MEASUREMENT OF PERMEABILITY OF CONTINUOUS FILAMENT MAT GLASS-FIBRE REINFORCEMENTS BY SATURATED RADIAL AIRFLOW

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ABSTRACT: The measurement of fibre reinforcement permeability is important for the understanding, optimisation and modelling of RTM and resin infusion processes. This work investigates the use of a saturated radial air flow experiment for measuring the permeability of continuous filament mat (CFM), which is a common reinforcement type used for industrial RTM parts. The use of air, rather than liquid resin, is cleaner, quicker and potentially easier to control. The paper considers the problems inherent in using a compressible fluid, and the requirements for maintaining laminar flow. It describes the instrumentation used for flow and pressure measurement, and the effect of varying flow rate. Results compare favourably with published permeability values based on liquid flow experiments, and are independent of flow rate within the range of values investigated.

KEYWORDS: Continuous filament mat, air permeability, saturated radial flow, resin transfer moulding.

INTRODUCTION

Resin Transfer Moulding (RTM) and Light-RTM (L-RTM) are closed mould processes used for the manufacture of fibre-reinforced polymer composite components, ranging from industrial to aerospace applications. Continuous filament mat (CFM) glass-fibre reinforcement materials are suitable for many industrial RTM parts, due to their lofty, in-plane isotropic nature and low cost compared to more organised fabrics. They are relatively preformable, and produce composites with moderate fibre content (typically less than about 40% by volume).

There is both industrial and academic interest in the characterisation and understanding of the factors affecting CFM permeability (K). This is conventionally defined by Darcy's law [1-3], where the volumetric flow rate (Q) of resin through cross-section A depends on the pressure gradient (∇P) and the resin viscosity (μ):

$$Q = \frac{KA}{\mu}.\nabla P \tag{1}$$

The measurement of permeability is usually carried out by observing either one-dimensional linear or radial flow [2, 4]. Either a transient/wetting flow or a steady/saturated flow may be used, and either the flow rate or the pressure gradient must be held constant. There is a large body of literature on this subject [1, 4-13], including some novel approaches to permeability measurement [14-16].

The traditional approach is to use either thermosetting resin or some substitute liquid of comparable viscosity. This is messy, involves high in-mould pressures and is 'destructive', meaning that the technique is not suitable for on-line, in-situ measurement in an industrial context. To combat these problems, investigations involving the flow of air and other gases instead of resin have been made [17-23], which range from macro-scale permeability testing through to localised measurements using arrays of sensors. These have been used for localised preform defect detection and investigation of inertia effects.

The use of air flow is therefore an attractive proposition for permeability measurement, and prompted this work to investigate the saturated radial flow of air for the permeability characterisation of CFM at various fibre fractions.

THEORY

Air Flow Considerations

Various concerns are associated with the use of air as a fluid for permeability measurements. These including matching the creeping or laminar flow seen in RTM processing [24] and the density and viscosity effects of using a compressible fluid. In the literature, both flow characteristics and compressibility are discussed in terms of the Reynolds number (Re):

$$\mathrm{Re} = \frac{\rho l u}{\mu} \tag{2}$$

where ρ is density, u is flow velocity and l is a reference length.

The Darcy model is considered to be satisfied at Re < 1 [25], therefore suggesting that numbers at these levels reflect laminar flow. In addition, it is considered that the compressibility of gases and inertia effects may be ignored at Re < 0.1 [24, 26]. Here, though, care must be taken; due to the impracticalities of measuring localised flow velocities and pore diameters the reference length (l) and flow velocity (u) are taken as fibre diameter and superficial flow velocity respectively. Therefore, as flow path diameters and localised flow differ considerably between CFM and ordered fibres, inconsistencies may exist between the flow regimes. However, the literature does document appropriate Reynolds numbers and the use of specific flow rates of gases in order to ensure laminar flow [17, 18, 22-24].

As long as compressibility effects are avoided, the viscosity of air depends only on the absolute temperature [27]:

$$\mu_2 = \mu_1 \left(\frac{T_1 + C}{T_2 + C} \right) \left(\frac{T_2}{T_1} \right)^{3/2} \tag{3}$$

where μ_2 is the viscosity of air at temperature T_2, and μ_1 and T_1 are reference values (e.g. μ_1 = 1.81 x 10^{-5} Pa.s at T_1 = 293 K) . C (= 117 K) is Sutherland's constant. This applies to dry air; reference [27] also provides a correction factor for relative humidity (RH), which causes only a 0.25% variation in density over a 60% range in RH, therefore indicating that humidity is an negligible factor in viscosity calculations.

Experimental Design

The experimental design is shown schematically in Fig. 1. Here a volumetric flow controller (Omega Engineering) with a zero to 8.33 x 10^{-5} $m^3.s^{-1}$ range and a certified calibrated accuracy of 1% of full scale, controls the volumetric flow of air which then passes through the base mould platen and permeates out radially through the 300 mm diameter samples. In order to measure the resultant pressure gradient across the sample a Setra differential pressure transducer (Kempston Controls Ltd) was used. This had a zero to 623 Pa range and a certified calibrated accuracy of 0.25% of full scale. Data were captured on a Datataker DT500 data logger with Delogger software, which also measured air flow temperature via a K-series thermocouple mounted in the base mould platen.

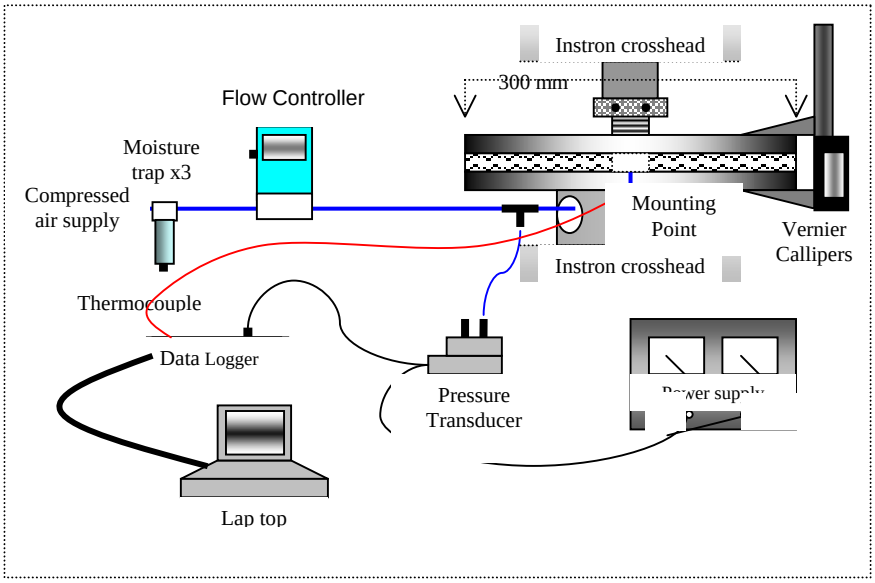

Fig.1: Schematic illustration of the experimental design

Permeability Calculation

Calculation of permeability from the experimental parameters is shown as Eq. 4, which is obtained by integrating Eq. 1. Note that measured permeability K depends on the radius of the central injection hole (r_0):

$$K = \frac{\mu Q}{\Delta P 2\pi d} \ln\left(\frac{r}{r_0}\right) \tag{4}$$

ΔP is the pressure difference between r_0 and radial position r, and d is the cavity depth.

METHODOLOGY

Unifilo U813-300 was kindly donated by Saint-Gobain Vetrotex for these experiments. The nominal reinforcement areal weight is 300 gm^{-2}, with a tolerance of between 225 and 345 gm^{-2} [28]. Each 300 mm-diameter sample comprised 6 layers, with 13.6 mm diameter injection holes, cut using a hydraulic press and cutting tools. These were then accurately weighed, and a fibre volume fraction (V_f) calculated from measured cavity thickness.

The samples were placed between the aluminium mould platens and compressed using an Instron Universal testing machine to the approximate depth required for a fibre volume fraction of 10%. The cavity depth was then measured accurately using Vernier callipers.

Air flow rate through the samples was controlled initially at 1.67 x 10^{-5} m^3s^{-1} (1 $Lmin^{-1}$) and differential pressure and airflow temperature recorded every second over a 20 s period. This was then repeated at flow rates of 3.33 x 10^{-5}, 5 x 10^{-5}, 6.67 x 10^{-5} and 8.33 x 10^{-5} m^3s^{-1} (1, 2, 3, 4 and 5 $Lmin^{-1}$ respectively, as shown on the flow controller).

The whole process was then repeated at progressively smaller cavity depths to a V_f of approximately 35%, over 10 samples in total.

This experimental method was then repeated, (over a limited range of flow rates) on 10 and 14-layer samples. This was to investigate whether inter-ply pore spaces had any influence on measured permeability.

RESULTS AND DISCUSSION

Experimental Errors

The effects of random measurement errors on calculated V_f and permeability were considered in terms of the combination of worst case inaccuracies. These included E-glass density of between 2550 and 2620 kgm^{-3} [28], flow controller accuracy to 1% of full scale, pressure transducer accuracy to 0.25% of full scale, vernier calliper's in-house calibrated accuracy to 5 x 10^{-6} m, sample outer radius (r) to 5 x 10^{-4} m, and viscosity to 5 x 10^{-7} Pa.s.

Permeability Results Analysis

Fig. 2 illustrates the experimental results obtained, including an experimental uncertainty of 2 standard deviations, for the various flow rates within the flow controller's working range. This shows that at all but the lowest V_f, where pressure differences were very small and therefore least precise, that the variation of results between test samples was significantly larger than the results obtained at different flow rates. A 'significant' variation is here taken to mean that a value falls outside the ± 2 standard deviation range.

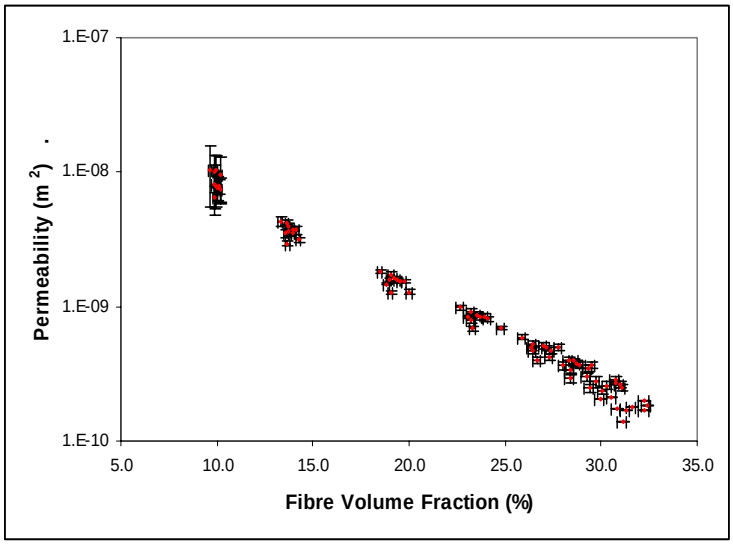

Fig. 2: Permeability vs. fibre volume fraction including 2-standard deviation error bars for permeability across flow rates used and random error bars for V_f.

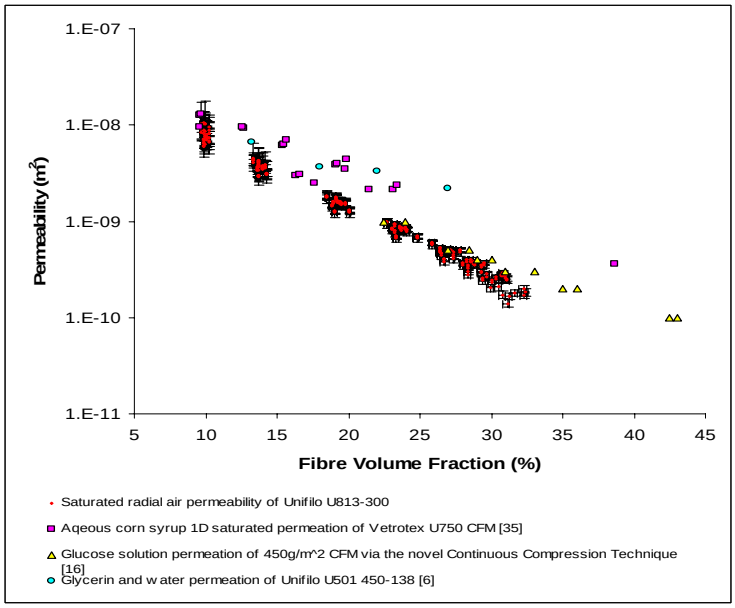

Fig. 3: Measured permeability vs. V_f, including random error bars, compared with published liquid permeability data.

Fig. 3 includes the random error bars for both permeability and V_f and compares these with published data for measurement of permeability using liquids [8, 15, 29]. In

general this plot shows that the results achieved using radial flow of air have a lower level of scatter than published data for the liquid techniques. It should also be noted that the published data are for a CFM of higher areal weight (450 gm^{-2}) than used in these experiments, which might be expected to return a difference in permeability due to variations in fibre architecture. Therefore close agreement with published liquid permeability data for CFM has been shown.

CONCLUSION

By comparison with published liquid permeability results for similar reinforcements, confidence in permeability measurement using the steady-state radial flow of air has been achieved. Statistical analysis of the results has verified the precision of the equipment used to measure experimental parameters. Varying the flow rate (within the range of the flow controller used) did not have a significant effect on measured permeability.

Thus the cleaner and more versatile technique using air as a permeating fluid may be considered suitable for the permeability measurement of CFM reinforcement. The practical implementation of these results could permit the benchmarking of a given reinforcement type against reference material, by direct comparison of pressure difference and/or air flow. The equipment could be easily adapted to measure fibre loft (resistance to compression), while simultaneously measuring permeability, thus providing important characterisation information to the moulder. Work is in progress to extend the technique to other fibre architectures, and to develop models for permeability optimisation.

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