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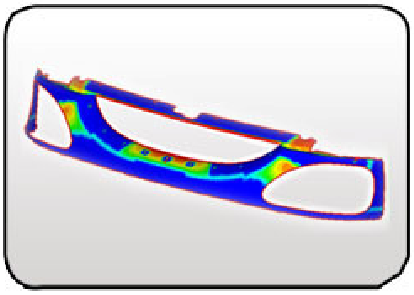
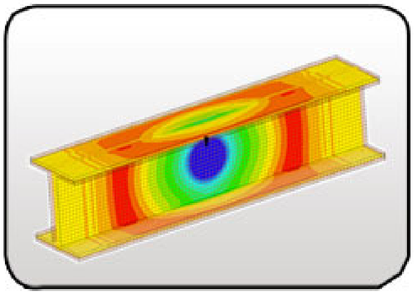
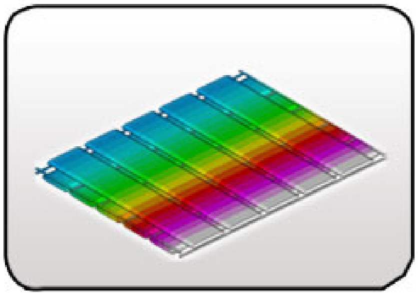
PORE-FLOW ©

A Finite Element Code for Porous Media Flows

- Mold-filling in LCM, a process to make polymer composites
- Wicking flow in rigid and swelling materials
- Permeability prediction
- General laminar flow







Laboratory for Flow
and Transport
Studies in
Porous Media

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PORE-FLOW©

Features and Benefits

- **Unique cutting-edge science** – Only available code that can do: 1) Multiscale flow, heat transfer and species transport in stitched and woven fabrics (dual-scale porous media), 2) 2-D and 3-D wicking in rigid and swelling porous media, 3) State-of-the-art flow simulation on porous-media open-channel interface, 4) Accurate reactive-flow simulation using the novel Flux-Corrected Transport (FCT) algorithm which removes localized wiggles often seen in temperature and species solutions obtained using the SUPG algorithm
- **Extensive validation** - Modeling tools have been extensively validated against controlled mold-filling and wicking experiments (many such validations published in peer-reviewed technical journals)
- **More accuracy** – Much better agreement with experiments compared to current alternatives
- **Versatility** – Flow modeling different mat types such as random mats as well as woven/stitched mats; Numerical estimation of porous-medium permeability using micro-structure information, 2-D and 3-D wicking modeling; Flow and wicking in packed plant-fibers (swelling and liquid absorbing porous media)
- **Cost reduction** - Minimizes cost through optimization of mold or wick design, lower design costs, lower prototyping costs, and lessens need for reworking of molds or wicks
- **Easy implementation** – Can be used with current software (ANSYS pre-processing and Tecplot post-processing)

Markets and Applications

- **Aerospace and Aviation**
- **Boating**
- **Automotive**
- **Sporting equipment**
- **Appliances**
- **Food and Beverage**
- **Oil and gas**
- **Metals, minerals, mining**
- **Nuclear power industry**
- **Biomedical, healthcare, and pharmaceutical**
- **Paper and sanitary products**
- **Diaper industry**
- **Environmental**
- **Water quality and filtration**

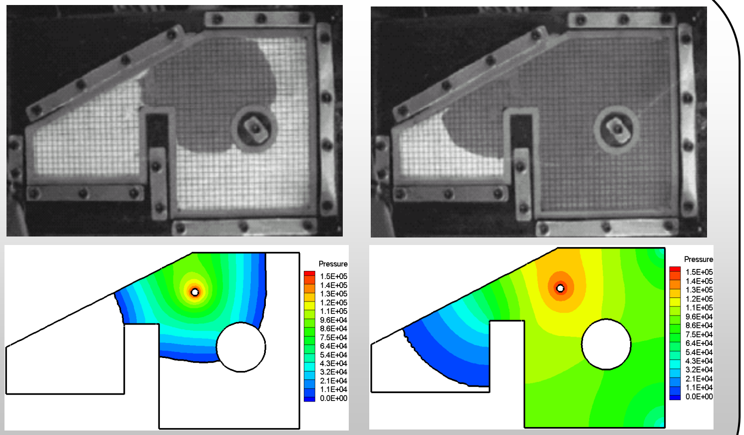
PORE-FLOW©

PORE-FLOW© is a comprehensive computational fluid dynamics tool that solves flow infiltration/wetting problems encountered in industrial porous media. The finite element/control volume 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 to give maximum flexibility to the user. The porous-medium flow in the code is governed by either Darcy's law or Brinkman equation, depending on the user's choice. PORE-FLOW© also 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.

►Mold-filling in Single-Scale Porous Media

Isothermal Flow

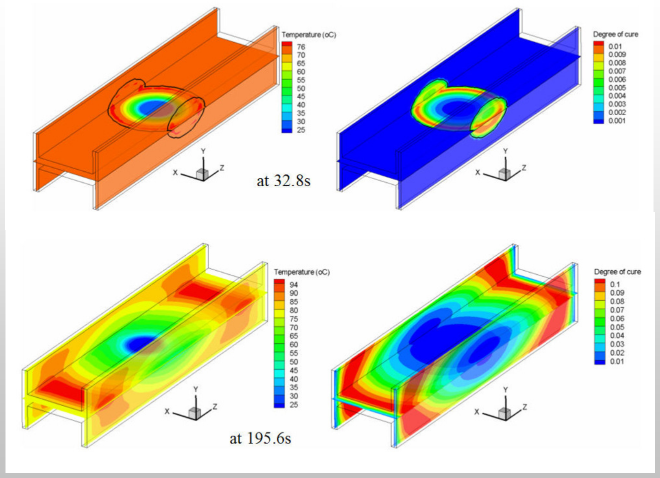
PORE-FLOW© views the fiber preforms packed in the mold as the single-scale porous media, with the pore size in same order of magnitude. Assuming that the pores in the fiber preform behind the flow front are fully saturated with resin, the liquid resin impregnating the dry fiber preform during the mold-filling stage in liquid composite molding (LCM) can be modeled using Darcy's law. The heat transfer and the chemical reaction are neglected in isothermal simulation.



Progression of resin flow front at different times: Experiment (top) and simulation (bottom).

Non-isothermal Reactive Flow

Although isothermal modeling of the LCM mold-filling process is feasible by ignoring the accompanying thermo-chemical reaction kinetics, the heat transfer and the curing reaction must be considered for an accurate mold-filling simulation. PORE-FLOW© uses the flux-corrected transport-based finite element method to stabilize the convection-dominated heat transfer and species transport equations.

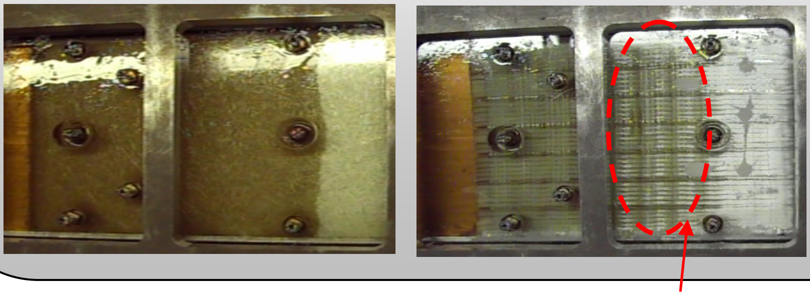


Distributions of temperature and degree of cure.

►Mold-filling in Dual-Scale Porous Media

Background

Conventional flow physics fail to predict the experiments for certain types of fabrics where a partially wetted region behind the flow front can be found during impregnation. 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 fiber bundles 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.

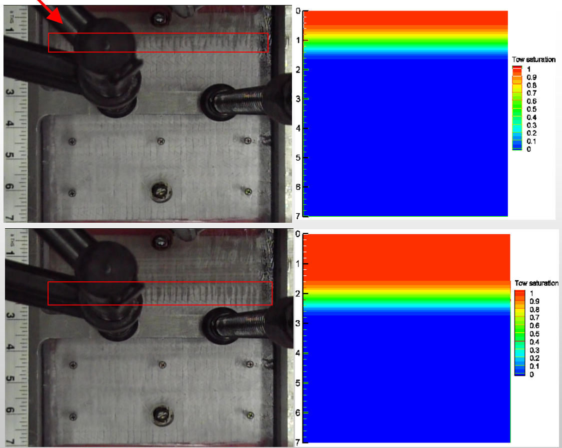


Comparison of impregnations of fiber mats in 1-D flow mold: random fiber mat (left, single-scale); biaxial stitched fiber mat (right, dual-scale porous medium).

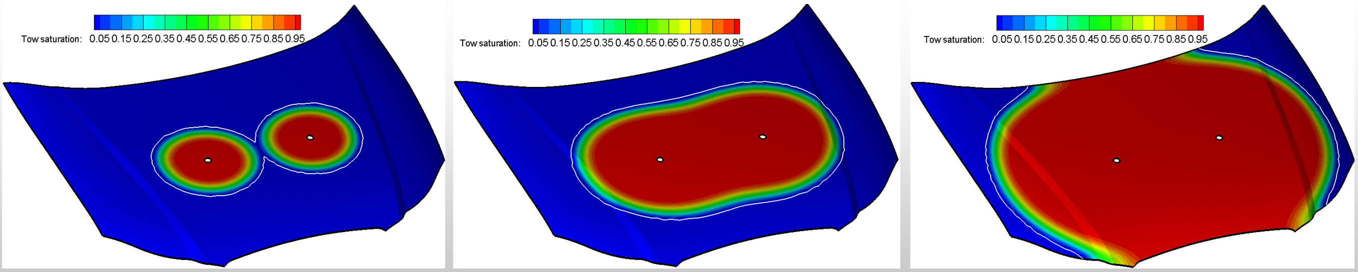
Partially saturated region

Modeling

We developed two approaches to model the flow through dual-scale fibrous preform: 1) a ***fast method*** where the macro gap flow is coupled with the micro tow impregnation through a sink term in the mass balance equation representing the mass absorbed by the fiber bundles from the gaps; 2) a ***multiscale method*** where global and local FE models are created separately and targeted at global mold-scale flow-domain and local tow-scale flow-domain, respectively. Validation of the multiscale approach is shown (right). An isothermal mold-filling simulation of a car hood made from dual-scale fibrous preform is shown below.



Snapshots of the tow-saturation distributions in the 1-D flow: experiment (left); simulation (right).



Evolution of tow-saturation during mold-filling for a car hood (white line indicates the position of the macro-flow front):90s, 238s, 470s.

PORE-FLOW©

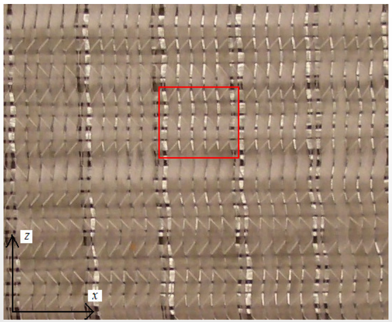
► Permeability Estimation

Permeability

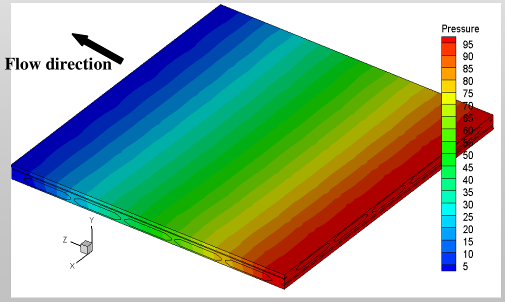
Permeability, a fundamental parameter for accurate mold-filling simulation in LCM, is a property of the porous preform that describes the ease with which a fluid flows in the material.

Numerical Estimation

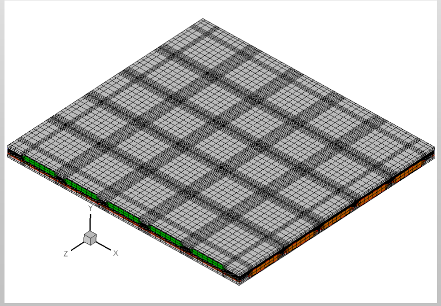
PORE-FLOW© can predict the permeability of a fiber mat. First, a unit-cell is identified in woven or stitched fabrics. Then, the flow simulation is carried out within the unit-cell in which the inter-tow and intra-tow flows are solved using the Stokes and Brinkman equations, respectively. Lastly, permeability is calculated from Darcy's law using the average velocity through the unit-cell and the corresponding flow-direction pressure drop across the unit cell.



A biaxial stitched glass fabric (unit-cell indicated by red rectangle).



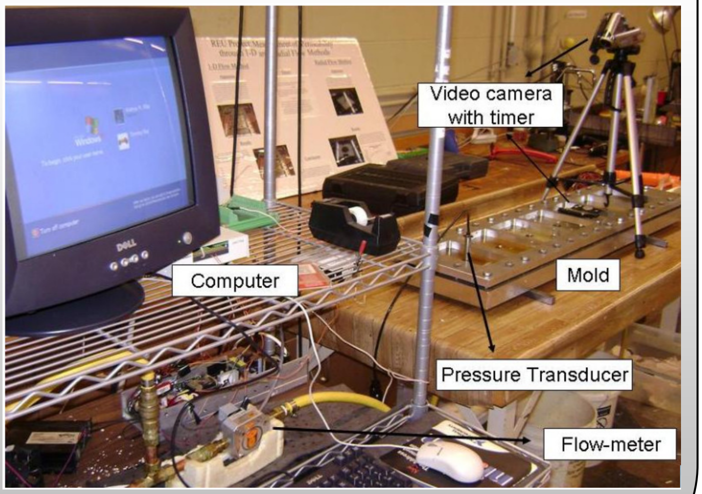
Pressure distribution.



Finite element model of entire unit-cell including tows and gaps.

Experimental Estimation

We have the ***1-D (unidirectional) flow*** and ***radial flow*** based experimental techniques to measure the permeability of fiber mats in our lab. The 1-D flow setup typically uses a rectangular mold with its length much larger than the width, and the test fluid flows along the mold length during the experiment. In the radial flow setup, the injection from an inlet-port centered in the mold creates a radial flow in the mold cavity. The data is automatically collected through the LabView system. We also developed novel calibration methods to ensure the accuracy and repeatability of these devices. We also are developing a new device to measure the out-of-plane permeability of fibrous preforms.



Permeability-measuring devices.