VALIDATION OF FLEXIBLE PERMEABILITY CHARACTERIZATION METHODS IN NUMERICAL SIMULATION OF INFUSION PROCESSES

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ABSTRACT: In the present work, a specific method for permeability measurement of monolithic and sandwich preforms, which are generally employed in the infusion process is detailed. The method shows advantages when compared to the traditional ones: on one hand, the permeability is determined in similar conditions to the infusion process, so a pseudo or *flexible* permeability is obtained, which can be used, as an approximation, directly in finite element methods to describe the flow of the resin inside the flexible mould without additional considerations, such as the variation of the porosity of the preform due to the variation of thickness of the cavity of the mould. On the other hand, the experimental set up allows the characterization of flexible permeability for different radius of the mould, what permits to relate the effect of such deformation of the reinforcement to the flexible permeability. Finally, several simulations of the filling stage of an infusion mould are carried out in this work. By means of them is possible to analyse the accuracy of the presented solution, comparing the simulated flow pattern of the resin, versus its real behaviour.

KEYWORDS: permeability, infusion, simulation, flexible permeability, RTM, VARTM, sandwich, preform.

1.- INTRODUCTION

The *Vacuum Assisted Resin Transfer Moulding* (VARTM) is a widely employed approach in order to manufacture composite parts for several applications, such as windmill blades or vessels. VARTM is a cost-effective method because it allows the use of a lower cost tooling compared to traditional *Resin Transfer Moulding* (RTM). In a particular type of this technique, the *Resin Infusion* (RI), are only necessary one sided mould and a vacuum bag that is placed over the preform to produce high quality composite parts. The resin impregnates the reinforcement thanks to the gradient of pressure between the vacuum inside the mould and the atmospheric pressure of the resin container. In addition, to enhance the flow of the resin, several distribution media are often included inside the cavity. During manufacture of VARTM, typically the operator has just a reduced control over the process, so well experienced engineers and technicians are needed to produce high quality parts at an affordable cost, reducing to

the minimum the expensive trial and error approach. In fact, the design of the mould, the position of the distribution media and the number and location of injection gates and vents are practically the only prior control decisions that can be taken in order to ensure the absence of dry spots in the part after the injection of the resin. However, several attempts have been made in order to control the process: for instance, Bender et al [1] controlled the pressure gradient of the resin to freeze or speed it up, Johnson et al. [2] suggested an induction heating approach in order to reduce the viscosity of the resin in certain sections of the mould or Modi et al. [3] installed controlled valves to permit/avoid the flow of the resin. Despite of that, a good understanding of the physical process can lead to an accurate simulation of the flow of the resin inside the mould as is well documented for the RTM process [4,5]. When a VARTM process is studied, an important factor needs to be taken into account: the preform is a compressible media, so the fibre volume fraction and, hence, the behaviour of the resin will vary during the injection. As will be discussed later, there exist different analytical approaches to overcome this topic but, in the present work a low time consuming experimental method to obtain effective or flexible permeability has been validated. In addition, the suggested approach takes into account the flow behaviour of several distribution media and cores generally employed in the RI manufacturing of large composites parts.

2.- FLEXIBLE PERMEABILITY

The pressure driven flow phenomenon is described by Darcy's law (1). It has been validated the extension of the Darcy's law to describe the flow of viscous, polymeric resin through a stationary fibre-bed.

$$\overline{U} = -\frac{\overline{K}}{\mu}\nabla P \tag{1}$$

Where U is the velocity of the fluid through the fibre-bed, μ is the dynamic viscosity, ∇P is the pressure gradient of the fluid and the tensor K is the permeability, which represents the ease of the fluid to pass through the preform.

As it has been mentioned before, during a RI injection the fibre volume fraction of the reinforcement varies throughout the whole section of the preform as a function of the gradient of pressure inside the cavity of the mould. The thickness of the part varies during the injection due to the effect of varying compaction pressure on the vacuum bag. Hence, figure 1 shows a one dimensional diagram typically employed to determine permeability of performs and its pressure distribution.
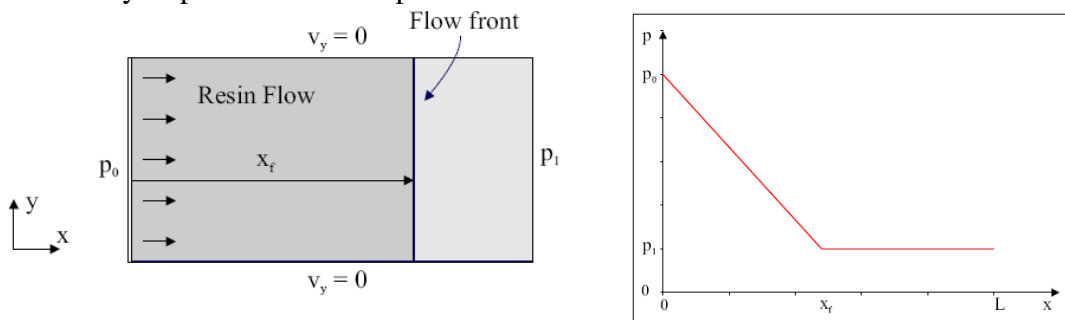

Figure 1.- 1D permeability measurement method

As was explained by Correia et al.[6], to employ a model that analytically describes the flow behaviour in a VARTM process is necessary to know previously two different characteristics of all the reinforcements and distribution media that form part of the

different laminates of the part: i. the thickness of a dry/wet fabric preform at different compaction pressures and ii. the permeability of the preform at different thicknesses. Although some models were built to calculate the permeability of reinforcements, such as the Kozeny-Carman equation [7] or flow across aligned cylinders [8], they have found a limited range of application to determine permeability of preforms in VARTM process. On the other hand, the experimental determination of permeability (both *in plane* and *through the thickness*) to determine the permeability tensor has been widely described and employed [9-13]. The main disadvantage of the experimental method in the analytical solution of the VARTM process is the high time consuming approach that represents its determination as a function of the thickness.

An experimental solution to the problem above might be the use of a *pseudo-permeability* or *flexible permeability* which is obtained in an experimental set up in vacuum conditions [14]. **Figure 2** shows a scheme of the experimental set up employed to measure flexible permeability.

Figure 2.- Experimental set-up for 1D flexible permeability measurement

In the present work, the possibility of include different distribution media and cores in the characterization of the flexible permeability inside the laminate has been also tested. The main purpose is to enhance the accuracy of the experimental results in front of those obtained by the numerical simulation. As is shown in figure 3, a high velocity of the flow front can be expected when balsa wood cores are employed in the manufacturing of parts with RI. In order to take into account these channels, a modification of the set up has been carried out: the cores and reinforcements have been tested under different radius of curvature.
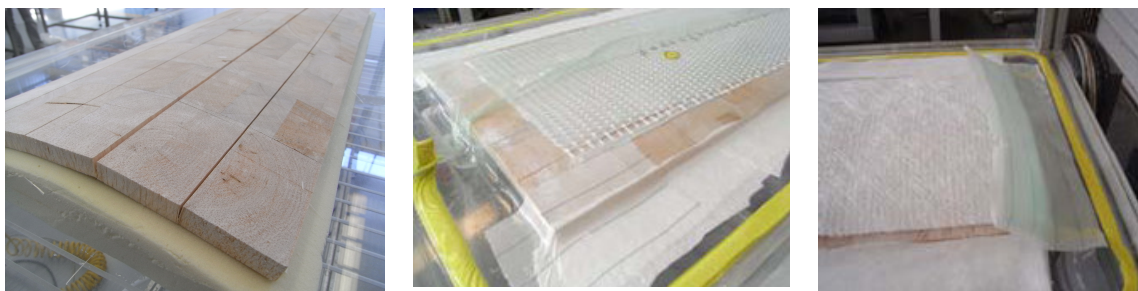

Figure 3.- Determination of the effect of the cores and radius over the flow of resin

Correia [15] showed that for 1D flow, the flow patterns in the RTM and the RI processes are identical in space and differ only in time, i.e. the results form simulation tools modelling the infusion inside a rigid mould can be used with an appropriate scaling factor, reflecting the process conditions and material properties under analysis, to model infusion inside a flexible mould. Hence, the flow advance simulations in this work were carried out using LIMS (UDEL), with RI process approximated as RTM. By

doing that, the compression of the reinforcement is not taken into account, so the effort needed to optimize the mould design is considerably reduced.

3.- EXPERIMENTAL

The aim of the present work is to validate the accuracy of the flexible permeability in the numerical simulation of the flow front in a large part manufactured by using RI. Table 1 shows the flexible permeability of the reinforcements that have been employed to produce the part.

Table 1.- Flexible Permeability

Reinforcement	Type	Weight (g/m^2)	K0 (m^2)	K90 (m^2)
Glass	Woven	700	See Fig. 4	3.5e-11
Glass	Mat	450	1,50E-10	1,50E-10

Figure 4 shows the variation of the measurements of permeability with different radius of curvature of the woven textile over the balsa core (BL6.5R from NIDACORE®).
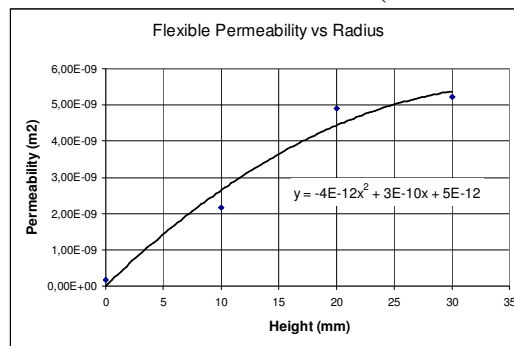

Flexible Permeability vs Radius

$y = -4E-12x^2 + 3E-10x + 5E-12$

Figure 4.- Flexible Permeability (K0) of Woven Glass

Figure 5 shows the experimental set up of the RI and the analysis of the curvature of the final part. The simulation of the filling stage takes into account such curvature and varies the value of the permeability in the required elements of the mesh.
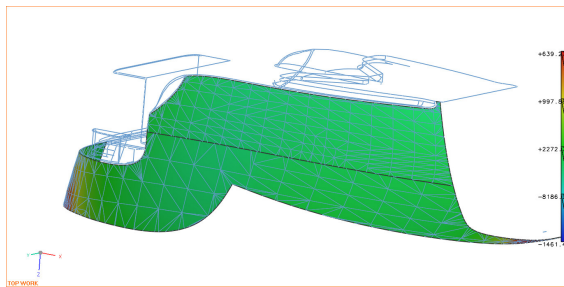

Figure 5.- Analysis of curvature and experimental set up

In order to validate the experimental approach, a simulation of the filling stage has been carried out. Results in terms of time to fill the cavity have been compared against the experimental infusion, which are shown in table 2

Table 2.- Results

Test	Time (s)	Error (%)
Simulation	1815	10,37
Experimental	2025	

4.- CONCLUSIONS

As a result of the present work, an experimental validation of the optimization of the filling stage is completed. Results are limited to the part studied, but it has demonstrated to be a low consuming time approach in order to optimize the filling strategy for RI compared to a more accurate method to relate permeability to compression and pressure gradient during the injection. Due to the promising results, new experimental studies will be carried out in the next months.

5.- ACKNOWLEDGEMENTS.

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