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Modeling of resin flow in natural fiber reinforcement for liquid composite molding processes

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ABSTRACT

A model for the resin flow in natural fiber preform is developed and validated by experimental measurements. During the resin flow in natural fiber reinforcement, the fiber diameter increases as the liquid resin is absorbed into the natural fiber. It has been well known that the fiber swell leads to a time-dependent change of reinforcement permeability. Moreover, the increase of fiber diameter and the liquid resin absorption affect the resin flow velocity by changing the volumes of fiber and resin, which has been ignored in the conventional modeling approaches. We propose a new resin flow model considering the volumetric changes of resin and of fiber as well as the permeability change because of the fiber swell. A new experimental method is employed to obtain the liquid absorption characteristics of fiber immersed in liquid resin. The validities of several models in the literature and of the present model were evaluated by comparisons with experimental data of mold filling process. The conventional model approaches show significant discrepancy with the experimental results, in the case of high fiber volume fraction, whereas the current model predictions always show good agreements.

1. Introduction

Natural fiber reinforced composites are becoming more and more popular in automotive and construction industries by dint of their environmentally friendliness, low density and good mechanical properties [1,2]. Currently, most applications of natural fiber reinforced composites are non-structural or semi-structural parts, however, because discontinuous fibers are mainly employed as reinforcement. To further improve the mechanical performance, it is advantageous to adopt textile reinforcement with high fiber volume fraction. Therefore, liquid composite molding (LCM) processes such as resin transfer molding (RTM) process and vacuum assisted resin transfer molding (VARTM) process, can be effective manufacturing techniques to obtain natural fiber composites with high mechanical performance [3,4]. Another advantage of LCM processes for natural fiber composites manufacturing is the use of low processing temperature that can avoid the thermal degradation of natural fiber during composites processing.

In terms of process optimization, the resin flow analysis is important to estimate process cycle time and to improve product quality. The research work on the LCM process analysis with natural fiber reinforcement has been relatively rare, however, whereas the research on the mechanical characterization of natural fiber composites can be frequently found in the literature [3,4]. There are a couple of particular features in LCM processes with natural fibers that are distinguished from those with synthetic fibers. Natural fibers absorb the liquid resin and the fiber diameter increases accordingly when they are in contact with the resin during the resin impregnation process. As the fiber diameter increases, the size of the pore between fibers decreases. Subsequently, the size of the flow path decreases and the flow characteristics may also be altered. It is well known that this fiber swell phenomenon leads to a change of reinforcement permeability during the mold filling process [5–8]. This mechanism is illustrated in Fig. 1.

Masoodi et al. performed the flow modeling in swelling porous medium such as natural fiber reinforcement considering a time-dependent change of permeability because of the fiber swell [5,6]. In their work, the permeability was assumed to be uniform in the wet preform even though it was modeled as a time-dependent variable. This assumption of uniform permeability can be misleading, however, because the fiber diameter is not uniform in the preform at a given instant. During the mold filling process, the immersion time of the fiber in the resin at the upstream is longer than at the downstream. Hence, the fiber diameter at the upstream is greater than at the downstream and there is a difference of permeability between the two zones at a given instant. Francucci et al. proposed a new modeling approach for resin flow

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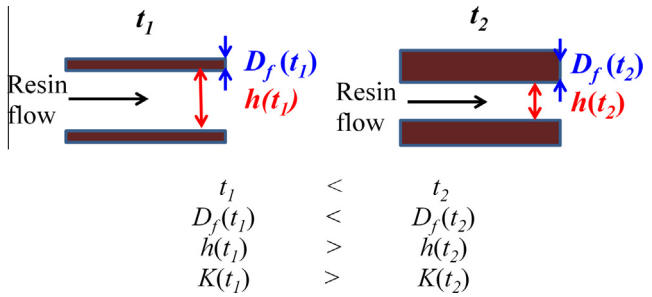

Fig. 1. Change of fiber diameter and permeability because of liquid absorption phenomenon (t_1 and t_2: time instants, D_f: fiber diameter, h: distance between fibers, K: permeability of fabric).

analysis by addressing this non-uniform permeability issue [7]. They modeled the permeability in terms of fiber swell ratio that is a function of immersion time. Hence, permeability was considered to be a spatially and temporally varying parameter.

In addition to permeability change, fiber swell and liquid absorption have an influence on the resin flow by altering the volumetric rate of resin and fiber. The liquid resin absorbed into the fiber can be considered in the mass conservation equation as a mass loss that delays the resin flow velocity. In contrast, the increase of fiber diameter that pushes the resin outward can be regarded as a mass generation that increases the resin flow velocity. Masoodi et al. proposed a new mass conservation equation by introducing mass sink and source terms representing these counteracting mass loss and generation effects [5,6]. In their work, it was however assumed that the fiber volume increase by the fiber swell was equal to the liquid volume absorbed into the fiber, and consequently, these mass loss and generation effects were cancelled out with each other [5,6].

In the current work, we propose a new resin flow model in the natural fiber reinforcement considering these two particular features; the first one is the permeability change because of the fiber swell and the second one is the mass sink and source effects owing to the liquid absorption and fiber swell, respectively (Fig. 2). The latter issue will be rigorously addressed in a following section. In particular, we investigate, by direct experimental measurements of liquid absorption and of fiber swell, mass sink and source effects on the mass conservation condition that have always been ignored in the literature.

The liquid absorption into the natural fiber immersed in the liquid has been rarely investigated whereas the vapor sorption behavior has been extensively studied [9–12]. We adopt a new experimental method using a centrifuge to measure the liquid mass absorbed into the natural fiber. Concerning the fiber swell and the corresponding permeability change, we use the model

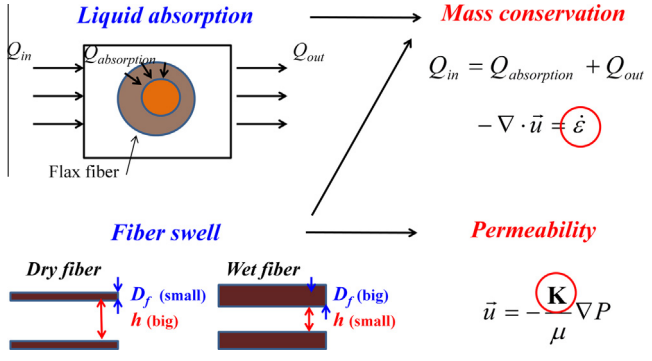

Fig. 2. Modeling approach considering liquid absorption and fiber swell.

and data obtained in our previous work [8]. Then, we obtain the data for flow front advancement with time in mold filling experiments. Especially, we conduct a number of measurements using the same reinforcement for a wide range of fiber volume fraction values. We also perform numerical predictions of resin flow front advancement by conventional resin flow models in the literature as well as by the new model proposed in this work. The validities of the conventional models and of the proposed model are evaluated by comparisons between the experimental data and the modeling results.

2. Materials and experimental procedures

In this section, we will describe the materials, such as reinforcement and test liquids, and the experimental procedures for the measurement of liquid absorption and of flow front advancement during the mold filling process.

The fiber reinforcement used in this work was flax 3 × 3 twill weave mat (Biotex). The fiber swell behavior and the permeability of this fabric had been analyzed in the previous work of which data and model were used again for the current work [8]. All the other information on this fabric can also be found at the same reference [8]. The change of fiber diameter can be represented in terms of fiber swell ratio that is the ratio of wet fiber diameter to dry fiber diameter [8].

$$f_{sw}(t) = \frac{D_{f,t}(t)}{D_{f,O}} = \exp\left(\frac{a_1 t}{b_1 t + c_1}\right) \quad (1)$$

where f_{sw} is the fiber swell ratio, $D_{f,t}$ is the wet fiber diameter, $D_{f,O}$ is the dry fiber diameter, and, a_1, b_1 and c_1 are the model constants. The densities and the fiber swell model constants for two test liquids namely distilled water and engine oil (Mobil DTE Oil Heavy Medium produced by Exxon Mobil Corporation) are listed in Table 1 [8].

The liquid absorption behavior of the flax fiber was analyzed for the same test liquids as used in the fiber swell characterization. We introduced a new measurement method of liquid absorption of flax fiber immersed in the liquid, using a centrifugal rotary machine (Hettich zentrifugen D7200 tuttlingen). The experimental procedure is illustrated in Fig. 3. For each test, a small piece of flax fiber bundle with the dimensions of 20 × 20 mm^2 was taken at random from the flax fabric. The mass of this dry fiber sample was measured (M_D at the Step 1 in Fig. 3) by a microbalance (RADWAD type AS220X) with the accuracy of 10^{-6} g. The fiber sample was then immersed in the test liquid for a preassigned period (Step 2 in Fig. 3). Then, the mass of this wet fiber sample was measured. At this stage, the wet fiber sample's mass was the sum of the dry fiber mass and the liquid mass in the fiber sample. The liquid in the wet fiber sample was composed of the liquid between the individual elementary fibers, that was taken up by capillary wicking, and the liquid absorbed into the elementary fiber by the liquid absorption phenomenon. In fact, it is the mass of the liquid inside the

Table 1
Material parameters and model constants.

Property	Parameter	Distilled water	Engine oil
Liquid density [8]	ρ_l	995 (kg/m^3)	875 (kg/m^3)
Fiber swell (Eq. (1)) [8]	a_1	0.073	0.022
	b_1	0.244	0.233
	c_1	30.000 (s)	29.994 (s)
Liquid absorption (Eq. (4))	a_2	0.202	0.144
	b_2	−2.056 (s^{-1})	−0.012 (s^{-1})
	c_2	0.798	0.856
	d_2	−0.545 (s^{-1})	0.314 (s^{-1})