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Numerical prediction of saturation in dual scale fibrous reinforcements during Liquid Composite Molding

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ABSTRACT

This paper presents a fractional flow model based on two-phase flow, resin and air, through a porous medium to simulate numerically Liquid Composites Molding (LCM) processes. It allows predicting the formation, transport and compression of voids in the modeling of LCM. The equations are derived by combining Darcy's law and mass conservation for each phase (resin/air). In the model, the relative permeability and capillary pressure depend on saturation. The resin is incompressible and the air slightly compressible. Introducing some simplifications, the fractional flow model consists of a saturation equation coupled with a pressure/velocity equation including the effects of air solubility and compressibility. The introduction of air compressibility in the pressure equation allows for the numerical prediction of the experimental behavior at low constant resin injection flow rate. A good agreement was obtained between the numerical prediction of saturation in a glass fiber reinforcement and the experimental observations during the filling of a test mold by Resin Transfer Molding (RTM).

1. Introduction

Understanding the formation of voids in LCM is necessary for proper manufacturing of composite structural parts. Many studies exist on void formation in LCM. A comprehensive review of these methods in [1,2] confirms the interest of understanding void creation mechanisms and transport in order to develop new optimization strategies. Despite continual progress in the last decades, still many unresolved issues and limitations exist in current numerical approaches.

The resin flow in a partially saturated region can be modeled as a two-phase flow (resin and air) through a porous medium. The numerical modeling and analysis of two-phase flows in porous media has arisen interest for several years and different approaches have been developed. However few studies were carried out in LCM with the multiphase approach. Pillai and Advani [3] were the first to propose a two-phase flow model in LCM based on the Buckley–Leverett formulation. Later, Chui et al. [4] implemented the Buckley–Leverett model numerically, using a front-tracking scheme, to predict the distribution of voids in RTM. They considered the relative permeability to depend on saturation and pressure. More recently, Nordlund and Michaud [5] have also applied a numerical multiphase flow model derived from soil mechanics to LCM processes. It is based on the Richard's equation, combined with van Genuchten expressions for the saturation and relative permeability. In this case, an optimal combination of the parameters of van Genuchten's equations has been calculated from the experimental and numerical data using a curve fit optimization by the Response Surface Method.

The equations of two-phase flow are derived from Darcy's law and mass conservation for each phase (resin/air). The property of the fluid fills up the volume and capillary pressure is given as a function of saturation to close the system of equations. In this case, relative permeability depends on the degree of saturation of the fibrous reinforcement and describes how each phase flows with respect to the other. Hence, the choice of a constitutive relation between relative permeability and saturation represents a key issue in LCM processes to describe the fluid flow.

In order to analyze the formation of voids during reinforcement impregnation, a one-dimensional solution based on two-phase flow through a porous medium has been proposed by Gascón et al. [6]. This model is based on a fractional formulation and leads to a coupled system of a nonlinear advection–diffusion equation for saturation and an elliptic equation for pressure and velocity.

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Nomenclature

α	subscript for phase (r resin, a air)
$\mathbf{q}_\alpha$	velocity of the phase α
$\mathbf{q}_t$	total flow
$\mathbf{q}$	total velocity approximation
p_α	pressure of the phase α
p	pressure approximation
$p_c(S)$	capillary pressure
ρ_α	density of the phase α
μ_α	viscosity of the phase α
ϕ	porosity
S_α	saturation of the phase α ($S_r = S$)
K	intrinsic permeability
$k_{r,\alpha}(S)$	relative permeability of the phase α
$\lambda_\alpha(S)$	mobility of the phase α
χ	parameter that controls the void fraction
M	inverse of the endpoint mobility ratio
$\widetilde{c}_a$	air compressibility coefficient
c_a	parameter that controls the air compressibility
$f(S)$	fractional flow
$\mathbf{F}(S)$	flux function in saturation equation
$C(S)$	diffusive function in saturation equation
$D(S)$, $D_c(S)$	diffusive coefficients in saturation equation
$\widehat{F}^{L\pm}_{j+\frac{1}{2}}$, $\widehat{F}^{H}_{j+\frac{1}{2}}$	first and second order numerical fluxes
$L(r^{\pm}_{j+\frac{1}{2}})$	limiter function to avoid oscillations
p_1, p_2	critical pressures between which air is compressible
p_i	Leverett coefficient in capillary pressure

In [6] permeability was assumed to be a quadratic function of saturation and the continuity equation that governs the pressure distribution includes a source term depending on saturation. Not only can the choice of relative permeability have a significant impact on the predicted saturation, but the quality of the approximation is also affected by the numerical method used to solve the saturation equation. In [6] the elliptic pressure equation was approximated by finite elements and a modified flux limiter technique [7] applied to solve the saturation equation.

In order to test and evaluate the ability of the proposed model, the numerical results of saturation were compared to experimental injections carried out in a glass RTM mold under controlled manufacturing conditions [8]. The experimentally observed saturation for different constant injection flow rates were compared to numerical simulations. The validation of the mathematical model and of the numerical technique was performed for a moderate constant resin injection rate of 0.1 ml/s [6,9]. Numerical results in agreement with experiments were obtained with the new fractional flow model with a quadratic power law to model the relative permeability and a modified flux limiter technique to simulate the evolution of saturation in the mold. However, the model did not reproduce the filling behavior of the mold at lower constant injection flow rates when the effect of capillary forces becomes significant. As observed in Fig. 1 experimental results show that the resin saturation increases at the beginning and then decreases in time at the break points. This indicates the necessity to model a new behavior connected with void formation and transport in the numerical simulation of LCM processes. As described in detail in the sequel, it appears that air compressibility plays an important role in this case.

It is well known that multiphase flows in porous media exhibit hysteresis [10]. The relative permeability and capillary pressure have long been recognized in multiphase processes to depend not only on saturation, but also on the direction of saturation changes. This hysteretic behavior is typically modeled by modifying the model of relative permeability as a function of saturation and using different expressions of capillary pressure, depending on the imbibition or drainage stages during the filling process (see Fig. 2).

The objective of this study is propose a new model to simulate LCM processes taking into account void formation, and air compression and transport. This requires an hyperbolic conservation law for the saturation equation coupled with an appropriate pressure equation. The numerical model presented here introduces two

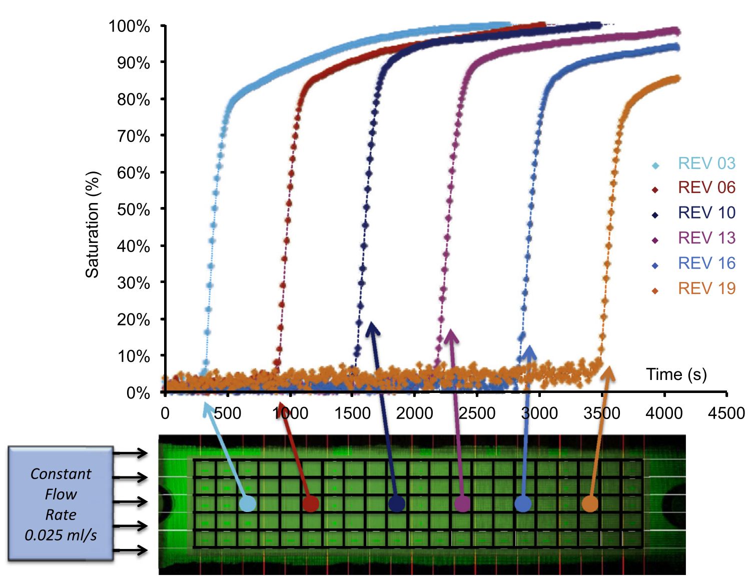

Fig. 1. Schematic representation of experimental saturation at different times during mold filling for the injection at constant flow rate of 0.025 ml/s. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)