EXPERIMENTAL EVALUATION OF TEMPERATURE EFFECT ON THE TRANSVERSE PERMEABILITY OF A FIBROUS PREFORM

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Abstract

Study of the transverse permeability of fibrous reinforcements became increasingly important when liquid molding processes started being more widely employed to obtain more complex-shaped or thicker parts. In this paper, a system specially built to measure transverse permeability of fabrics based on the correlation between pressure difference and flow rate was used to evaluate the effect of temperature on the measurements of the transverse permeability of a E-glass fiber fabric. Three fiber volume fractions (38-61%) and three temperatures were studied (20-63ºC). The results have shown that the effect of the temperature on the transverse permeability was limited.

Keywords: Transverse permeability, Fibrous preform, Temperature effect.

1. INTRODUCTION

Efficient fiber impregnation is essential for the production of good quality polymer composite materials via any technique in the liquid molding processing family. The properties of the final products are dependent on how the resin advances inside the mold cavity forcing out the air within the preform, which is based on parameters like injection pressure, fluid velocity and reinforcement permeability [1].

Indeed, permeability of the fibrous reinforcement is a key parameter governing mold filling and preform impregnation. It is a measure of the resistance to flow of the fluid imposed by the reinforced medium. Permeability of a fabric may vary in the various directions, and precise characterization of all principal permeabilities (K_{xx}, K_{yy} and K_{zz}) of a preform is of uttermost importance, especially for more complex-shaped or thicker parts [2].

Past research on experimental permeability mostly focus on in-plane (K_{xx} and K_{yy}) measurements, in detriment of the through-the-thickness permeability. This is partly justified by the relative importance between them for a particular set of flowing parameters.

Previous studies on transverse viscous flow through square arrangements have concluded that the overall permeability of a fabric with porous tows is 25% greater than the permeability of solid tows [3]. Despite that, intra-tow porosity appears to have little effect on overall permeability [4]. The inter-tow porosity, on the other hand, has a prominent influence on the overall permeability and when it is increased the permeability does not increase uniformly and becomes more isotropic. Also, fiber nesting and non-uniform compaction of the layers change inter-tow spaces for different numbers of stacked layers, leading to variation in permeability values [5].

Depending on the type and architecture of the fabrics, the nesting degree may change the flow path and significantly contribute to permeability variations. Also, as the angle between successive plies increases, permeability in the transverse direction increases in a non-linear fashion due to the creation of empty spaces, i.e. low resistance pathways between layers [6]. In [7] and [8], the transverse permeability of fibrous preforms at various fiber contents was evaluated and low flow-rate was found crucial for continuous and discrete permeability measurements to avoid non-uniform flow.

The flow paths in the fabric transverse direction are mainly through meso-pores distributed through-the-thickness and they may be aligned or not (non-nested and fully nested, respectively). For large V_f (over 50%), the degree of nesting increases, leading to greater flow through the fiber tows (intra-tow flow) which is governed by micro-scale tow permeability [9]. Indeed, size of the inter-layer gap, inter-yarn spacing, yarns aspect ratio and intra-tow porosity were all reported to influence transverse flow for quasi-unidirectional non-crimp fabrics. And for high fiber content (from 48% to 60%), the influence of microscopic intra-yarn on in-plane and transverse permeabilities becomes greater [10].

In this article, a system developed to measure transverse permeability of reinforcements was used to evaluate the influence of temperature and fiber volume fraction on transverse permeability of a fibrous preform.

2. EXPERIMENTAL

2.1. Materials

The fabric chosen for the tests was an E-glass fiber fabric with a plain weave pattern (areal density of 303 g/m^2 and 405 tex) (Figure 1) supplied by Owens Corning. The fabric was cut manually using scissors and handled with care before they were placed within the mold cavity, as will be described later.

The working fluid was soy oil and its viscosity was measured using a Brookfield viscometer (Figure 2) with spindle configuration. Viscosity was evaluated in a range of temperature within 10-70 °C, based on the temperatures used in the permeability tests.

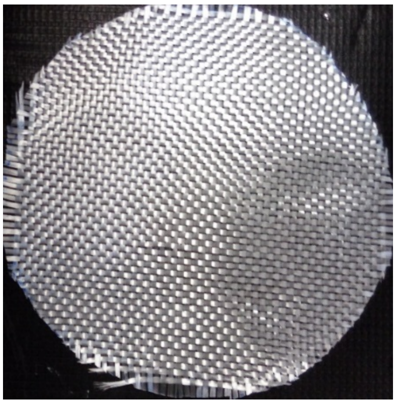

Figure 1: Plain-weave E-glass fiber used.

Figure 2: Viscosity evaluation of the soy oil used.

2.2. Permeability measurements

An apparatus specifically built for measuring transverse permeability (Figure 3) was used in this work. It consists of a lower cavity (entrance chamber) containing an opening for a pressure transducer and an inlet gate (8.4 mm diameter) for the fluid. This cavity is filled before the fluid reaches the first perforated plate and the preform. The other perforated plate limits the final thickness of the fibrous reinforcement and this height may be varied using spacers (3-22 mm), as needed.

The design of these perforated plates was chosen based on the findings of [11], being built with 68 holes of 8 mm diameter, which are positioned aligned in the set-up. These plates compact the reinforcement and prevent movement during testing, also allow a more uniform transverse flow through the reinforcement. On top, there is a conical chamber that converges the flow towards the outlet, which is coupled to a second pressure transducer. In this work, the height of the mold cavity was kept at 16.35 mm, and the final fiber volume fraction was varied (38%, 50% and 61%).

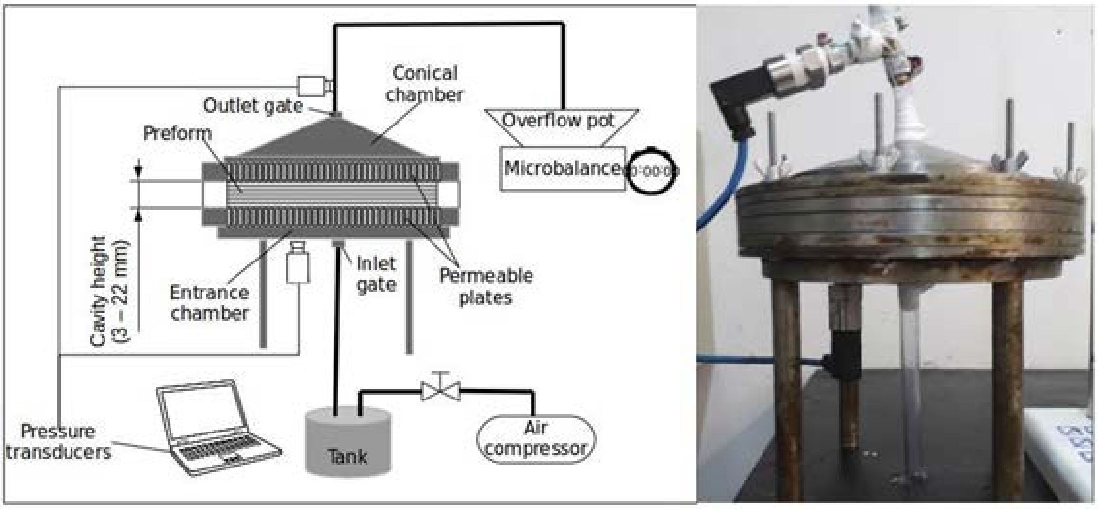

Figure 3: (a) Experimental set-up; (b) actual transverse permeability system.

After the mold is fully assembled, pressure is applied to a pressure pot containing the working fluid which is then forced through the mold. The fluid leaves the mold and is discharged into a beaker placed on top of a balance. Flow rate measurements, i.e. the weight of collected fluid as a function of time, started only after total impregnation of the fabrics by the fluid and when the flow became stationary.

The applied pressure was varied six times in each test in order to obtain different flow rates. The pressure at the entrance was varied from 10 until 100 kPa. A linear relationship between pressure drop and flow rate (ΔP *vs*. Q) was obtained allowing calculation of the transverse permeability (K_{ZZ}, in [m²]) using 1-D Darcy's law.

(1)

where: *Q* is the volumetric flow rate [m³/s] calculated according to Equation 2, *ΔP* is the pressure drop [Pa], *μ* is the fluid viscosity [Pa.s], *h* is the preform thickness [m] and *A* is the cavity cross-section area [m²].

(2)

where *ρ* is fluid density [kg/m³], *m* is mass [kg] and *t* is time [s].

Before actual testing of the preforms, a series of tests were carried out with an empty mold, to determine the pressure drop as a result of the mold geometry. Then, a corrected correlation between flow rate and pressure drop was established for each experimental condition.

Considering the interest in this work to evaluate the effect of temperature on flow, the working fluid was heated in an oven up to a determined temperature, slightly higher than the desired temperature. This was necessary due to the delay between taking the fluid from the oven and starting the actual measurement. In addition, the metallic device was heated using domestic heaters close to it. A thermocouple was placed at the exit of the device (close to the second pressure transducer) and the temperature measured by it was identified as the test temperature. This temperature was used to correct the fluid's viscosity.

3. RESULTS AND DISCUSSION

Figure 4 presents the results of dynamic viscosity for the soy oil, which varied within 104-14 cP in that temperatures range (10-70 ºC). An exponential relationship between viscosity and temperature was fitted to allow a suitable viscosity reading according to the actual temperature in each experiment. The coefficient of determination of the best fitting equation was higher than 0.98.

Soy oil is a Newtonian fluid, which is important since the experimentally obtained dynamic viscosity is used directly into the Equation 1 that governs fluid flow and used to calculate permeability.

Therefore, soy oil was applied in every measurement of transverse permeability performed in this paper. This is justified taking into account that it is considerably less expensive, less dangerous and easier to handle than most other options. Another important advantage in using soy oil is the shorter time to achieve steady-flow conditions due to its lower viscosity.

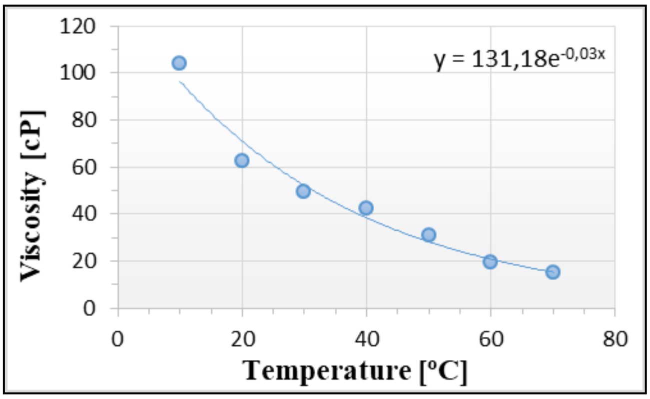

Figure 4: Working fluid viscosity results.

Transverse permeability results are presented in Figure 5a-b. As expected, the fiber volume fraction showed a remarkable effect on permeability. As one can see in Figure 5a, a change in V_f of 10% can alter the K_{zz} three-fold. Lower V_f values means less fibers (more pores) and lower level of preform compaction. When the V_f is higher, the resistance to the flow imposed by the fabrics is increased due to greater difficulty imposed to the flow in transverse direction.

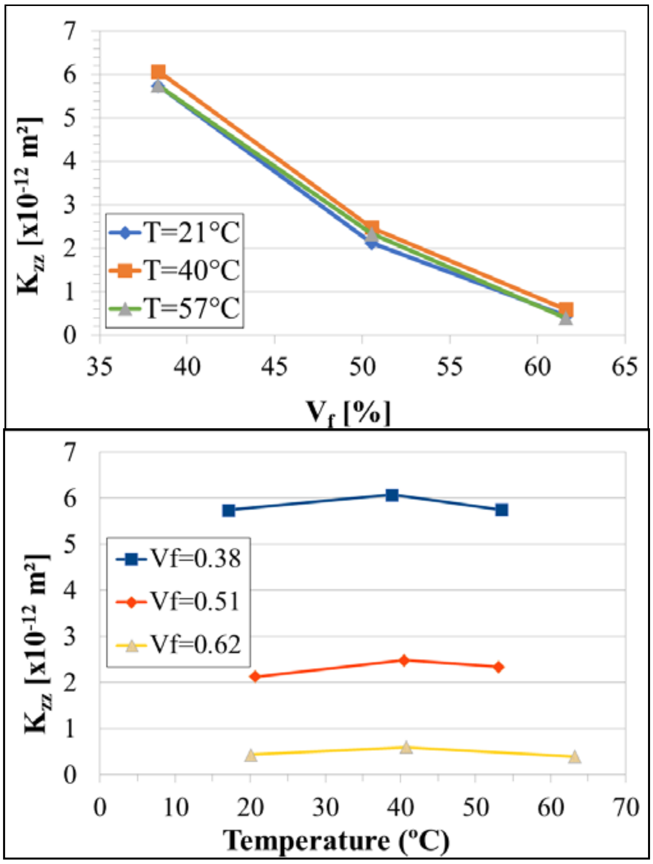

Figure 5: Transverse permeability results.

For the transverse flow through the meso-pores, large yarns (high tex) force the fluid to follow tortuous paths, and the tortuosity of the reinforcement has a more pronounced effect on the flow. Reinforcements with meso-pores structure will present higher macro-transverse permeability at higher V_f. For lower values of V_f, the transverse flow goes through a meso-pore until it reaches the next layer and, thus, the transverse permeability is related with the space between layers and the resistance to flow of the empty spaces (in this case, a meso-pore) that depends on the dimensions of the hole

Considering now the effect of temperature, Figure 5b, there is no clear trend in the variation of values from 21 °C to 63 °C. Thus, the temperature is not influencing the measurement of transverse permeability, even though it greatly alters the working fluid viscosity. Also, this implies that general experiments can be carried out freely, at any room temperature for a particular test, when measuring transverse permeability of reinforcements.

The decrease in viscosity did not alter the K_{zz} values because the pressure gradient necessary to generate a similar flow rate also reduces accordingly, confirming the assumptions from the Darcy's Law.

4. CONCLUSIONS

Determination of transport characteristics of a fluid through a porous medium is not an easy task because it may depend on parameters such as pressure gradient, flow front velocity, viscosity and fluid compressibility. The device designed and constructed to measure the transverse permeability of preforms was tested and successfully obtained the desired results.

An E-glass plain-weave fabric was evaluated at three fiber volume fractions (38, 50 and 61%) and, as expected, transverse permeability decreased for higher fiber content, i.e. lower porosity between yarns. This is also related to the level of fabric compression at each V_f.

The temperature showed no significant effect on transverse permeability of the tested fabric, even though it greatly alters the working fluid viscosity. This implies that general experiments can be carried out freely, at any room temperature for a particular test, when measuring transverse permeability of reinforcements, as long as the viscosity is corrected. This is due to the balance between fluid viscosity and pressure difference applied to the system to generate a similar flow rate.

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