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Estimation of local permeability/porosity ratio in resin transfer molding

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ABSTRACT

Resin transfer molding (RTM) is a promising technique for manufacturing fiber-reinforced plastic (FRP) composites. In RTM, the permeability/porosity ratio of the preform is a critical process parameter, which varies with the geometric formation of the fiber reinforcement. This parameter dominates the characteristics of resin flow and influences the final product quality. Most of the existing measurement methods treat the material porosity as a constant and estimate the permeability of the entire fiber preform as a single value, while local variations are ignored. In this study, a measurement system is developed to estimate the local values of the permeability/porosity ratio, which does not require mounting pressure sensors in the mold. Instead, at each sampling time point, the overall (global) permeability/porosity ratio of the fiber preform between the injection gate and the flow front is calculated. Then, the local ratio is derived based on the relationship between the overall and local values.

1. Introduction

In manufacturing processes of polymer composites, such as resin transfer molding (RTM), final product quality is affected by multiple material and process parameters, among which the permeability of fiber reinforcement is critically important. Permeability is related to the pore structure of porous media. Specifically, the permeability of porous fiber media depends on the fiber diameter, the porosity, and the network geometry [1], representing the ability of the fibers to transport fluids. Therefore, an accurate measurement of the permeability of the fiber preform is a necessity for effective simulation and control of the RTM processes [2,3].

There have been a number of research studies concerning the measurement of permeability in porous media of fiber-reinforced plastic (FRP) composites [4]. To completely characterize fluid flow in an anisotropic media, three permeability components (often denoted as K_1, K_2, and K_3) are needed, where K_1 and K_2 refer to the permeability values along the two principal directions in the horizontal plane and are defined as in-plane permeability, and K_3 is the out-of-plane permeability in the thickness direction. Most research studies are devoted to the measurement of in-plane permeability, which is also the focus of this study.

In-plane permeability measurement methods can be classified according to several different criteria [5], including saturation state of the fabric specimen, injection boundary condition, and flow geometry. In detail, some measurement instruments are designed for estimating the saturated permeability, which are often operated at constant flow rates; the others are developed for unsaturated permeability measurements, where either constant flow rates or constant pressures can be adopted. In addition, the former generate linear flow by using a rectangular flow channel with an injection gate located at one end of the mold, while in the latter case the flow may be either linear or radial. The radial flow pattern is often caused by central injection. In RTM, the unsaturated permeability is more important, because the resin flow in the mold is unsaturated. Therefore, in this paper, only this type of permeability is considered.

A particular study [5] shows that there is no dominant method in the field of permeability measurement. The results are often affected by various types of factors. In many experiments, transparent molds are often used to enable the visibility of the flow, so that the positions and velocities of the flow fronts can be obtained in real time. For example, Wang et al. [6] studied the properties of various fabric reinforcements by using a flow visualization system. The principal directions were observed and the in-plane permeability coefficients were estimated from the relationship between the pressure and flow rate. A similar idea was adopted by Lee et al. [7] in their measurements. They discovered that the porosity

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of the preform often changes with the number of fiber sheet layers used in the experiments, leading to changes in the permeability. Simacek and Advani [8] studied the relationship between resin pressure, thickness, and permeability, and derived a model for calculating the equivalent permeability. Luo et al. [9] investigated the effect of using different test fluids in the permeability measurement. They concluded that the choice of test fluid has little influence on the measurement results. Ameri et al. [10] adopted analysis of variance (ANOVA) to explore the important parameters affecting the permeability coefficients. In addition to the studies mentioned above, other relevant studies include [11–13]. Comprehensive reviews of different methods for permeability measurements can be found in the cited papers [4,5].

Considering flow-front monitoring, besides the visualization system, different types of sensors have been designed. Matsuzaki et al. [14] developed an area-sensor array to achieve a full-field monitoring of the resin flow inside the mold cavity. Yenilmez and Sozer [15] embedded a grid of dielectric sensors in the walls of the mold to monitor the process of mold filling. In addition, other flow monitoring devices have been introduced [16,17].

Most studies on permeability measurement of fibrous reinforcements in RTM ignore the effects of local variations and only obtain a single value for each permeability coefficient. However, in fact, the fiber permeability values in composite manufacturing often follow a certain statistical distribution [18]. As pointed out in [19], the permeability depends on the fiber volume fraction and preform architecture. Any changes in these during the placement of the reinforcement preform and the impregnation of the resin into the fiber structure lead to variations in the local permeability values. In addition, the local permeability data is meaningful for product quality control [20]. To obtain local permeability measurements, Ding et al. [21] proposed using a gas flow and a mounted pressure sensor array to measure the gas permeability profile for the fiber preform. Then, according to the correlation between the gas and liquid permeability, the local permeability variation information is acquired. In their method, the ratio between two in-plane permeability coefficients is assumed to be known. A more direct method was proposed by Nielsen and Pitchumani [22], which estimates the local permeability values (which are, in fact, the local values of the permeability/porosity ratio) by using a fuzzy logic model. Their method utilizes a large amount of simulated data for model training. As a result, the estimated values may be closer to the values of the simulation parameter instead of the real process parameter. Most recently, Wei et al. [20] developed a visualization system to record the flow front positions and employed a pressure sensor array mounted inside the mold to measure the local pressure values in real time. Then, the local values of the ratio of permeability to porosity were derived from Darcy's law, based on the information collected online.

It is reasonable to measure the permeability/porosity ratio instead of the permeability itself when local variations are considered, because the porosity varies and cannot be considered as a known constant in such a case. However, the methods mentioned in the previous paragraph often rely on a complex sensor arrangement. To solve this problem, this paper studies the relationship between the values of the overall permeability/porosity ratio and the local values, based on which in-situ method for measuring the local permeability/porosity ratio is proposed. Similar to [20], linear flow is studied in this paper. Therefore, only the parameter along the resin flow direction is measured.

2. Instrumentation and equipment

The piping and instrumentation diagram (P&ID) of the experimental system used in this study is shown in Fig. 1. The resin is stored in a container linked to the inlet of a mold, while the outlet of the mold is connected to a vacuum pump. During the vacuum-assisted infusion, the resin is driven by the pressure difference and injected into the mold to impregnate the preform. The top plate of the mold is transparent, facilitating the flow visualization, while the bottom plate is made of metal alloy, with a cavity to contain the preform. The dimensions of the mold cavity are $30\,\text{cm} \times 12\,\text{cm} \times 0.3\,\text{cm}$. During the experiments, the flow-front data is captured in real time by a CCD camera and a National Instruments (NI) IMAQ frame grabber card. In addition, as shown in Fig. 2, a 3×8 pressure sensor array is embedded in the bottom plate to record the pressure distribution during infusion. It should be noted that these sensors are not needed by the proposed method. Here, they are utilized to get the information necessary for conducting the method developed in [20]. Then, the feasibility of the proposed method can be verified through comparison. In this study, the hardware devices are integrated using LabVIEW. Fig. 3 displays the mold used in the experiments. The positions of the pressure sensors can be observed through the transparent top plate.

The epoxy resin is adopted as the raw material in the experiments, whose viscosity is about 550 cp in room temperature. The preform is composed of glass fibers, which are often used as a reinforcing material for polymer composites. A piece of fiber mat is shown in Fig. 4.

3. Measurement of local permeability/porosity ratio

In this section, an in-situ method is proposed for measuring the local values of the permeability/porosity ratio of the fiber preform used as reinforcement in RTM. The basic idea is as follows. At each sampling time point after the infusion begins, the overall value of the ratio of permeability to porosity between the injection gate and the current flow-front position is calculated. Then, the local value between two consecutive flow-front positions can be derived from the relationship between the overall and local ratio values. The details are presented below.

The motion of incompressible fluids flowing through porous fiber structure is governed by the well-known Darcy's law

$$\mathbf{u} = -\frac{1}{\mu}\mathbf{K} \cdot \nabla P \tag{1}$$

and the continuity equation

$$\nabla \cdot \mathbf{u} = 0, \tag{2}$$

where $\mathbf{u}$ is the vector of Darcy velocity, $\mathbf{K}$ is the permeability tensor, μ is the viscosity of the resin, and ∇P denotes the pore-average pressure gradient inside the mold. These equations describe the macroscopic relationship between the Darcy velocity and the drop in pressure. Therefore, they are often used in permeability estimation.

In this study, linear flow experiments were conducted in a rectangular mold. Therefore, it is reasonable to make the following assumptions [23]: the flow coordinate is along the principle direction of fiber; resin flows along a one-dimensional direction, *i.e.*, the x-axis; and the z-axis scale is neglected. The behavior of the resin flow is then described with the following simplified one-dimensional equation:

$$u = -\frac{K}{\mu}\left(\frac{\partial P}{\partial x}\right), \tag{3}$$

where u, K, and $\frac{\partial P}{\partial x}$ are the Darcy velocity, permeability, and pressure gradient along the flow coordinate, respectively.

The above equation cannot be used in permeability estimation directly, because the flow-front velocity captured by the CCD camera is the seepage velocity instead of the Darcy velocity. The