MODELING HYSTERESIS IN LIQUID COMPOSITE MOLD FILLING PROCESSES WITH VOID FORMATION

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Introduction

Understanding of the formation of voids in LCM is necessary for proper manufacturing of composite parts. Even the continual progress made in the last decades, there still exist many unresolved issues and limitations with current numerical approaches. In order to analyze the formation of voids during the resin impregnation process, a one-dimensional solution based on two-phase flow through a porous medium, has been proposed by the authors in a previous work [1]. This model leads to a coupled system of a nonlinear advection-diffusion equation for the saturation and an elliptic equation for pressure and velocity. The permeability is assumed to be a function of the saturation and depending on a new parameter which varies linearly with the pressure, and then the continuity equation that governs the pressure distribution, includes a source term which depends on the saturation. The choice of relative permeability function can have a significant impact on predicted saturation. Furthermore, quality of numerical solution is affected by the numerical method to solve the saturation equation.

In order to test and evaluate the ability of the proposed model in LCM, results of numerical saturation were compared to experimental data obtained on a glass RTM mold under controlled manufacturing conditions [2]. Saturation results for different experiments, injecting at constant flow rates, were compared with numerical simulation for the saturation. The validation of the mathematical model and the numerical technique for the saturation simulation was based on the experimental RTM filling with moderate constant resin injection rate of 0.1 ml/s. The authors found that numerical results obtained with a quadratic power law model for relative permeability using a flux limiter technique to simulate the saturation were in excellent agreement with the experimental solutions for this case, where capillary effects and air residual saturation were ignored. However, the model didn't reproduce the complete behaviour for lower and higher constant injection rate cases. Experimental results for the lower resin injection rate case exhibits hysteresis (resin saturation changes from increasing to decreasing with time at the flow front) and shows the necessity to model for hysteresis relative permeabilities into the LCM processes with void formation.

The objective of this study is to test the capability of a numerically stable hysteretic model that can be used to simulate the LCM process with voids formation. This will require an hyperbolic conservation law for the saturation equation with a history-dependent flux function. To validate the proposed model, numerical predictions for the saturation will be compared with experimental data, injecting with constant resin injection rate of 0.025 ml/s.

Hysteretic Permeability Model

During resin injection voids are created at the flow front. Initially, the resin saturation progressively decreases with time as the flow front progresses because of the void formation. This process is called drainage. As the flow front advances, some voids remains immobiles (air residual saturation) and others move with the resin flow. Some air bubbles immobiles decrease their sizes due to the progressive resin saturation [3]. So, initially, the relative permeability of air falls gradually until a threshold is reached, at which stage the relative permeability of air begins to decrease sharply. This latter stage is termed imbibition.

Hysteresis behaviour of relative permeability and capillary pressure has long been recognized in other processes. It is well known that multiphase flow in porous media exhibits hysteresis. Relative permeability and capillary pressure are usually assumed to be a unique function of saturation, but it is well known that the relationship between relative permeability - capillary pressure and saturation demonstrates memory effects. Relative permeability and capillary pressure generally depend not only on the fluid saturations but also on the direction in which the saturations are changing. This is typically modeled by modifying the saturation dependence of the relative permeability and using different expressions for the capillary pressure, depending on the imbibition and drainage curves.

Mathematically, hysteresis effects are modeled by assuming that there are two irreversible permeability curves, the imbibition and the drainage, and there is a continuous family of reversible curves, called scanning curves [4]. During a scanning flow the air relative permeability does not decreases along the drainage path, but rather decreases faster. In this paper, we propose a mathematical model to accommodate this behaviour. We neglect the hysteresis effect in the resin phase and assume that only the air phase exhibits relative permeability hysteresis.

Explicit representation of full hysteresis with scanning curves in models of multiphase flow has been a difficult problem. A second complication relates to the fact that capillary pressure-saturation relationships are determined under static conditions and are not necessarily valid under dynamic flow conditions. According to a recent theory, one has to redefine capillary pressure in order to include dynamic effects. This could be the reason of the non-monotonic saturation profiles observed experimentally for low resin injection rate.

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