INPUT DATA DETERMINATION FOR RTM SIMULATION OF COMPOSITE MATERIALS

M. Laspalas[a*], M. Lizaranzu[a], M. Castrillón[a], A. Gimeno[a], S. Izquierdo[a], L. Bergamasco[a], F. Martín de la Escalera[b], J.R. Sainz de Aja[b], M.A. Jiménez[a]

[a]*Technological Institute of Aragon, Materials and Components Division,8María de Luna st 50018 Zaragoza Spain*
[b]*Aernnova Engineering Solutions Iberica, R&T Department, 20 Manoteras Av. 4-5 floor, 28050 Madrid Spain*
**mlaspalas@ita.es*

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Abstract

Accurate RTM simulation requires precise determination of input properties of reinforcements and resins. In this paper, an example of characterization and associated models adjustment is presented. The contribution focuses on the reinforcement permeability measurement and resin rheology and cure kinetics. For completeness, the research activity of the group related to multiscale computational prediction of the permeability is outlined.

1. Introduction

Simulation tools for liquid resin composite manufacturing processes, are increasingly being applied to determine optimal mould configurations and process set-ups, in order to minimize further unexpected results in the workshop and high cost trial and error testing. However, the accuracy of the simulation results strongly depends on the accuracy of the supplied input parameters. The flow of a liquid through a fibrous preform is modeled according to the Darcy's law, so permeability of the fibrous preform and viscosity of the resin are the key properties that determine the reliability of mould filling process simulations. The process is completed with a curing phase, whose simulation also requires proper adjustment of the curing kinetics model of the resin.

In this work, the focus is put on the experimental determination of the permeability of a fabric and the further numerical simulation of a Resin Transfer Molding manufacturing process. A specifically developed mould and the associated data treatment methods are explained. The out of plane permeability component is measured separately using a different test rig.

The obtained properties are introduced together with the fluid viscosity properties in a PAM-RTM simulation of the tests. The predicted arrival times to the different sensors are compared with the experimental values showing excellent correlation, confirming the accuracy of the inverse algorithm used to treat the experimental data.

In parallel to the experimental determination of the permeability, an active field of research of this group is the investigation of the computational methods to determine the permeability numerically. In this contribution some outlines are presented of a multiscale model developed for this purpose.

On the other hand, the resin related input parameters determination is commonly based in a program of rheological and differential scanning calorimetry tests. The obtained data are used to fit appropriate cure kinetics and viscosity models. A complete characterization example is presented and some recommendations are given in order to make these two models consistent.

2. Input data determination for RTM simulations

2.1 Characterization of the reinforcement permeability

A prototype test bench for permeability measurement has been developed at the Technological Institute of Aragon. This bench uses a mould with radial flow configuration and is monitored by means of in house developed fluid detection sensors, distributed through the mould cavity in order to track the fluid flow front progress. The bench operates with an alternative fluid with well characterized viscosity.

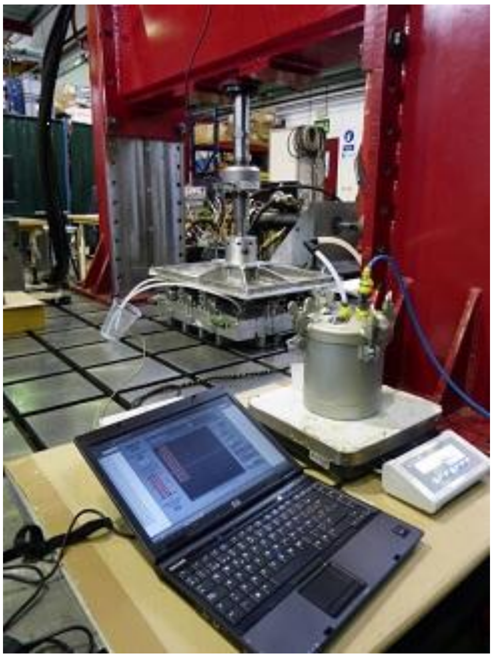

Figure 1. Test bench for in plane permeability measurement and software interface

An inverse method is used to treat the arrival times of the fluid to the different sensors and determine the in plane permeability principal values and directions. The inverse method is based on the analytical solution for radial flow [1] and an optimization algorithm that minimizes the error in the arrival times in a least squares sense. This test configuration allows the determination of the in-plane principal permeability components and its orientation with regard to the reference warp direction.

The test must be conducted for the range of fiber volume fraction of interest and the results can be fitted in an analytical model, such as the given in (1), in order to be used in RTM simulations.

$$K = A\exp\left(BV_f\right) \qquad K = AV_f^{\,B} \qquad K = A\frac{\left(1-V_f\right)^3}{V_f^{\,2}} \tag{1}$$

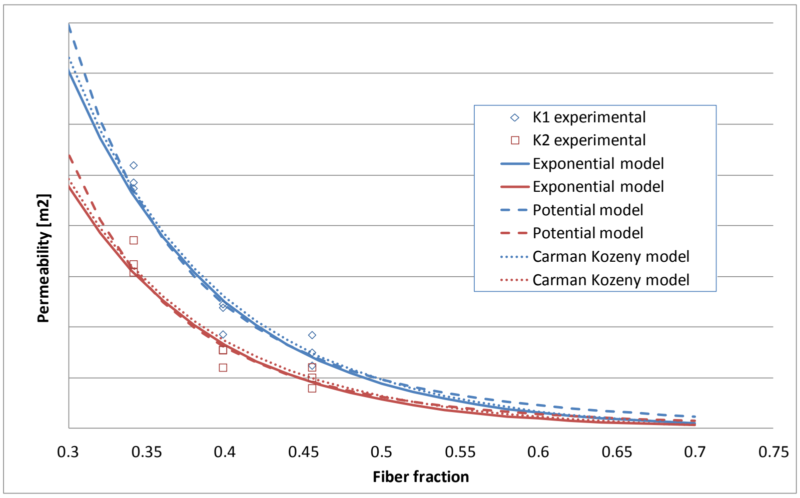

Figure 2. Permeability measurements in a fabric. Adjustment of analytical models

For the determination of the out of plane permeability a specific rig is developed. The test rig operates in uniaxial flow conditions and is equipped with resin detection sensors that allow precisely determining the fluid in and out times. This test rig allows obtaining the out of plane permeability in unsaturated as well as saturated conditions.

Figure 3. Test bench for out of plane permeability measurement.

2.1 Characterization of the reinforcement compressibility

Compressibility of the reinforcement is relevant because of two different aspects, in one hand, it determines the force necessary to close the RTM mold, which is an important information when dimensioning the mould in order to limit deflections that would affect resulting thickness and associated fiber fraction. On the other hand, it drives the thickness variation in resin infusion processes.

The compressibility of the reinforcement is analyzed by means of a conventional universal testing machine, where the pressure- fiber volume fraction relation is determined. In order to be introduced in the simulation program, it can be used as a set of points or fitted to an analytical model.

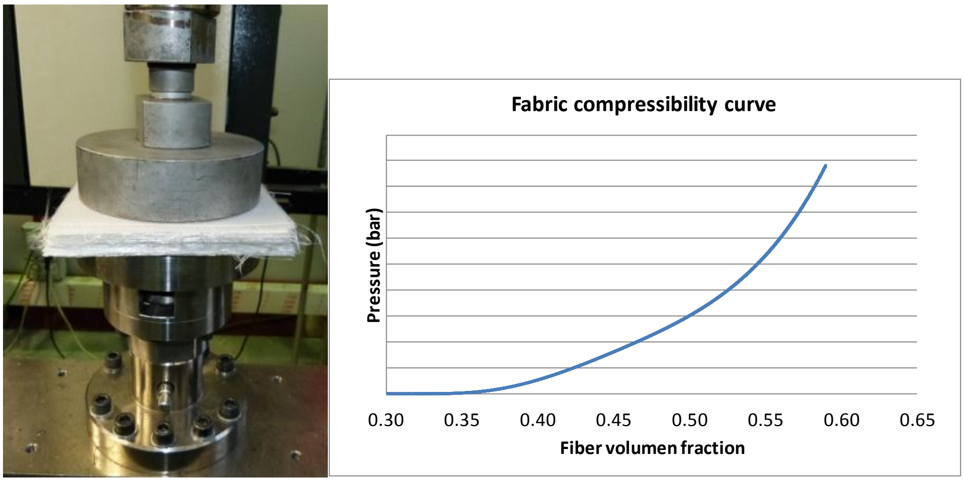

Figure 4. Compressibility test assembly and typical result

2.2 Characterization of the cure kinetics

Thermosetting resins exhibit a significant exothermic behavior during its curing process, which allows the progress of the kinetic reaction to be properly monitored by means of differential scanning calorimetry (DSC) tests. Typical testing plans for characterizing the kinetic reaction involve both isotherm and dynamic tests. With the first ones, the evolution of the kinetics reactions at fixed temperatures are registered. The dynamic tests, can be used to determine the total heat of reaction and the residual heat after vitrification at each temperature in the isothermal analysis.

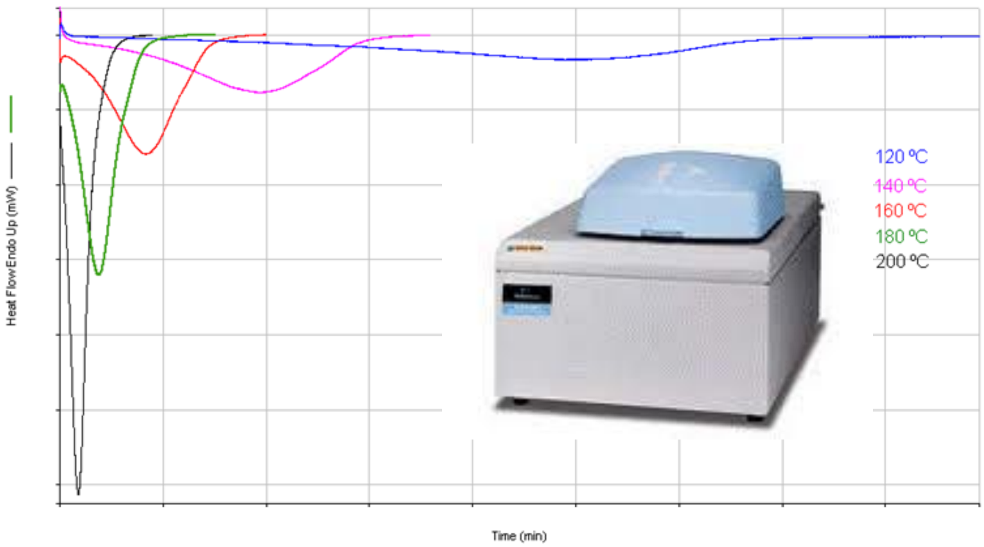

Figure 5. Example of cure kinetics characterization with a DSC equipment.

The DSC raw data is base line corrected and normalized with the total heat of reaction at each temperature in order to obtain the conversion rate, and by means of numerical integration, the degree of conversion evolution. This set of data is used to adjust the parameters of the kinetic model, using best fitting optimization tools. One of the more general kinetics models is the Kamal-Sourour model (2), which in liquid composite simulation programs, such as PAM-RTM (Esi-Group) [2], is implemented with a 2nd order polynomial description of some of the parameters, allowing more flexibility for the phenomenological adjustment of the experimental data. Figure 6, shows the comparison of the experimental data and the predicted with the adjusted kinetic model.

$$\frac{d\alpha}{dt} = (K_1 + K_2\alpha^m)(B-\alpha)^n \qquad (2)$$

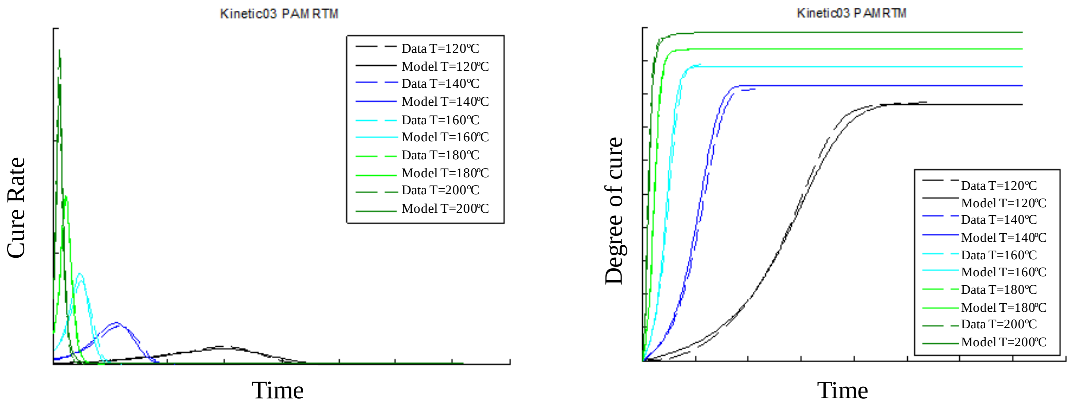

Figure 6. Cure kinetics model adjustment.

2.3 Characterization of the rheological behavior

Another relevant input parameter is the viscosity of the material. The viscosity of a resin must be characterized as a function of the temperature and the degree of conversion. First a testing plan is performed, consisting in a temperature scan, in order to determine the dependence of the initial viscosity with the temperature, and then peak hold tests, where the temperature is keep constant and the viscosity variation registered as a function of time. Using both sets of data a rheological model is adjusted. One of the simplest ones is the Arrhenius type model (3), that allows the parameter fitting to be performed in two steps, first for the temperature dependence, and after for the degree of cure.

$$\eta = Ae^{\left(\frac{B}{T}+C\alpha\right)} \qquad (3)$$

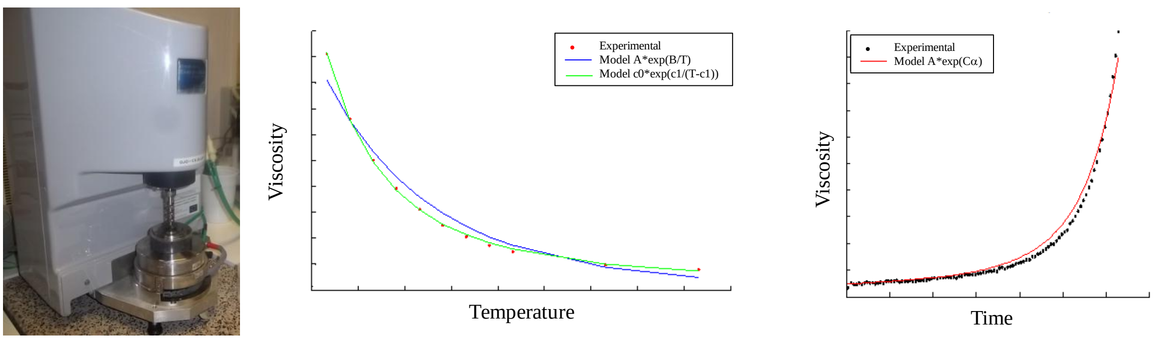

Figure 7. Example of rheological characterization

One relevant issue is that to perform this second adjustment, the evolution of the degree of conversion with the degree of cure must be known. However, usually the experimental determination of this evolution at the typical injection temperatures of the resin is not possible

using standard DSC equipment, because the release of heat is so low that is out of the sensitivity range of the equipment.
The proposed approach is to use the previously kinetic model to extrapolate the degree of cure evolution at the injection temperatures. Then rheological model and kinetic model are not independent anymore and must be used together for consistence.

3. Simulation of the RTM process

In this contribution the input parameters are introduced in PAM-RTM software and different simulations of the RTM process of the permeability prototype mould are performed.

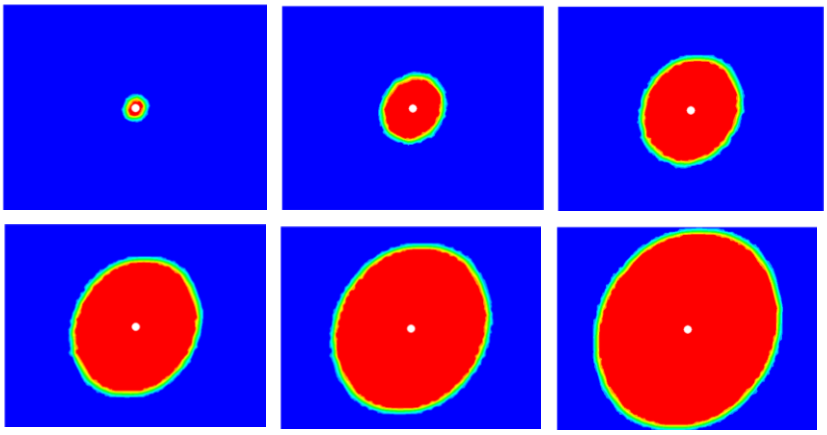

Figure 8. RTM simulation

The correspondence between the numerical and experimental arrival times to the different sensors positions is compared in next figure for different volume fractions, sowing the good correspondence between the analytical solutions used in the permeability tests post-processing with the computationally solved solution of the Darcy's law by means of the finite element program.

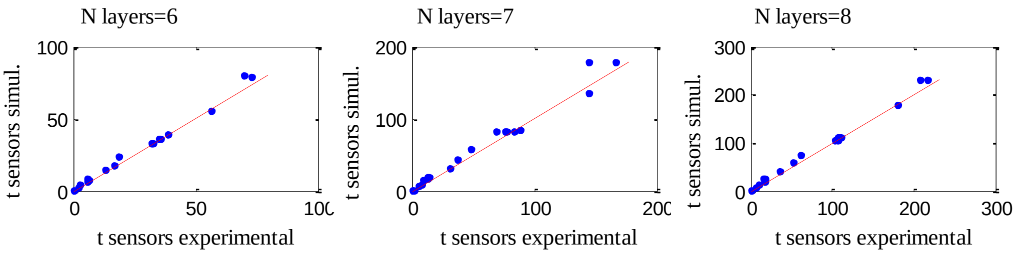

Figure 9. Correlation in arrival times to the sensor locations

4. Multiscale simulation for permeability prediction

Although current approach for the determination of the permeability is based on experimental programs, there is an increasing interest of being able to determine this property numerically, first to better understand the physics behind and second in order to decrease the experimental programs effort. This is the reason why, in the Technological Institute of Aragon, one of the research lines on multiscale simulation focus on the extension of the numerical methods to account for non considered effects, trying to improve the accuracy of the permeability predictions.

The contribution of fiber dynamics to the effective permeability in hierarchical fibrous media is poorly understood, due to the complex fluid-structure interactions taking place at different scales during the injection stage. Textile preforms for these applications indeed, generally present a hierarchical structure and therefore different length scales to be taken into account (typically ranging between one and three orders of magnitude). As a consequence, the numerical solution of the fluid flow in the real geometry is computationally expensive or even not affordable with standard techniques when length scales diverge. For this reason, a common practice consists in separating scales and/or reducing the dimensionality of the problem. This allows for analytical solutions or experimental correlations which serve as auxiliary tool for the numerical simulations. Several correlations for regular arrangements have been proposed, as for example by Gebart [3] for aligned fiber beds. The multi-scale nature of the problem has been also addressed, as for example by Papathanasiou [4], who derived a permeability law for porous yarns. However, due to the geometrical dependence on the percolation threshold, the validity of the above mentioned correlations (or similar) is limited to strictly regular layouts, either at the macro- and microscopic scales. Consequently, their use for the numerical simulation of textile geometries often results in an unacceptable loss of accuracy due to the assumption of regular topologies and the deformation of the structures induced by the fluid flow. In order to overcome the first issue, random or realistically-reconstructed fiber configurations have been extensively studied [5, 6] and statistical descriptors have been proposed to relate the permeability to non-regular fiber arrangements [7, 8]. The effect of several micro-structural parameters on the effective permeability has been also investigated by up-scaling techniques [9, 10]. However, despite the intense work on configurations and up-scaling, the fluid-structure interaction problem is poorly addressed in this framework. The flow-induced deformation of fibers however, affects the interconnectivity of the porous matrix and thus the percolating paths, which in turn affect the permeability [11]. Recent works on the permeability of deforming porous matrices indeed, relies on the idea that the flow resistance of particle clusters is larger than that justifiable by the single particle contributions. This is basically due to the entrapment of fluid within the clusters, which increases the apparent volume fraction reducing the hydraulic area [12]. Therefore current efforts are focused on the development of a multi-scale framework for the analysis of the local fiber topology induced by the fluid flow. A two-dimensional mesoscopic model for the fluid-structure interaction problem at the microscopic scale is under development at ITA. The model relies on a Fokker-Planck equation, which is statistically derived from the dynamic equilibrium of the fibers. The solution of the Fokker-Planck equation yields information about the local changes in the structures at the microscopic scale, which finally allows quantifying local change in permeability due to the clustering of fibers.

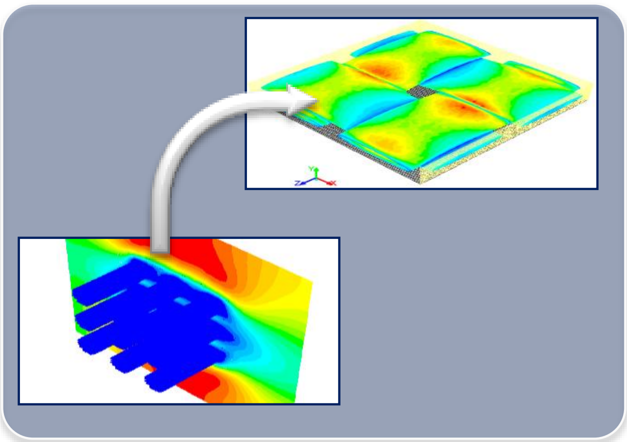

Figure 10. Multiscale approach in the simulation of the permeability

5. Conclusions

Input data determination for RTM simulations requires a combination of different characterization techniques in order to adjust properly the required material models. A typical example of such a characterization has been presented in this paper. One of the most challenging properties is the characterization of the permeability of the reinforcement, for which a prototype test bench has been developed. Complementarily, state of the art computational methods are being developed at ITA to predict the permeability numerically.

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