examined the flow between two fibres and collected capillary pressure values based on approximations for the maximum and minimum directional body angles to estimate the average capillary pressure. Yeager et al. (2016) proposed a capillary pressure model that accounts for the influence of neighboring fibres in a closely packed tow. A compressed hexagonal packing arrangement, commonly found within fibre tows, is used as the unit cell. The model involves the effect of fibre orientation on the offset to determine an average capillary pressure, which influences capillary-driven resin flow (Balbinot et al., 2022). For these models, the factors should be considered, including the structural characteristics of the fibre bundles, their volume fractions, and the required level of computational accuracy. T-

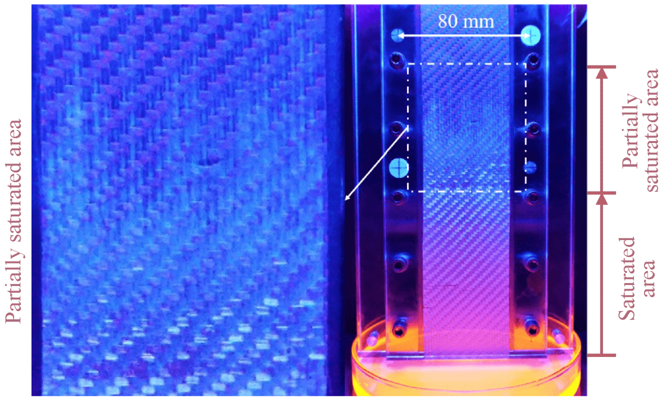

Fig. 3. Capillary wicking experiment with flow visualization (Facciotto et al., 2023).

he models proposed by Ahn et al. (1991) and Pillai and Advani (1996) offer convenient estimation methods for involving simple fibre bundle arrangements. This model has largely been used in the literature (Amico and Lekakou, 2002; Matsuzaki et al., 2015; Vilà et al., 2015; Willenbacher et al., 2019; Facciotto et al., 2021; Cui et al., 2024). Conversely, in cases requiring a more precise assessment of the effects of fibre orientation or in complex structures, the models developed by Yeager et al., Bayramli and Powell (1990) and Neacsu et al. (2006) could be employed.

3. Capillary pressure model for dual scale structure of preforms

Capillary pressure in the preform is commonly characterized using Washburn's method for capillary driven flow in porous media (Gambarini et al., 2024; Turner et al., 2024). The Darcy law is combined with the Washburn equation to express the capillary pressure for preforms with the permeability. Due to the intricate nature of preform structures, accurately determining permeability can be challenging. To quantify the capillary pressure in the preforms, capillary wicking experiments are employed in the context of RTM processing. Composite wicking exhibits capillary performance that integrates both permeability and capillary pressure. These experiments observe how fluids are drawn into and move through the porous material, thereby providing insights of the capillary forces. In this method, the sample material is immersed in a container filled with the infiltration liquid, and the progression of impregnation is tracked over time. Measurement approaches typically involve monitoring the liquid mass absorbed and the rise of the capillary front. Several visual techniques (infrared thermography, fluorescence visualization, tensiometric methods, or via X-ray computed microtomography) are available to measure the height of the fluid front, including capturing images during the capillary rise and using image processing to determine the position of the capillary front, as shown in Fig. 3. The capillary pressure models are listed in Table 2.

Verrey et al. (2006) proposed a capillary pressure model by a parameter (S_f) representing the area of fibre-matrix interface pre unit volume of matrix appears, which is suitable for input types of a constant applied pressure gradient and at a constant flow rate. It should be noted that the involved parameter is difficult to measure. Lebel et al. (2012, 2013) proposed a capillary pressure model for dual-scale fabrics by estimating the relationship between the parameter and the axial permeability of fibre tows based on capillary pressure at equilibrium. Pucci et al. (2015) proposed a tensiometric model incorporating geometrical parameters and fluid-solid interactions. To examine these parameters, the three principal directions of flow in quasi-UD carbon fabric were measured. The permeability ratio between unsaturated and saturated conditions was analyzed to reveal the influence of capillary effects (Caglar et al., 2019). Most of these experiments have focused on the wicking behavior of a single fabric ply and several plies in the in-plane direction. These measurement systems are not suitable for determining capillary pressure in the out-of-plane direction. Furthermore, Willenbacher et al. (2019) introduced a novel measurement system for out-of-plane capillary pressure based on wicking experiments of a random mat, a 2/2 twill woven fabric, and a biaxial non-crimp fabric. Simultaneously, capillary pressure models of natural fibre reinforcements undergoing swelling were established (Yin et al., 2018; Vo et al., 2020; Lu et al., 2022).

Wicking flow could occur in longitudinal, transverse, and out-of-plane directions during RTM. As the fibre volume fraction increases, the flow rate accelerates, leading to higher capillary pressure. Variations in reinforcement materials and their architecture also affect capillary pressure. During resin infiltration, capillary pressure is highly sensitive to the type of fibre reinforcement and the arrangement of the fibres (Abaimov et al., 2020; Kim et al., 2022; Facciotto et al., 2023; Shen et al., 2024; Ying et al., 2024). Different materials, such as glass or carbon fibres, exhibit distinct wetting behaviors and pore structures, influencing overall flow characteristics (Li et al., 2024; Mahmood et al., 2024). The weave types of the fibre preform introduce variability in resin flow paths, resulting in differences in capillary pressure (Xiao et al., 2021; Trofimov et al., 2023). These variations in material properties and structural configurations have led researchers to extend capillary pressure models to account for the diverse characteristics of reinforcement materials and fibre architectures. Significantly, for the capillary wicking experiments, the accuracy of measurements is constrained by the pixel resolution of the camera and the contrast between the fluid and fibres during filling (Facciotto et al., 2023). For the capillary pressure models, it is difficult to accurately characterize capillary effects in the RTM process by predicting capillary pressure using an average model based on the assumption of ideal fibre arrangement. Therefore, artificial intelligence (AI) methods could be provided to establish accurate capillary pressure model, which widely used in scientific researches and industries for years.

4. Conclusions

Capillary effects occur across various length scales in RTM processing. They manifest at the meniscus line in resin flow front where the fluid, solid, and air phases meet. Although capillary forces are generally not the primary driving factors in resin impregnation, compared to injection pressures or controlled flow rates, they play a significant role in void

Table 2. Capillary pressure model of deal-scale fabrics.

References	Average capillary pressure models	Fabric types
Verrey et al. (2006)	$\overline{P_c} = -S_f \gamma \cos\theta$	Biaxial woven fabrics with a stacking sequence of (±45°)
Lebel et al. (2012)	$\overline{P_c} = \frac{f_{geo}}{4k_o\tau^2}\frac{D_f(1-V_f)}{V_f}\frac{\varepsilon}{\kappa}\gamma\cos\theta$	Biaxial woven e-glass fabric
Pucci et al. (2015) Caglar et al. (2019) Willenbacher et al. (2019)	$\overline{P_c} = c\bar{r}\varepsilon\frac{\gamma\cos\theta}{4\kappa}$	Carbon quasi-UD fabrics and Twill 2/2 woven E-glass fabric
Vo et al. (2020)	$\overline{P_c} = c\left[(1-\phi_{yarn})\overline{R_1} + \phi_{yarn}\overline{R_2}\right]\varepsilon\frac{\gamma\cos\theta}{4\kappa}$	Flax quasi-UD fabrics

Notes: κ is the permeability of preforms, f_{geo} is a geometrical constant, ε is the porosity, k_o is Kozeny geometrical constant and τ is tortuosity. $\bar{r}$ is mean capillary radius. c is a parameter related to tortuosity. $\overline{R_1}$ and $\overline{R_2}$ are the mean capillary radii before swelling between the individual yarns, and between the elementary fibres, respectively. ϕ_{yarn} is the surface ratio of yarns for a cross-section of the composite.

formation. Achieving an optimal flow front velocity, which balances the contribution of capillary pressure in dual-scale flow, can help minimize air entrapment during impregnation. There is increasing recognition of the importance of the geometric features of fibres in tows and preforms when evaluating capillary effects.

Current research focuses on enhancing the understanding of these effects to model capillary pressure more accurately and improve part quality. Modeling efforts aim to connect local wetting phenomena with the geometric characteristics of pores, which contribute to macroscopic, volume-averaged capillary effects. The ongoing development of capillary pressure models has provided valuable insights into optimizing resin flow in RTM processes, particularly for dual-scale fibre-reinforced composites. These advancements contribute to improved manufacturing quality, ensuring consistency and reliability in composite material production.

5. Perspectives

To ensure the mechanical performance of composites produced via the RTM process, it is essential to control capillary effects during impregnation flow for minimizing both micro- and macro-scale void defects. Although significant efforts have been made to analyze and model the capillary pressure in textiles, most related research on accurate capillary pressure prediction focuses on plate-shaped components, often through capillary wicking experiments.

AI-enhanced method would apply to restructure pore structures and identify the wicking front for dual-scale preform. Traditional models often assume idealized or uniform fibre distributions, but textiles exhibit stochastic features in fibre alignment, space distribution and pore structure. These geometric characteristics directly influence the capillary wicking behavior and, subsequently, fluid flow during resin impregnation. By integrating AI techniques, such as computer vision and deep learning, it becomes feasible to analyze high-resolution images or 3D scans of reinforcements to extract precise geometric features, including fibre orientation, pore size distribution, and porosity. These features can then be used to inform more accurate capillary pressure models that account for local heterogeneities. Moreover, the drive to reduce void formation and enhance mechanical properties has spurred the development of methods that couple multiscale physical fields. These advancements hold significant potential for the production of high-performance composites.

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Conflict of interest

The authors declare no competing interest.

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