EXPERIMENTAL INVESTIGATION OF THE COMPRESSIBILITY AND PERMEABILITY OF FABRIC REINFORCEMENTS

E.C. van de Ven, R. Loendersloot, R. Akkerman

UNIVERSITY OF TWENTE
Faculty of Engineering Technology, P.O. Box 217 NL-7500AE Enschede, The Netherlands:
e.c.vandeven@utwente.nl

ABSTRACT: A measurement method for the out-of-plane permeability is presented in this paper. The developed permeameter is capable to measure both compression as well as the out-of-plane permeability. First results show an out-of-plane permeability that is in accordance with values found elsewhere. The compression test needs some more refinement and is not discussed here. The design of the instrument is such that it is relatively easy to change a preform between subsequent tests. A first attempt has been made to measure the viscosity of the test fluid in-line.

KEYWORDS: composites, transverse permeability, determination, design, experiment

INTRODUCTION

In Resin Transfer Moulding (RTM) a porous pre-placed preform is impregnated by a resin in a closed mould. The flow in thickness direction of a preform is often regarded as negligible. This simplification is allowed for products with a small thickness compared to the in-plane dimensions. The flow in the mould will be approximately two-dimensional. However, the increasing application of RTM for structural components has led to thicker components in which the flow through the thickness can not be neglected. Consequently, knowledge of the permeability in transverse direction, K_z, is receiving an increasing amount of attention.
Another field in which the permeability in transverse direction is needed is the field of the infusion technologies. The resin is generally injected through a transport medium on top of the preform, after which the resin impregnates the fibres in transverse direction. A second aspect of the infusion technologies is the compression behaviour of the fabric. The compressibility and the permeability are interrelated [1] and therefore it is desirable to gain knowledge on both simultaneously.
The presented work comprises the design of a permeameter and results of measurements of the transverse permeability during impregnation of the fabric. Measurements at a fixed cavity height are possible. The design of the instrument is largely based on standard tools [2]. This work was a part of a project in which the National Aerospace Laboratory and the Centre of lightweight constructions participated together with the University of Twente and was financed by the Netherlands Agency for Aerospace Programmes.

EQUIPMENT AND DESIGN

The functions that have to be fulfilled are translated into design constrains resulting in the following list:

- The cavity size has to be adjustable.
- Race tracking must be avoided at all times.
- The diameter of the cavity must be such that a steady-state flow through the preform is established during the measurement.
- It has to be possible to measure both unsaturated and saturated permeability.
- The pressure before and after the preform has to be measured.
- The wetting time of the preform should be measured.
- The permeameter does not need to handle thermosets, only test fluids will be used during measurements.
- The permeameter does not require vacuum to be applied.
- The permeameter must be capable to measure the compression force before as well as during injection.

The design constrains led to the permeameter presented in this paper. It consists of five parts: the lower section, upper section, internal section, top lid and the compressing section. See Fig. 1.

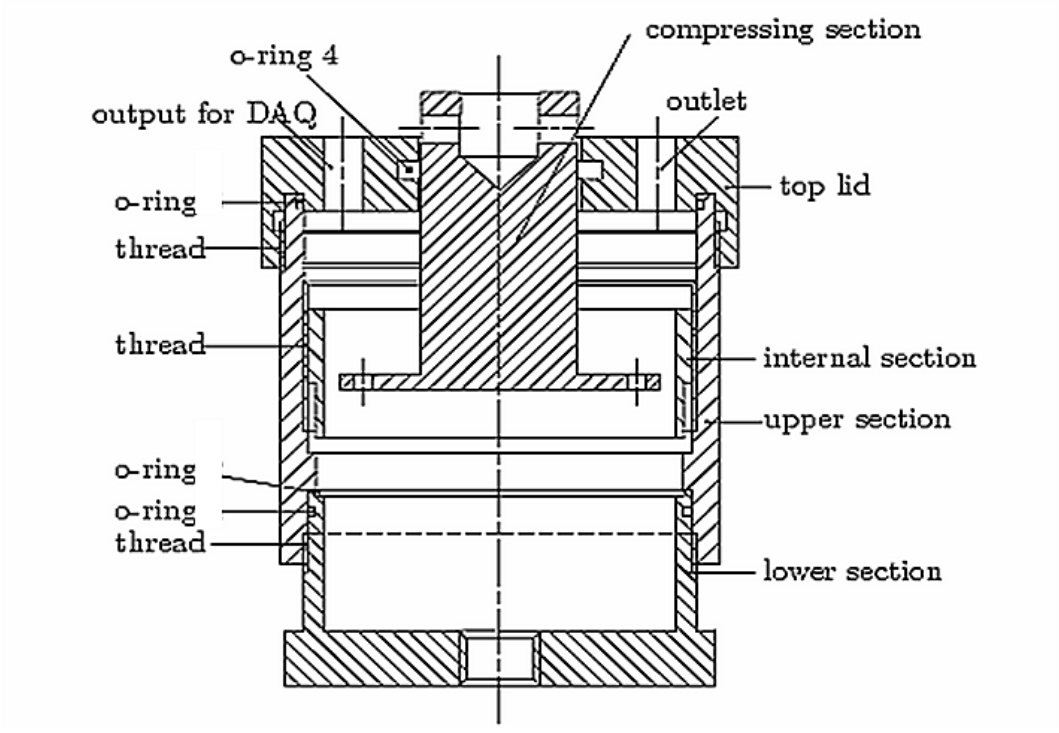

Fig 1 Composition drawing of the design of the permeability instrument.

The liquid enters the permeameter through an inlet in the bottom. The fluid flows in upward direction. The lower section reaches up to the bottom of the preform. The preform edge rests on a sealing ring inside this part. The upper section is connected to the lower section with a thread on the outside of the lower section. This simplifies preform change between experiments.

The internal section is placed inside the upper section. The function of this part is to compress the preform on its edge. A thread is present on the internal section. The preform is tightly sealed by screwing it downwards onto the preform. It ensures that no race tracking occurs.
The edge of the preform is covered with Poly Ethylene (PE). It serves as adhesive between the different layers that form the preform and tight sealing of the preform is ensured in combination with sealing rings. The top lid closes the cavity. A piston is present through the top lid. The piston can be translated vertically to control the cavity height inside the body. With this feature the fibre volume fraction (V_f) can be preset prior to the measurement.
The preform is placed in the tubular cavity. Each side of the tube is closed with a lid, such that a completely closed system is formed. Fixation and compression of the preform is achieved by a set of soldered copper pipes. The fluid obstruction of the copper pipes is small compared to the obstruction by the preform itself. Fig. 2 illustrates the position of the copper pipes in relation to the preform.

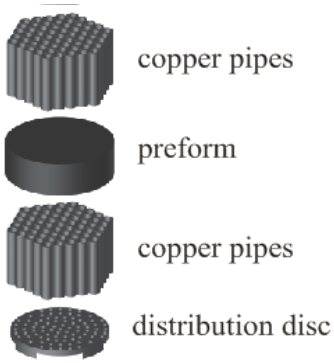

Fig 2 The position of the copper pipes in relation to the preform.

The permeameter is placed in a press, which controls the required vertical position of the piston to be set at the desired height. A load cell connected to the piston measures the applied closing force. A linear variable displacement transducer (LVDT) is placed outside the cavity to measure vertical motion and the resulting cavity height. A perforated aluminium disk is placed underneath the lower set. This disk ensures the liquid to be distributed evenly prior to entrance into the lower copper pipes set. Visual inspection of the preform showed that the liquid level is even when the preform is reached. The cavity height and compression are better controlled, if the vertical motion of the copper pipes is restricted to the motion of the compression section.
The viscosity is measured in-line in a section of the inlet tube. This section has a reduced diameter. This viscosity can be calculated using the Hagen-Poiseulle equation, which relates the pressure drop ΔP to the viscosity μ:

$$\Delta P = \frac{128 Q_v L}{\pi d^4} \mu \tag{1}$$

Here μ is the viscosity, Q_v the volume flow, L the tube length and d the tube diameter.
The permeameter placed in the press is shown in Fig. 3.

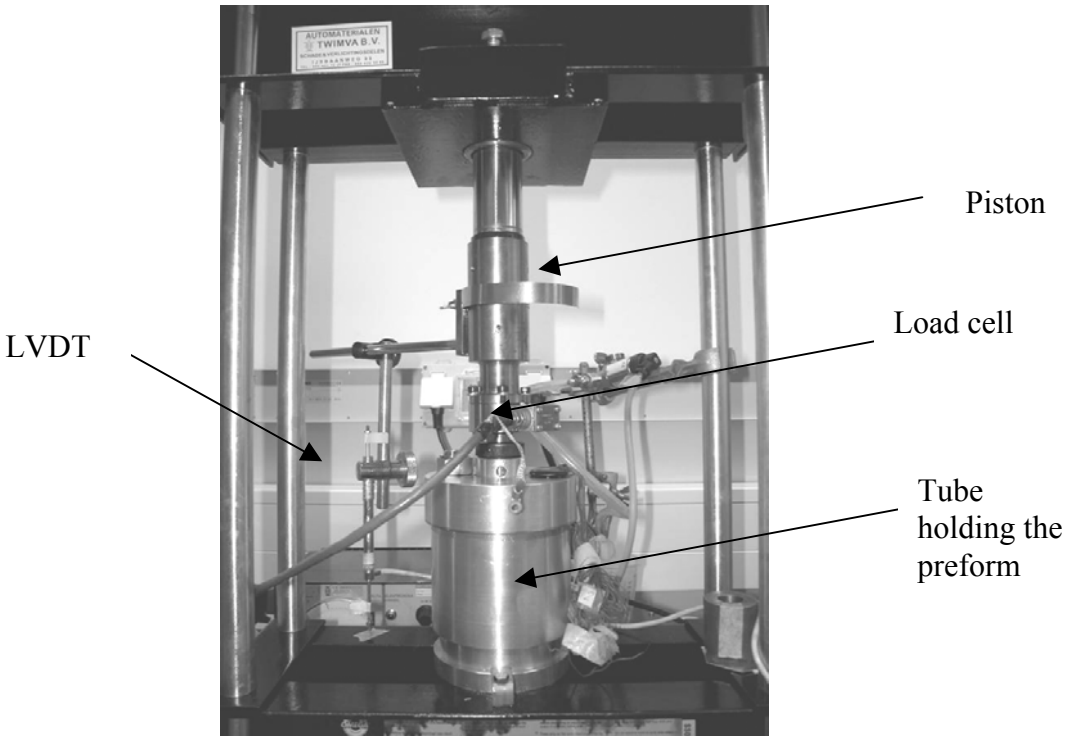

Fig 3 Overview of the instrument placed in the press

DATA ACQUISITION

The load on the preform is measured with a 10 kN load cell. The output is between 0 and 10 volts and fed into a data shuttle.
The pressure is measured by pressure transducers KOBOLT type 3272.072.192 at three locations: two underneath and one above the preform. See figure 4.

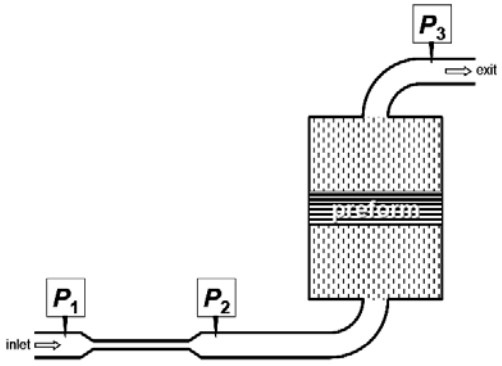

Fig 4 Location of the pressure transducers

A reference pressure transducer is connected directly to the pressurised air system to monitor the injection pressure. The range of the transducers is 0 to 2.5 bars absolute pressure. The output of the transducers is a 0 to 10 Volt signal.
The mass flow has to be measured to determine the saturated permeability. The mass of the pressure vessel holding the test liquid is measured as a function of time, obtaining the mass flow Q_m. The decrease of mass is constant in time if a steady-state flow is obtained,

$$\frac{dm}{dt} = Q_m = \text{constant} \qquad (2)$$

The weight of the pressure vessel itself is large compared to the decrease of its weight. An accurate measurement is therefore difficult. It is necessary to compensate a large part of the total weight of the vessel. A spring was connected to the top of the pressure vessel to this end. This spring compensates for the net weight of the vessel. A small load cell is used to measure the change of weight of the vessel. Evidently, the flow going into the instrument should be equal to the flow through the preform. The pressure and flow measurement are synchronized.

PREFORM PREPARATION

The preform consists of a stack of circular shaped fibre mats. The stack has to be high enough to provide sufficient flow length through the preform.
The preforms were prepared at the National Aerospace Laboratory (NLR) using a computer controlled cutting machine type (Zund M1600). The stack cannot be cut at once. The layers were cut individually.
The cutting procedure, developed at the NLR, enables to produce automatically cut, circular preforms with smooth, non ravelling edges. Ravelling of the edges occurs when the blade of the knife is oriented parallel to the fibre bundle. The fibres are then pushed aside rather than cut, due to the relative loose structure of the fibre mat. The structure is stabilized by applying a Poly Ethylene (PE) film to the fibre mat. See Fig 5.

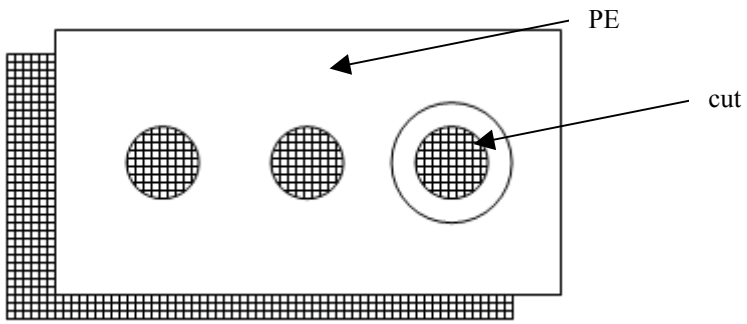

Fig 5 PE film on the fibre mat

The cut is made through the PE stiffened part, leaving a circular region free of PE.

The preform, consisting of 30 layers (depending on the fabric about 10-12 mm thickness), is made by stacking the single layer preforms onto each other. A weight is placed on top to provide some compressive force. The PE is melted during 15 min at 150°C causing the individual single layer preforms adhere together. The result is shown in figure 6.

Fig 6 A stacked 30 layer preform

The fluid is injected with a constant pressure. A pressure vessel is used to this end. The injection pressure is 0.2-0.3 bars. No vacuum is being applied to the instrument. Only saturated flow is measured.

RESULTS & DISCUSSION

A number of experiments were performed using a 2/2 twill carbon fibre fabric (Ten Cate CD 202). First the flow front shape was checked visually. To this end the preform was placed without the upper lid and piston to make the arrival of liquid visible. Thus no compression was exerted on the preform. This causes a lower fibre volume fraction and therefore a less favourable situation to obtain a flat flow front. Even in this situation the liquid arrived in the middle as well as in the edges on the same time. Therefore a flat flow front was assumed in further measurements. The flow front advances in the order of 0.02 mm/sec through the tube and through the preform.
The pressures at the entrance of the viscosity meter (P_1), at the entrance of the cavity (P_2) and above the cavity (P_3) were measured (see figure 4). ΔP_{visc} is the difference between P_1 and P_2, subscript "visc" denotes the viscosity. ΔP is the pressure drop between P_2 and P_3 that is used for the permeability calculation. Note that only the saturated permeability is measured. The permeability is calculated according to Darcy:

$$K_z = \frac{Q_v \mu h}{\Delta P A} \qquad (3)$$

Here K_z is the out-of-plane permeability, Q_v the volumetric flow rate, μ the viscosity of the test fluid, ΔP the pressure difference over the preform and A the area of the preform.
The pressure and the mass flow are recorded as a function of time during the measurement. Fig. 7 shows a typical output. The preform has been compressed to 55 % fibre volume fraction (V_f). The injection pressure is 0.2 bar.

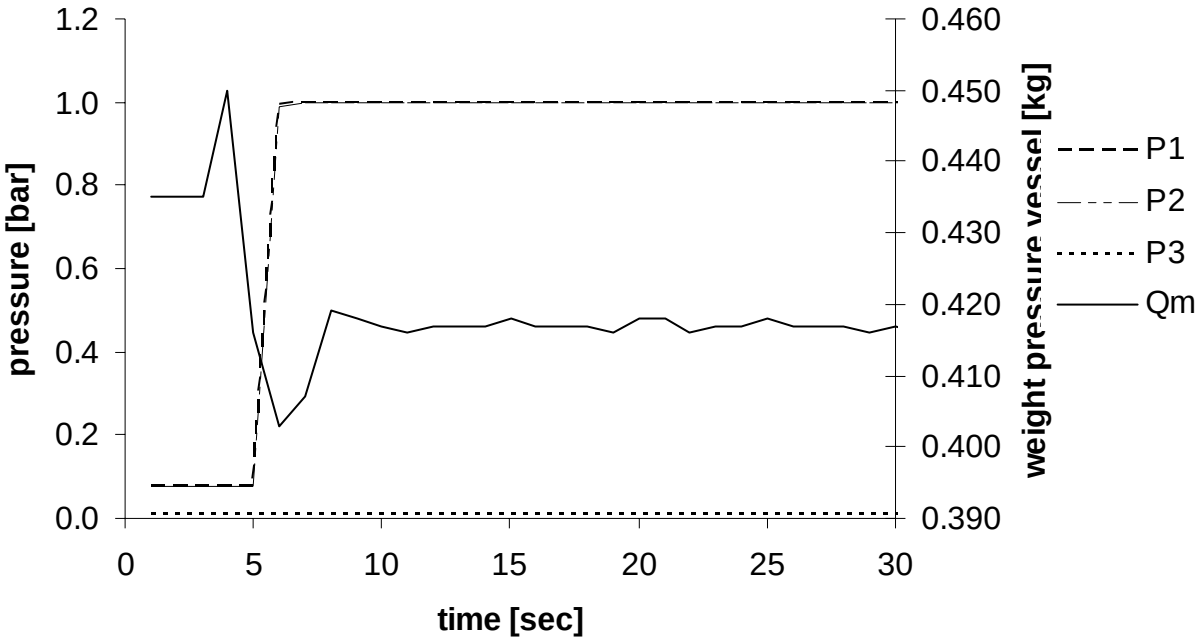

Fig 7 Pressure and flow rate versus time preform under compression to 55% V_f

The pressure transducer response at the start of the measurement is presented in Fig. 7.
The pressure difference between P_1 and P_2 is very small and hardly distinguishable. A fast increase of pressure at the moment the flow front reaches the preform is observed. The preform used has been impregnated already in previous experiments, the wetting process does not occur anymore. Table 1 shows measurement results of repeated experiments on a single preform.

Table 1 Results of a permeability measurement

Exp #	Q_m [kg/sec]	Q_v [m^3/sec]	μ [Pa.s]	h [m]	A [m^2]	ΔP [x10^5 Pa]	ΔP_{visc} [x10^5 Pa]	K_z [m^2]
1	$8.78x10^{-5}$	$8.25x10^{-5}$	0.03	0.0106	$4.3x10^{-3}$	0.990	0.002	$6.17x10^{-11}$
2	$6{,}74x10^{-5}$	$6{,}34x10^{-5}$	0.03	0.0106	$4.3x10^{-3}$	0.986	0.002	$4.75x10^{-11}$
3	$5{,}71x10^{-5}$	$5{,}37x10^{-5}$	0.03	0.0106	$4.3x10^{-3}$	0.978	0.002	$4.06x10^{-11}$
4	$4{,}87x10^{-5}$	$4{,}58x10^{-5}$	0.03	0.0106	$4.3x10^{-3}$	0.971	0.002	$3.49x10^{-11}$

From these results it can be seen that the viscosity cannot be calculated according to Eqn 1 as ΔP_{visc} shows to be too small to give a reliable result. This is due to the accuracy of the

pressure sensors and the low volumetric flow in combination with the diameter of the tube applied. Its diameter has to be modified, see Eqn 1.
When performing a measurement the volume flow rate reads an equilibrium value after a short settling time. This value is subsequently used for the calculation of the out-of-plane permeability.
The results depicted in table 1 show that the out-of-plane permeability changes to lower values when the measurement is repeated with the same preform kept in place. This is directly related to Q_v through the preform. The pressure over the preform (ΔP) changes slightly (-2%) during the measurements whereas Q_v decreases with 45%. The pressure change is due to the air supply system. Considering μ, and A constant, the change of Q_v is attributed to a change of out-of-plane permeability. Fibre bundles can slip to a more dense packing during loading and unloading due to lubrication by the test liquid. This results in a significant difference between dry and wet preform compaction [3]. So V_f is not constant and h is not constant as recorded by the LVDT. This means that only a first measurement is useful for actual process simulations.

CONCLUSIONS

The conclusions that can be drawn from the experiments to measure the permeability are:

- The several layers of a preform are molten together by use of an empirical process; the seal quality has to be controlled better.
- Out-of-plane permeability data are in accordance with the literature, reliable permeability data can be obtained from the permeameter.
- Slip between fibre bundles can occur in saturated permeability measurements due to lubrication. For actual process situations only the first measurement on a new preform is useful.

ACKNOWLEDGEMENTS

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