Microscale Permeability Prediction of Fibre Bundles Using Smoothed Particle Hydrodynamics

A. Koptelov[1*], A. Pirrera[1], and J.P.-H. Belnoue[1]

[1] Bristol Composites Institute, University of Bristol, Bristol, United Kingdom

* *Corresponding author (anatoly.koptelov@bristol.ac.uk)*

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1. Abstract

This work develops a computational pipeline for estimating the microscale permeability of composite materials. The approach combines virtual fibre bundle generation, Smoothed Particle Hydrodynamics (SPH) simulation of resin flow, and Darcy's-law-based permeability extraction for flow both along and transverse to the fibre direction. Preliminary results show that SPH captures the expected anisotropic flow behaviour and produces permeability estimates within the same order of magnitude as analytical predictions. The proposed framework therefore shows strong potential for local permeability assessment and resin flow analysis in composite infusion processed.

2. Introduction

Although permeability is a crucial parameter in composite manufacturing, it remains one of the most challenging to characterise accurately. Direct experimental measurement is highly sensitive to testing conditions, as even minor deviations can lead to significant variations in measured permeability values [1,2]. While recent standardisation efforts have improved reproducibility [3], experimental testing remains constrained by the high cost of composite materials and manufacturing trials. In addition, even small changes in design parameters, such as layup or part geometry, require new test campaigns. Moreover, permeability data obtained from small-scale coupons are often not representative of industrial-scale composites.

From a modelling perspective, permeability prediction is also challenging. To capture the influence of fibre architecture on resin flow accurately, effects at both the micro and meso scales should be considered. At the microscale, fibre-reinforced material volumes consist of densely packed, anisotropic fibre bundles with narrow flow channels, requiring high spatial resolution for accurate numerical representation. Consequently, modelling infusion through realistic three-dimensional textile geometries at this scale can become computationally demanding [4]. For this reason, the application of conventional Computational Fluid Dynamics (CFD) approaches to highly detailed permeability problems remains limited.

Smoothed Particle Hydrodynamics is an alternative numerical approach for modelling resin flow through fibre beds. SPH is a mesh-free method in which the fluid is represented by moving particles rather than by a fixed computational mesh. This avoids the need for mesh generation in narrow and irregular fibre channels, making the method well suited to complex microscale geometries. Moreover, SPH can handle complex, transient, microscale flow phenomena, including high-velocity or locally disturbed flow. The method has been extensively developed for incompressible and compressible viscous flow simulations of both Newtonian and non-Newtonian fluids [5] and is, therefore, a promising candidate for modelling composite resin infusion.

The aim of this work is to investigate the feasibility of using SPH to estimate the microscale permeability of fibre bundles. Permeability is evaluated by modelling resin flow both parallel and transverse to the fibre direction, enabling the principal components of the permeability tensor to be obtained.

3. Modelling approach

Fibre bundles for microscale permeability assessment were generated as 3D geometrical objects using the Fibre Packer framework developed by Dahl [6]. This framework enables randomly distributed fibres to be generated within a user-defined domain at a prescribed fibre volume fraction. The resulting fibres include variations around the target radius, allowing the non-uniformity of real fibre bundles to be represented realistically. In addition, different levels of fibre waviness can be introduced, which is particularly relevant for permeability assessment, as waviness directly affects the connectivity and size of resin flow channels. Depending on the arrangement of fibres, waviness may either promote flow by creating larger interconnected channels (especially for flow transverse to fibre direction) or restrict it by closing narrow gaps. Examples of generated fibre bundles with different fibre volume fractions are shown in Figure 1.

The generated fibre bundle geometries were then imported into the SPH software SPlisHSPlasH, developed by Bender et al [5]. Examples of simulation scenes used for the longitudinal and transverse permeability assessment are shown in Figure 2.

Resin particles were introduced into the computational domain using an emitter object with a predefined initial velocity. Depending on the flow configuration, the emitter was positioned either at the base or to the side of the fibre bundle to drive the flow parallel or transverse to the fibre direction, respectively. To control the number of fibres engaged by the incoming resin flow, a circular emitter was used for the longitudinal configuration, while a rectangular emitter was used for the transverse configuration. Boundary objects were introduced to prevent lateral spreading of the resin outside of the intended flow region. The boundary shape was selected to match the emitter geometry and extruded through the full length of the fibre bundle.

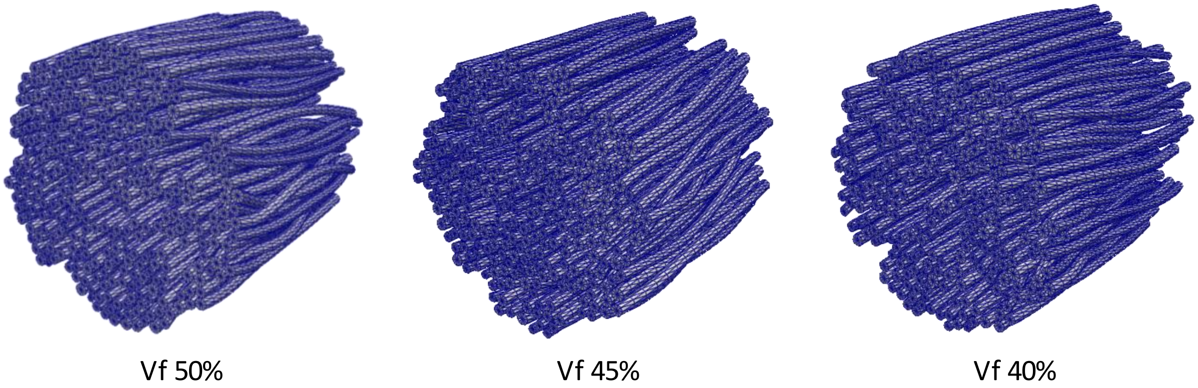

Figure 1. Examples of fibre bundles with different fibre volume fraction level.

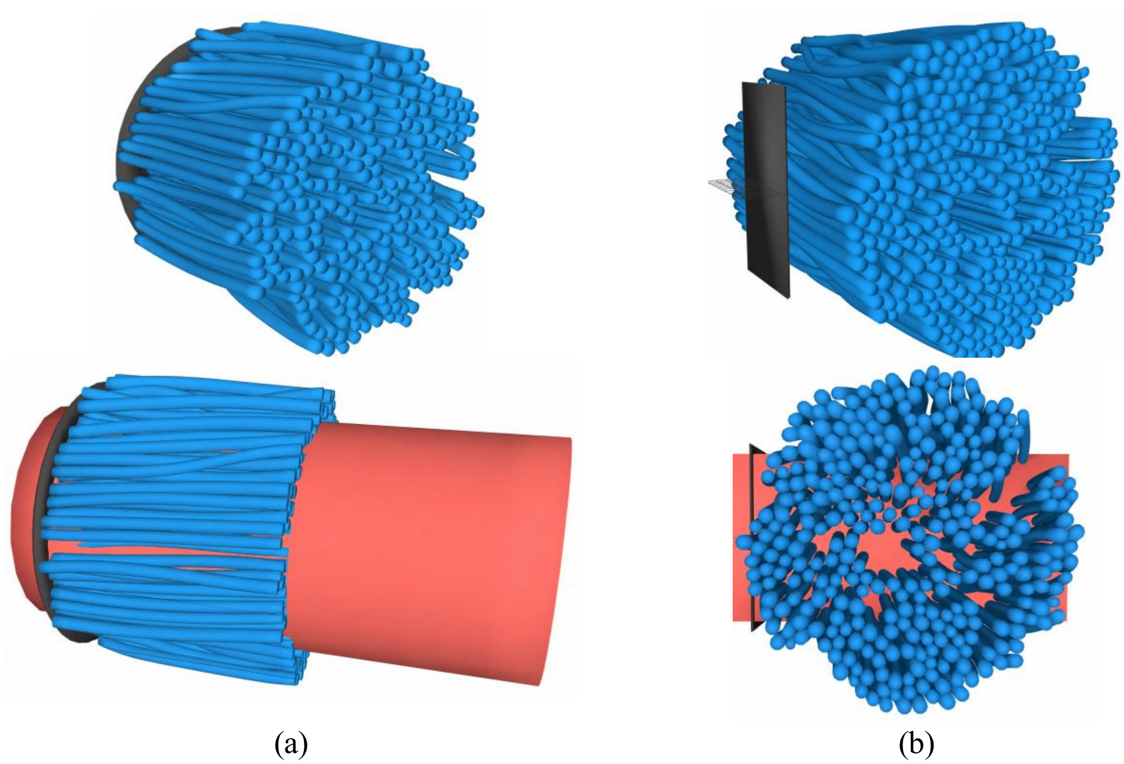

Figure 2. Problem setup; blue – fibre bundle, black – emitter, red – flow boundary object. A) longitudinal permeability assessment B) transverse permeability assessment.

During infusion, the resin was treated as an incompressible fluid. In such formulation, the pressure field is computed so as to maintain the fluid's density close to its rest density, which is consistent with the physical behaviour of resin during infusion. The resulting pressure drop, ΔP, was then used together with the average flow velocity, v, the characteristic flow length, L, and viscosity, μ, to estimate permeability, K, using Darcy's law:

$$K = \frac{\mu v L}{\Delta P}. \quad (1)$$

Since the fibre bundle geometry was scaled for numerical convenience before being imported into the SPH solver, permeability was first obtained in simulation length units squared and then converted to m^2 using the corresponding geometrical scale factor.

The Laplacian-based SPH viscosity formulation was selected in this work to reduce velocity differences between neighbouring fluid particles, thereby promoting smooth and stable flow. The model defines a viscous contribution from the relative velocity between neighbouring particles, with the magnitude of this contribution depending on the distance between them; closer particles therefore have a stronger influence on the damping effect. The model therefore acts as an internal resistance that damps sudden changes in particle motion during infusion. This model assumes a constant viscosity coefficient and does not explicitly capture shear-rate-dependent viscosity effects associated with non-Newtonian fluids. Nevertheless, this simplification is considered acceptable for the present study, because permeability is primarily a geometrical property of a fibre bundle. As long as resin properties are kept consistent, the permeability value can be extracted via Darcy's law. More advanced viscosity models may improve the representation of non-Newtonian fluids, but this model was selected here because of its numerical stability and computational efficiency.

The radius of fluid particles was selected to provide sufficient spatial resolution for the resin to pass through the gaps between fibres, while keeping the simulation computationally feasible. If the particle radius is too high, the fluid may be unable to enter narrow channels, leading to an underprediction of the fibre bundle permeability. Conversely, if the particle radius is too small, the required number of particles increases significantly, resulting in higher computational cost and potential convergence difficulties. Partial blockage of fluid particles was observed in some transverse flow simulations. Therefore, the relationship between particle radius, fibre waviness, fibre spacing, and fibre volume fraction is particularly important for transverse permeability estimation.

For each simulation, the pressure drop across the fibre bundle in the direction of resin flow and the average flow velocity were extracted once the flow had become sufficiently developed. The corresponding permeability value was then calculated via Darcy's law.

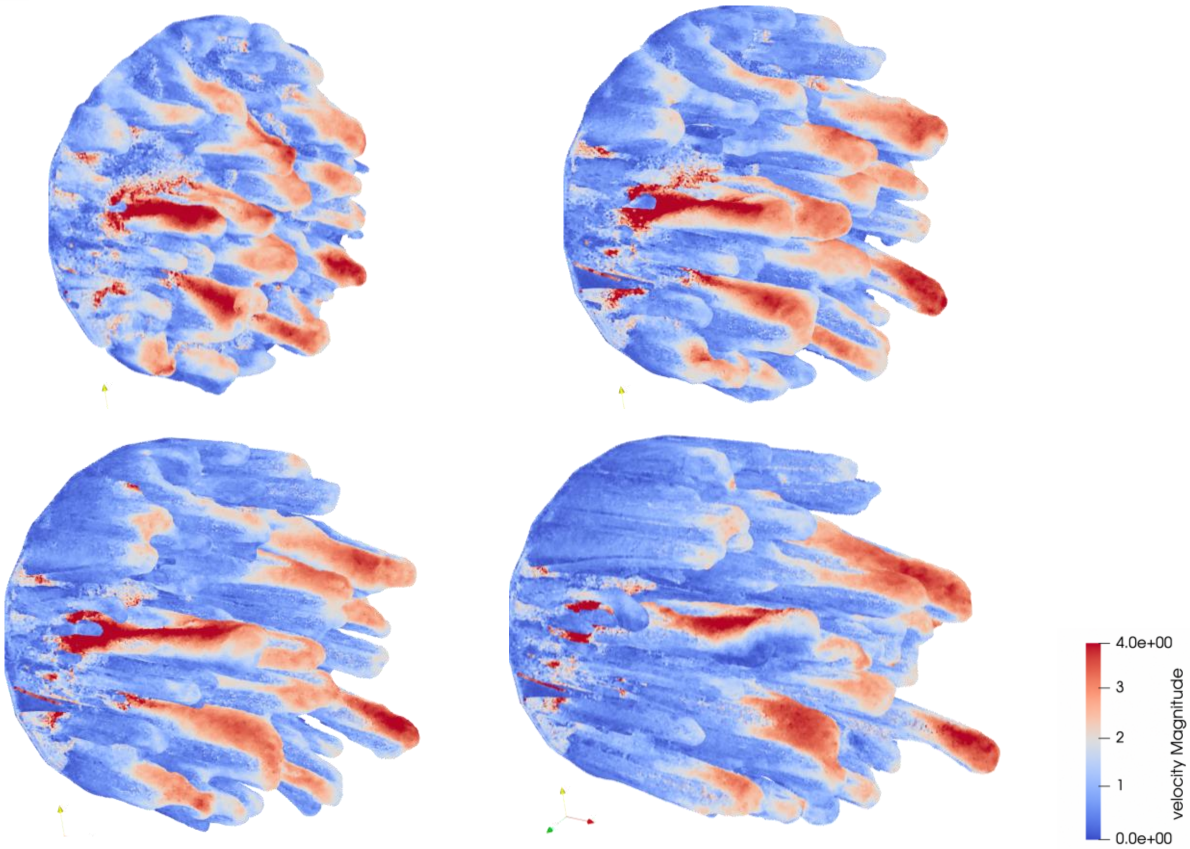

Figure 3. Stages of longitudinal flow (fibre bed is not shown, colour represents velocity gradient).

4. Results and discussion

The conducted simulations demonstrate that the proposed SPH-based pipeline is capable of representing resin flow through complex 3D fibre bundles. The longitudinal and transverse configurations produced clearly distinct flow patterns as expected from the anisotropic nature of the fibre architecture. Example of different flow stages for both cases are shown in Figures 3 and 4. Colour gradient represents the velocity of fluid particles, with blue corresponding to lower velocities and red corresponding to higher velocities. Red regions therefore indicate preferential flow paths through the fibre bundle.

In the longitudinal case, the resin propagated mainly through channels aligned with the fibre bundle direction. The flow front advanced progressively along the entire bundle length, with preferential paths forming in regions where larger connected channels were available, as shown in Figure 3. This behaviour is consistent with the expected lower flow resistance along the fibre direction as continuous channels are more likely to exist comparing to a transverse case.

The transverse flow simulation showed a more complex and less uniform flow front evolution, as illustrated in Figure 4. In this configuration, resin particles were forced to pass across the fibre bed, where the available channels are narrower and, in some cases, partially blocked by local fibre spacing and waviness. The flow front therefore developed unevenly, with localised high-velocity regions and areas of delayed resin penetration. This behaviour is physically plausible for the transverse flow and highlights the benefit of SPH in resolving microscale flow features that are difficult to observe experimentally. In some cases, partial blockage of particles flow was observed. This indicates that transverse permeability estimation is particularly sensitive to particle radius, fibre volume fraction, and local fibre waviness. Sufficient spatial resolution of the fibre bundle model is therefore essential to avoid artificial flow restriction.

Table 1. Permeability estimation results.

	Longitudinal permeability, m^2	Transverse permeability, m^2
SPH based	$8.89\ 10^{-13}$	$1.07\ 10^{-13}$
Analytical (Gebart)	$2.81\ 10^{-13}$	$5.17\ 10^{-14}$

The permeability values extracted from the SPH simulations were then converted from simulation units to SI units using the same geometrical scaling factor applied during model preparation. The final values are therefore reported in m^2 and can be compared with analytical estimates based on the Gebart model [7], as shown in Table 1.

Both the longitudinal and transverse permeability values were found to be of the same order of magnitude as the corresponding analytical predictions. These results suggest that the SPH-based pipeline is able to capture the main features of anisotropic permeability while representing local fibre-scale imperfections that are neglected in analytical models. The observed differences between the SPH and analytical predictions are therefore not necessarily indicative of modelling error, but rather reflect the fact that the two approaches describe different fibre architectures: the analytical model assumes idealised fibre packing, whereas the SPH simulations are performed on randomly distributed and wavy fibres. Moreover, experimental permeability measurements often vary by up to one order of magnitude between test facilities [1,2], indicating that exact agreement with a single reference value should not be expected. A stochastic analysis based on multiple fibre bundle realisations is therefore required to assess the mean permeability and associated scatter.

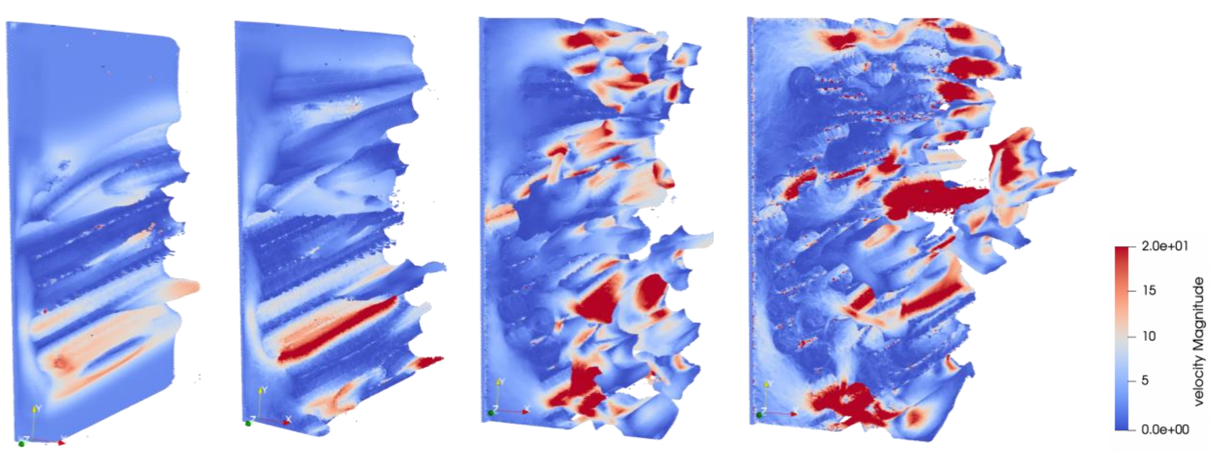

Figure 4 Stages of transverse flow (fibre bed is not shown, colour represents velocity gradient).

5. Conclusions

The results show that the proposed SPH-based pipeline can capture main features of both longitudinal and transverse resin flow at the microscale level. The method is particularly useful for visualising preferential flow paths and identifying local regions where fibre arrangement promotes or restricts resin distribution during infusion. However, permeability estimation remains sensitive to numerical parameters, including fluid particle radius and pressure sampling region.

The extracted permeability values were found to be within the same order of magnitude as analytical estimates, supporting the feasibility of using SPH as a tool for microscale permeability assessment. Further development of the proposed pipeline will include a sensitivity study of the extracted permeability with respect to resin and interface parameters, such as viscosity, friction, and surface tension effects. This will help assess the limits of Darcy's law applicability.

6. References

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