IMPROVED FINITE VOLUME MULTIPHASE FLOW SIMULATION MODEL FOR STRONGLY INHOMOGENEOUS POROUS MEDIA

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Abstract
In all liquid composite molding (LCM) technologies, dry fiber preforms are placed into a mold which is subsequently closed or sealed with a flexible bag by drawing a vacuum. Placing a highly permeable flow distribution medium (DM) on top of the fiber preform (FP), often separated by a perforated release film or peel ply, allows for fast in-plane resin distribution and subsequent preform impregnation in out-of-plane direction. FP and DM typically exhibit differences in permeability of several orders of magnitude. Fluid flow through stacked layers of FP and DM can be studied experimentally by means of linear or radial flow experiments as well as by methods of Computational Fluid Dynamics (CFD), i.e. numerical filling simulations.

The following Initial-Boundary-Value (IBV) problem describes viscous multiphase flow through a porous cavity. The 3D volume geometry of the porous cavity (395 × 295 x 3 mm³ in size; a central inlet with a diameter of 13 mm; 0.6 mm DM placed on top of a 2.4 mm FP) is meshed. Different values for in-plane and out-of-plane permeability as well as porosity are assigned to the DM and FP cells. During the filling process, discretized versions of the governing equations (volume-averaged incompressible continuity equation, momentum equation with Darcy term and Volume-of-Fluid (VOF) equation) for pressure, superficial velocity and filling fraction must be upheld in every cell. At cell faces which are visible from the outside, boundary conditions are specified (for example: constant pressure or constant volume flow at the inlet ports; constant pressure at the outlet ports; slip flow conditions at the walls). The simulation model is initialized with a cavity pressure, zero superficial velocity and zero filling fraction in all cells.

The preform parameters used in this study are chosen such that there is fast in-plane flow propagation through the DM, followed by out-of-plane impregnation of the FP. Material properties as well as process conditions are listed in Table 1. Here, the subscripts x, y and z denote the in-plane and out-of-plane directions respectively. The in-plane directions x and y correspond to the major and minor in-plane flow directions. All entries outside the main diagonal in the permeability tensor are zero (k_{xy}=0 follows from the definition of the x and y directions; k_{yz}=0 and k_{zx}=0 are assumptions).

Table 1: Material properties and process parameters used in the study.

Materials	*Porosity,* ε *(-)*	*Major in-plane permeability,* k_x (m^2)	*Minor in-plane permeability,* k_y (m^2)	*Out-of-plane permeability,* k_z (m^2)	*Mass density,* ρ (kg/m^3)	*Dynamic viscosity,* μ (Pa.s)
DM	0.9	$1.0{\cdot}10^{-9}$	$1.0{\cdot}10^{-9}$	$1.0{\cdot}10^{-9}$	-	-
FP	0.5	$15{\cdot}10^{-12}$	$15{\cdot}10^{-12}$	$0.5{\cdot}10^{-12}$	-	-
Fluid	-	-	-	-	960	0.06
Air	-	-	-	-	1.225	0.000018
Boundary conditions	*Injection pressure,* p_{inj} *(Pa)*			191000		
	Initial cavity pressure, p_{init} *(Pa)*			100000		

Two different solvers were studied: OpenFOAM's interFoam with an added porosity model, using a constant cavity thickness or variable cavity thickness (as used for vacuum infusion filling simulations) as well as Ansys Fluent, with a constant cavity thickness. Figure 1a shows the simulated filling fraction after 30 s for the first solver using a representative mesh consisting of 4+8 cells through the DM+FP thickness. All considered solvers show incomplete filling of the last FP cell at the wall. The out-of-plane flow was analyzed. Filling of the FP in the out-of-plane direction occurs with almost constant z-velocity until the flow front reaches the last cell at the wall. At this point, the filling fraction in the last cell increases proportionally to the z-direction velocity in the cell above the last cell, which itself is proportional to the pressure gradient in z-direction (as shown in the pressure curves to the right of Figure 1). Based on this analysis, the incomplete filling effect was studied by means of two different, phenomenologically driven hypothesis and solution approaches, respectively:

1. Compressible air flow model: The flow front pushes air downwards, which results in an air pressure increase and thus, a decrease in the fluid pressure gradient if the sidewards air flow is not fast enough. As a solution approach, the IBV problem was modified to cover the flow of compressible air and incompressible resin.
2. The zero-gradient boundary condition reduces the pressure gradient at the second to last cell if all except the last cell are filled (see last column of Figure 1a). As a solution approach, the IBV problem was equipped with dynamic boundary conditions at the wall at the bottom: a Dirichlet boundary condition is assigned with the initial cavity pressure until the last cell at the wall is completely filled and a zero-gradient pressure boundary condition is set thereafter.

Both modified IBV problems improve the filling prediction in the last cell at the wall. The filling behavior for the model with dynamic boundary conditions is shown in Figure 1b, indicating a significant improvement w.r.t. the original solution shown in Figure 1a. The physical justification for dynamic boundary conditions comes from inspection of the pressure distribution during filling. The pressure in all cells outside of the flow front is the initial cavity pressure. The dynamic boundary condition at the bottom wall ensures that the pressure in the last cell at the wall is not changed by the evaluation of a boundary conditions and remains at the initial cavity pressure until fully filled. The compressible air flow model fails if the ratio between highest and lowest permeability value becomes too large.

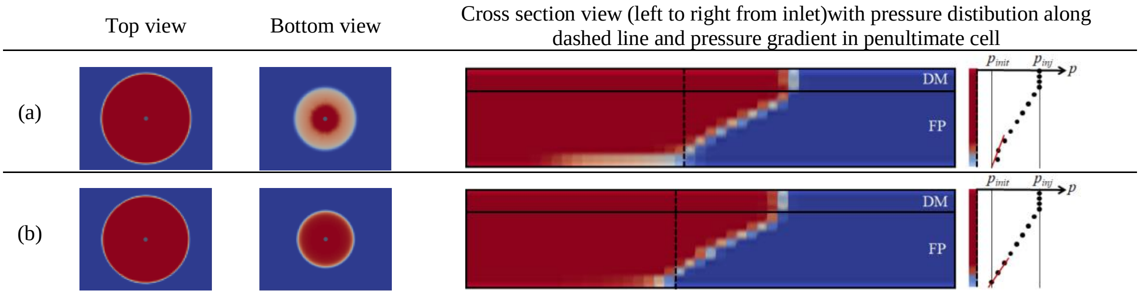

Figure 1: Filling state after 30 s using interFoam with (a) slip wall and (b) dynamic boundary conditions.