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A MODEL FOR PREDICTING THE FLOW FREE SURFACE OF RTM PROCESSING

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Summary. Based on the Theory of Porous Media, we propose a model that considers both resin and air as a multi-phase flow to simulate the resin flow free surface during RTM processing. A closed-form nonlinear diffusion equations system is set, which contains two unknowns - the global flow pressure and resin saturation, and solved by using Finite Element Method with a staggered approach.

1 INTRODUCTION

In order to increase productivity for the manufacturing of polymeric structural components, the Resin Transfer modeling (RTM) process is likely to be exploited for automotive components. To this end, Computer Aided Engineering (CAE) tools are been introduced to simulate the resin flow and wetting out of the preformed dry fiber beds instead of using costly physical trials. As the development of the theory of porous media, the application of the porous media theory has been extended from petroleum industries and groundwater hydrology to composites manufacturing processes. Many simulations of resin flow passing through the fiber bed in the RTM process have been investigated, only considering the resin flow, e.g., Lim and Lee (2000)[1] and Larsson, Rouhi and Wysocki (2012)[4]. This simplification neglects the capillary effect between the residual air and resin, which leads to imperfect prediction of flow front pressure and saturation. However, introducing resign-gas flow in the model gives rise a computational challenge. This paper suggests a weaker coupled and robust model by using the ideal of mixture pressure assumption to substitute the intrinsic pressure of each phase. Besides, this model shows high relevance with another assumption that is introduced by Chavent and Jaffré (1986)[2], and provide a possibility to transfer the mixture pressure between these two assumptions.

2 GOVERNING EQUATIONS

The RTM process can be considered as immiscible two-phase flow pass through a porous media. The corresponding governing equations can be derived from the mass conservation and Darcy's law applied to each of fluid phases.

$$\phi \frac{\partial}{\partial t}(\rho_\alpha S_\alpha) + \nabla \cdot (\rho_\alpha v_\alpha) = q_\alpha \,, \qquad (1) \qquad\qquad v_\alpha = -\frac{\mathbf{K} k_{r\alpha}(S_\alpha)}{\mu_\alpha} \nabla p_\alpha \,, \qquad (2)$$

where α represents resin phase ($\alpha = \ell$) and the phase of residual gas ($\alpha = g$); ϕ is the porosity of the dry fiber beds; ρ_α, S_α, v_α and μ_α denote the density, saturation, Darcy velocity and viscosity of the α-phase respectively; $\mathbf{K}$ is the absolute permeability tensor, whilst $k_{r\alpha}$ is the relative permeability of the α-phase; q_α is the source or sink, which is zero herein and the pressure of α-phase is represented by p_α. Apart from (1) and (2), other two supplementary equations can be given from the homogenization of porous media and capillary effect, which is proposed by Brooks and Corey (1964)[3].

$$S_g + S_\ell = 1 \,, \qquad (3) \qquad\qquad p_c = p_g - p_\ell = p_e \left(\frac{\xi - \xi_r}{\xi_M - \xi_r}\right)^{-\frac{1}{n_b}} \,, \qquad (4)$$

where p_c denotes the capillary pressure. The phenomenological parameter n_b and p_e are pore-size distribution factor and air entry pressure respectively. The saturation of resin is denoted by ξ, moreover ξ_r and ξ_M are residual and maximum saturation respectively.

3 GLOBAL LEVEL FORMULATIONS

Because the resin density ρ_ℓ can be considered as constant, so (1) can be simplified to the *saturation equation* as (5). By adding (1) and (2) together, the mixture mass balance equation can be written as (6) - *pressure equation*,

$$\phi\, \dot{\xi} + \nabla \cdot v_\ell = 0 \,, \qquad (5) \qquad\qquad \phi\, \dot{\rho_f} + \nabla \cdot (\rho_f\, v_f) = 0 \,, \qquad (6)$$

where ρ_f and v_f are global density and global Darcy velocity respectively. Following the homogenized theory, the ρ_f can be represented as a linear combination of ρ_α. Similarly we propose the assumption that the global pressure is a linear combination of the pressure for each of phase (8),

$$\rho_f = (1-\xi)\rho_g + \xi \rho_\ell \,, \qquad (7) \qquad \text{and} \qquad p = (1-\xi) p_g + \xi p_\ell \,. \qquad (8)$$

Using (7) and homogenization theory, the relation between global Darcy velocity and phase velocities can be derived,

$$v_f = \frac{(1-\xi)\frac{\rho_g}{\rho_\ell}}{\xi + (1-\xi)\frac{\rho_g}{\rho_\ell}}\, v_g + \frac{\xi}{\xi + (1-\xi)\frac{\rho_g}{\rho_\ell}}\, v_\ell \,. \qquad (9)$$

From (2), (4), (8) and (9) we can rewrite ρ_f as $\rho_f(p, \xi)$, and v_f as $v_f(p, \xi)$. Inserting

$\rho_f(p,\xi)$ and $v_f(p,\xi)$ into (4), a closed-form equations system is set with two primary unknowns - p and ξ.

4 NUMERICAL EXAMPLE

A one dimensional problem is simulated as example. In this case, the pure resin is injected into the preformed dry fiber bed initialized with 90% gas. A 1 meter long sample discretized to 100 elements. The following boundary conditions and initial values are used to implement this simulation:

$$\xi(x=0,t)=1, \quad p(x=0,t)=4[\text{MPa}], \quad p(x=L,t)=0.5[\text{MPa}], \quad \frac{\partial}{\partial x}\xi(x=L,t)=0,$$
$$\xi(x,0)=0.1, \quad p(x,0)=0.5[\text{MPa}]$$

In addition, the ξ_r and ξ_M are set to 0 and 1 respectively. The *implicit pressure - implicit saturation* method is use to solve (5) and (6). After simulation startup, (5) is used to solve for ξ^{t+1} from the given data p^t and ξ^t; next (6) utilizes ξ^{t+1} and p^t to look after p^{t+1}. By repeating these steps, ξ and p values at all time steps can be solved. The characteristics of the simulation is given as below. The parameter k is Kozeny constant used to calculate absolute permeability.

$$P_e=0.2[MPa],\ n_b=1.9,\ \mu_l=0.6[Pas],\ \mu_g=1.983[Pas]\times10^{-5},\ \phi=0.35,\ k=10$$

By comparing with a preliminary analytical method for the signal flow phase problem introduced by Larsson, Rouhi and Wysocki (2012)[4], Fig.1 presents that the average saturation of the whole domain from the new model shows more agreements with the analytical method than the former model[4].

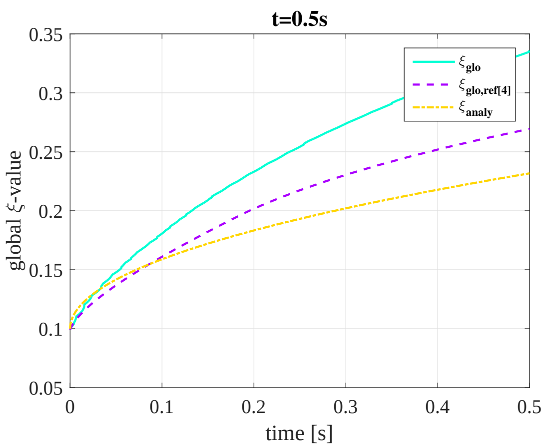

Figure 1: Saturation distribution

The resin saturation of the new model (ξ), Chavent's model[2] ($\xi_{Chavent}$) and our former model ($\xi_{ref[4]}$) are plotted in Fig.2. There is large difference between the new and former model. The new model keeps in line with Chavent's model very well except nearby the flow front region. Moreover, both the new model and Chavent's model show less diffuse behavior than the former model, which matches with the practical observation. Fig.3 shows the comparison of the global and phase pressure by different models. The new model and Chavent's model give almost sharp pivot point at flow front rather than diffusive turning from the former model. In addition, when the saturation goes to maximum, the global pressure from new model and Chavent's model will hold each other; and keep parallel along the unsaturated region, which implies these two models can be transfered. But as investigated, the new model is much simpler and more computational efficient than Chavent's model.

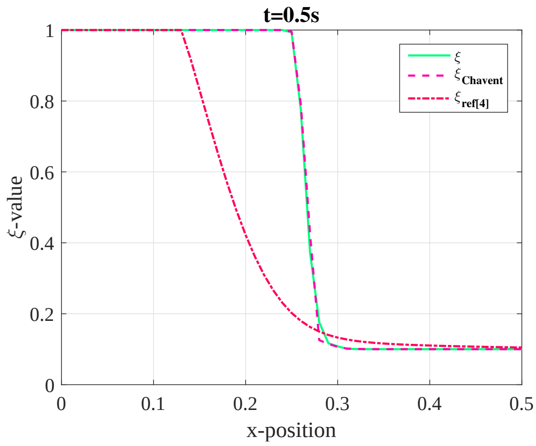

Figure 2: Saturation distribution

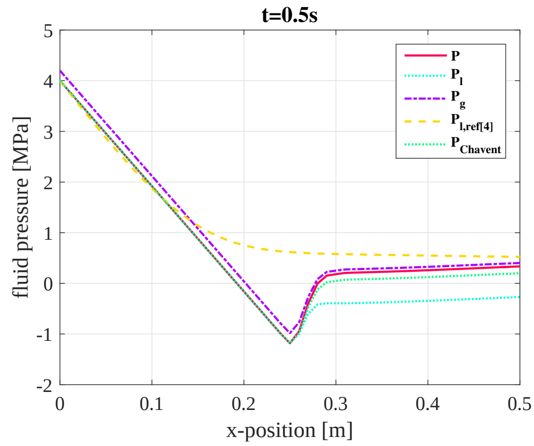

Figure 3: Pressure distribution

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