DTU Library

The effect of saturation on resin flow in injection pultrusion: a preliminary numerical study

Spangenberg, Jon; Larsen, Martin ; R. Rodríguez, Rosa; M. M. Sánchez, Pablo ; Rasmussen, Filip S. ; Sonne, Mads Rostgaard; Hattel, Jesper Henri

Publication date:
2017

Document Version
Peer reviewed version

THE EFFECT OF SATURATION ON RESIN FLOW IN INJECTION PULTRUSION: A PRELIMINARY NUMERICAL STUDY

Jon Spangenberg[1,*], Martin Larsen[2], Rosa R. Rodríguez[1], Pablo M. M. Sánchez[1], Filip S. Rasmussen[1], Mads R. Sonne[1], and Jesper H. Hattel[1].

[1] Produktionstorvet Building 425, DK-2800 Kgs. Lyngby, Department of Mechanical Engineering, Technical University of Denmark.
[2] Barmstedt Allé 5, DK-5500 Middelfart, Fiberline Composites A/S

[*] Corresponding author: josp@mek.dtu.dk

Keywords: Composites, Pultrusion, Resin flow, Saturation, Modelling.

ABSTRACT

In this study, a 2-D Darcy's law based numerical model is developed in order to investigate the effect of saturation on the propagation of the resin in the die chamber of a pultrusion line. The numerical model is established using the finite volume method and alternating direction implicit scheme. The implemented saturation and relative permeability curves are adopted from relationships presented in the literature. The results of the numerical model highlights the importance of accurately determining the saturation curve when included in a numerical solver that is used to predict the resin flow in injection pultrusion. Further research is planned within this field in order to identify realistic saturation curves for fiber reinforcements used in resin injection pultrusion.

1 INTRODUCTION

Resin injection pultrusion (RIP) is a widely used process to produce composite profiles whose application ranges from building facades to components for the wind turbine industry. The process is continuous as seen in Fig. 1, and it consists of guiding fiber reinforcement into the die chamber in which they are impregnated by resin via a pressure. Subsequently, the resin is heated in order to cure and then pulled out of the die chamber before being sawed into the proper length dimension.

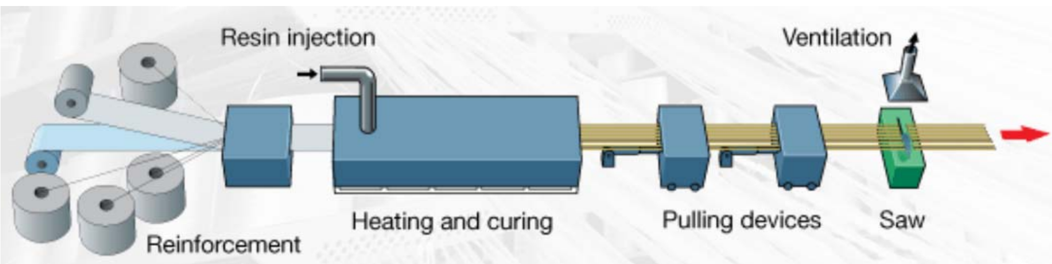


Figure 1: Sketch of the RIP process (courtesy of Fiberline).

For the past two decades, a number of works have been published on numerical analysis of the impregnation process in RIP. These works have primarily focused on the impregnation in a tapered die chamber. K. S. Raper et al. [1] developed a finite volume based numerical model in order to investigate the pressure rise in the pultrusion die. The same phenomenon was studied by S. U. K. Gadam et al. [2], but in a cylindrical die inlet geometry. S. S. Rahatekar and J. A. Roux [3] investigated numerically how the impregnation was affected by the resin viscosity, pulling speed, fiber volume fraction and level of fiber compression in a tapered die chamber. B. K. Ranga et al. [4] showed via a numerical model that the injection pressure necessary to obtain complete wet-out of the fiber reinforcement strongly depends on the pull speed, and that the die chamber exit pressure strongly depends on its length.

In the present study, a 2-D numerical model that accounts for the saturation and relative permeability curves is developed to simulate the impregnation process in RIP. The objective is to quantify two different saturation curves effect on the resin flow in a non-tapered die chamber. The paper is divided into four sections. First, the governing equations for the resin flow in the fiber reinforcement are presented. Second, details about the numerical model such as boundary conditions and material properties are described. Third, the results of the numerical model are presented and discussed. Finally, the main points of the paper are summarized in the conclusion.

2 GOVERNING EQUATIONS

The governing equations for the flow of the resin in the die are Darcy's law and the continuity equation with an added advection term to account for the pulling speed. Darcy's law relates the local pressure with the fluid velocity assuming laminar flow in the porous medium [5]:

$$q = v_r \theta_r = -\frac{k_s k_r}{\mu}\frac{\partial p}{\partial x}, \tag{1}$$

where q is the flux, v_r is the velocity of the resin, θ_r is the volume fraction of the resin, k_s is the permeability, k_r is the relative permeability, μ is the viscosity, p is the pressure, and x is the spatial coordinate. In the representative elementary volume (REV), three phases are present, the resin, fibers, and void [6]:

$$\theta_r + \theta_f + \theta_v = 1\,, \tag{2}$$

where θ_f and θ_v are the volume fraction of fibers and void in the REV, respectively. The saturation, S, is defined as the volume fraction of resin in the REV divided by the initial void space:

$$S = \frac{\theta_r}{1-\theta_f} = \frac{\theta_r}{\theta_p}, \tag{3}$$

where θ_p is the porosity (initial void space).

The 2-D continuity equation in Cartesian coordinates with advection for the resin in the REV is written as

$$\frac{\partial}{\partial t}(\rho_r\theta_r) + \frac{\partial}{\partial \boldsymbol{x}}(\rho_r\theta_r(\boldsymbol{v_r} + \boldsymbol{v_a})) = 0\,, \tag{4}$$

where ρ_r is the density of the resin and $\boldsymbol{v_a}$ is the advection vector. Assuming a constant resin density, zeroes in the non-diagonal entries of the permeability tensor, constant advection in the horizontal direction, zero advection in the vertical direction, constant porosity, and constant permeability in the horizontal and vertical direction, one can rewrite Eqn. (4) into the following by the use of Eqns. (1) and (3):

$$\theta_p \frac{dS}{dp}\frac{\partial p}{\partial t} - \frac{k_{s,xx}}{\mu}\frac{\partial}{\partial x}\left(k_r\frac{\partial p}{\partial x}\right) - \frac{k_{s,yy}}{\mu}\frac{\partial}{\partial y}\left(k_r\frac{\partial p}{\partial y}\right) + v_{a,x}\theta_p\frac{dS}{dp}\frac{\partial p}{\partial x} = 0\,, \tag{5}$$

where x and y refers to the horizontal and vertical direction, respectively.

3 NUMERICAL MODEL

The numerical model is developed in the technical computing language MATLAB. The finite volume method is used to discretise Eqn. (5). The pressure field is found by the alternating direction implicit method where the advection term is treated with an upwind scheme. The geometry and boundary conditions of the computational domain are seen in Fig. 2. The initial pressure in the die is atmospheric pressure and the resin inflow is enforced via an inlet pressure of 2.6 MPa. At the left boundary, the pressure is atmospheric, while a pressure outflow condition is imposed at the right boundary. At the horizontal boundaries, except at the inlet, a wall condition is prescribed by imposing a zero pressure gradient. The flow is considered isothermal and curing effects during impregnation are in this preliminary study assumed negligible. The viscosity of the resin is 0.2 Pa.s and the fiber reinforcement has a volume fraction of 0.6 as well as a specific permeability of k_{xx} = 2.0e-11 m^2 and k_{yy} = 1.0e-11 m^2. The pulling speed is 0.005 m/s.

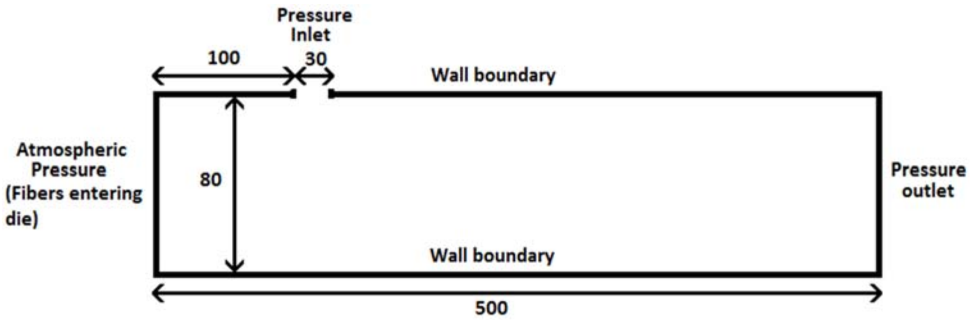


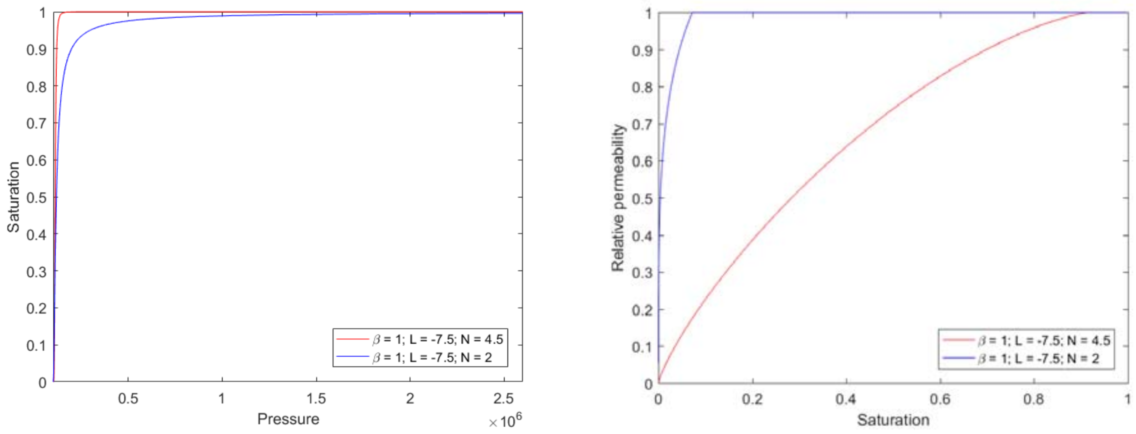
Figure 2: Geometry and boundary conditions of the computational domain.
Note that lengths are given in mm.

The two different saturation curves analysed in this study are illustrated in Fig. 3 together with their appurtenant relative permeability curves. The saturation and relative permeability curves are obtained by the relationships developed by van Genuchten [7] and Mualem [8]:

$$S = 1 - \frac{1}{\left(1 + \left|\beta \frac{p}{\rho g}\right|^{N}\right)^{M}} \tag{6}$$

$$k_r = S^L \left(1 - (1 - S)^{\frac{1}{M}}\right)^{2M} \quad with \quad M = 1 - 1/N \, , \tag{7}$$

where N , β , and L are the van Genuchten parameters [9], which typically are experimentally determined. In Fig. 3, the red curves are adapted from [9] and emulate a flow condition where the unsaturated zone is relatively short, while the blue curves mimics a relatively long unsaturated zone.



a) b)

Figure 3: a) Saturation curves and b) relative permeability curves.

4 RESULTS AND DISCUSSION

In Fig. 4, the simulated impregnation process is visualized after 25, 50, and 75 seconds, when using β = 1; L = -7.5; N = 4.5 (red curve in Fig. 3). It is seen that substantially more resin is located to the right of the injection point, as the profile is pulled towards this side, and that the resin slowly fills up the die chamber.

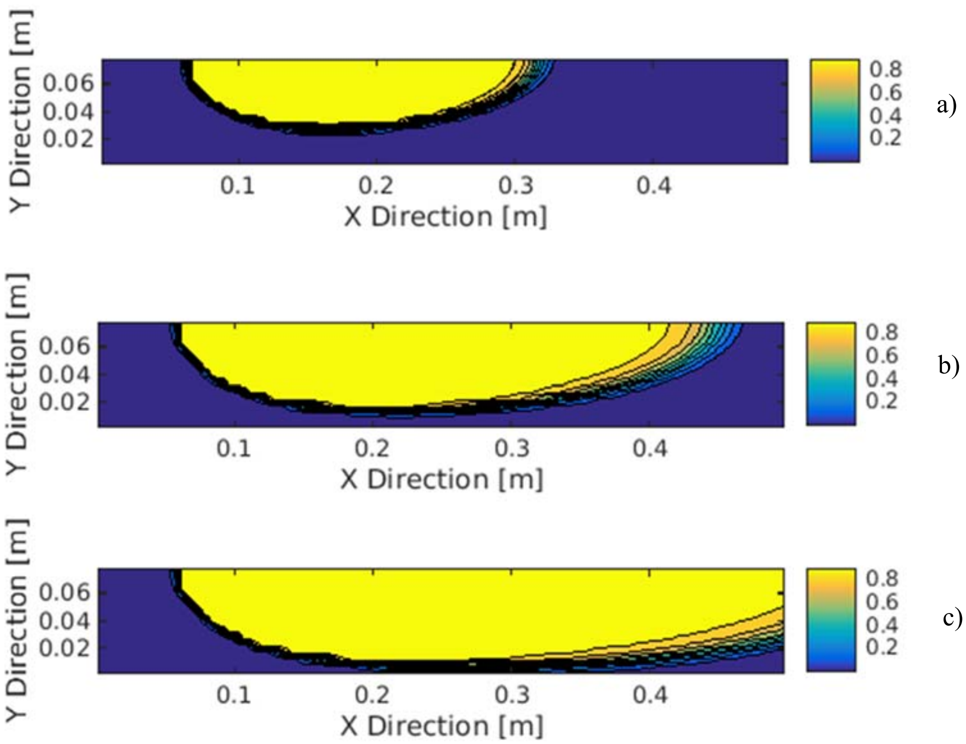


Figure 4: Saturation fields found by the numerical model after a) 25, b) 50, and c) 75 seconds, when using β = 1; L = -7.5; N = 4.5.

In Fig. 5, the stationary saturation field is illustrated in the die for the two different saturation curves with appurtenant relative permeability curves. In none of the cases, a back flow is experienced, but only in the case where the unsaturated zone is relatively short, the profile becomes fully wetted. Thus highlighting how important it is to correctly quantifying the saturation curve when utilizing it in the numerical tool that predicts the impregnation process in injection pultrusion.

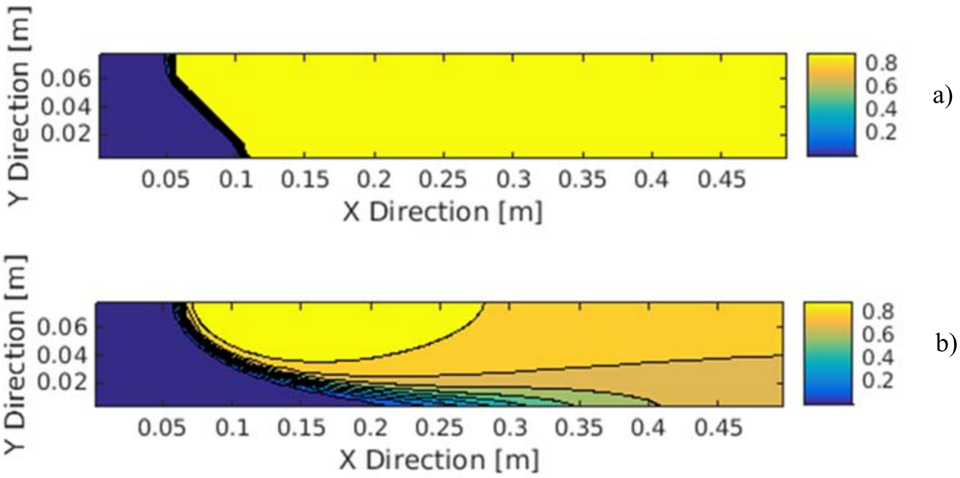


Figure 5: Stationary saturation fields for the two scenarios:
a) $\beta = 1$; L = -7.5; N = 4.5; and b) $\beta = 1$; L = -7.5; N = 2.

7 CONCLUSIONS

The results of the numerical model indicate that the advection which accounts for the pulling speed is correctly implemented. In addition, the results show that complete wet-out of the fiber reinforcement is a function of the saturation curve, hence stressing the importance of precisely determining the relationship between pressure and saturation. In future research, realistic saturation curves for RIP will be quantified experimentally and implemented in the numerical model. Subsequently, the numerical model will be utilized to optimize process parameters in RIP.

ACKNOWLEDGEMENTS

This work is funded by the Danish Council for Independent Research | Technology and Production Sciences (Grant no. DFF-6111-00112: Modelling the multi-physics in resin injection pultrusion (RIP) of complex industrial profiles).

REFERENCES

[1] K. S. Raper, J. A. Roux, T. A. McCarty, J. G. Vaughan, Die inlet contour impact on the pressure rise in a pultrusion die, *Journal of Composite Materials*, **34**(2), 2000, pp. 199-216.

[2] S. U. K. Gadam, J. A. Roux, T. A. McCarty, J. G. Vaughan, The impact of pultrusion processing parameters on resin pressure rise inside a tapered cylindrical die for glass-fibre/epoxy composites, *Composites Science and Technology*, **60**, 2000, pp. 945-958.

[3] S. S. Rahatekar, J. A. Roux, Numerical simulation of pressure variation and resin flow in injection pultrusion, *Journal of Composites Materials*, **37**(12), 2003, pp. 1067-1082.

[4] B. K. Ranga, J. A. Roux, J. G. Vaughan, A. L. Jeswani, Effect of injection chamber length and pull speed of tapered resin injection pultrusion, *Reinforced Plastics & Composites*, **30**(16), 2011, pp. 1373-1387.

[5] T. Dopler, A. Modaressi, V. Michaud, Simulation of metal-matrix composite isothermal infiltration processing, *Metallurgical and Materials Transactions B*, **31B**, 2000, pp. 225-234.

[6] J. Wolfrath, V. Michaud, A. Modaressi, J.-A.E. Månson, Unsaturated flow in compressible fibre preforms, *Composites: Part A,* **37**, 2006, pp. 881-889.

[7] M. TH. van Genuchten, A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Science Society of America Journal*, **44**, 1980, pp. 892-898.

[8] Y. Mualem, Hydralic conductivity of unsaturated porous media: generalized macroscopic approach, *Water Resources Research,* **14**(2), 1978, pp. 325-334.

[9] M. Nordlund, V. Michaud, Dynamics saturation curve measurement for resin flow in glass fibre reinforcement, *Composites: Part A,* **43**, 2012, pp. 333-343.