DEVELOPMENT OF A PROCEDURE FOR ACCURATE SIMULATION OF THE RESIN TRANSFER MOULDING PROCESS

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Abstract

Numerical simulations can aid cost-effective optimisation of manufacturing processes such as Resin Transfer Moulding (RTM). To realise the full potential of numerical simulations, it is critical that the underlying models, algorithms, methods and datasets are validated scientifically. The work carried out at the National Composites Centre as part of the MODCOMP project (European Union H2020 Collaborative Project - modcomp-project.eu) aimed at developing a procedure for simulating resin flow in RTM processes. To accurately simulate resin flow progression through the porous reinforcement, the fundamental properties of the matrix resin (HexFlow® RTM6-2) [1] and the fibrous reinforcement (HexForce® G0926) [2,3,4] were quantified. A bespoke RTM mould was manufactured. Eight DC resistance sensors (Optimold, Synthesites Ltd) were fitted in the mould to monitor resin flow front arrival and aid with validation of the simulation models. A series of panels were produced for validation purposes and the arrival times at each sensor were recorded. The experimental setup was replicated within a number of software tools, such as PAM-RTM, LIMS and Moldex3D, modelling the resin flow process and back-calculation of permeability values was carried out based on the data recorded from the sensors [5].

1. Introduction

Numerical simulations can aid cost-effective optimisation of manufacturing processes. This is true for any process and material, but is notably applicable for expensive materials such as polymer composites. This work aims to demonstrate the developmental stages of resin flow simulations for the Resin Transfer Moulding process. In the Resin Transfer Moulding (RTM) process (Figure 1), a preform made from porous, fabric reinforcements is laid on the bottom, rigid mould half. The mould is then closed with another rigid mould half on the top. Resin is injected through an injection line which can be mounted in either of these mould halves. In general, the mould halves, as well as resin, are heated in order to lower the resin viscosity. The injected resin infiltrates the preform to reach the vent where excess resin bleeds out. Once the resin cures, the mould is opened to extract the finished part. Accurate control over part thickness, excellent surface finish and part quality are the main reasons for the popularity of RTM composites manufacturing process.

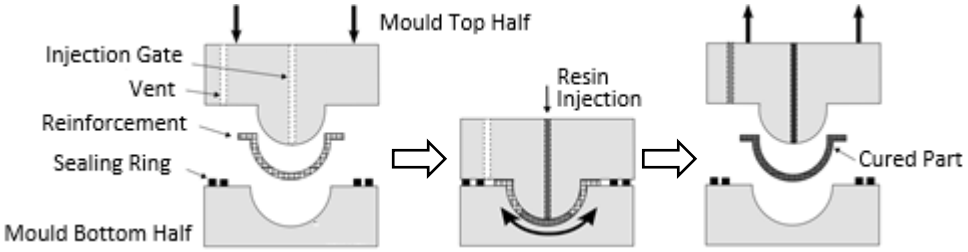

Figure 1. General steps of the Resin Transfer Moulding (RTM) process

The fluid flow in reinforcement is modelled using Darcy's law (Eq.1)

where: v is the fluid velocity, μ is the fluid viscosity and $\partial P/\partial r$ is the pressure gradient.

$$v = -\frac{K}{\mu}\frac{\partial P}{\partial r} \quad (1)$$

K is a constitutive parameter called permeability, *K* is a second order symmetric tensor, i.e. it has six independent components in a reference Cartesian co-ordinate system. Aligning the flow and the reference co-ordinate systems allows it to be reduced to three independent components, called principal permeability values, in three principal directions of the reference co-ordinate system.

As the flow resistance directly affects the time required to fill a part, permeability is considered to be one of the most important processing parameters. Furthermore, to capture or model accurate flow process physics in any numerical models/simulation tools, one also requires correct values of reinforcement fibre volume fraction as well as resin viscosity (as a function of temperature) and density.

2 Materials selection

Due to the availability of reliable and sufficient historical data [2,3], the following materials (Table 1) were down-selected at the onset of the project.

Table 1. Details of the fabric reinforcement for the MODCOMP project

Fabric Reinforcement		***Resin System***	
Designation	HexForce® G0926 D 1304 TCT INJECTEX E01 2F	Designation	HexFlow® RTM6-2
Architecture	5 Harness Satin	Components	Two
Yarn	Tenax E HTA 40 E13 6K	Mixing Ratio (Weight)	100 (Part A) to 68.1 (Part B)
Construction	Warp: 4.6 yarns/cm	Density	1110 kg/m3 @25ºC
	Weft: 4.6 yarns/cm	CTE	52.7E-06 (1/K)
Nominal Weight	375 g/m^2	Injection	Resin Preheat: 80ºC; Mould Preheat: 120ºC
Binder	Epoxy powder binder E01 2.5% per side	Gel Time (after mixing)	> 240 min @ 120ºC
		Cure	90 minutes @ 180ºC or 120 minutes @ 180ºC

3. Intelligent Resin Transfer Moulding monitoring system

An automated intelligent Resin Transfer Moulding (RTM) system has been developed and has been demonstrated for the manufacturing of aerospace grade composite parts [6,7,8]. The resin's temperature and electrical resistance was measured at 8 different locations in the mould cavity. The injection process is also monitored via the simultaneous measurement of the arrival of the resin at the sensors. This, in conjunction with pressure measurements at the inlet and outlet gates provides all the necessary information for controlling the injection stage.

Figure 2 shows the schematic of the mould design. It consisted of a top half, which had two layers of sealing ring on its vertical, peripheral surface to prevent the injected resin from leaking out. The bottom mould half was of flat, circular shape and contained a peripheral groove in it to allow the excess injected resin to drain. The circular peripheral flange of the bottom half, outside the groove, accommodated a circular spacer ring to create a mould cavity, in which the top half of the mould could be inserted to close the mould after placing the fabric reinforcement. The cavity size in the mould can be increased by placing additional spacer shims on the spacer ring.

Resin was injected from a central hole located in the top half of the mould. To facilitate development of a circular flow, a similar sized circular hole was also created in the fabric reinforcement. All the mould components, including both the halves and spacer ring, were manufactured from a tool-grade steel (P20 moulding steel) that can withstand temperatures of up to 400ºC without significant loss of rigidity. The surface quality of the components was checked during final acceptance of the mould and was found to be within the specified tolerance limits (±50 microns).

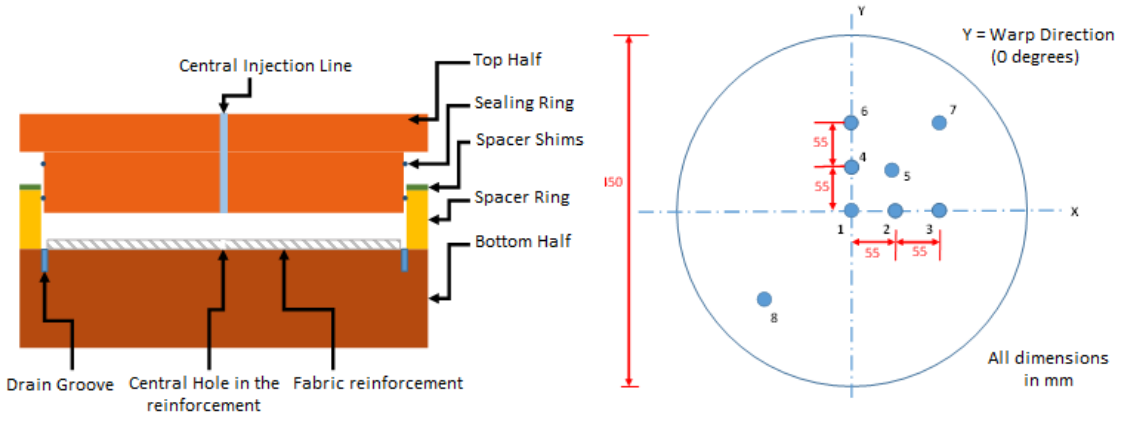

Figure 2. Schematic of the mould for the RTM process under investigation and the location of the resin flow and cure sensors mounted in the bottom half of the mould

Eight DC resistance sensors shown in Figure 2 measure the arrival of the resin flow front (during the injection phase) as well as resin cure (during the curing stage). The monitoring method is proven using correlation of the electrical resistance with key properties of the moulded composite component. The results gathered in this project demonstrate the accuracy and the repeatability of the flow and cure measurement from the start of injection to the end-of-cure for aerospace grade components. The accuracy of the estimated T_g has been validated in comparison with DSC analysis of samples from the produced parts. In addition to the eight sensors (Optimold, Synthesites Ltd) the injection is monitored by inlet and outlet gate pressure sensors and temperature sensors (thermocouples). The absolute pressure sensor is located at the inlet valve in order to monitor the injection pressure while a vacuum sensor (absolute pressure sensor) has also been installed at the outlet gate. The control of these lines is logged within the software against time in such a way that the lag between the command to open the valve and the actual opening of the valve is captured fully.

4 Resin Transfer Moulding (RTM) equipment

All panels at the NCC were manufactured using a 100T hydraulic press (P.J. Hare Ltd) with a maximum temperature capability of 400˚C. The injection process for the specific resin system in use is isothermal and the temperature increased after injection completion to achieve the cure of the moulded composite part. The injection machine CIJECT-3 (Composite integration Ltd) was used with demand value for the injection pressure p=4 bar (absolute) and resin temperature in the injection machine set to T=80°C. The reference temperature profile for the cure step following injection completion is detailed on Figure 3. An image of the press equipment is also shown in Figure 3. The mould incorporated a new sensor specifically designed with a housing which minimises the thermal field disturbance caused by the sensors [9].

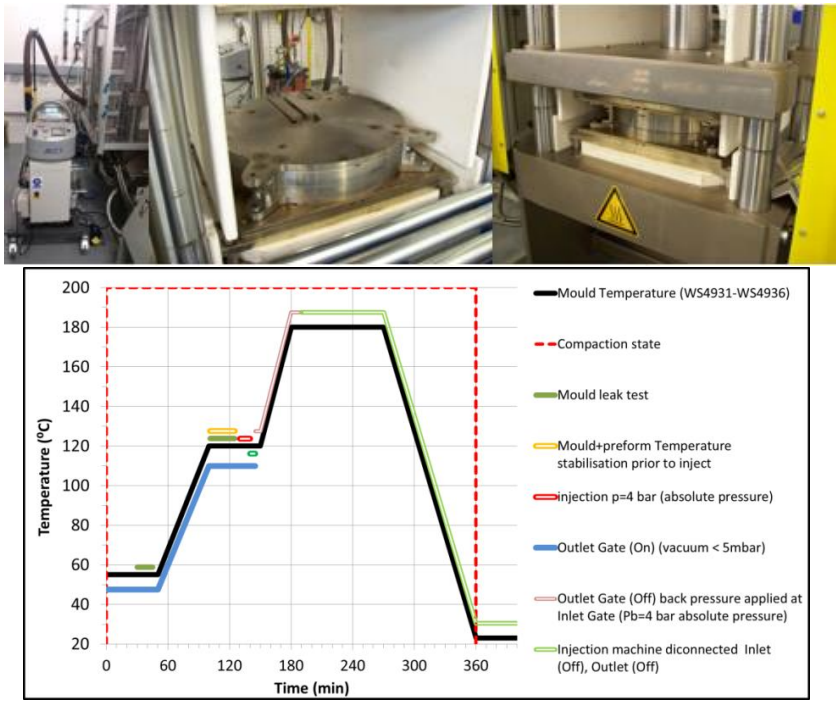

Figure 3. The RTM equipment and the process map.

3 Moulding of panels

A number of panels were manufactured, using the RTM mould shown on Figure 3 after treating the mould surface with Frekote 770NC release agent. The fabric reinforcement was unrolled in a consistent manner along the warp direction. Eight circular plies of 486 mm diameter were cut with a set of shears. These layers were then laid according to Table 2.

Table 2. Lay-up details for panels manufacturing

Ply Number	***Ply orientation (Ref. Y-axis)***	***IN-side***
Plies 5-8	warp direction	IN-side of the roll – DOWN
Plies 2-4	warp direction	IN-side of the roll – UP
Ply 1 – mould side	warp direction	IN-side of the roll – UP
Mould Bottom Surface		

The preform stack weight was recorded before de-bulking it under vacuum at 105°C for 30 minutes, following the recommended procedure for the reinforcement. The stack was then cut to a sample size of 450 mm and a central injection hole, of 10 mm diameter, was punched in the stack. After the preform stack was located on the mould, with the warp tows aligned along the Y-direction, the mould was closed to test for vacuum integrity. Then, resin and hardener were mixed in the recommended proportion, before degassing the mix. Following this, sufficient quantity of resin was injected until it started to bleed from the vent. After the resin has cured, the mould was opened to extract the moulded panel. Data collected from the eight resistance sensors were recorded and displayed on a laptop using the Optiview software (Synthesites Ltd) together with the injection pressure and vacuum measurements during the execution of the whole manufacturing process.

The quality of the moulded panels was evaluated by measuring the fibre and void fractions, T_g and degree of cure. Acid digestion was used to determine the fibre and void volume fraction in the manufactured panels. Figure 4 shows the locations from which the specimens for acid digestion were obtained. Tests revealed a volume fraction range of 56-57% and a void content of 0.7-0.8%.

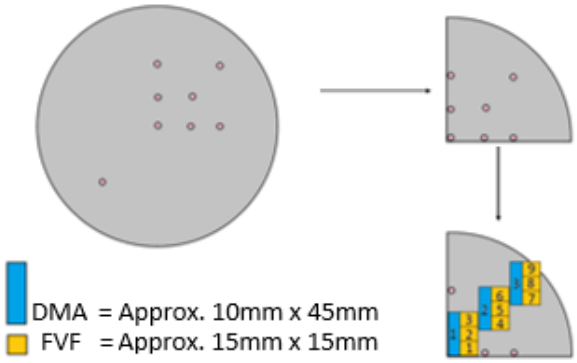

Figure 4. Map of the locations from where acid digestion specimens were obtained from each panel

4 Permeability measurements (test campaign using oil as wetting fluid)

Permeability was measured experimentally at three different volume fractions using oil as wetting fluid. A total of five repeats were performed for any value of the fibre volume fraction. Here, V_f is the fibre volume fraction and K_1 and K_2 are the permeability values in the first and second principal directions. The angle, θ, is the angle between the main directions in the reference co-ordinate systems. The average values, listed in Table 3, were then fitted to Kozeny-Carman and Power law models to represent the principal permeability values for different fibre volume fractions (Figure 5). For the fabric tested, the power law function best represented the variation of permeability against fibre volume fraction (Figure 5, Table 4).

It is worth noting that permeability values calculated using the interpolation functions are valid only for the same test specimen conditions i.e. if the specimen is un-sheared, then the value of permeability obtained will be valid for the un-sheared fabric only [10].

Table 3. Average values of K_1 and K_2, as a function of the fibre volume fraction

V_f (%)	K_1 (m^2)	K_2 (m^2)	θ (°)
52	(38.2±16.9) 10^{-12}	(17.5±4.8) 10^{-12}	45±7
57	(16.1±3.2) 10^{-12}	(11.5±1.8) 10^{-12}	71±20
63	(8.2±0.6) 10^{-12}	(6.6±0.8) 10^{-12}	61±17

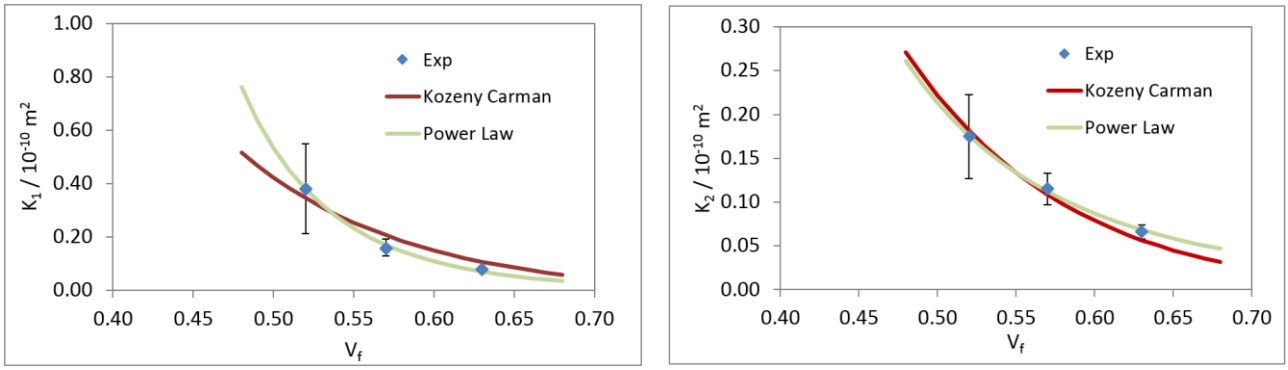

Figure 5. Curve-fitting of the experimental permeability values with Kozeny-Carman and Power law

Table 4. Permeability values, as a function of the fibre volume fraction, predicted using the power law function. The target values for test panels are highlighted in yellow

V_f (%)	K_1 (m^2)	K_2 (m^2)
56	19.9 10^{-12}	12.2 10^{-12}
57	17.0 10^{-12}	11.2 10^{-12}

Measured principal permeability values differs from values reported in literature for similar carbon reinforcement with the really same architecture. However, it is worth noticing the values available in open literature were measured for the same carbon reinforcement loaded with powder binder E01 on one side only (HexForce® G0926 D 1304 INJ E01 1F) [4].

5 Resin viscosity measurements for resin flow simulations (NCC test campaign)

The viscosity of the resin was measured using TA HR1 discovery rheometer at 80ºC and 120ºC, as seen in Figure 6. It is clear that at 80ºC temperature, resin viscosity does not increase significantly, even after 12 hours. On the other hand, at 120ºC, resin viscosity increases rapidly, after 3 hours. Nonetheless, one can safely assume negligible change of viscosity during the resin heat up, decanting and injection phases, all of which should be finished in less than an hour.

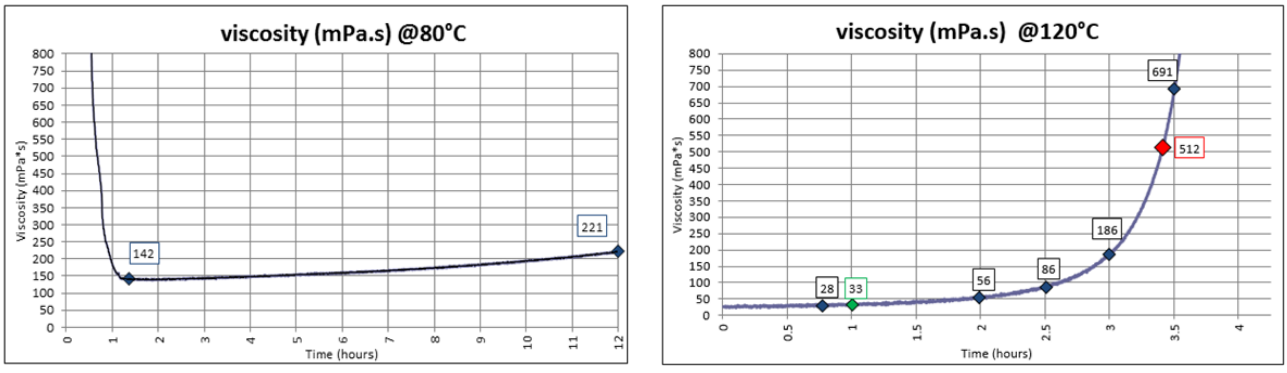

Figure 6. Evolution of RTM-6 resin viscosity, measured at 80ºC and 120ºC temperatures

6 Proposed process simulation procedure

A number of tools, such as PAM-RTM, LIMS and Moldex3D, were used to simulate the flow process. Table 5 lists the process parameters that were used in all flow simulations.

Table 5. Resin and fabric properties used during infusion simulation

Part	*Property*	*Value*	*Units*
Resin	Density	1110	kg/m^3
	Viscosity	33 / 38 / 43	mPa*s
Reinforcement	Density	1780	kg/m^3
	Permeability K_1	$19.9\ 10^{-12}$	m^2
	Permeability K_2	$12.2\ 10^{-12}$	m^2
	θ	70	Degrees
	Porosity ($1-V_f$)	44	%
Injection Pressure		400000	Pa

6.1 Resin flow simulation results

Figure shows a numerically predicted fill-time map for one of the cases investigated, using the experimentally-measured permeability values. The resin is injected from a central injection gate. As expected, the different permeability values in two principal directions result in an elliptical flow front. Moreover, the flow ellipse is rotated with respect to the reference x-axis. This map also allows extraction of flow arrival times, at various locations, that can then be compared directly with the experimental measurements. Figure 7 shows such a comparison for a number of moulding trials, where a clear mismatch between experimental and numerical results is evident.

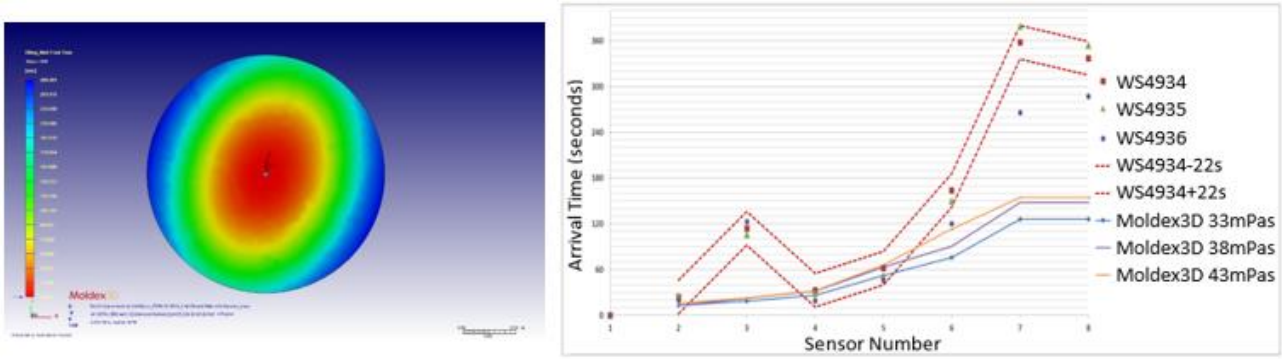

Figure 7. Example fill-time map from Moldex3D, for a central injection case (left) and comparison of numerically predicted and experimentally measured flow arrival times at various sensors (right); the dotted lines indicate the band within which experimental arrival times fall

6.2 Assessment of the permeability values mismatch

In order to better understand the issue it was decided to use the experimentally recorded flow arrival times, in a previously reported analytical solution [5], to back-calculate permeability values.
Table 6 compares these back-calculated permeability values with original measurements, where a large difference is self-evident.

Table 6. Comparison of the back-calculated and original permeability values

	Original	***Back-calculated***
K_1 (m^2)	16.1 10^{-12}	6.75 10^{-12}
K_2 (m^2)	11.5 10^{-12}	5.0 10^{-12}

Figure 9 compares the numerically predicted flow arrival times (using all the three simulation tools) with the experimental measurements. It is clear that the back-calculated permeability values give an excellent agreement in fill-time predictions at all sensor locations. Both, LIMS and PAM-RTM, give a maximum error of approximately 10%, while the error in Moldex3D results is slightly higher at 20%.

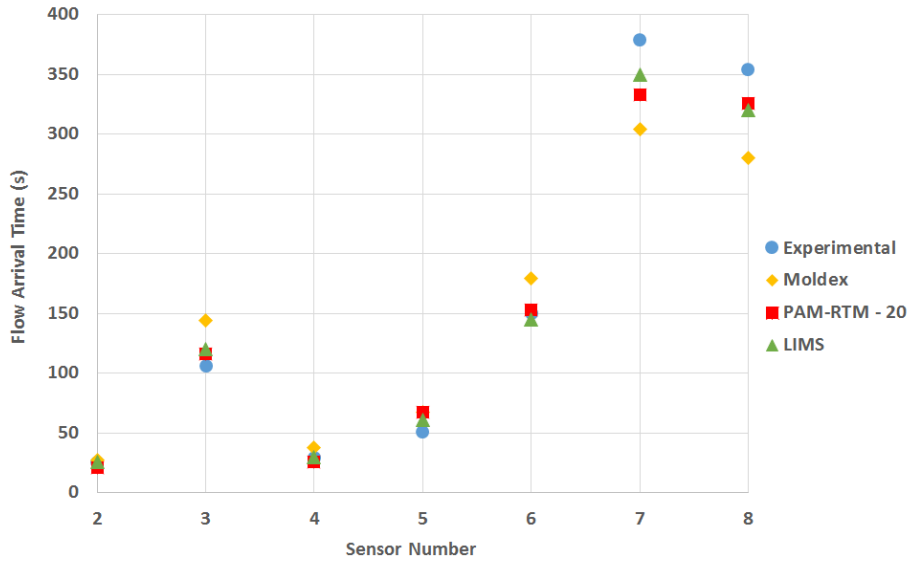

Figure 9. Use of back-calculated permeability values leads to a close match between the numerically predicted and experimentally measured flow arrival times at various sensors

It is worth noting the effect of the permeant on the measured permeability values should be carefully considered [11]; however, Luo et al [12] highlighted that also if the selected wetting fluid exhibits a different behaviour with regards to the fibre wetting, the difference in measured permeability values, is not significant when compared with scatter for experimental measurement or the intrinsic variability of the liquid composite moulding processes. It is also with noticing that in some cases the design or the monitoring system embedded into the specific permeability testing rig does not allow using the real resin system undergoing real/industrial composites manufacturing conditions including the need of applying a release agent on the surface of the mould [13, 14]. The convenient use of alternative wetting fluids and low temperature ranges represents in this case the only possible use of the testing rig. The procedure proposed in this paper allows using an industrial monitoring system to verify the flow front development in a simple test case before attempting using sourced values for a the simulation of the flow front development for more complex composite component with complex stacking sequences.

7 Conclusions

The proposed process simulation procedure starts with the aim of sourcing the permeability values in available open literature or alternatively using a convenient wetting fluid (e.g. engine oil or alternative wetting fluids commonly used by the wide community) and performing a statistically representative number of repetitions of the measurement within the really same testing conditions. This approach allows lowering the cost of sourcing the initial dataset for process modelling. When the exercise of sourcing an initial dataset for process simulation is complete, a mandatory step consists of the verification of the values gathered for permeability and resin viscosity. The proposed procedure consists of a practical way of verifying the input datasets, to be then used when modelling complex part manufacture, using an instrumented mould operating with industrial equipment and replicating the really same process conditions foreseen for the complex composite component.

This important part of the proposed procedure was revealed to be a relevant mid-step to be considered before deploying the values sourced using oil as a wetting fluid or viscosity values for the resin system sourced from available technical datasheets to the numerical model predicting the moulding process of complex component parts with complex stacking sequences.

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References

[1] HexFlow® RTM6-2 epoxy resin datasheet (www.hexcel.com) [visited on 01/05/2018]

[2] HexForce® G0926 D 1304 TCT INJECTEX E01 2F carbon fibre reinforcement datasheet (www.hexcel.com) [visited on 01/05/2018]

[3] Direct Process Technology manual (www.hexcel.com)

[4] A. Endruweit, P. McGregor, A.C. Long, M.S. Johnson. Influence of the fabric architecture on the variations in experimentally determined in-plane permeability values. *Composites Science and Technology*, 66:1778-1792, 2006

[5] J.R. Weitzenbock, R.A. Shenoi, P.A. Wilson. Radial flow permeability Measurements. Part A: Theory. *Composites Part A: Applied Science and Manufacturing*, 30:781–796, 1999.

[6] N. Pantelelis. Combining process simulation and sensing for optimised composites manufacturing. *Proceedings of the International Conference on Flow Processes in Composites Manufacturing FPCM-12*, Enschede, The Netherlands, 2014.

[7] R. Meier, N. Pantelelis, M. Hauber, C. Wolf, K. Drechsler. Process monitoring and control for an aerospace application *Proceedings of the 10th International Conference in Advanced Manufacturing of Composites ICMAC 2015*, Bristol, UK, 2015.

[8] N. Pantelelis, P. Ballocchi, W. Wenger, A. Brødsjø, J. Breuer. Intelligent process monitoring and control: 2 industrial applications. *Proceedings of the 10th International Conference in Advanced Manufacturing of Composites ICMAC 2015*, Bristol, UK, 2015.

[9] C. Lira, M. Holt, D. Fishpool, I. Papasideris, N. Pantelelis. Automating Resin Transfer Moulding. *Proceedings of SAMPE Europe Conference.* Stuttgart, Germany 2017.

[10] M. McLean, M. Stojkovic, A. George, A. Kabachi, P. Ermanni, M. Danzi, C. Lira. Facilitating process simulation through a shared permeability resource. *Proceedings of the 14th International Conference on Flow Processes in Composites Manufacturing FPCM-14*, Luleå, Sweden, 2018.

[11] J. Summerscales. The effect of permeant on the measured permeability of a reinforcement. *Proceedings of the 7th International Conference on Flow Processes in Composite Materials FPCM-7*, Newark, Delaware, USA, 2004)

[12] Y. Luo, I Verpoest, K. Hoes, M. Vanheule, H. Sol, A. Cardon. Permeability measurement of textile reinforcements with several test fluids. *Composites Part A: Applied Science and Manufacturing*, 32:1497-1504, 2001.

[13] N. Vernet, et. Al. Experimental determination of the permeability of engineering textiles: Benchmark II. *Composites Part A: Applied Science and Manufacturing*, 61:172-184, 2014.

[14] E. Fauster, D.C. Berg, D. May, Y. Blößl, R. Schledjewski. Robust evaluation of flow front data for in-plane permeability characterisation by radial flow experiments, *Advanced manufacturing: Polymer & Composites Science*, 4(1):24-40, 2018