Computation of permeability of textile reinforcements

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ABSTRACT: Permeability of textiles is a key characteristic for composite manufacturing. Measurement of textile permeability is a time and resource consuming process, hence numerical prediction of the permeability is required. Using the law of Darcy, permeability can be derived from a simulation of the fluid flow, i.e. after solving the Navier-Stokes or Brinkman equations. In this paper we present results of simulations with a solver for the incompressible Navier-Stokes equations. Results are compared with theory and recent experimental data.

Key words: Textile composites, Permeability, Finite difference discretization, CFD.

1 INTRODUCTION

Liquid Composite Moulding (LCM) is a rapidly developing manufacturing process. It involves: laying up of a textile reinforcement in a mould cavity of a desired 3D shape; injection of a liquid resin; polymerization (thermosets) or solidification (thermoplasts) of the resin [1]. The permeability of a textile is a key characteristic for composite manufacturing and is of particular importance for the injection stage of LCM. The evaluation of textile permeability gained importance due to the often encountered problems of non-uniform impregnation, void and dry spot formation. The permeability is a geometric characteristic related to the structural features of the textile at several length scales. Textile is a porous medium, so permeability can be defined using Darcy's law

$$\langle \vec{u} \rangle = -\frac{1}{\upsilon\rho} \underline{\underline{K}} \cdot \nabla \langle P \rangle, \quad (1)$$

with $\vec{u}$ the fluid velocity, υ and ρ the fluid viscosity and density, P the pressure, < > volume averaging and K the permeability tensor of the porous medium. Equation (1) is a homogenized equation, the information of the internal geometry of the reinforcement being "hidden" in K. Finite element or finite difference Darcy solvers require the input of K. Unfortunately, measurements of textile permeability are time and resource consuming [2],

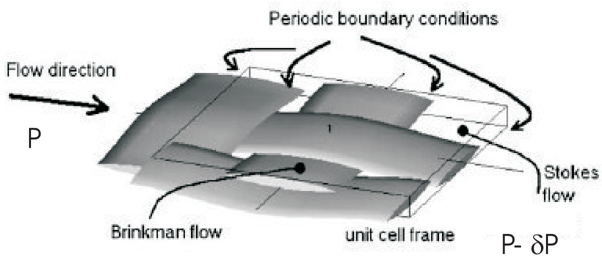

Fig. 1. A unit cell setup

hence reliable numerical prediction of K is required for the Darcy solvers. For the calculation of K, we simulate the flow in a unit cell, shown in figure 1, since textile has a periodic pattern.

In case the model is limited to creeping, single-phase, isothermal, unidirectional saturated flow of a Newtonian fluid, the inter-yarn flow is described by the incompressible Navier- Stokes equations,

$$\begin{cases} \dfrac{\delta \vec{u}}{\delta t} + (\vec{u} \cdot \nabla)\vec{u} = -\dfrac{1}{\rho}\nabla\langle P \rangle + \upsilon \Delta \vec{u} \\ \nabla \cdot \vec{u} = 0 \end{cases} \quad (2).$$

The first equation states the conservation of momentum (momentum equation), the second equation states conservation of mass (continuity equation).

Intra-yarn flow depends on the local permeability tensor of the tow K_{tow}, and is described by the

Brinkman equations [3] without neglecting the convection,

$$\begin{cases} \dfrac{\delta\vec{u}}{\delta t} + (\vec{u}\cdot\nabla)\vec{u} + \upsilon \underline{\underline{K_{tow}^{-1}}} \cdot \vec{u} = -\dfrac{1}{\rho}\nabla\langle P\rangle + \upsilon\Delta\vec{u} \\ \nabla\cdot\vec{u} = 0 \end{cases} \quad (3).$$

A key task in permeability modelling is the characterization of the reinforcement. For the creation of a single layer of the reinforcement, we use the WiseTex software [4], [5]. In practice however, often the permeability of a multi-layered reinforcement is required. Building the geometry model of a multi-layered reinforcement is a complex additional step, for which the LamTex software has been developed [6]. The results of WiseTex and LamTex provide the input for the flow simulation tool.

We develop a software package, FlowTex, for the computation of the permeability tensor of textiles. A first module of FlowTex, based on a lattice Boltzmann model for fluid flow, has been developed, tested and validated [7]. In this paper we discuss the module of FlowTex, based on a finite difference discretization of the Navier-Stokes equations (2) and the Brinkman equations (3). Results of the permeability predictions with the new module are compared with results obtained with the lattice Boltzmann module, with analytical results for a model problem and with experimental data. Note that experimental validation is often missing in papers describing other software for permeability prediction.

2 NUMERICAL APPROACH

2.1 Solution of the Navier-Stokes equations

For flow simulations in the irregular geometry of a textile, we have chosen to solve equations (2) and (3) numerically on a regular staggered grid with a finite difference discretization. An example of a textile geometry and its discretization on a regular grid is shown in figure 2. One could also use an irregular (unstructured) grid and a finite element or finite volume discretization. However, generating appropriate 3D meshes is difficult and time consuming.

If we neglect the intra-yarn flow, the yarns are treated as solid. Grid points can be in the fluid domain ("fluid points"), or in the solid yarn domain ("solid points"). At the boundaries between fluid and solid cells, first order no-slip boundary conditions are imposed.

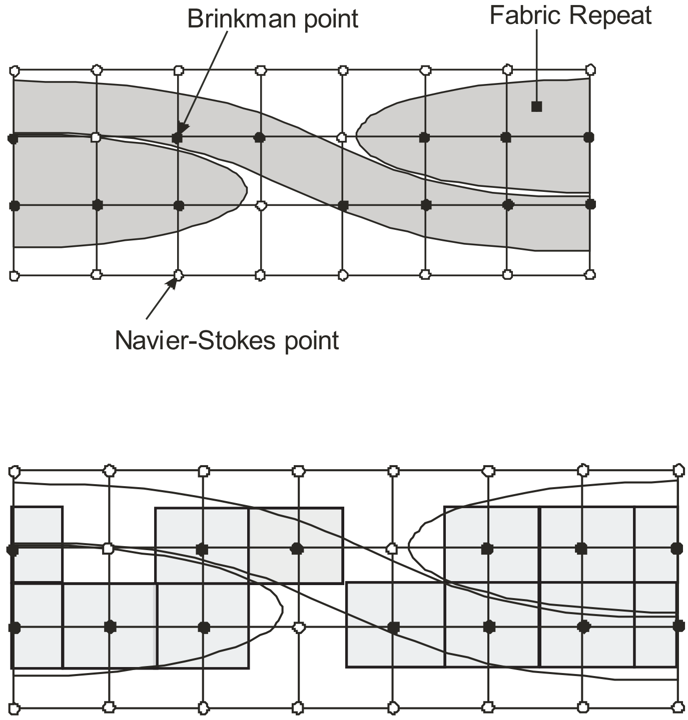

Fig. 2. (Top, Bottom) A 2D-textile model and its first order approximation on the grid

2.2 Solution of the Brinkman equations

If we take the intra-yarn flow into account, the Brinkman equations (3) must be solved in the yarn points. The Brinkman equations are similar to the Navier-Stokes equations, and the same approach can be used. Equations (3) converges to the Navier-Stokes equations (2) for large K_{tow}. We solve (3) on the whole domain with $K_{tow}=\infty$ at fluid points, while for yarn points K_{tow} is typically $10^{-4}<K_{tow}<10^{-7}$. This penalisation approach introduces a locally varying resistance force which leads to discontinuous velocities across the boundary between fluid and yarn points. To avoid numerical instabilities induced by this discontinuity, we apply a high order total variation diminishing (TVD) scheme for the convective terms discretization.

2.3 Implementation

A parallel finite difference incompressible Navier-Stokes solver, NaSt3DGP, has been developed by the research group of Prof. Michael Griebel in the Institute of Numerical Simulation at the University of Bonn [8],[9]. The solver uses the Chorin projection method, provides several second order TVD upwind schemes for space discretization and an explicit Euler as well as a second order Adams-Bashfort scheme for time discretization.

Furthermore, NaSt3DGP offers several iterative solvers (SOR, Red-Black, BiCGStab) for the Poisson equation for the pressure, which has to be solved each time step of the Chorin method. The parallelisation of NaSt3DGP code is based on MPI [10]. We have adapted the code to our needs, so that the code can be used for the flow simulation in a unit cell and for the solution of the Brinkman equations. A new interface is developed, and the FlowTex software is extended for a fast and clear input of the WiseTex models.

3 VALIDATION

In this paper we present two validation experiments, other results can be found in [11].

3.1 Parallel square array

3.1.1 Impermeable array

For the flow through a parallel square array of impermeable tows, theoretical, numerical and experimental data are available [12],[13]. Figure 3 compares the theoretical permeabilities (full lines) with the results of the finite difference Navier-Stokes solver (squares) and results of a lattice Boltzmann solver (circles).

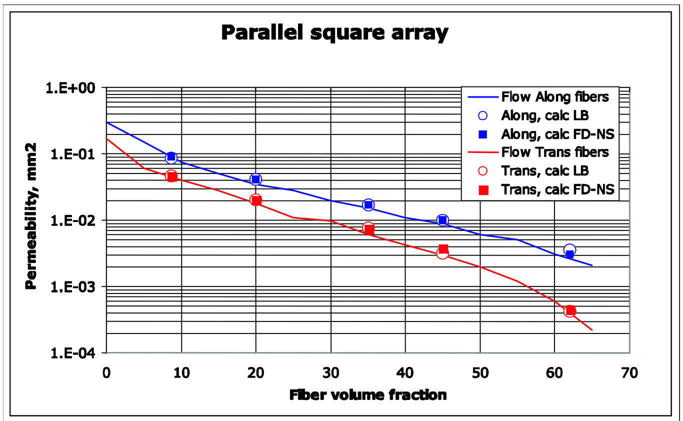

Fig. 3 Permeability results of Parallel Square Arrays with different fibre volume fractions

3.1.2 Permeable array

Fig.4 shows the results of permeability predictions with the Brinkman solver. For a fixed volume fraction (60%), the permeability is calculated for different cylinder permeabilities K_{tow}. For large K_{tow}, the permeability of the unit cell increases to the permeability of an empty unit cell. As K_{tow} decreases, the cylinders become more and more solid and the unit cell permeability converges to the permeability of an impermeable array.

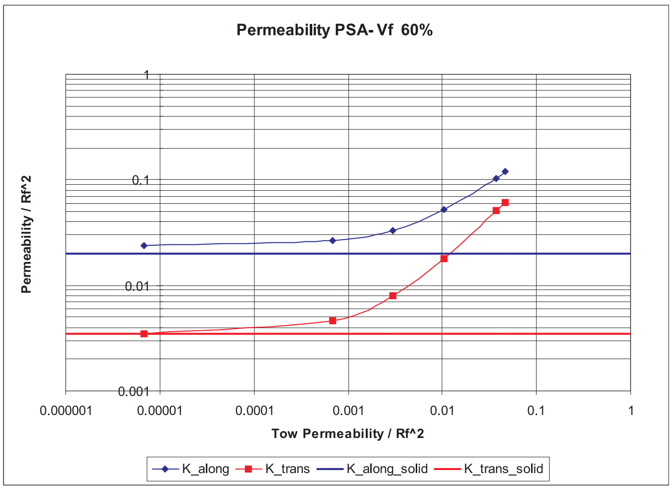

Fig. 4 Permeability of a PSA with changing K_{tow}

3.2 VUB-Structure

At the Vrije Universiteit Brussel (VUB), a special validation specimen is developed [14], and produced by a stereolithography technique in epoxy material. This solid structure can solve some problems with experimental permeability predictions, e.g. the deformation of the textile test specimens. It allows to eliminate experimental scatter caused by micro flows and nesting [15]. Also, the CAD designed form of the structure enables precise modelling for comparison with numerical computation of the permeability.

As the financial cost of the stereolithography specimen is rather high, permeability predictive calculations must be performed on computer models, in order to develop a specimen with a desired anisotropy and permeability value. Figure 5 shows the SL specimen on which calculations were performed. The structure contains several layers, of which 2D-cuts are shown in the figure. These led to the isotropic results shown in table 1: permeability in x- and y-direction are similar, and so anisotropy is negligible. Anisotropy flow is obtained with the structure shown in figure 6. The permeability is of order of magnitude $10^{-9} m^2$, which leads to an acceptable flow rate through the specimen during the tests. This last specimen was produced and experiments are performed.

Table 1. Computational results for the VUB-Structure

Structure	Grid spacing	K_x	K_y
Structure 1	0.0125	0.011	0.0089
	0.00625	0.0089	0.0073
Structure 2	0.0125	0.0075	0.0027
	0.00625	0.0060	0.0023

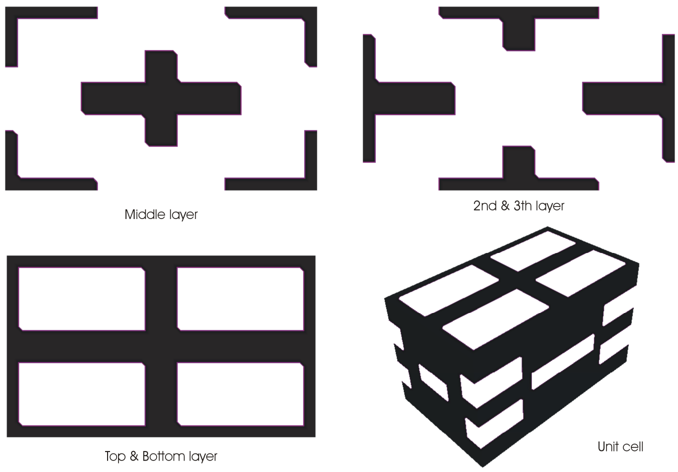

Fig. 5. VUB Structure 1

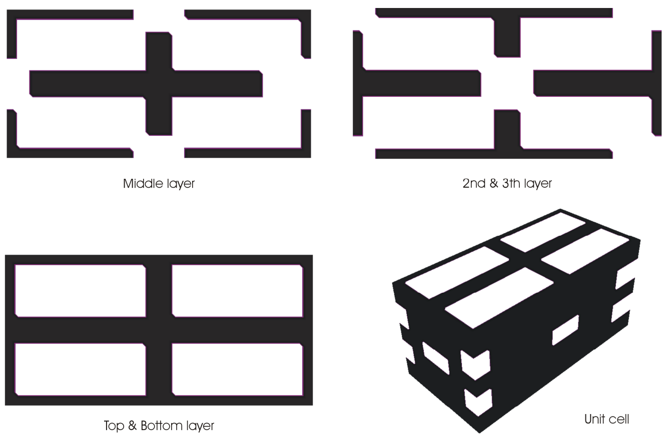

Fig. 6. VUB Structure 2

4 CONCLUSIONS

We presented a software package for the computation of the permeability of textile reinforcements.
Using an accurate geometric model of the textile (obtained from another software package), flow simulations are performed to predict the permeability. The Navier-Stokes and Brinkman equations are solved with the finite difference discretization. The method is validated on a parallel square array of cylinders, and a new validation structure is presented.

5 FURTHER RESEARCH

Further validation of the software will be performed. The computational cost of the current version of the Navier-Stokes solver is rather high. We will improve the numerical procedures to speed up the code.

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REFERENCES

1. R.S. Parnas, *Liquid Composite Molding,* Hanser Publishers, Munich (2000).
2. K. Hoes, D. Dinesku, M. Vanhuele, H. Sol, R. Parnas, E.B. Belov, and S.V. Lomov. Statistical distribution of permeability values of different porous materials. In: *10th European Conference on Composite Material,* eds, H. Sol and J. Degrieck, CD-edition(2001).
3. J.C. Slattery. *Momentum, energy and mass transfer in continua.*McGraw-Hill, New York, (1972).
4. S.V.Lomov, G. Huysmans, Y. Luo, R. Parnas, A. Prodromou, I. Verpoest and F.R. Phelan, Textile composites models: Integrating strategies, *Composites part A,* 32 (2001) 1379-94.
5. S.V. Lomov, G. Huysmans and I. Verpoest, Hierarchy of textile structures and architecture of fabric, *Textile Reseach Journal,* 71 (2001) 534-43.
6. S.V. Lomov, I. Verpoest, T. Peeters, D. Roose and M. Zako, Nesting in textile laminates: geometrical modelling of the laminate, *Composites Science and Technology,* 63 (2002) 993-1007.
7. E.B. Belov, S.V. Lomov, I. Verpoest, T. Peeters, and D. Roose. Modelling of permeability of textile reinforcements: lattice Boltzmann method. *Composites Science and Technology*. 64 (2004) 1069-80.
8. http://wissrech.iam.uni-bonn.de/research/projects/NaSt3DGP/index.htm
9. M. Griebel, T. Dornseifer, and T. Neunhoeffer. *Numerical Simulation in Fluid Dynamics, a Practical Introduction*. SIAM, Philadelphia (1998).
10. http://www-unix.mcs.anl.gov/mpi/
11. B. Verleye, M. Klitz, R. Croce, D. Roose, S. Lomov and I. Verpoest, Computation of Permeability of Textile Reinforcements, In: *Proc. IMACS 2005*, CD-Edition.
12. J.V.D. Westhuizen and J.P. De Plessis, Quantification of unidirectional fiber bed permeability, *Journal of Composite Materials,* 28 (1994) 38-44.
13. B. R. Gebart, Permeability of unidirectional reinforcements for rtm, *Journal of Composites Materials,* 26 (1992) 1100-33.
14. G. Morren, J. Gu, H. Sol, B. Verleye, S. V. Lomov, Stereolithography specimen for benchmarking the permeability measurements of fibrous reinforcements for RTM (in preparation).
15. K. Hoes, H. Sol, D. Dinescu, S. Lomov, R. Parnas, Study of nesting induced scatter of permeability values in layered reinforcement fabrics, *Composites part A*, 35 (2004) 1407-18.