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 the results of simulations with an extended version of the freely available finite difference CFD software package NaSt3DGP and we compare the results with those obtained from a Lattice-Boltzmann code. The results are validated with theory and experimental data.

Keywords—**Textile composites, Permeability, Finite difference discretization, Lattice-Boltzmann, Computational fluid dynamics.**

I. INTRODUCTION

Liquid Composite Molding (LCM) is a rapidly developing manufacturing process. It involves: laying up of a textile reinforcement in a mold of a desired 3D shape; injection of a liquid resin; polymerization (thermosets) or solidification (thermoplasts) of the resin [12]. Permeability of textiles 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

$$\langle \vec{u} \rangle = -\frac{1}{\nu\rho}\underline{\underline{K}} \cdot \nabla \langle P \rangle, \tag{1}$$

with $\langle \vec{u} \rangle$ the fluid velocity, ν and ρ the fluid viscosity and density, P the pressure, $\langle\rangle$ volume averaging and $\underline{\underline{K}}$ 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 $\underline{\underline{K}}$. Finite element or finite difference Darcy solvers require the input of $\underline{\underline{K}}$. Unfortunately, measurement of textile permeability is time and resource consuming [8], hence reliable prediction of $\underline{\underline{K}}$ is required for the Darcy solvers.

For the calculation of $\underline{\underline{K}}$, we can determine the flow in a unit cell, since textile has a periodic pattern (Fig.1). The inter-yarn flow is described by the incompressible Navier-Stokes equations (2), in case the model is limited to creeping, single-phase, isothermal, unidirectional saturated flow of a Newtonian fluid. The first equation states the conservation of momentum (momentum equation), the second equation is the continuity equation (conservation of mass).

$$\begin{cases} \frac{D\vec{u}}{Dt} = \frac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u} = -\frac{1}{\rho}\nabla p + \nu\Delta\vec{u} \\ \nabla\cdot\vec{u} = 0 \end{cases} \tag{2}$$

Intra-yarn flow depends on the local permeability tensor of the tow $\underline{\underline{K_{tow}^{-1}}}$, and is described by

$$\begin{cases} \frac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u} - \nu\underline{\underline{K_{tow}^{-1}}}\cdot\vec{u} = -\frac{1}{\rho}\nabla p + \nu\Delta\vec{u} \\ \nabla\cdot\vec{u} = 0, \end{cases} \tag{3}$$

which are the Brinkman equations [13] without neglecting the convection.

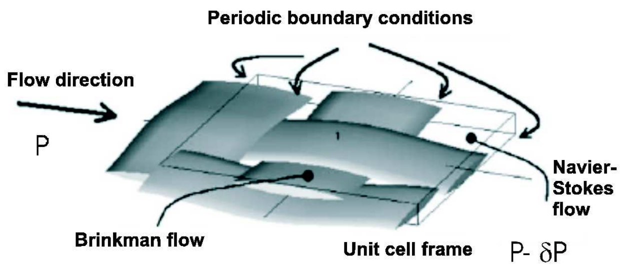

Fig. 1. A unit cell setup

A key task in permeability modeling is the characterization of the reinforcement. For the creation of a single layer of the reinforcement, we use the WiseTex software [9], [10]. 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 [11]. 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 version of FlowTex, based on a Lattice Boltzmann model for fluid flow, has been tested and validated [3]. In this paper we discuss a new 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

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obtained with the Lattice-Boltzmann software, 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.

II. Numerical approach

A. Solution of the Navier-Stokes equations

For simulations in an irregular geometry, typically finite volume or finite element discretizations are used. They have the advantage that irregular and/or adaptively constructed meshes can easily be dealt with. However, for the flow through a complex fibrous structure, it is very difficult and time consuming to generate appropriate meshes. For that reason, we have chosen to solve equations (2) and (3) numerically on a regular staggered grid (Fig.2) with a finite difference discretization. In the staggered grid approach, the pressure is discretized at the center of the cells, while the velocities are discretized on the edges. This avoids the occurrence of non-physical oscillations in the pressure.

B. Geometry issues/Boundary conditions

If we neglect the intra-yarn flow, the yarns are treated as impermeable. Grid points can be in the fluid domain ('fluid points') or in the solid yarn domain ('solid points'). At the boundaries between the fluid and the solid, no-slip boundary conditions are set. We have chosen for a lineair approximation of the solution at the boundaries:

$$V_{i,j,k} = -V_{i+1,j,k},$$

if $V_{i,j,k}$ is a solid point, and $V_{i+1,j,k}$ is a fluid point. We use a second order discretization of the Navier-Stokes equations, but since the geometry is approximated to first order, we cannot obtain second order accuracy at the borders. Including a second order description of the geometry would not only lead to geometry problems we avoid by using the finite difference method, but a second order approximation of the boundary conditions would also create numerical stability problems.

Using a first order approximation of the yarns, means that fine meshes are required to obtain an accurate result. However, unlike accurate and automatic mesh-generators, some fast and stable PDE-solvers are freely available.

C. Solution of the Brinkman equations

If we include the intra-yarn flow, 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. Equation (3) converges to equation (2) for large K_{tow}. We solve (3) on the whole domain, now treating every point in a similar way. At fluid points, K_{tow} is set to ∞, for yarns $K_{tow}$is typically $10^{-4} \le K_{tow} \le 10^{-7}$. This leads to highly discontinuous coefficients in the discretized PDEs, at the boundaries between fluid and yarn points. However, the permeability term, which can be seen as a local reaction term, has only influence on the diagonal of the discretized system. Using a simple Jacobi preconditioner avoids numerical instabilities.

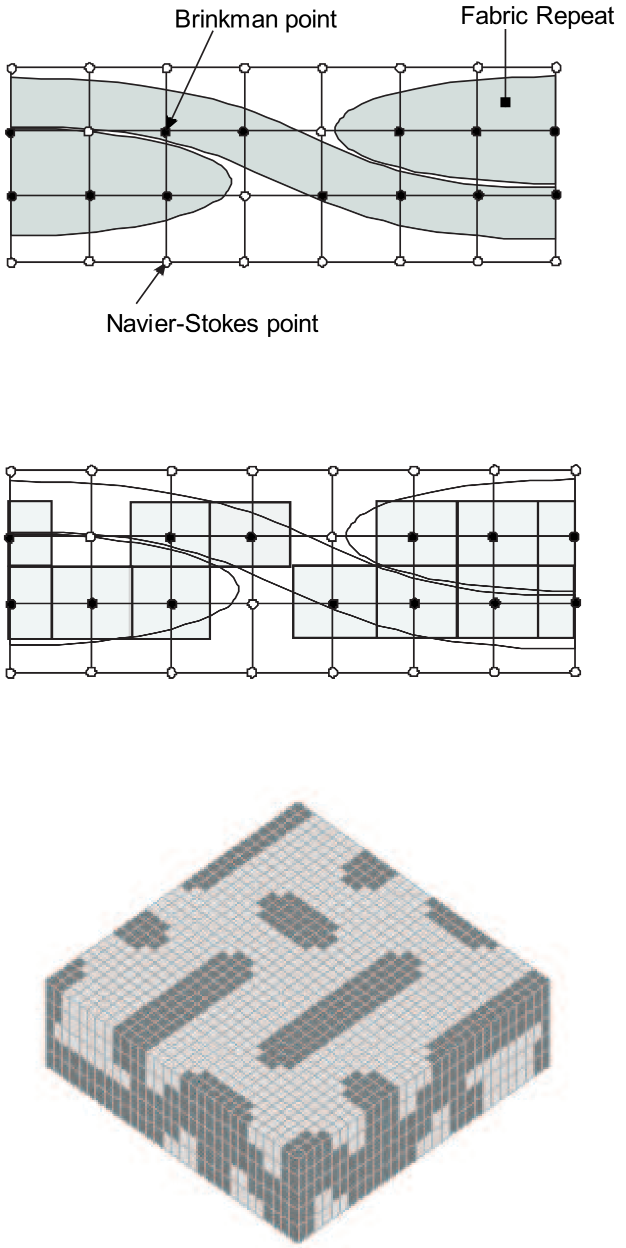

Fig. 2. Top,middle: A 2D-textile model and its first order approximation on the grid; bottom: 3D voxel geometry

D. Implementation

A finite difference Navier-Stokes solver, NaSt3DGP was developed by the research group of Prof. Michael Griebel in the institute of Numerical Simulation at the University of Bonn [6],[1]. For the solution of the Navier-Stokes equations (2), the Chorin projection method is used. First the

momentum equation is solved to predict a new velocity field. This new velocity field, however, will not satisfy the continuity equation. Substitution of the predicted velocity into the continuity equation, leads to a Poisson equation for the pressure. After solving the Poisson equation, the new divergence free velocity field is computed.
The NaSt3DGP code works completly in parallel on MPI [2] platforms and 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 according Poisson system.
The implementation of the boundary conditions and the spatial derivatives, does not allow solid cells bordered by two fluid cells in one direction. Otherwise boundary conditions cannot be set correctly. If, after discretization, such solid cells appear, they will be deleted.

We have adapted the code to our needs. For the unit cell setup, we implemented periodic boundary conditions in three directions for the velocities, and periodic boundary conditions up to a constant gradient for the pressure (Fig.1). Discretization of the Brinkman equations leads to a straightforward implicit implementation of the reaction term.
For the Brinkman solver, a nested iteration strategy is implemented. The flow is first computed on a coarse mesh, and the solution is then transferred to a finer mesh, with first order interpolation for both velocity and pressure values. Starting from this initial approximation, the flow is then computed on the finer mesh. This procedure is repeated until the solution is obtained on the finest mesh.
Using the average $\vec{u}$ over a cross section, the permeability $\underline{\underline{K}}$ is derived from Darcy's law (1) . Convergence of $\underline{\underline{K}}$, reaching the steady state or a maximum number of time steps, can be used as stopping criterion. For the input of the geometry, an interface between WiseTex and the Navier-Stokes and Brinkman code has been developed.

III. Results and Validation

Validation tests with the Navier-Stokes and the Brinkman solver show very good results. Here, we present the results of one artificial setup, and of two realistic reinforcements for which we have experimental verification. Forward Euler time integration, and the VONOS [15] scheme for the spatial discretization was used. The Poisson equation was solved using the BiCGStab [14] method with Jacobi preconditioning. Calculations are performed on a AMD Opteron(tm) Processor 244, 1.7GHz.

A. Parallel Square Array (PSA)

A.1 Impermeable Array

For the flow trough a parallel array of impermeable tows, theoretical, numerical and experimental data are available [16],[5]. Results can be found for different fiber volume fractions (Vf.), i.e. different radii (Rf) of the cylinders. Fig.3 shows the theoretical permeability, together with the calculated permeability, both for flow along the cylinders and for transversal flow. The graph also shows a comparison between the permeabilities obtained with the finite difference Navier-Stokes solver and the Lattice-Boltzmann method.
For two volume fractions, Table I shows calculated permeability for different grid spacings. With decreasing Δx, the permeability converges. Table I also shows the total number of iterations that are performed to solve the Poisson equations.
On a finer mesh more iterations are required because of two reasons: First, pseudo time stepping is used to reach the steady state. Inside explicit schemes the time-step is restricted by the local mesh size. Thus, a finer mesh requires a smaller time step, and therefore, more time-steps have to be taken. Second, the preconditioned BiCGStab scheme for the Poisson equation converges more slowly to a solution on a finer mesh [4], so in each timestep more iterations are required.

TABLE I
RESULTS OF THE PSA-SETUP

Vf	Δx	#gridpoints	#iterations	K_{along}
20	0.1	1000	1200	0.05876
	0.05	8000	3900	0.04881
	0.03	35937	10100	0.04626
	0.025	64000	19100	0.04537
62	0.1	729	350	0.004906
	0.05	5832	850	0.003374
	0.03	27000	2100	0.003337
	0.025	46656	2950	0.003178

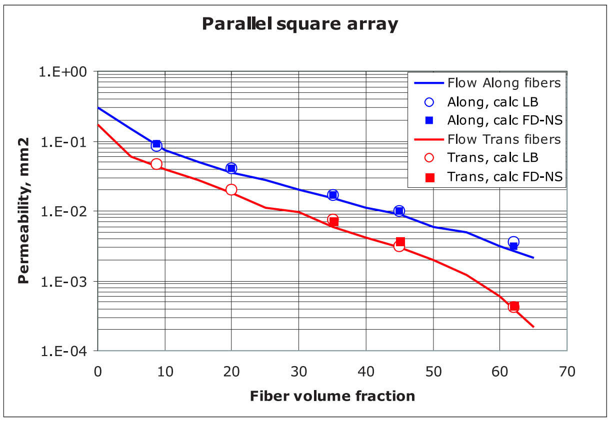

Fig. 3. Permeability of Parallel Square Arrays with different fiber volume fractions. Full lines: theoretical permeability; circles: Lattice-Boltzmann results; squares: Navier-Stokes results.

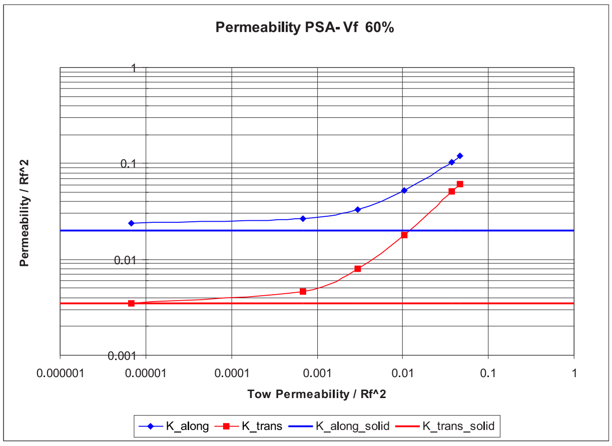

Fig. 4. Permeability of a Parallel Square Array with different local permeabilities

A.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 one. As K_{tow} decreases, the cylinders become more and more solid and the unit cell permeability converges to the permeability of an impermeable array.

A.3 Nested Iteration

For a parallel array of cylinders with a volume fraction of 60%, the Navier-Stokes solver, the Brinkman solver and the Brinkman solver with nested iteration are compared (Table II). The calculations are performed on a $(40 \times 40 \times 40)$ grid, for the nested iteration starting on a $(2 \times 2 \times 2)$ grid. Stopping criterion for the calculations is convergence of the permeability.
As the Navier-Stokes code only performs calculations on the fluid cells, the computational cost, expressed as the number of iterations multiplied with the number of active gridpoints, is smaller than for the Brinkman solver. The Navier-Stokes solver iterates on a smaller system of equations, and reaches steady state faster than the Brinkman solvers. The nested iteration converges faster than the non-nested iteration.
When reaching steady state (up to machine precision) is used as stopping criterion, the calculated permeability only differs 0.001%, but the computation time is much higher.

B. Monofilament fabric

The Monofilament fabric Natte 2115 is a more realistic structure which is close to actual textile reinforcements, and for which permeability is experimentally validated. The full description of the Monofilament Fabric Natte 2115 test-fabric can be found in [8],[7]. The yarns are impermeable, so only the Navier-Stokes equations are solved.

TABLE II
COMPUTATIONAL RESULTS

	Navier-Stokes	Brinkman	Brinkman nested it.
Total nb iterations	79.10^3	106.10^3	122.10^3
Iterations $\times$gridpoints	$2.0\ 10^9$	$6.6\ 10^9$	$5.6\ 10^9$
Time	2h00	4h05	3h27
Permeability/Rf^2 (10^{-3})	3.54	4.64	4.64

Fig.5 shows the experimental setup and WiseTex model. The third picture shows the flow velocity field in a 2D-cut. In the yarns and at the boundaries, the velocity is zero. The zero velocity surface shows a good approximation of the textile geometry. The picture shows two layers of textile, which are maximally nested. Permeability calculations will give different results for one layer setups and for setups with minimal, average or maximal nesting.
Fig.6 shows that the predicted permeability depends strongly on the grid spacing. The first order discretization of the geometry leads to a slightly different actual geometry. This means that for a coarse grid, we actually solve a different problem, which leads to a higher permeability.

C. Syncoglass

A second structure is Syncoglass (Fig.7). Full description of the Syncoglass structure can be found in [8],[7]. Fig.8 shows the results of experimental and computational experiments. Both Lattice-Boltzmann and FD-Navier-Stokes overestimate the permeability in this case. The Natte setup already showed that a fine mesh is required, and for the Syncoglass textile an even finer grid is needed. Not only the first order approximation has effect on the geometry, but a coarse grid also leads to more deleted cells.

IV. CONCLUSIONS

We presented a software package for the computation of the permeability of textile reinforcements.
First a textile model is designed with the WiseTex software. An accurate model is required as slight differences in the model lead to other permeabilities. Using the model resulting from WiseTex, flow simulations are performed to predict the permeability. We have chosen to solve the Navier-Stokes and Brinkman equations with the finite difference discretization.
The method was first validated with an artificial setup: a parallel array of cylinders. For such setup, the calculated permeability can be compared with theoretical results. The results show that for impermeable arrays, the results obtained with the finite difference Navier-Stokes method are accurate. For permeable arrays theory lacks, but the predictions of the Brinkman solver, including the intra-yarn flow, show acceptable convergence.

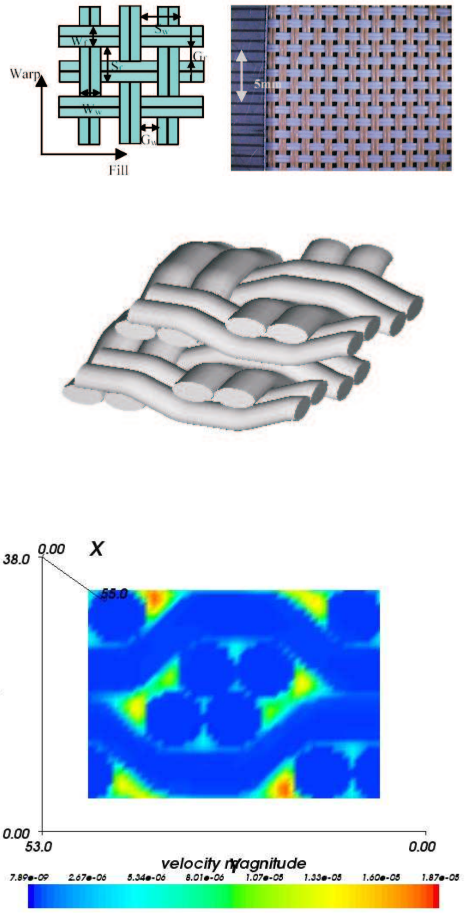

Fig. 5. The MonoFilament experimental setup and WiseTex model

To evaluate permeability calculations for real textiles, we presented validation results for Natte and Syncoglass textiles, for which experimental data are available.

V. Further Research

The presented results are promising, but further validation is necessary. At this moment, the computational cost of the Navier-Stokes and Brinkmann solver is quite high. We will develop a parallel version of the FlowTex software for permeability calculations of textiles, and include numerical improvements.

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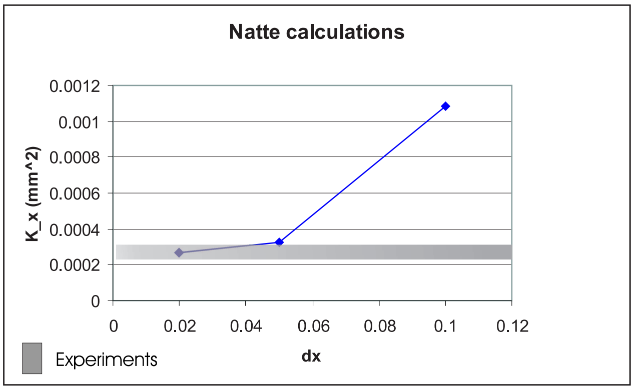

Fig. 6. Results of the Natte permeability calculations

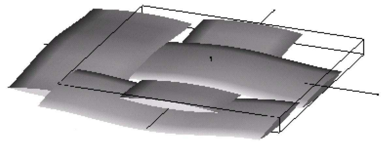

Fig. 7. The Syncoglass WiseTex model

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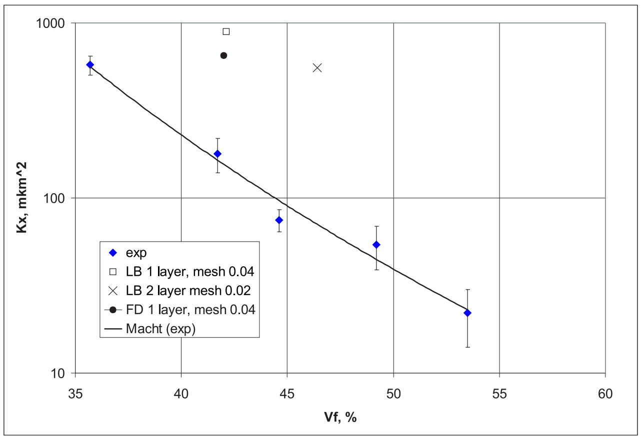

Fig. 8. Experimental validation with Syncoglass

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