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# Boundary element simulation of void formation in fibrous reinforcements based on the Stokes–Darcy formulation

Iván David Patiño Arcila[a], Henry Power[b,*], César Nieto Londoño[c], Whady Felipe Flórez Escobar[d]

[a] *Grupo de Investigación en Nuevos Materiales, Universidad Pontificia Bolivariana, Circular 1ra No 73-34 (Bloque 23), Medellín, Colombia*
[b] *School of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, B111, Coates Building, University Park, NG7 2DR, Nottingham, United Kingdom*
[c] *Grupo de Investigación en Ingeniería Aeroespacial, Universidad Pontificia Bolivariana, Circular 1ra No 73-34 (Bloque 22), Medellín, Colombia*
[d] *Grupo de Energía y Termodinámica, Universidad Pontificia Bolivariana, Circular 1ra No 73-34 (Bloque 22), Medellín, Colombia*

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**Abstract**

The Boundary Element Method (BEM) is applied for the solution of the problem of void formation in fibrous reinforcements used in composite materials. Stokes and Darcy formulations for the channel and porous medium are considered, including three main differences with most of the previous models reported in the literature that deal with this type of problem: the consideration of the general form of the Beavers–Joseph slip condition instead of the Saffman simplification, the calculation of the flow direction-dependent capillary pressure in the porous medium without experimental factors and the consideration of the surface traction effects in the channel fluid front. An analytical solution of a simple problem is presented to assess the accuracy and convergence of the BEM solution, obtaining good agreement between the results.

In order to evaluate the main differences between the Stokes–Darcy formulation and a dual-scale permeability Darcy approach, a problem of constant pressure filling is considered, showing significant differences in the evolution of the flow field as: filling times, shape of the moving fluid front and size and shape of the formed voids.

Finally, several simulations at constant flow rate are carried out to analyze the influence of the capillary number, tow porosity, width of transverse tow, fluid penetrability and RUC porosity on the size, shape and location of the void. In general, the void size and shape are influenced by the considered parameters, but the void location is not.


*Keywords:* Boundary Element Method; Stokes–Darcy; Fibrous reinforcements; Void formation

## 1. Introduction

In the processing of composite materials many kind of fibrous reinforcements have two well-differentiated domains at the mesoscopic scale, channels and tows. Some authors have modeled the filling of these fibrous reinforcements

* Correspondence to: B111, Coates Building, University Park, NG7 2DR, Nottingham, United Kingdom. Tel.: +44 1158466232.
*E-mail addresses:* ivandavidpatino@gmail.com (I.D.P. Arcila), henry.power@nottingham.ac.uk (H. Power), cesar.nieto@upb.edu.co (C.N. Londoño), whady.florez@upb.edu.co (W.F.F. Escobar).

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as a dual-scale porous medium, where the scale of permeability of the channels is considerably higher than the scale of permeability of the tows and both flow regions are modeled as a Darcy flow [1–4]. In this type of approach the low Reynolds number flow, creeping flow, inside the thin channels is approximated by the Hele-Shaw cross average flow with an equivalent permeability. By using this approximation some details of the interface process between the two media, channels and tows, are lost, allowing only mass conservation and continuity of pressure across the media.

An alternative approach, and more robust, is to model the flow in the channels as a Stokes flow, and the flow in the porous tows using the Darcy law (see [5–8]), with the corresponding coupling conditions between the two flow regions. This type of mathematical formulation will be used in this study. Besides, the solid phase is considered as non-deformable, the injected fluid is Newtonian and incompressible, inertial effects are neglected (creeping flow), the tow porosity is constant and the permeability changes according to the fibers orientation (anisotropic media).

The problem of simulation of the impregnation process of fibrous reinforcements at the mesoscopic scale comprises two general aspects: the solution of the coupled governing equations of the flow field and the concurrent advancement of the fluid front. The numerical simulation of both aspects have been previously considered in the literature using different numerical techniques, being the most popular ones the FEM/CV techniques (among others see [2,9–11]), where a conforming Finite Element Method (FEM) is used to solve the governing equations and obtain the nodal values of the pressure field. Since this type of FEM approach does not preserve locally mass conservation at the element level, each Finite Element is internally subdivided and coupled with the neighbors' subdivisions to form a local Control Volume (CV), i.e. one CV for each FEM node, where a mass flux balance is considered to evaluate at each CV, for a given time step, a filling or volume factor, $f$, which indicates the volumetric percent of fluid occupying the CV at a corresponding time evolution of the fluid front; a value of $f = 1$ corresponds to a completely filled CV and of $f = 0$, to a totally empty one, with a value between $f = 0$ and $f = 1$ implying that the CV is partially filled. For those CV's with $f$ between 0 and 1, the position of the fluid front is determined by a fitting geometric scheme (interface capturing). Several of these schemes have been proposed in the literature; among them, the Flow Analysis Network (FAN) approach, original proposed by Tadmor et al. [12], considers that each value of $f$ is associated to the center node of the corresponding CV, and that the position of the fluid front is determined by a weighted average value of the distances between the neighbor CV's nodes in terms of their corresponding nodal values of $f$. The FEM/CV approach was used by Pillai and Tan [2,11] with the objective to carry out simultaneous simulations at the mesoscopic and macroscopic scales using an iterative process, and to determine the position of the fluid front inside the tows, the level of saturation of such tows and the global position of the macroscopic flow considering the delayed absorption of the liquid into the tows *(sink effect)*.

Alternatively to the use of a FEM/CV conforming approach, a single CV formulation allows the nodal values of the pressure field as well as the mass flux balance at each CV to be determined without the need of creating auxiliary elements for a given discretization. Since this type of approach is locally mass conservative, this is achieved at the expense of lowering the convergence rate of the numerical solution in comparison with a FEM simulation, see Jinlian et al. [1], where a CV/FAN approach is used to study the mechanism of void formation during RUC filling processes. The CV formulation of Jinlian et al. [1] used non-structured CV elements with a generalized Finite Difference (FD) approach to evaluate the surface fluxes in terms of linear polynomial interpolation of the pressure field. To keep the rate of convergence of the FEM/CV approach without the need of defining auxiliary elements for the mass flux balance, it is possible to use a nonconforming FEM formulation instead of a CV, which is also locally mass conservative, allowing the evaluation of the filling factor, $f$, at each element of the FEM discretization and the corresponding position of the fluid front, see [13]. Instead of evaluating a filling factor $f$ by a mass conservation balance at each element and at each time step, it is possible to use a Volume of Fluid (VOF) multiphase flow formulation of the RUC filling process, where a single governing equation is defined for both phases, resin and air, with the fluid properties (viscosity in the present case) given as a weighted average in terms of the volume of fluid fraction, $f_v$, whose value also ranges between 0 to 1, with $f_v = 1$ corresponding to the liquid phase and $f_v = 0$ to the gas, and the fluid front located in the region where $0 < f_v < 1$, where the fluid front position is usually defined at $f_v = 0.5$. In this approach, the value of $f_v$ is determined by the solution of a pure advection transport equation (hyperbolic problem) instead of using an additional mass balance at elements level, as was the case of the filling factor approach. As a hyperbolic problem, solution of $f_v$ admits smooth shock profiles, confining the location of the moving fluid front to a small region of the problem domain. The main difficulty with this type of approach is the solution of the corresponding hyperbolic problem, which is known to be numerically unstable requiring the use of specific solvers. VOF solutions of RUC filling processes have been