ISOTHERMAL FLOW ANALYSIS IN LIQUID COMPOSITE MOLDING PROCESSES

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ABSTRACT: In this study, we present a simple technique for revealing of the key parameters of the RTM (resin transfer moulding) process, as permeability and the kinetics of the front. The variations of permeability during the treatment shows the capillary effect which is modelled for two configurations. The analysis of the front kinetics allowed making the identification of the tensor of permeability and the examination of the capillary number put in evidence a non saturated zone which can be characterized by a critical length.

KEYWORDS: Resin Transfer Moulding, Flow front, Relative permeability, Void, Capillary Pressure, Critical Length.

INTRODUCTION

Composite molding is a technique more and more used in the industry. The family of processes LCM "liquid composite molding" and it's by products (RTM, LRI, RFI) is commonly used at present in aeronautics, automobile industry, water sport, civil engineering and aeolian industry. In the case of the resin transfer molding (RTM), the process consists of the injection of a thermoset resin in a closed mold containing a fibrous glass reinforcement arranged in advance. This process allows the manufacture of high quality composite parts with complex geometries within limited dimensions. Numerical simulation tools of these procedures were finalized and are the subject of numerous programs of validation. The optimization of the parts material health remains a crucial point to go into.

With the use of Darcy's law, relation between the flow debit through a porous medium and the fall of pressure in the mold cavity, the process corresponding to the filling of the mold can be predicted. Several works were realized in the case of the RTM on this phase of filling [1-3]. Faced with the complexity of the identification of the tensor of permeability, several researchers concentrated their efforts on the experimental techniques. The influential factors in the estimation of permeability are the technique of measurement, the mold edge effect, the direction of the flow and the interaction between the resin and the reinforcement. Several authors tried to measure the loss of pressure according to the debit to verify the linear behavior described by Darcy's law. The anisotropy of reinforcements was also studied, among other things by [4-5]. These works have for common point the use of a central injection mould one of whose patches is transparent thus allowing to follow the flow front.

The knowledge of the permeability of fibrous reinforcements is essential to the simulation of the RTM process. In this article, we model permeability according to the parameters of control and we present the expression of the capillary number and of the critical length for 1D and 2D. We have measured permeability for a radial injection using a simple measurement technique. A mould has been designed and fitted out with a transparent patch displaying the front flow. The analysis of the front kinetics has allowed the identification of the permeability tensor. The measurement results and the consideration of the capillary number have revealed a non-saturated zone which is characterized by a critical length.

EXPERIMENTAL SETUP

The realized apparatus consists in a parallelepiped cavity with the dimensions 270x270x3.4 mm used for a radial injection. The mould consists of a steel bottom and of a glass or Plexi-glass top. Injection is done by means of a buzzard placed at the centre of the mould and connected to a hydraulic jack by a flexible hose equipped with a distributor to evacuate air bubbles. The hydraulic jack containing glycerine is activated by a drive machine (figure 1). The fluid impregnated the reinforcement inside the mould cavity according to a bidirectional flow (2D) before being evacuated to the other end of the mould by means of hole placed at the bottom of the mould. The technique of radial injection (2D) has some benefits on the measurement of the unidirectional permeability (1D). It allows to make a single measurement of the permeability tensor and to eliminate the edge effects usually met in the techniques of measurement of unidirectional permeability. Experimental setup allows following the evolution of the front flow according to time and to measure the fall of pressure of injection between two successive placements of the front. From this information, the permeability of the reinforcement can he easily inferred. The realized assembly allows only the resin injection with a constant debit.

Concerning the measurement of the pressure injection, a pressure sensor is placed exactly at the point of injection. A transparent upper patch containing several circles of various diameters and lines with various angles allows to display the forms and to measure the beams of the front flow (fig. 2) during the filling [6].

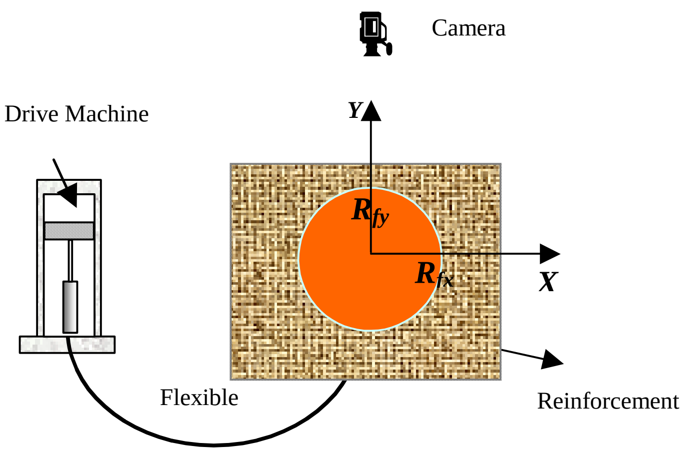

Fig. 1 Principle of experimental assemblies

Fig. 2 System of measurement

ANALYTICAL MODELLING

The pressure equation

The satisfaction of the reinforcement by the resin is likened to the flow of an incompressible and thermally insulated Newtonian fluid through a homogeneous porous medium. It is governed by the equation of continuance and Darcy's law. Within the framework of the radial injection, an analytical solution can be easily deduced. It leads to a ruling equation of the dynamics frontally according to the field of pressure.

$$P(r) = A \ln r + B \tag{1}$$

Table 1 Permeability, Capillary Number and Critical Length in injection 1D and 2D

	At constant debit (Qinj. = constant)	
Injection mode	1 D	2 D
K	$K = \frac{\mu\, Q_{inj}}{A\,\phi} \frac{x_f}{\Delta P}$	$K = \frac{\phi\,\mu}{2} \frac{\left(r_f^2 - r_0^2\right)\ln\left(r_f / r_0\right)}{t\ \Delta P}$
C_a	$C_a = \frac{K \Delta P}{\phi\ L\ \gamma\ \cos(\theta)}$	
C_a	$C_a = \frac{\mu\, Q_{inj}}{L A \phi^2\ \gamma \cos(\theta)} x_f$	$C_a = \frac{\mu Q_{inj}}{2} \frac{\left(r_f^2 - r_0^2\right)}{t} Ln\left(\frac{r_f}{r_0}\right)$
L_{cv}	$L_{cv} = D_f \left[\frac{\mu\, Q_{inj}}{L A \phi^2\ \gamma \cos(\theta)} x_f \right]^{-1}$	$L_{cv} = D_f \left[\frac{\mu Q_{inj}}{2} \frac{\left(r_f^2 - r_0^2\right)}{t} Ln\left(\frac{r_f}{r_0}\right) \right]^{-1}$

The pressure field depends only on the radial distance to the injection gate because the porous medium is ensured to be isotropic (i.e., $K_x = K_y = K_z = K$).

The conditions are as follows:
$r = r_0$ is the beam of the threshold of injection and the $r = r_f$ is the beam of the flow front;
With $P_i(t)$ is the pressure of injection and $P(t) = P_f$ is the pressure at the flow front.
By successive integrations, the pressure distribution in the mould is obtained:

$$P(r) = \left(P_i - P_f\right) \frac{\ln\left(r / r_0\right)}{\ln\left(r_f / r_0\right)} + P_i \tag{2}$$

Let us call back that from a numerical point of view within of the simulation of LCM processes, different approaches were used to resolve the continuity equation and Darcy's law [1-3]. The prediction of the permeability of reinforcements was also the subject of numerical approaches by resolving the equation of Stokes on an elementary volume. However, the use of this method remains still limited. For that reason, in practice, the measurement of the permeability is still essentially made from the study of some flow types which lead to some analytical solutions allowing the estimation of the permeability value.

Two methods can then be used. The first one is linked to a unidirectional flow (1D) and the second one for the radial flow (2D). In our study, we use an isotropic reinforcement. The general solution formulating the expression of permeability is presented in table 1. It is obtained by resolving the equation of pressure with a condition of injection with constant debit within the frameworks of unidirectional and radial flows.

Capillary effect

By observing the kinetics of the follow-up of the flow front, the evolution of the capillary number is examined. Several researchers concentrated on the one-dimensional shape of Darcy's law with the capillary pressure in the flow front [7-8]. As a result, the rigorous and precise description of the flow in the neighbourhood of the front cannot be treated on Darcy's [9] law basis alone. Indeed, this takes into account only driving forces due to pressure or to the compulsory debit. At the level of the front and because of the non saturation of the reinforcement, it becomes imperative to take into account the contribution of the capillary pressure. Wong [10] suggests defining a critical length of the flow L_{cv} (Cross-over length) to quantify the effect of the capillary pressure. This approach was resumed by Weitzenböck [11] who redefines this length by:

$$L_{cv} = \left(\frac{D_f}{C_a} \right) \tag{3}$$

Where: C_a is the capillary number and D_f (m) the diameter of the fibre where the pore is placed at the level of the supposed material front that one suppose subjected to the fall of pressure $\Delta P = P_{inj.} - P_{fr.}$ (with $P_{inj.}$ pressure of injection and $P_{fr.}$ pressure of the front).
On the basis of Ahn's works [7], Weitzenböck estimates capillary pressure P_c (Pa), on a function of the porosity and a parameter F called "Factor of Shape". This factor, often measured experimentally, depends on the alignment of fibres and on the direction of the flow. This capillary pressure for a fibrous reinforcement is defined by:

$$P_c = \left(\frac{F}{D_e} \right) \gamma \cos(\theta) \tag{4}$$

Where: γ is the superficial tension of the fluid (*N/m*), θ is the contact angle of solid liquid, D_e is the equivalent diameter of the pore and F is the factor of shape ($F = 4$ for a flow along the fibres and $F=2$ for a transverse flow in fibres). The advantage of relation 4 is that it makes it possible to consider a possible affinity between the fibres and the fluid used for the measurement of permeability through the contact angle.

Table 1 gives the expressions of the critical length that we have calculated for unidirectional and bidimensional flows. Critical length allows appreciating the importance of the effect of the capillary pressure for a given attempt. To estimate the importance of this capillary effect in our radial injection experiences, we calculated the capillary modified number according to the fall of pressure, to the physical properties of the fluid and the characteristics of the reinforcement.

$$C_a = \frac{\mu\, u}{\gamma \cos(\theta)} \tag{5}$$

Where, *u* is the relative velocity of flow when fluid soaks dry fibres.
By using Darcy's law, this capillary number becomes:

$$C_a = \frac{K}{\phi\,\gamma\,\cos(\theta)}\frac{\Delta P}{L} \tag{6}$$

$\frac{\Delta P}{L}$ is the pressure drop through the reinforcement of permeability *K*. Equation (6) was also used by Foley and al. [12] who found a transition where permeability decreases with a capillary number of the order of 0.01.

The analysis of the flow through a fibrous medium (particularly within the framework of the measurement of the permeability) can be examined by using critical length, which measures the importance of the capillary effect during the soaking of the reinforcement. This effect depends on the capillary number and on the type of reinforcement.

Afterward, values used in this study are: velocity of injection $U_{inj.}=0.35\ cm/s$ or $U_{inj.}=1.5\ cm/s$, a factor of shape $F=2$, $\mu= 0.12\ Pa.s$ (glycerine), superficial tension of the fluid $\gamma=60\ 10^{-3}\ N/m$ and the contact angle of solid liquid $\theta=0°$ [13].

We present the evolution of the critical length of the flow according to the capillary number for two flow configurations of 1D and 2D (figure 3). Results show that when the capillary number increases, the critical length of the flow decreases considerably. Also one note that from a capillary number of the order of 10^{-4} the critical length of the flow becomes very short which means a transition toward saturation. Figure 4 represents the ratio between the critical lengths of the flow and the position of the front according to the kinetics of the front for two configurations (1D and 2D). At the beginning of the experiences an important decrease in the ratio is observed, which is more important for 1D than for 2D.

The importance of the capillary effect depends on the parameters of the moulding. Thus effect decreases if the time of filling decreases; that is, if the pressure where the debit of injection increases. It also decreases if the porosity decreases. The curves also show that this effect is important at the beginning of injection and decreases with the length the front (figure 3).
Figure 5 shows also that the critical length and therefore the capillary effect decreases when the speed of injection increases [14] and decreases when the porosity decreases (figure 6) in agreement with the literature.

Figure 7 represents the rate of void according to the capillary number for two different velocities of injections. This percentage is calculated by means of the model formulation in (7) with couple reinforcement / fluid equivalent for a flow through an isotropic medium. We observe that the rate of void decreases also when the capillary number increases as noticed by [13].

$$V = -57.849 - 17.16 Log(C_a) \tag{7}$$

Where: *V* is the percentage of void and C_a the capillary number.

DISCUSSION

The results that we present here are obtained for a central injection whose beam of injection is R_0=2 *mm*. The flow of the injected fluid is realized through an isotropic medium with velocities of injections of 0.35 cm/s, 1.5 cm/s and a viscosity of 0.121 Pa.s. Permeability is measured by means of a radial injection mould with reinforcements of 8 and 9 plies corresponding respectively to porosities 0.69 and 0.65.

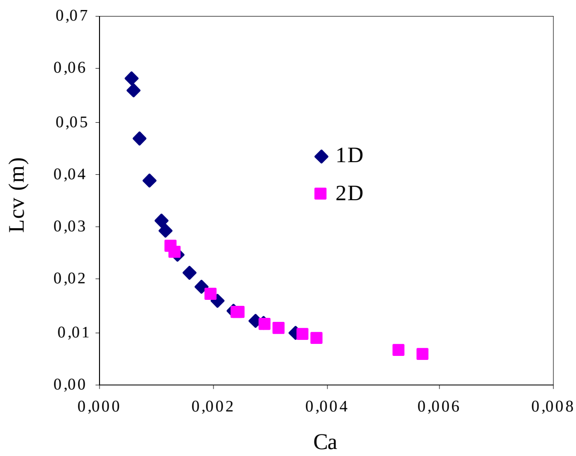

Fig. 3 Evolution of the critical length vs the capillary number for Unidirectional and Radial injections

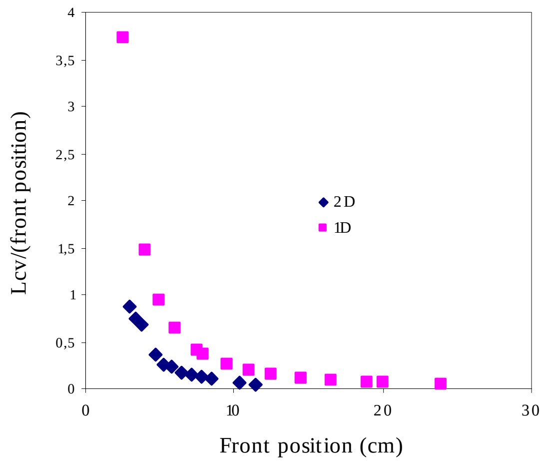

Fig. 4 Evolution of the ratio of the critical length and the position of the front for 1D and 2D injections

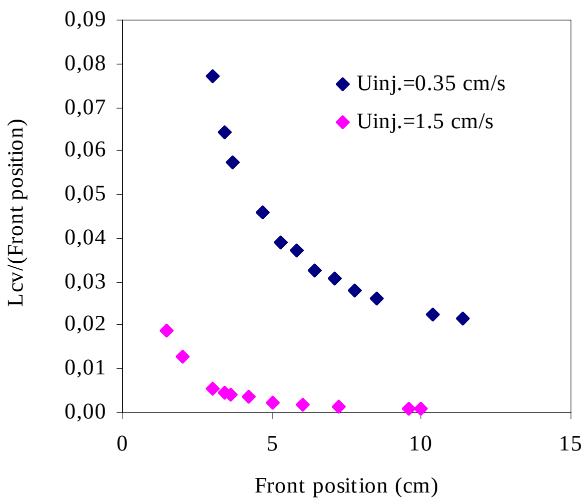

Fig. 5 Evolution of the report of the critical length and the position of the front for two debits of injection

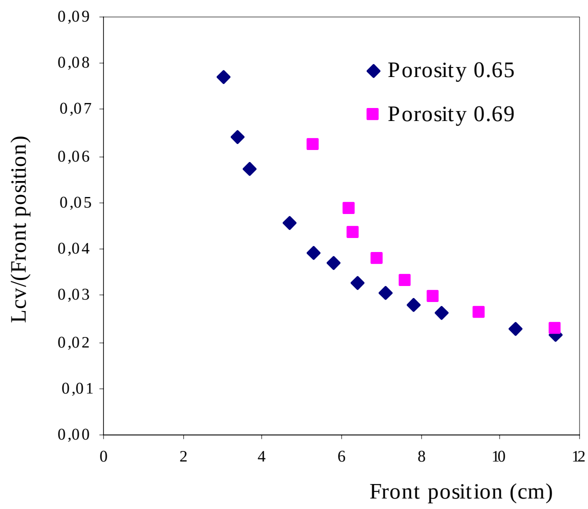

Fig. 6 Evolution of the critical length for two different porosities

During the experiments, the fall of pressure varies between 0 and 1 Bar. For a velocity of constant injection or constant debit), we measure the fall of pressure (ΔP), the position of the flow front (r_f) and corresponding time (t). Permeability K is then calculated (table 2) knowing the beam of injection r_0, the porosity of the reinforcement ϕ and the viscosity of the fluid μ.

In figure 8, we present calculated permeability (table 1) according to the pressure of injection measured for two different porosities. Results show that when the fall of pressure increases, permeability decreases. This last one becomes constant from a fall of pressure of 0.25 Bar and this independently from the pressure. This variation of permeability can be explained by a non linear behaviour of Darcy's law, and can also be accounted for by a non-saturation of the environment. The result represented in figure 8 is in agreement with the evolution of the critical length according to the position of the front (figure 6).

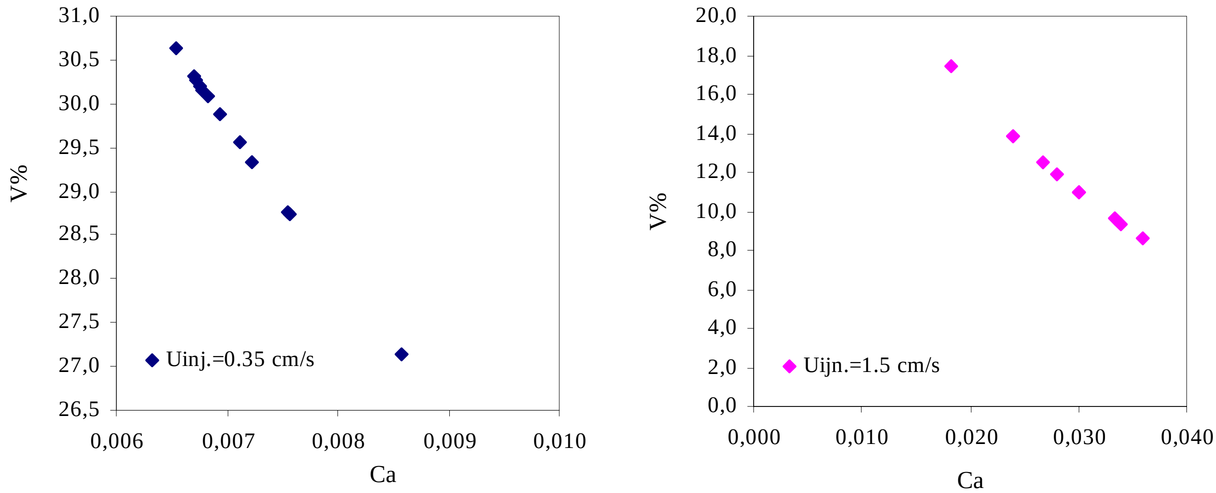

Fig. 7 Percentage of the void for two velocities of injection.

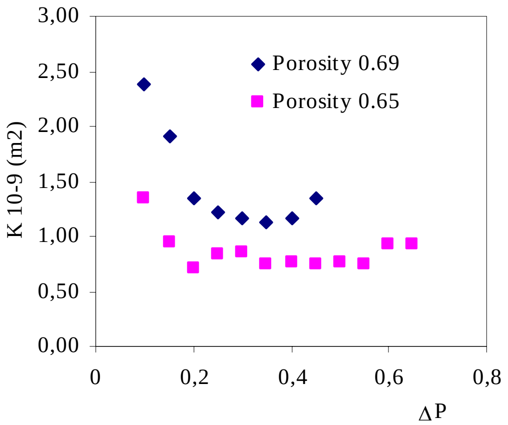

Fig. 8: Evolution of permeability vs the fall injection of pressure (2D)

Number of plies	8	9
Porosity	0.69	0.65
Permeability (Averaged value) (10^{-9} m^2)	1.45	0.85
Permeability (Averaged value) (10^{-9} m^2) [15]	0.462	

Table. 2 Values of permeability for a 2D radial injection (isotropic reinforcement)

The values of permeability obtained spread out between 1.12 10^{-9} and 2.38 10^{-9} m^2 for a porosity of 0.69 whereas those for a porosity of 0.65 are contained between 0.74 10^{-9} and 1.35 10^{-9} m^2. Average values are respectively of 1.45 10^{-9} and 0.85 10^{-9} m^2.
To estimate the accuracy of measurement, we took into account the uncertainties of all the values. The relative error of permeability is of the order of 16 %.

CONCLUSION

A simple experimental assembly was finalized and allows making measures of pressure and flow front to calculate permeability for different porosities.
The objective of the work is to estimate the importance of the capillary effect for the made tests. This capillary effect is modelled by the critical length whose expression was calculated in 1D and 2D. The obtained results show that this effect is important at the beginning of the injection and becomes unimportant for a fall of pressure of the order of 0.25 Bar. The used assembly and the chosen parameters of moulding allow to make reliable measurement of permeability.

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