

# GEOMETRICAL DESIGN OF CELLULOSE NANOFIBRE COMPOSITES FOR ENHANCED IMPREGNATION DURING VACUUM INFUSION

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## Introduction

In a recent study the out-of-plane permeability of cellulose nanofibre networks was measured to be in the order of  $10^{-18}$  m<sup>2</sup> [1] and hence governed by the nanoscale. Although the networks are thin this results in relatively long processing times for out-of-plane impregnation with vacuum infusion. Methods to facilitate impregnation without losses in mechanical properties should therefore be developed. One way to do this is to exploit the layered structures that can be formed in the manufacturing of cellulose nanofibre networks, thus making use of the two-scale porosity. Such a geometry makes it, for instance, possible to do in-plane impregnations of non-crimp fabrics [2]. For the non-crimp fabric case the scales are  $< 10^{-5}$  m within bundles of micro-sized fibres and  $> 10^{-4}$  m between the bundles. It is, however, crucial that the two scales match the impregnation distance into the denser areas to avoid void formation [3]. In the current study out-of-plane channels or holes are introduced in the nanofibre networks and the position of the liquid flow front is theoretically studied for different densities of the holes formed in the nanofibre networks. This is done with a theory founded on developments in [4] including geometrical effects as well an applied pressure and capillary action.

## Theory

To facilitate the impregnation, holes can be stamped into the sheets of cellulose nanofibre networks since the layered structure implies that the in plane permeability is much larger than the out of plane permeability. For a quadratic pattern of stamped holes a simplified geometrical model may be studied for the impregnation consisting of a hole of radius  $a$  and regions outside the hole  $a < r < b$  of the cellulose nanofibre network. Creeping flow is assumed so that Darcy's law is valid. By letting  $P_n(x, r, t)$  denote the pressure in the fibre network,  $P_h(x, r, t)$  the pressure in the stamped holes and with different permeability in the fibre network,  $K_p, K_{\perp}$  and in the holes  $K_h$ , the Laplace equation in cylindrical coordinates reads

$$K_p \frac{\Pi_b}{1 - \Pi_b} \frac{\partial^2 P_n}{\partial x^2} + K_{\perp} \frac{\Pi_b}{1 - \Pi_b} \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial P_n}{\partial r} \right) = 0 \quad (1)$$

$$K_h \frac{\partial^2 P_h}{\partial x^2} + K_h \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial P_h}{\partial r} \right) = 0 \quad (2)$$

where  $\Pi_b$  is the volume fraction of fibers. To simplify these equations into a one-dimensional form similar to the equations given in [4] and for further deduction of equations for the motion of liquid fronts in the hole and nanofibre network, a trial function is introduced for the radial pressure variation that fulfills the boundary conditions. After an averaging procedure over the cross section equations similar to those in [4] are derived with the difference that, in the present model, the size of the nanofibre network region is taken into account.

## Numerical set-up and results

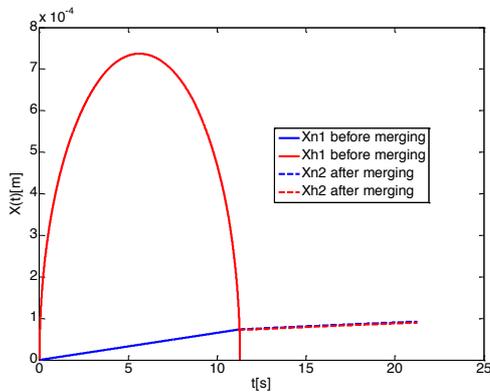
As indicated in Table 1 the permeability in the plane of cellulose nanofibre networks is typically several orders of magnitude smaller than the perpendicular permeability and therefore without the holes the processing time is long although the thickness of the medium,  $h$ , is small. To avoid void formation it is crucial that the liquid flow front moves in the same speed in the holes and within the nanofibre network during the impregnation process. It is therefore interesting to know how the geometry affects this. A numerical solution needs to be employed for the equations derived. This is done using the ordinary differential equation solvers in MATLAB. At the merging point between the flow in the hole and in the nanofibre network the differential equations are very stiff and therefore the solver ODE15s is applied.

**Table 1. Parameters for the derivations.**

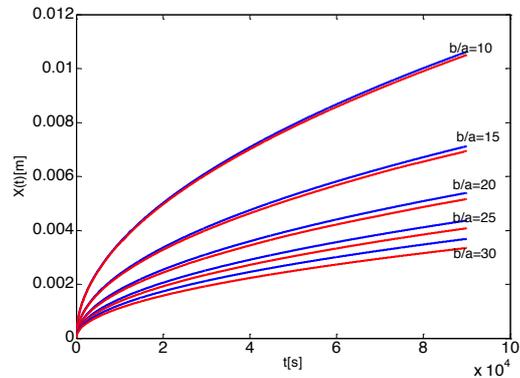
$K_p$	$K_{\perp}$	$\Pi_b$	$P_{cap}$	$P_{in}$	$\mu$	$h$	$a$
$8.83 \times 10^{-19} m^2$	$3.5 \times 10^{-12} m^2$	0.6	$1.2 \times 10^{-6} bar$	5 bar	0.152 kg/ms	4.6 mm	150 $\mu m$

During the initial phase the liquid front in the hole is leading due to the much higher permeability, see Figure 1 where the development of the fronts are shown for the case  $b/a = 20$ . After the initial phase the flow in the gap is transported into the nanofibre network. Note the transport from the hole into the nanofibre network is so strong that after a few seconds the front in the hole is moving backwards until a point where the liquid front in the nanofibre network catches it. Next, consider the development after the meeting point for different  $b/a$ , see Figure 2. The front in the nanofibre network slightly leads over the front in the hole and the time for impregnation is strongly dependent on  $b/a$ . For the set-up in Table 1 the impregnation time for  $b/a = 10$  becomes about 15000 s or 4.2 hours. Hence a more dense distribution of holes is required or a special resin system with a long gel time and low viscosity is required.

To conclude there is an initial transient behavior during a short period of time of a few seconds. In a second phase the fronts develop rather close to each other and develop closer for small values of  $b/a$ . As anticipated smaller  $b/a$  also give a much shorter processing time. Usage of small  $b/a$  must however be matched to the strength of the cellulose nanofibre networks.



**Figure 1.** Position of fronts before merging.



**Figure 2.** The position of liquid fronts for different  $b/a$  after the point of merging.

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## References

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