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Laboratory for Flow and Transport Studies in Porous Media

PORE-FLOW ©: A Finite Element Code to Model Flow in Single- and Dual-Scale Porous Media

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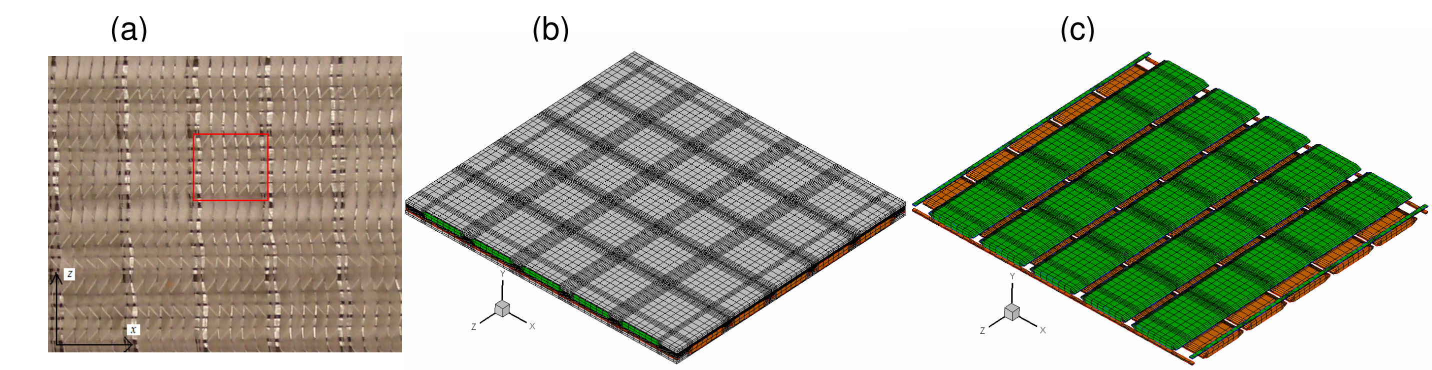
Overview of PORE-FLOW

PORE-FLOW © is a comprehensive computational fluid dynamics (CFD) tool focused primarily on solving flow infiltration/wetting of porous media type problems. The Finite Element/Control Volume (FE/CV) method is implemented in the code to simulate flow behind a moving-boundary. The algorithm is efficient and robust for solving the moving-boundary problems in complex domain geometries. The geometry may be 2D or 3D and the mesh may be structured or unstructured, giving maximum flexibility to the user. The porous-medium flow in the code is governed by either Darcy's law or Brinkman equation depending on user's choice. Besides the porous-medium flow, PORE-FLOW can solve the fluid flow problems governed by Stokes or Navier-Stokes equations. The heat flow as well as certain types of reactive flows can be simulated by the code. Some specific applications of the code include:

- Permeability prediction in stitched or woven fabrics in Liquid Composites Molding (LCM) technologies (such as RTM)
- Isothermal/non-isothermal mold filling in single- or dual-scale fiber preforms in LCM
- Mold filling in Injection Molding process involving thermoplastics
- General laminar flow with/without the moving-boundary

Permeability prediction

Permeability is a property of the porous preform that describes the ease with which a fluid flows in the material, which is fundamental to an accurate simulation of mold-filling in LCM. Since experimental measurements are usually time-consuming and laborious, CFD has been found to be very useful in predicting the permeability of different kinds of fibrous preforms. A biaxial stitched fabric made from glass fibers by Owens Corning, Inc. (Fig. 1(a)) is chosen in this example [1]. The FE models of the unit cell and fiber bundles are shown in Figs. 1(b) and 1(c), respectively. The pressure and velocity contours for the z-direction flows are shown in Figs. 1(d) and 1(e), respectively. The comparison of numerical prediction using PORE-FLOW© and experimental results is listed in Table 1.



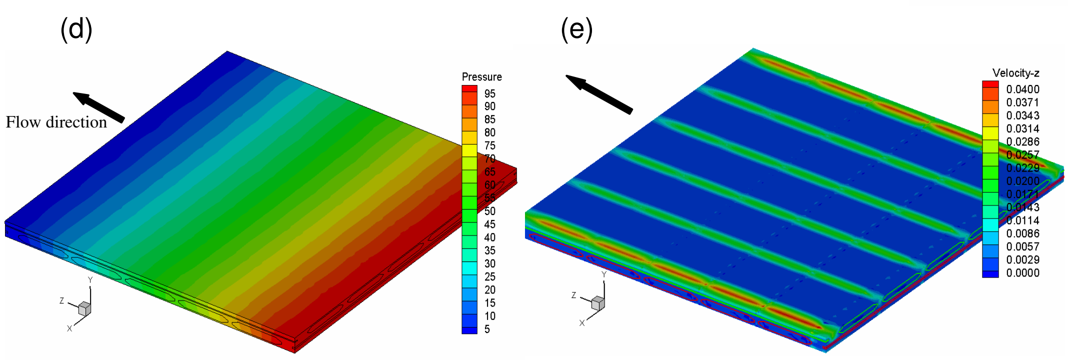


Table 1

	PORE-FLOW	Experimental
$K_0{}^0$ (× 10^{-9} m^2)	1.786	2.036
$K_{90}{}^0$ (× 10^{-9} m^2)	1.279	1.615

Figure 1: Permeability prediction using PORE-FLOW.

Mold filling of LCM involving single-scale porous preform

Numerical mold-filling simulation is essential for optimizing mold design of LCM through various parameters including the locations of resin-inlet gates and air-vents, resin infusion pressure, and temperature, etc. Traditionally, the fiber preforms are viewed as the single-scale porous media with pore-size in same order of magnitude. Assuming that the pores in the fiber preform behind the flow front are fully saturated with resin, the liquid resin impregnating the dry fiber preform during the mold-filling stage of LCM can hence be modeled using the Darcy's law. Fig.2 shows that a mold-filling simulation using PORE-FLOW© agrees well with the experiments available in [2].

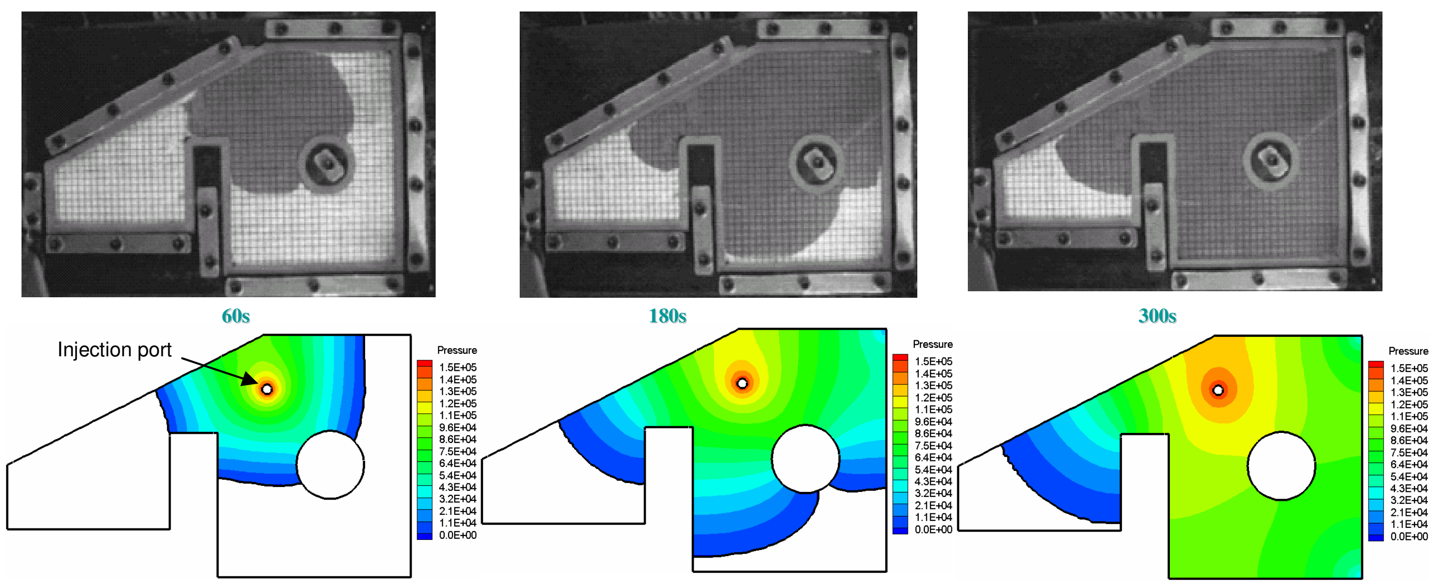


Figure 2: Experimental results (top) and numerical prediction (bottom) of resin flow at different times.

Dual-scale porous media flow

❖ **Background:**

The prediction using conventional flow physics doesn't match the experiments for certain types of fabrics where a partially wetted region behind the flow front can be found during impregnation (Fig. 3). A careful examination of the micro-structure of such fabrics indicates that the inter-fiber distance within the fiber bundles is of the order of micrometers, whereas the distance between them is of the order of millimeters. This order-of-magnitude difference in the pore size within the same medium leads to its classification as a 'dual-scale' porous medium. Liquid infiltrating such dual-scale porous media is shown schematically in Fig. 4.

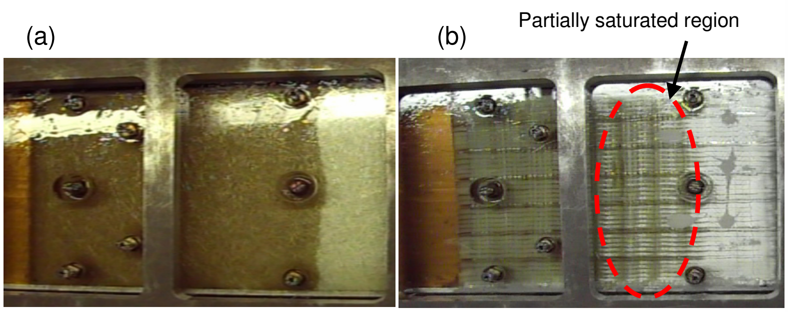


Figure 3: Snapshot of impregnation of fiber mats in 1-D flow mold: (a) random fiber mat (single-scale); (b) biaxial stitched fiber mat (dual-scale porous medium).

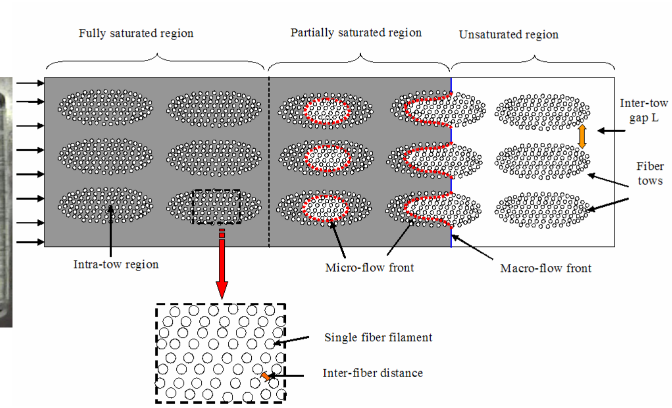


Figure 4: The characteristic of a typical unsaturated flow within dual-scale fiber preforms.

❖ **Modeling & numerical examples :**

We developed a continuum model for resin flow in dual-scale fiber mats in LCM, where the macro-flow through gaps is coupled with the micro-flow (tow impregnation) through a sink term S in the mass balance equation representing the mass absorbed by the fiber bundles from the gaps (Fig.5) [3]. The dual-scale flow simulation using PORE-FLOW© has been validated experimentally (Fig. 6). An isothermal mold-filling simulation of a car hood made from dual-scale fibrous preform was carried out using the code. The resin was injected at a constant-flow-rate. The partially saturated region during the impregnation are plotted [Fig. 7(f)-(j)].

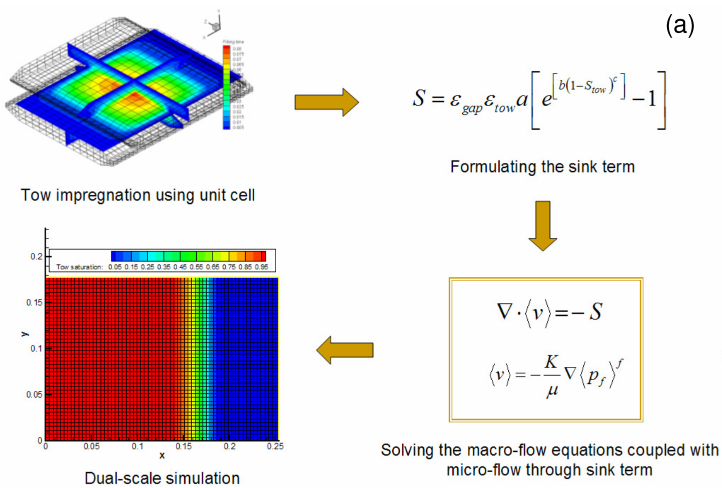


Figure 5: the continuum modeling of dual-scale flow of LCM.

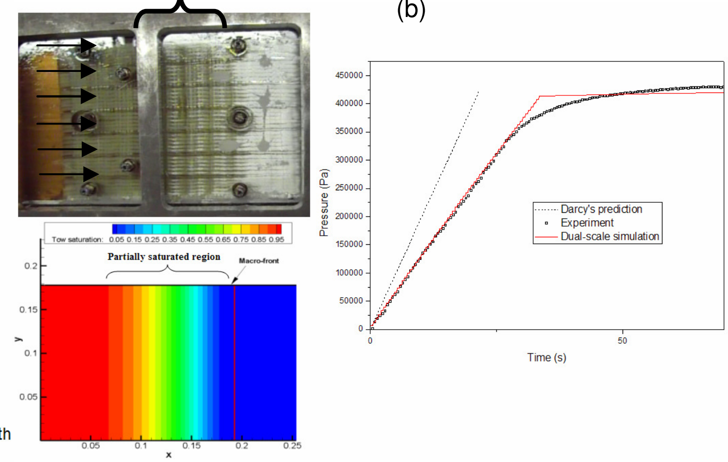
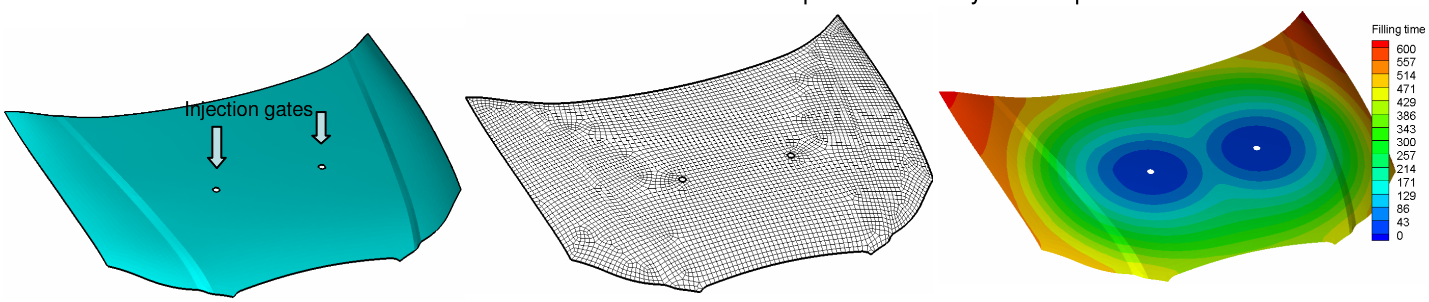
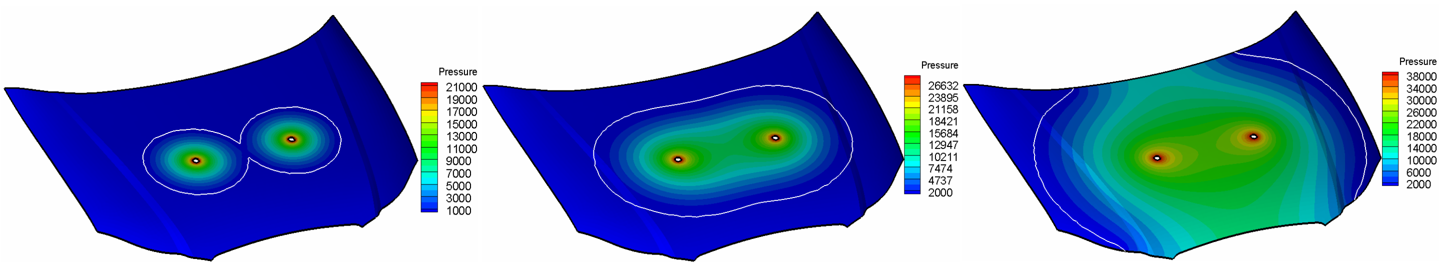


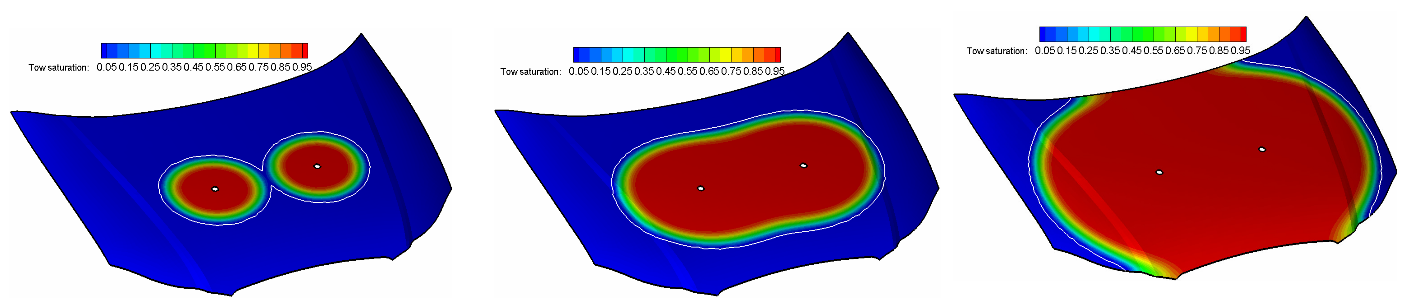
Figure 6: a) comparison of partially saturated regions from experiment (top) and PORE-FLOW© (bottom); b) comparison of inlet pressure history from experiment and PORE-FLOW©.



(a): geometrical model of car hood (b): FE mesh of car hood (c): Macro-flow front position in time



(e): pressure contour 90s (f): pressure contour 238s (g): pressure contour 470s

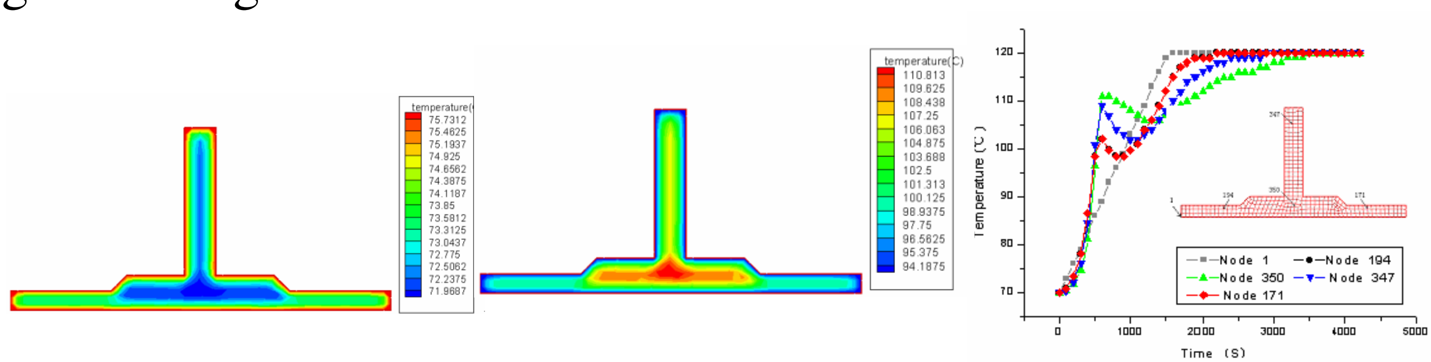


(f): tow-saturation contour at 90s (i): tow-saturation contour at 238s (j): tow-saturation contour at 470s

Figure 7: A dual-scale LCM flow simulation for a car hood (white line indicates the position of the macro-flow front).

Curing reaction of thermosetting

The kinetic reaction model has been incorporated into PORE-FLOW© to simulate the curing reaction of thermosetting resins. An example of curing simulation of a blade-stiffened panel was given in Fig. 8.

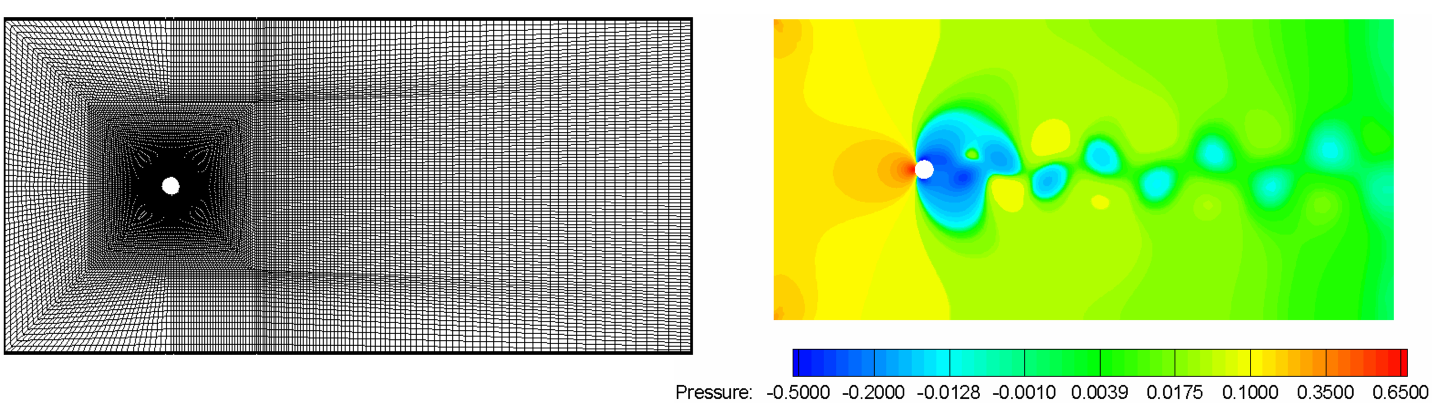


(a): temperature contour at 200s (b): temperature contour at 700s (c): Temperature history at different locations

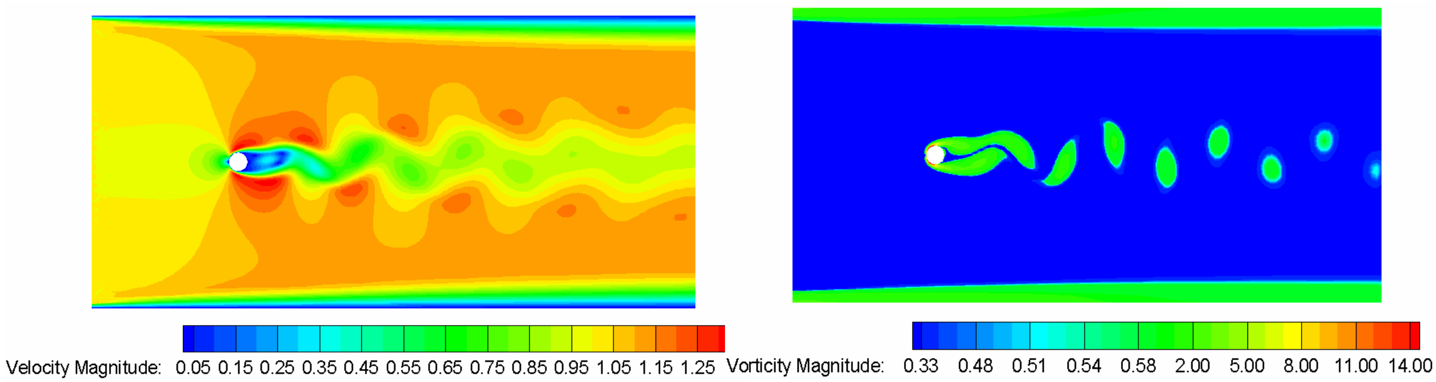
Figure 8: Curing reaction simulation of a panel using PORE-FLOW

General laminar flow

PORE-FLOW© can simulate the general laminar flow by solving the Navier-Stokes equation in transient or steady-state conditions. A benchmark problem of Karmen vortex street was solved using PORE-FLOW© (Fig. 9). The Reynolds number is 100.



(a): FE mesh of computational domain (b): pressure contour at a time slice



(c): velocity contour at a time slice

(d): vorticity contour at a time slice

Figure 9: Flow through a solid cylinder.

References

[1]H. Tan and K. M. Pillai, Finite element implementation of stress-ump and stress-continuity conditions at porous medium, clear-fluid interface, *Computers &Fluids,* 2009 (In press).

[2]M. K. Kang, J. J. Jung, Woo Il Lee, Analysis of resin transfer molding process with controlled multiple gates resin injection. Composites: Part A 31 (2000) 407–422.

[3]H. Tan, K. M. Pillai, Simulating unsaturated flow in dual length-scale porous media, 1st international conference on changes of porous media and inaugural meeting of the international society for porous media, Kaiserslautern, Gemany (2009).

Acknowledgements

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