TITLE: Permeability averaging for linear unsaturated resin flow through materials in series, and comparison to the harmonic average used for saturated flow

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ABSTRACT:

Vacuum Assisted Resin Infusion (VARI) is a manufacturing process commonly used for large composite structures such as wind turbine rotor blades. These components often require complex layups consisting of multiple layers of reinforcement fabrics, core materials, and consumable materials (e.g. resin distribution media, peel-ply, and perforated release film), each with distinct permeability properties. Accurate prediction of resin flow during infusion can help mitigate defects such as dry spots and allow for advanced process optimisation. Direct simulation of resin flow through a detailed multi-layer model, with individually assigned permeability properties, can be computationally expensive, particularly for large-scale parts [1]. To reduce this cost, averaging methods are commonly used to represent a layered layup as an equivalent homogeneous medium, thereby enabling faster process modelling and design optimisation. However, the accuracy of these averaging methods critically affects the reliability of simulation results.

A commonly used approach for permeability averaging computes the effective permeability using a weighted harmonic average of the individual layer permeabilities:

$$K_{HA} = \frac{\sum_{i=1}^{n} l_i}{\sum_{i=1}^{n} \frac{l_i}{K_i}}$$

where K_i and l_i are the permeability and dimension in the flow direction of layer i, respectively. This formulation is derived under the assumption of fully saturated flow, where all material sections share the same flow rate [2]. Applying this method during unsaturated flow, typically in the context of manufacturing and part filling, can lead to significant errors, affecting prediction accuracy and increasing the risk of defects.

Fundamentally, this work introduces a new analytical permeability averaging method that is tailored for unsaturated flow through a sequence of materials in series. The unsaturated average is derived analytically from Darcy's law under the assumptions of unidirectional flow, constant resin viscosity, and constant inlet pressure. Unlike the harmonic average, the proposed formulation explicitly accounts for the sequential filling of layers and local fibre content.

The new formulation is implemented in a numerical simulation framework to compare its performance against the harmonic average method. Simulations have been conducted for representative layups with varying permeability and layer thicknesses. The performance of both approaches is evaluated in terms of filling time prediction for unidirectional flow through a series of materials, and inverse permeability determination, i.e. back-calculating the permeability of one material when all other parameters are known.

The new averaging method enables reliable permeability back-calculation, which is critical for homogenising non-homogeneous layers such as perforated release films or perforated core materials. The proposed approach enhances process modelling for VARI by providing a physically consistent permeability average for unsaturated flow. This improvement supports better simulation and design optimisation.

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