MEASUREMENT OF THE PRINCIPAL COMPONENTS OF THE IN-PLANE PERMEABILITY OF WOVEN FABRICS

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ABSTRACT

This study covers the evaluation of the principal components of the in-plane permeability of fabric reinforcements from experimental data using a resin transfer moulding (RTM) machine. Various techniques are presented for the mathematical analysis of the flow data, including radial flow in an isotropic porous medium or in an orthotropic porous medium, with the material axes at a certain angle with respect to the experimental system of coordinates, and one-dimensional rectilinear flow. Inlet conditions may include either constant mould inlet pressure or transient inlet (changing pressure and flowrate) conditions. A differential and an integral numerical method are proposed for the analysis of flow data under transient inlet conditions. Two techniques are investigated for the monitoring of the flow progress: (a) monitoring of the moving flow front with a camera and (b) measurement of the weight loss in the injection pot on a mass balance.

1. INTRODUCTION

In-plane resin flow through the fibre reinforcement is the dominant type of flow in composite processing techniques such as resin transfer moulding (RTM) and structural reaction injection moulding (SRIM). Resin through the fibre reinforcement is usually described by a general form of Darcy's law. Infiltration time depends on the driving pressure, the filling length, the resin viscosity and the permeability of the fibre reinforcement.

Analytical solutions for Darcy's type of flow equations in experiments used in the determination of in-plane permeability have been suggested in the literature in the case of (a) constant inlet pressure [1,2] and (b) constant inlet flowrate [3]. This study extends their solutions further by proposing numerical techniques to deal with varying inlet conditions. Regarding radial flow Adams and Rebenfeld's solutions cover isotropic reinforcement and orthotropic reinforcement [also 4] where the major axes coincide with the experimental axes. This study includes proposals for the evaluation of the in-plane permeability in radial flow through an orthotropic reinforcement whose material axes are at angle with the experimental axes. Two different techniques of monitoring the progress of flow front were also investigated.

2. EXPERIMENTAL PART: MATERIALS AND PROCEDURES

The present study is concerned with the measurement of the in-plane permeability of a Newtonian fluid flowing through an assembly of woven fabrics. The experimental data presented in this paper are related to in-plane isotropic or orthotropic assemblies of woven fabrics. For the purpose of this study the various runs differ in terms of the type of fabric used (in-plane isotropic or anisotropic) and the fibre volume fraction of the compressed assembly. The model fluid is silicone oil of a viscosity around 150 mPa s.

Measurements of the in-plane permeability were carried out in an instrumented Resin Transfer Moulding (RTM) apparatus. The mould was supplied by Plastech Ltd. and the mould cavity is of 550 mm x 350 mm. It comprises a steel-reinforced, high temperature composite resin base, with a steel framed, clear, toughened glass top. Most of the measurements of this study are associated with central injection of the liquid and subsequent radial, in-plane flow through the reinforcement. Some measurements are associated with side injection resulting in rectilinear flow. The fluid is injected with the aid of gas pressure from a pressure vessel supplied by Motivair Compressors Ltd. Injection pressures of approximately 0.2 MPa were used in the reported runs whereas the apparatus has been designed for injection pressures up to 0.7 MPa.

The injection pressure was measured at the outlet of the pressure vessel and at different locations in the mould, by using piezoresistive type of transducers supplied by RS Components. Each transducer was secured at the end of a short plastic tube, attached at the transducer port in the mould, and was covered with a buffer liquid (silicone oil) up to the mould surface. The pressure data were continuously passed through an analogue-to-digital converter unit and fed to a personal computer. The flow front was always monitored by a programmable, analogue camera which took photographs at preset, regular, short intervals. Another method, which was also tested in this study, was to use a mass balance to monitor the mass loss of the injection pot, as the liquid was injected. The mass loss data were also continuously fed into a personal computer.

Before every permeability run, the viscosity of the silicone oil was measured in a Brookfield Programmable LVDV-II+ viscometer.

3. VARIABLE INJECTION PRESSURE

3.1 MATHEMATICAL ANALYSIS

The velocity of the flow front in Darcy's flow through a porous medium is given by the equations displayed in Table 1 in the cases of (a) one-dimensional rectilinear flow and (b) radial flow through an in-plane isotropic medium. Table 1 also displays the analytical solution giving the flow distance as a function of time in each case under constant pressure difference. Symbols are defined as follows: x: flow distance on the x-axis, R_f: radial flow distance, R_o: inlet radius, t: time, k: permeability, μ: viscosity of infiltrating liquid, ε: porosity, ΔP: pressure difference.

Table 1. Darcy's law in one-dimensional rectilinear and radial flow and the analytical solution in each case under constant pressure difference.
$F = R_f^2 [2 \ln (R_f/R_o) + (R_o/R_f)^2 - 1]$

	One-dimensional rectilinear flow	Radial flow through an isotropic medium
Darcy's law	$\frac{dx}{dt} = \frac{k_{xx}}{\mu\varepsilon}\frac{\Delta P}{x}$	$\frac{dR_f}{dt} = \frac{k}{\mu\varepsilon}\frac{\Delta P}{R_f \ln\frac{R_f}{R_o}}$
Constant ΔP	$x^2 = \frac{2k_{xx}}{\mu\varepsilon}\Delta Pt$	$F = \frac{4k}{\mu\varepsilon}\Delta Pt$

However, it is possible that the pressure difference is not constant either because the flow cannot be approximated as fully developed or due to the injection pressure varying with time. In this case a numerical procedure is proposed following a differential or integral approach.

Table 2. Differential and integral approach for the numerical solution of Darcy's law under varying pressure difference.

	One-dimensional rectilinear flow	Radial flow through an isotropic medium
Differential approach	$x\frac{dx}{dt} = \frac{k_{xx}}{\mu\varepsilon}\Delta P$	$R_f\frac{dR_f}{dt} = \frac{k}{\mu\varepsilon}\frac{\Delta P}{\ln\frac{R_f}{R_o}}$
Integral approach	$x^2 = \frac{2k_{xx}}{\mu\varepsilon}\int_0^t \Delta P dt$	$F = \frac{4k}{\mu\varepsilon}\int_0^t \Delta P dt$

3.2 MEASUREMENT AND EVALUATION OF THE IN-PLANE PERMEABILITY UNDER VARIABLE PRESSURE CONDITIONS

In all experimental runs, even if the pressure in the injection pot was maintained approximately constant at 0.2±0.01 MPa, the pressure at different points in the mould would not be constant due to the fact that steady state conditions were not achieved in the course of a single experiment of mould filling. In each experiment, pressure was measured just before the inlet and at different points in the mould. After a certain time, the pressure difference over the total flow length between the inlet and the flow front was considered constant and the analytical solutions displayed in Table 1 were applied for the evaluation of the in-plane permeability. At the same time varying pressure conditions were considered for the pressure data from transducers at different points in the mould. For the latter data, the numerical procedures suggested by the equations in Table 2 were applied for the evaluation of the in-plane permeability.

Table 3. Permeability values (in m^2) evaluated under different pressure conditions and numerical procedures.

Run No	Type of flow	Constant ΔP	Varying ΔP Differential approach	Varying ΔP Integral approach
Run 1	rectilinear	5.2×10^{-10}	6.5×10^{-10}	3.5×10^{-10}
Run 2	radial	6.7×10^{-11}	6.9×10^{-11}	5.7×10^{-11}
Run 3	radial	2.2×10^{-11}	1.6×10^{-11}	1.8×10^{-11}
Run 4	radial	4.1×10^{-12}	4.4×10^{-12}	3.7×10^{-12}

Table 3 presents data from four experimental runs concerning flow through assemblies of fabrics which were considered to have in-plane isotropy, resulting in a nearly circular flow front in radial flow. The different runs are associated with different fabric assemblies and differences between these assemblies are outside the scope of this paper. What is of interest in this study is the methodology of evaluating the in-plane permeability: Table 3 compares for each run the values obtained under the assumption of approximately constant injection pressure to the values obtained from the varying pressure of transducers, following either the differential or the integral numerical approach. It is noticeable that the comparison is worse in the case of rectilinear flow, possibly due to edge effects which would have worsened the difference between a pressure difference assumed homogeneous across the flow width (constant ΔP methodology) and the varying ΔP which is based on data of transducers located along the middle-line.

4. RADIAL FLOW: ORTHOTROPIC FABRIC AT AN ANGLE WITH THE EXPERIMENTAL AXES

4.1 MATHEMATICAL ANALYSIS

The case is illustrated in Fig.1 where the orthogonal system of coordinates (x',y'), representing the principal flow directions in the orthotropic fabric, is at an angle θ with the experimental system of coordinates (x,y). So, whereas the progress of the elliptic flow front is followed from measurements of the major and minor axis of the ellipse in the x' and y' directions, respectively, the position of the pressure transducers are on the x and y axes. The transformation of coordinates from (x',y') to (x,y) is given by the relations:

$$x = x'\cos\theta - y'\sin\theta \quad (1)$$

$$y = x'\sin\theta + y'\cos\theta \quad (2)$$

If the ratio of the major and the minor axes is m

$$x'/y' = m \quad (3)$$

it follows that

$$\frac{x}{y} = \frac{m\cos\theta - \sin\theta}{m\sin\theta + \cos\theta} = M \quad (4)$$

If the set of coordinates (x',y') of the orthotropic system is transformed to the set of (x_e,y_e) of an equivalent isotropic system with effective in-plane permeability k_e, it can be derived that

$$x'\frac{dx'}{dt} = \frac{mk_e}{\mu\varepsilon}\frac{\Delta P}{\ln(x/x_o)} \quad (5)$$

$$y'\frac{dy'}{dt} = \frac{k_e}{m\mu\varepsilon}\frac{\Delta P}{\ln(y/y_o)} \quad (6)$$

where ΔP is considered between the positions x and x_o or y and y_o on the x and y axis, respectively.

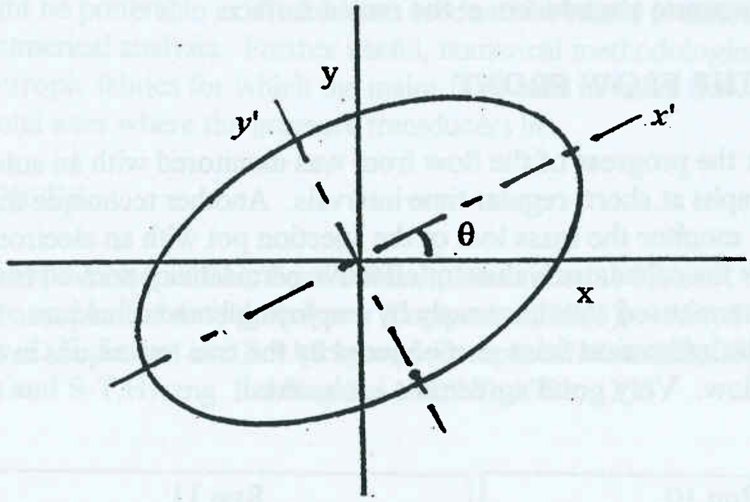

Fig.1. Elliptic flow front in orthotropic fabric where the system of the major flow axes (x',y') is at an angle θ with respect to the system of laboratory axes (x,y).

4.2 MEASUREMENTS AND EVALUATION OF THE IN-PLANE PERMEABILITY IN ORTHOTROPIC FABRICS

Table 4 presents experimental runs of radial flow for the measurement of permeability of assemblies of orthotropic fabrics where the system of major flow axes (x',y') was at an angle θ with respect to the experimental axes (x,y). The liquid was injected at the centre under an approximately constant pressure in the injection pot. One or two pressure transducers were located in the (x,y) experimental system of coordinates at a distance of about 25 mm from the centre. The value of the effective permeability for each run was calculated either under constant ΔP (pressure in the injection pot) or varying ΔP (pressure at the mould transducer).

In the latter case, equation (5) or (6) was used depending upon the position of the transducer, i.e. on the x or y axis respectively.

Table 4. Permeability experiments involving radial flow of silicone oil through assemblies of orthotropic fabrics. The permeability values have been calculated either under constant or varying ΔP.

Run No	θ (°)	$k_{x'x'}/k_{y'y'}$	k_e (m^2) Constant ΔP	k_e (m^2) Varying ΔP x transducer	k_e (m^2) Varying ΔP y transducer
Run 5	38	1.6	2.8×10^{-12}	1.7×10^{-12}	2.1×10^{-12}
Run 6	15	2.5	1.7×10^{-10}		2.2×10^{-10}
Run 7	30	1.6	1.8×10^{-10}	2.3×10^{-10}	
Run 8	22	1.9	2.1×10^{-12}	2.1×10^{-12}	
Run 9	27	2.2	1.8×10^{-12}		1.6×10^{-12}

It can be noticed in table 4 that the various runs yielded different permeability and anisotropy ($k_{x'x'}/k_{y'y'}$) due to the different type of fabric assembly. A certain degree of error is expected in the measurements of the pressure transducers at the mould surface.

5. MONITORING OF THE FLOW FRONT

In the runs reported so far the progress of the flow front was monitored with an automatic camera by taking photographs at short, regular time intervals. Another technique that was also tried was to continuously monitor the mass loss of the injection pot with an electronic mass balance. Table 5 presents the calculated values of effective permeability derived from runs where the flow front was monitored simultaneously by employing both techniques. Fig.2 presents the progress of the infiltration front as monitored by the two techniques in equivalent in-plane isotropic, radial flow. Very good agreement is observed.

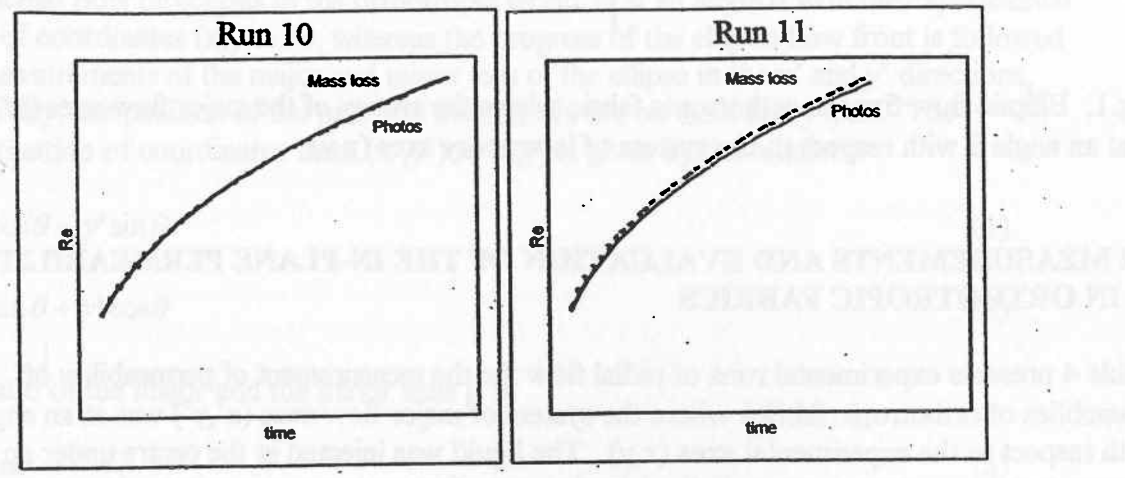

Fig.2. Comparison of equivalent isotropic radii, Re, as calculated by monitoring the flow front either from mass loss data or with a camera.

Table 5. Comparison between the values of effective permeability calculated in radial flow experiments by using the two alternative methods of monitoring the progress of flow front.

Run No	$k_{x'x'}/k_{y'y'}$	k_e (m^2) Photographs	k_e (m^2) Mass loss
10	1.4	3.1×10^{-12}	2.9×10^{-12}
11	1.3	3.1×10^{-12}	3.0×10^{-12}
12	1.2	2.2×10^{-11}	2.3×10^{-11}

6. CONCLUSIONS

This paper includes techniques for the measurement of permeability and the numerical analysis of the experimental data. Two alternative methods were employed for the monitoring of the flow front: photographing the flow front or monitoring the mass loss of the injection pot. Very good agreement was observed between the two techniques in the reported experimental runs. Another issue of interest was the analysis of the pressure data if the pressure varies with time: a differential and integral numerical technique were suggested of which the integral approach might be preferable as it takes into account the whole pressure history for each data point in the numerical analysis. Further useful, numerical methodologies were suggested for in-plane orthotropic fabrics for which the major flow axes in radial flow are at an angle with the experimental axes where the pressure transducers lie.

7. REFERENCES

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