IMPREGNATION SIMULATION AND DESIGN OF INJECTION BOXES APPLIED TO PREPREGGING FOR WIND TURBINE ROTOR BLADES

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Introduction

The wind turbine industry is a heavily cost-driven business. Therefore, components such as the rotor blades need to be economical yet reliable. Robust and efficient industrialized manufacturing processes can reduce the costs of rotor blades. Pre-impregnated semi-finished products with a thickness of at least 1 mm might yield economical solutions for the manufacture of fiber composite blades and reduce the risk of dry spots in the blade.

The BladeMaker prepregging process

A prepregging process has been developed that uses an injection box to impregnate a set of glass fiber rovings with an epoxy resin. The fibers and the resin are heated before impregnation and cooled down again afterwards. Today, the two major prepregging processes are the hot melt process and the solution coating process [LWK16]. Both require comparably expensive equipment like several calender stages or a drying tower. The prepregging process with the injection box has been implemented in a relatively compact and cost-effective machine.

Injection boxes are a well-known impregnation device from the injection pultrusion process where the resin is cured in a closed cavity directly after impregnation. The resin is injected into the cavity of the injection box and impregnates the passing fibers under elevated pressure.

In the current prepregging application as well as in potential applications like filament winding, the resin does not cure when it leaves the injection box. Therefore, a potential leakage of liquid resin does not only have to be prevented at the inlet, but also at the outlet. Furthermore, a much higher process speed can be achieved without the aim to cure the resin. The open question is how the injection box needs to be designed to achieve a high process speed, good wetting of the fibers without any leakage. A first indication can be gained from an impregnation simulation.

Impregnation simulation

The resin flow through the fiber bed is an incompressible, creeping flow of a *Newton*ian fluid through a porous medium and can therefore be described by *Darcy*'s law [Dar56]. The three-dimensional form for anisotropic porous media was derived from the *Stokes* equations [Whi86], which are valid for small *Reynolds* numbers and neglect inertial effects. An additional convective term including the fiber bed velocity $\vec{v}_f$ needs to be added to account for the moving fiber bed [MKK99, DLY00, Liu03, JR10a, JR10b, MRJ16]. Inserting the extended equation into a balance equation of the resin mass and assuming a constant resin density yields the governing differential equation:

$$\iiint_V \frac{\partial \varphi_m}{\partial t} dV + \iint_{\partial V} \varphi_m \, \vec{v}_f \cdot \vec{n} dS - \frac{1}{\eta} \iint_{\partial V} \left(\boldsymbol{K} \vec{\nabla} p \right) \cdot \vec{n} dS = 0 \qquad (1)$$

The first author implemented a simulation tool that discretizes equation (1) with the finite volume method like in [JR10a, JR10b, MRJ16]. The injection box cavity of the prepreg machine has two symmetry planes. Therefore, a two-dimensional simulation of a half-domain is sufficient to describe the flow (Figure 1). The cavity geometry is discretized through a mesh of quadrilateral control volumes. For each control volume V and each time step the liquid matrix volume content φ_m and the pressure field p are calculated. Measured values for glass fiber rovings from [SSE07] are used to populate the permeability tensor $\boldsymbol{K}$. The dynamic viscosity of the resin η depends strongly on the temperature. The simulation tool has been verified through a comparison to an analytical solution for a simple test case. Simulation results for a tear-drop shaped prototype injection box (Figure 1) suggest that a full wetting of a 1 mm thick glass fiber bed is possible at pull-off speeds of 1 m/s and more. The tapered section of the cavity creates to a strong pressure gradient in fiber direction which can transport entrapped air back towards the inlet. The taper also leads to a high pressure peak and high pull-off forces. The cavity contour and the process parameters need to be adjusted to reduce these forces. The simulation also reveals a volume flux of the liquid resin at the outlet which is 2-3 % higher than the desired value based on the fiber volume fraction. If the 300 mm long outlet section behind the taper is shortened to 100 mm, the resin volume flux at the outlet exceeds the desired value by 7 %.

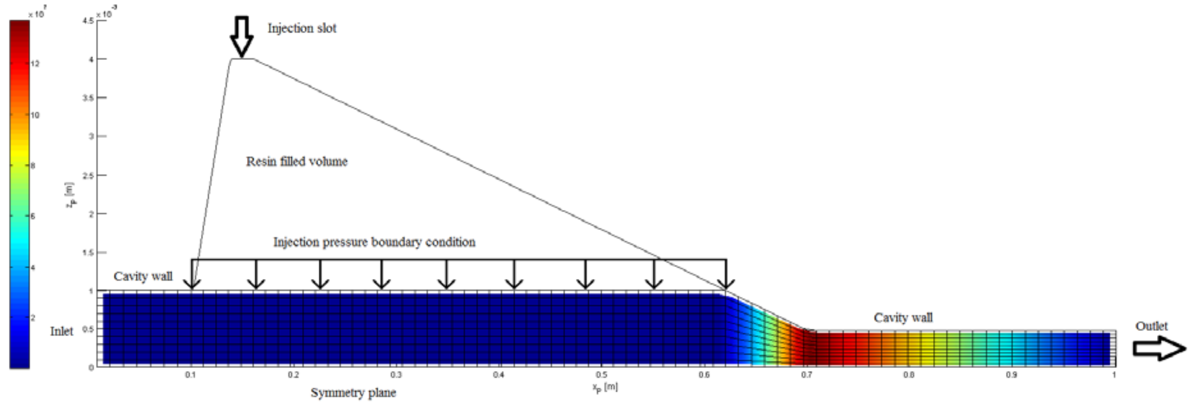

Figure 1: *Injection box model, boundary conditions and pressure field.*

Outlook

The presented results are based on the assumption that the fiber bed is only compacted by the cavity walls and not by the resin pressure. Further work is required to include the fluid-structure-interaction between the resin and the fibers. The compaction behavior and its effect on the permeabilities of the fiber bed need to be measured. The calculated resin flow shall be experimentally validated with the BladeMaker prepreg machine. The simulation code will be used to compare different injection boxes and to establish design references for injection boxes.

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