PREDICTIONS AND MEASUREMENT OF THE PERMEABILITY AND CAPILLARY PRESSURE IN CAPILLARY FLOWS THROUGH WOVEN FABRICS

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ABSTRACT

The present work refers to the capillary flow of Newtonian fluids along E-glass fibre yarns and through a plain-woven fabric. In the first case, one-dimensional Darcy's flow is considered through the micropores of the fibre yarns. In the second case, two-dimensional in-plane network infiltration is considered through the micropores of the network of fibre bundles in the fabric. In both cases predictions include the infiltration length as a function of time, the apparent permeability and the capillary pressure. The latter case also includes the number of unsaturated transverse yarns and the degree of saturation. All predictions are compared to experimental measurements and the agreement is very good.

1. INTRODUCTION

Resin transfer moulding (RTM) has been increasingly used in the processing of composites. In this process, a dry reinforcement is placed in the cavity of a mould, the mould is closed and resin is forced to flow through the fibrous preform. Modelling the flow of resin during the infiltration stage of the RTM process is justified by the importance of this stage on the manufacturing of high quality parts. Furthermore, reliable mould filling modelling with an accurate description of the flow has the potential of enabling a proper choice of mould and process parameters, addressing critical issues in the process, such as dry spots and voids [1].

Understanding of the flow requires the knowledge of the permeability of the reinforcement, which is correlated to the velocity of the flow front and the pressure gradient. Flow models usually consider the flow to occur in a porous medium based on Darcy's law. Although the validity and applicability of this law through a structured reinforcement have been questioned [2, 3, 4], Darcy's law is still by far the most used model to describe the flow of resin in reinforcements during the processing of composites. Depending on process conditions, the influence of capillary pressure on the overall flow can be of relative importance. In fact, as mentioned in the literature [5] many of the discrepancies in the literature about this model may be due to neglecting the effects of microscopic flow phenomena in the interpretation of the macroscopic flow.

The aim of this study is to apply mathematical modelling for the prediction of the permeability and capillary pressure in capillary flows through woven fabrics and to validate the models with previous experimental data.

2. MODELLING OF DARCY'S FLOW THROUGH A FIBRE YARN

Capillary experiments were carried out to follow the capillary impregnation of a fibre yarn and an E-glass, plain woven cloth. The experimental procedure and the obtained results, mentioned in this work have been described in an earlier study [6].

The vertical advancement of the fluid front along the axial yarn direction was numerically evaluated in this study. Darcy's law was used to model the flow in the yarn micro-pores, correlating flow-rate and pressure drop according to equation 1.

$$u = \varepsilon \cdot \frac{dh}{dt} = -\frac{\kappa}{\mu} \cdot \left(\frac{dP}{dh}\right) \quad \therefore \quad \upsilon = \frac{\kappa}{\mu.\varepsilon} \cdot \left(\frac{P_c - \rho.g.h}{h}\right) \tag{1}$$

where u is the superficial fluid velocity and υ is the interstitial velocity. For resin systems which show highly non-Newtonian behaviour, a viscosity-shear rate relationship such as the power law must be employed.

The theoretical value for the capillary pressure is estimated from the Young-Laplace equation, with a form factor of 4 (axial flow). The micro-pores were assumed to be uniform or with an averaged pore distribution and fibre twist in the yarn and any defects at the fibre surface were neglected. As a common practice, the permeability is calculated from the Carman-Kozeny equation. It is important at this point to remember that, as quoted by Gauvin *et al.*, 1996, flow predictions are as good as the accuracy of the permeability value entered in the simulation.

The finite difference method was used for the numerical solution of equation 1. At every new step, the time is increased by a constant value and the length step is evaluated. Error estimation controls if the length step was appropriate, i.e. error smaller than a given tolerance. Otherwise, the length is re-evaluated until convergence.

The model was implemented in a simple computer code written in Fortran77. This program allows for different Newtonian fluids by inputting the density and viscosity values. The fibre radius, micro-porosity (i. e. porosity of the yarn), micro-axial permeability and capillary pressure are the other input parameters. The latter is the driving force responsible for the rise of the liquid in the yarn. As the infiltration starts, the weight of the column of liquid in the yarn acts against the capillary pressure, slowing down the rate of infiltration (dh/dt).

3. MODELLING THE VERTICAL CAPILLARY FLOW THROUGH A PLAIN WOVEN FABRIC

It is necessary to understand the flow pattern in the plain-woven cloth in order to realistically model the flow. Figure 1 shows an experiment of capillary infiltration of a vertical piece of cloth at the flow front where three major macroscopic features can be noticed:

i. The flow front is not homogeneous, with some yarns showing a more developed flow. Since other factors concerning the flow are supposed to be constant, this is likely to happen due to characteristics of the individual yarns, with their own pore distribution;

ii. The flow progresses axially in the vertical yarns and the horizontal yarns are then filled in such a way that there are, at any time, at least 3 partially filled transverse yarns. The precise number is however not possible to be estimated by visual observation of the flow only;

iii. There are clear unfilled gaps between the yarns (macropores). These gaps can be seen even in the portion of the cloth closest to the liquid surface (figure 1-b). Therefore, the vertical capillary infiltration process through a plain-woven cloth was modelled considering the macroflow to be absent.

Since the model had to consider the presence of microflow only, the reinforcement was represented as a network of porous rods linked at junctions and figure 2 shows a schematic representation of the cloth with its repeating basic column. The axial ($Q_{a,i}$) and transverse ($Q_{t,i}$) flow rates at an *i* junction are given by:

$$Q_{a,i} = A_b \cdot \frac{\kappa_{mi,a}}{\mu} \cdot \frac{\left(P_c - \rho . g . (H_f - H_i)\right)}{H_f - H_i} \tag{2}$$

$$Q_{t,i} = A_b \cdot \frac{\kappa_{mi,t}}{\mu} \cdot \frac{P_c}{X_f} \tag{3}$$

where X_f is the horizontal distance from the flow front to the junction and (H_f -H_i) is the height difference between the flow front and the junction.

At every junction the flow splits between axial and transverse yarns according to the coefficients defined by equation 4, where $coef_{a,i} + coef_{t,i} = 1$.

$$coef_{a,i} = \frac{Q_{a,i}}{\left(Q_{a,i} + Q_{t,i}\right)} \qquad coef_{t,i} = \frac{Q_{t,i}}{\left(Q_{a,i} + Q_{t,i}\right)} \tag{4}$$

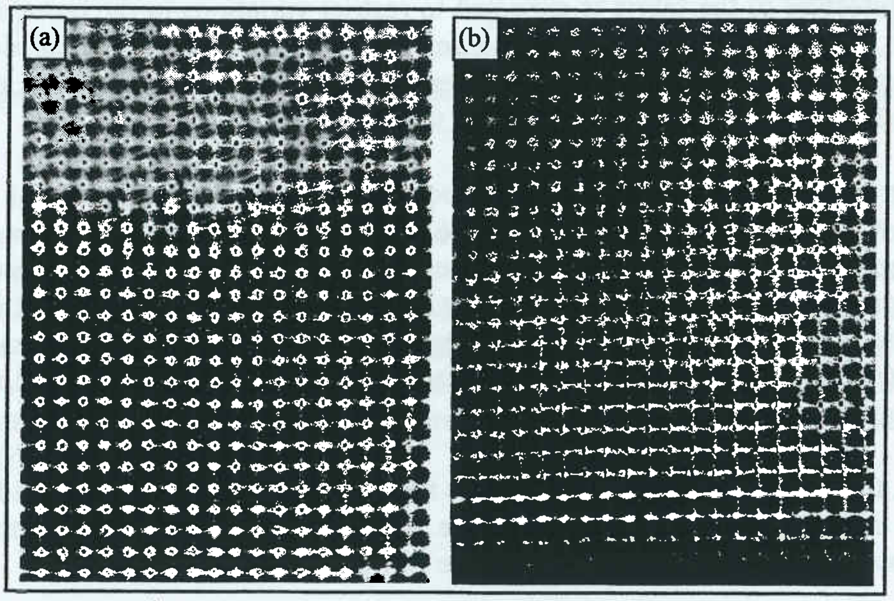

Figure 1: Photograph of the infiltration of the cloth, (a) at the flow front and (b) close to the liquid surface

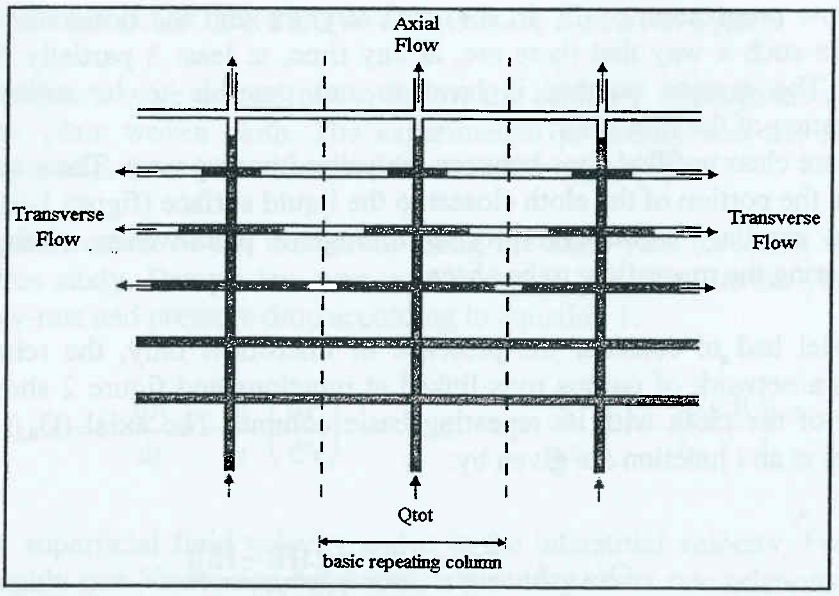

Figure 2: Simplified representation of the network flow in the plain-woven fabric

The transverse flow will be responsible for filling the transverse yarns whilst the axial flow will proceed until the next junction is reached and at this time a new split will occur. A few models can be proposed, regarding the unknowns $coef_a$ and $coef_t$: *model 1* - $coef_a$ is the same for all junctions throughout the infiltration process; *model 2* - $coef_a$ is the same for all junctions but varies with infiltration time; and *model 3* - $coef_a$ is different for each junction and varies with infiltration time. *Models 2* and *3* require $coef_a$, and consequently $coef_t$, to be estimated regarding current local pressures and flow distances.

The described model was implemented in numerical form in a Fortran77 computer code. The yarns were considered to be uniform and equally spaced. Capillary pressure and permeability values were estimated according to experimental data and the Young-Laplace and Carman-Kozeny equations, respectively. The overall porosity was considered to be constant, since the intricate architecture of the fabric is expected to restrict variations in the cross sectional area of the yarns and the gap between them. A few other constants, namely the density of the liquid, the radius of the yarn, the transverse permeability, the distance between two junctions and the length of the transverse yarn were also used as input values.

In this program, the transient infiltration process is regarded as a numerical sequence of steady state solutions at each time step where the finite difference method is employed. If there are junctions with transverse flow (active junctions), the flow is split between the axial and transverse yarns and a new height and transverse position of the flow front is calculated. If new junctions are reached, the number of open junctions is increased, if a junction is fully filled in the transverse direction, that junction is closed. This process is repeated for each time step until equilibrium is reached.

At any time, the number of open junctions, the time necessary to close an individual junction, the position of the flow front in the transverse active yarns and the height of the axial flow front are known, allowing the description of the flow.

4. RESULTS AND DISCUSSION

4.1. NUMERICAL STUDIES FOR A SINGLE YARN

Figures 3 and 4 present the predictions for the vertical capillary flow of a model fluid in an E-glass fibre yarn. Figure 3 illustrates the influence of the inputted permeability value on the final curve. As expected an increase in κ increases the rate of height rise. It is important to mention that the three curves in this figure will eventually reach the same equilibrium position, which is dependent only on P_c. Likewise, if κ is kept constant, an increase in P_c also shifts the curve upwards.

Figure 4 shows different predicted flow curves for different pairs of inputted values for permeability and capillary pressure. It can be seen that several pairs of P_c and κ can satisfy the experimental data. Thus, for an accurate estimate of P_c, for example, we should have some idea about the expected value of the permeability κ.

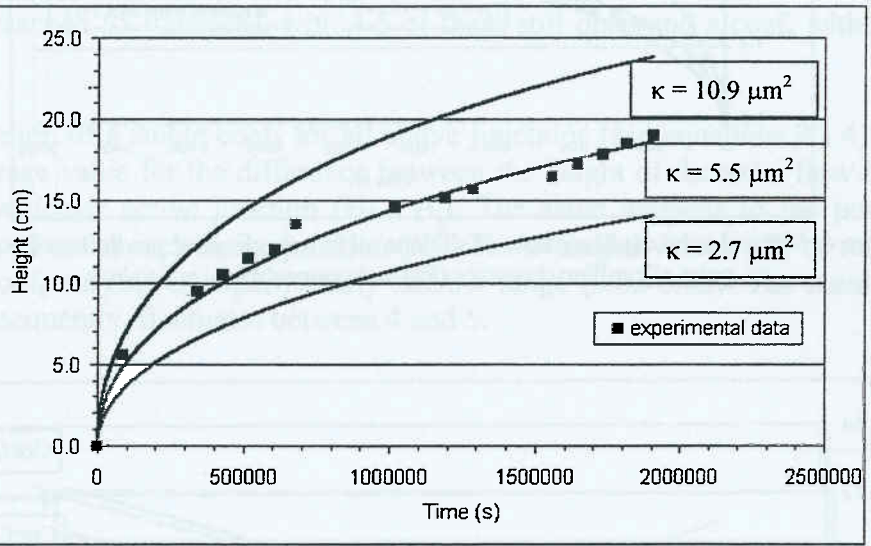

Figure 3: Vertical axial capillary flow of epoxy resin in a single yarn: curves for different permeability values; P_c = 4013 Pa for all curves

Considering the presented data it could be said that if the experiment is not left for sufficiently long time to approach equilibrium, the proposed model is likely to lead to an underestimation of P_c and, consequently, increasing κ. This is expected to happen because the insufficient experimental time misleads the estimations, as it was discussed in the literature [6, 8]. Although a wide number of combinations of these parameters can fit the experimental data for short infiltration time, such combinations are more restricted for longer infiltration times, making the fitting procedure more reliable.

4.2. NUMERICAL STUDIES FOR THE WOVEN FABRIC

The height versus time curves for five experiments carried out for up to 5.5 hours of infiltration time are shown in figure 5. The experimental points are reasonably close and minor deviations can be attributed to inherent characteristics of the cloth or its handling prior to the experiment.

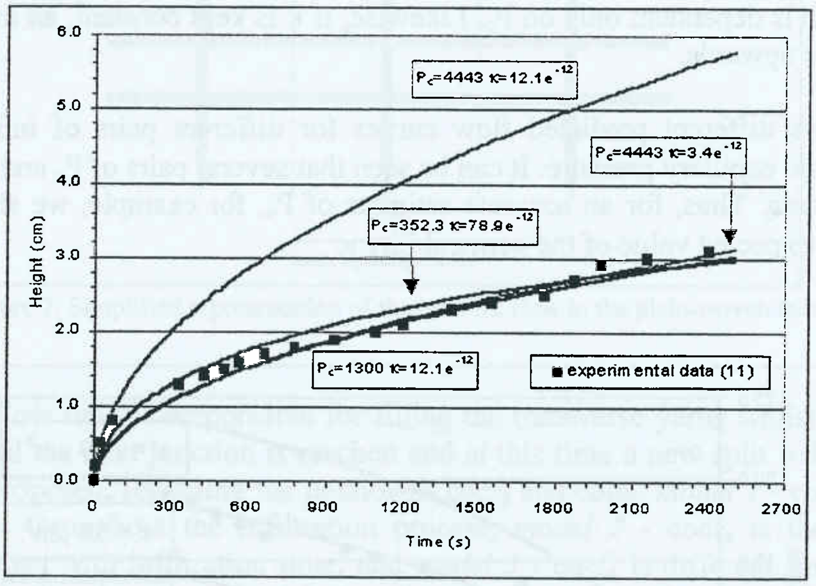

Figure 4: Vertical axial capillary flow of silicone oil in a single yarn: predictions for different pairs of capillary pressure (Pa) and permeability (m^2) values

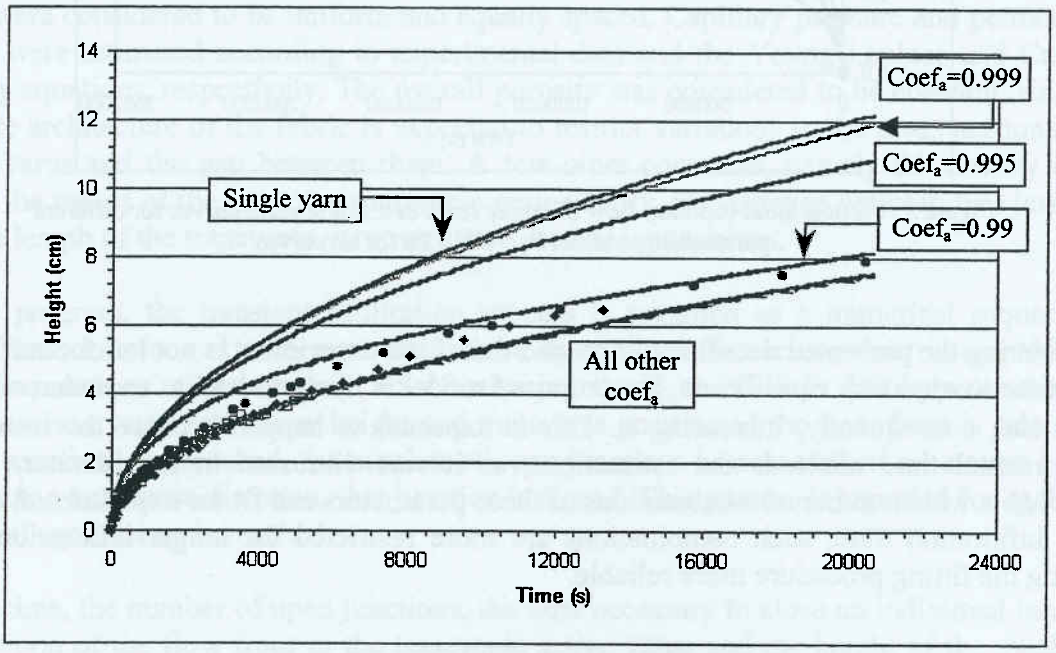

Figure 5: 5 short term silicone oil experiments through a plain-woven cloth and *model 1* for different $coef_a$ values.

Figure 5 also shows curves predicted by *model 1*, when $coef_a$ was pre-set at 0.01, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 0.99, 0.995 and 0.999. It is also shown what the flow curve would be if the flow was modelled as through a single yarn with the same porosity as that of the cloth (upper curve on figure 5). The curves for $coef_a$ in the range of 0.01 - 0.90 are practically coincident. This can be explained by the fact that the faster the axial flow (for a higher $coef_a$), the more junctions will be open, and hence, the axial flow becomes further reduced. The runs for a lower $coef_a$ will not only open junctions at a lower rate but also close those junctions faster (higher $coef_t$).

Curves for $coef_a$ in the range of 0.99 - 0.9999 shift from the others due to the fact that the vast majority of the flow is being used in the axial flow, tending to neglect the presence of transverse flow, which is especially right for $coef_a$ = 0.999, hence by the end of 20,500 seconds it has the same number of active junctions and open junctions, i.e. no junction was closed.

Models 2 and *3* are shown in figure 6. *Model 2* (the same $coef_a$ for all junctions for a specific time) slightly overestimates the experimental data whilst *model 3* shows a good agreement with the experiment for most of the time. When the time reaches around 20500 seconds, *model 2* has reached 55 junctions, with 4-5 of them still open and a $coef_a$ within a range of 0.82-0.83.

The determination of a single $coef_a$ for all active junctions (see equations 2 - 4) requires the use of an average value for the difference between the height of the axial flow front and the height of a particular active junction (H_f - H_i). The same happens to the position of the transverse flow front at each active junction (X_f). The averaged values will be responsible for keeping the $coef_a$ varying in a particularly narrow range (0.82-0.83). The number of active junctions, consequently, fluctuates between 4 and 5.

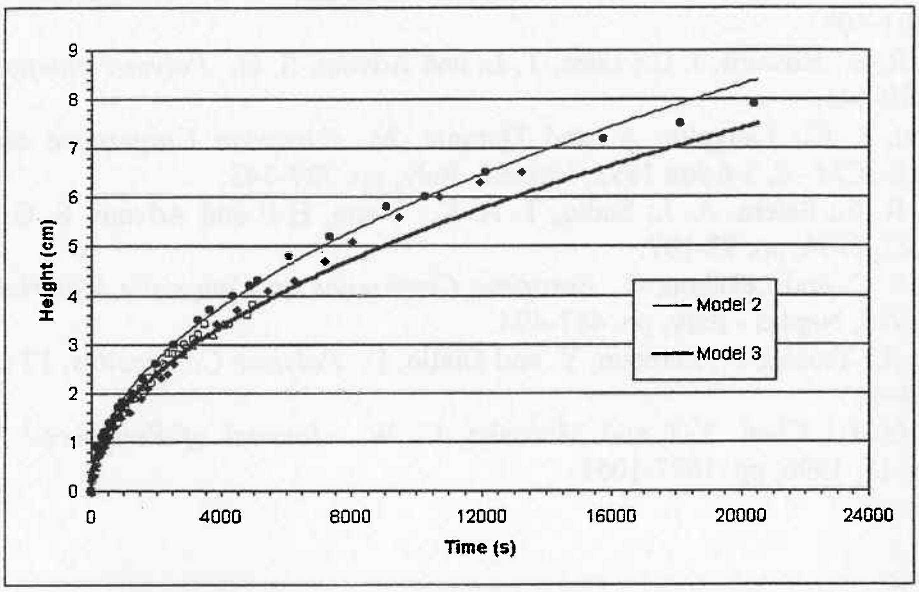

Figure 6: 5 short term experiments with *models 2* and *3*

As could be expected, the use of a different $coef_a$ for each junction generates results closer to the experimental ones for the curve of *model 3*. $Coef_a$ values were in the range of 0.67 - 0.81 depending on the position of the junction and by the end of the experiment, there were between 3-4 active junctions. This is in accordance to what was expected by analysis of the photographs of the actual flow (figure 1-a) which was used to predict that at least 3 junctions were partially filled.

5. CONCLUSIONS

The suggested numerical model for the axial capillary flow through a single yarn proved that predictions represent the experimental data for the duration of the experiment and different combinations of P_c and κ can fit the data for the initial portion of the flow curve. For long run experiments, the possibilities are restricted, becoming more accurate and proving the importance of the duration of the experiment when mathematical curve fitting is used.

The impregnation of the cloth exclusively by capillary pressure revealed the presence of micro-flow only. *Model 3* showed the best agreement with the experimental results, since it allows a more appropriate distribution of the flow, with a $coef_a$ in the range of 0.67 - 0.82, which is in accordance with experimental data describing the number of unfilled transverse yarns at junctions.

ACKNOWLEDGEMENTS

This work is part of a PhD degree sponsored by **CAPES** - Brazil.

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