Composites: Part A 67 (2014) 157–170

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

# Analytic method to estimate multiple equivalent permeability components from a single rectilinear experiment in liquid composite molding processes

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ARTICLE INFO

*Article history:*
Received 23 July 2013
Received in revised form 21 July 2014
Accepted 30 August 2014
Available online 6 September 2014

*Keywords:*
A. Fabrics/textiles
B. Rheological properties
D. Process monitoring
E. Resin flow

ABSTRACT

Presented is an approach for determining multiple permeability components from a single rectilinear experiment modeled similarly to a VARTM infusion. Values are estimated for in-plane and transverse (through-thickness) permeability of the fabric, as well as distribution media permeability in the flow direction. An effective permeability for the combination of fabric and distribution media is also defined. The approach is based on tracking the resin flow-front during linear infusion along the top and the bottom surface over a sample representing several material layups (a segment of which includes the flow enhancement media). Analytic solution of flow progression is used to derive estimates for permeability of all components/layups. The solution, the error due to the assumptions and approximations made, and its limits of applicability are presented. Experimental validation is also provided. Numerical techniques using flow simulation results are utilized to execute a data correction algorithm to further improve experimental estimates.



## 1. Introduction

The basis of describing fluid behavior in a porous medium stems originally from studies conducted by Darcy [1]. Introducing permeability as a material parameter, he produced an empirical formula to determine the flow velocity of water through a column of sand. This was extended to describe the flow through fiber preforms in which the fiber preforms are considered as anisotropic porous media, allowing one to generalize Darcy's law as follows:

$$\langle v \rangle = -\frac{K}{\eta} \cdot \nabla p \tag{1}$$

Here $p$, $\eta$ and $K$ are the resin pressure, resin viscosity and second order fiber preform permeability tensor respectively, and $\langle v \rangle$ is the volume averaged velocity.

The determination of permeability of various preforms and distribution media systems is useful to design the resin injection or infusion process, be it by well-established LCM process modeling [2–8] or by using simple analytic formulas [9]. A variety of methods have been established to experimentally characterize the preform permeability components. These methods are typically classified under two categories: one-dimensional rectilinear flow and radial flow. Each method has its advantages and disadvantages. For unsaturated rectilinear flow, injection experiments are conducted in a linear flow channel [10–15], forcing the flow to be one-dimensional allowing one to determine the permeability component of the preform in the flow direction. A drawback is the possibility of race tracking along the specimen edges, which has been shown to be a common occurrence in linear flow experiments [16–18]. Gaps at the preform edges can result in resin racing through these gaps resulting in two dimensional flow and hence invalidating the one dimensional analysis used to calculate the permeability component. This can be avoided by infusing the preform in a radial injection system [19–30]. This method again requires visual tracking of the elliptical flow front of anisotropic preforms but, unlike linear flow methods, provides all the in-plane permeability components in a single experiment.

Three-dimensional permeability experiments have also been attempted [31–39]. They again require tracking flow front with time in all directions. Gokce et al. [31] developed a technique using a SCRIMP layup and known preform in-plane permeability to determine transverse permeability as well as permeability of the distribution media within the same experiment. Okonkwo et al. [32] used electrical sensors embedded into a RTM mold to gather resin arrival information and determine 3D permeability components from a radially injected experiment.

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http://dx.doi.org/10.1016/j.compositesa.2014.08.031
1359-835X/

So, although many methods exist to characterize permeability, it has been difficult to obtain repeatable values in permeability measurements. It is not unusual to find variations on the order of 20–50% for the same fabric in the measurement of the permeability from the same laboratory. In order to address this, researchers have come together to perform benchmark studies [40–43]. The first international benchmark study [42] was conducted and the result on the same preform showed a wide scatter, up to 90% difference in certain cases. The second permeability benchmark [43] specified the mold geometry, injection fluid, and the procedure along with the same fabric and number of layers. The error reduced significantly, and 20% error could be attained.

There are several issues associated with the practical determination of "permeability". The first one arises due to type of mold in which fabric is placed during resin infusion. For methods that utilize a rigid mold, the sample thickness dimension is well controlled by the constraint of the stiff mold as in RTM. For compliant molds, whether a compliant shell as in RTM light or just a plastic bag as in VARTM systems, the preform thickness will change with time. As the resin lubricates the preform, one will generally see the thickness decrease and then increase again as the resin pressure builds up and counters the compaction load. This phenomenon has been studied before [44,45]. Unfortunately, the characterization of visco–elasto–plastic compaction behavior is very difficult and may introduce further errors in permeability characterization. Consequently, permeability estimation for VARTM is usually carried out without considering this deformation with the reasoning that if the experiments are conducted under VARTM conditions, then this "effective" value of permeability can be used in RTM process models with some "representative" thickness obtained from the experiments. The accuracy suffers, the dimensional tolerances are not addressed but, overall, the estimated values and simplified modeling still provide a reasonable practical process estimates.

Second issue worth highlighting is the difference between the saturated and the unsaturated permeability as experienced in dual scale materials (most woven, stitched and braided structures). This effect is related to the saturation delay (size of unsaturated flow domain) and the sample size. As this work introduces a method with fairly large sample size, we will not address this issue. Note, however, that the inclusion of this phenomenon in modeling may be important and is possible [46].

Another reason for scatter in permeability values is due to the effects of nesting multiple layers of fabric. These effects can differ from one experiment to the next, particularly if materials vary, layers are few and distribution media and peel ply/breather cloth, are added to preform plies. Traditional utilization of individual component properties to "assemble" the effective property set [47] may prove inaccurate. As a result, there is a desire to measure the effective properties of actual preform stack-up.

Process modeling requires material data for all (or at least the "representative") layouts within the infused part including the properties of distribution media and other disposable plies in the mold/bagging system. This issue poses a few challenges. First, one needs a method to quickly estimate the "system" permeability experimentally. That is, measuring the combination of different components into one bulk permeability value. We may then compare them with those values obtained by some averaging method of component properties.

Second, it would be beneficial to measure the "system" properties rapidly and efficiently, even at the cost of lower accuracy. As was stated above, some generous assumptions are used to model the process, and the accuracy is limited. We need a method that only provides us with estimates as accurate as the computations in which they will be used. For a typical flow model we need three estimated values for a certain layup: two permeability components of the preform (in-plane and through-the-thickness) and one value for the distribution media permeability. As these are "effective" values, all of them should be obtained in settings similar to the VARTM process they will be used to describe.

The characterization using conventional 1D or radial-injection methods may be tedious. Depending on the setup, such methods often do not take into account the effects of the additional layers present in a typical VARTM setup: peel ply, breather material and distribution media. The measurement of through-the-thickness permeability would require a more involved method.

The 1D VARTM setup can be used to measure the in-plane permeability in the flow direction and a second experiment is necessary to determine the distribution media and through-the-thickness permeability values using a VARTM set-up with the distribution media and Permeability Estimation Algorithm (PEA) [31]. Here we introduce a method in which these two experiments may be combined into a single experiment to extract all three values. Note that we will be obtaining "effective" values based on several assumptions. When these assumptions are violated, substantial error may be introduced, and the error should be estimated.

There are several restrictions when using this method: The first is the method assumes "homogenous" behavior through the preform thickness hence it should not be used for preforms in which different materials are grouped together and placed in layers. Second, if the fabric has significant anisotropy in the in plane direction, that will skew the results so it should be only used for fabrics that do not have very high anisotropy in-plane. Note that just as with the usual 1D experiments, the issue whether the flow direction is a principal permeability direction cannot be resolved from this experiment and if significant in-plane anisotropy is suspected, 2D experiment – or multiple (three) 1D experiments – might be necessary. For this restriction, we will later describe some limitations to the aspect ratios of the experimental specimen, which may make the method impractical for some materials or layups.

We will first outline the experimental layout for this experiment and the analytic solution used to extract the permeability values from the flow front location data recorded from the experiment. Then, we will analyze the error introduced due to the assumptions in the analytic solution by comparing the analytical results with a set of numerically performed experiments with known permeability values in order to establish the limitations of its applicability. Finally, results from laboratory experiments will be presented to validate the method against the material data obtained by individual 1D VARTM setup/PEA experiments.

## 2. Experimental layup

The proposed experiment is conducted similar to a typical VARTM infusion. The measured fabric preform is partially covered with the distribution media assembly, compacted under vacuum and the experimental fluid is infused at atmospheric pressure. On top of the fabric, the distribution media spans a predefined amount of the entire preform length, next to the injection line (Fig. 1). It is possible to modify this experiment in which the distribution media is placed next to the vent instead of placing it next to the injection line. We will briefly analyze that case later. The length of distribution media is $L_{DM}$ and the remaining length of fabric without the distribution media is $L_{NDM}$. These regions induce two very different flow behaviors, which are dependent on properties of the segments such as preform and distribution media thickness ($h$ and $h_{DM}$, respectively), the lengths of the segments, and the ratio of their permeability components. These effects and how they are related are discussed later.

The schematic illustrated in Fig. 1 shows the proposed layup infused from left to right. Both the top and bottom flow front progressions ($T$ and $B$, respectively) are recorded. This would require