PREDICTION AND CHARACTERIZATION OF THE RESIN FLOW AND THE FIBROUS PREFORM BEHAVIOUR DURING LIQUID RESIN INFUSION (LRI)

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ABSTRACT

Direct processes called Liquid Composites Molding (LCM), like Resin Transfer Moulding (RTM) or Resin Infusion Process (LRI, RFI), where liquid resin infuses fibrous preforms, are developed as alternative processes to prepregs to manufacture new types of aircraft structural parts, which tend to be thicker and have more complex shapes. At the present time, around 5 to 10% of parts are manufactured by direct processes and the current trend is to go ahead. Dedicated simulation and optimisation tools are currently under development to control the resin flow and the curing process, reduce the defects and cut costs finally. Particular attention is paid here to Liquid Resin Infusion (LRI) process which looks very promising. A general model to analyse the non-isothermal fluid flow through highly compressible porous media such as fibrous preforms has been recently proposed by Celle *et al.* [9]. One key question is to validate the model. Therefore an original experiment has been set up to follow the resin flow through the preform in industrial conditions and check the basic assumptions of the numerical model. Two different measurement techniques have been utilized : micro-thermocouple sensors and fringe projection technique to characterize the flow. The paper shows that the results derived from both techniques are in agreement and prove that the resin flow is transverse to the preform.

1. INTRODUCTION

Weight saving is still a key issue for aerospace industry. Till now, Carbon Fibre Reinforced Polymers prepregs have been extensively used to lighten aircraft structures, for instance 50% in weight of the B787 and A350 aircrafts is made of CFRP. To reach a weight ratio of 60% of high performance composites in the next aircraft programmes, it is necessary to manufacture lighter thick and complex parts, which are submitted to severe mechanical service loading: wing boxes, support and structural rods, stiffeners, airframes, multipoint junction beams etc.

Direct processes called Liquid Composites Molding (LCM), such as Resin Transfer Moulding (RTM) or Resin Infusion Process (LRI, RFI), where liquid resin infuses fibrous preforms, are developed as alternative processes to prepregs. At the present time, around 5 to 10% of the parts are manufactured by direct processes and the current trend is clearly to go ahead. RTM process consists in injecting resin into fibrous preforms placed between rigid moulds. Therefore, dimensional tolerances and porosity fraction can be kept under control and high quality parts produced. The industrialisation of this process is complex at the present time and refined models are still needed. *Intermediate* processes such as Vacuum Assisted RTM (VARTM) and RTM light combine positive and negative pressures and permit to use semi-rigid moulds. This type of process is adapted to reduce cost but advanced mechanical models taking account of the mould deformations are required. The resin infusion process type (Vacuum Infusion Processing or VIP) can be utilized in flexible conditions, such as in low cost open moulds with vacuum bags in nylon or silicone. This type of process only requires low resin pressure and the tooling is less expensive than RTM rigid moulds. Therefore LRI and RFI processes are suitable for small and medium size companies. Dedicated modelling and simulation tools should be provided to account for the large volume change of the preform when vacuum is applied and pressure is acting onto the vacuum bag. Figure 1 below gives a schematic view of the LRI set-up.

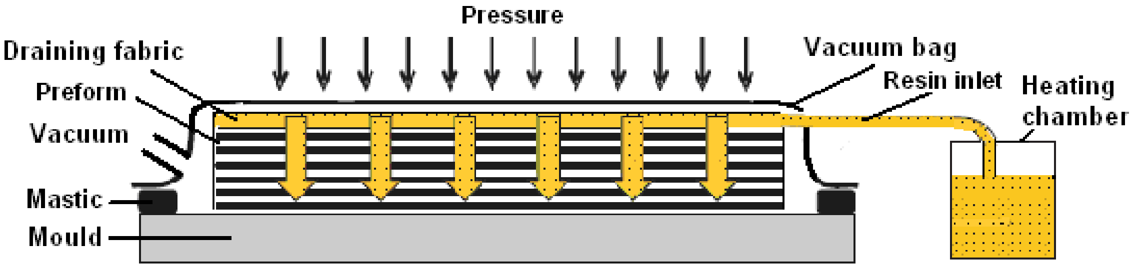

Figure 1: Schematic view of LRI-like process.

The resin flows through the peel ply and distribution layer which is placed above the dry fibrous preform. The assembly is enclosed in a vacuum bag. A punched mold can be employed to improve the surface quality. Then, the pressure and temperature cycles lead to the impregnation of the compressible preform in the transverse direction. The LRI process leads to final part quality improvement since resin infusion and its cure are dissociated. However, the thickness and the porosity of the final part are not controlled because of the use of a vacuum bag instate of a rigid mould and the large variation of the pre-form volume when vacuum and pressure are applied. A new isothermal model which describes the mechanical interaction between the deformations of the porous medium during the resin flow has been developed recently [9]. The paper focuses on a first attempt to validate the basic assumptions experimentally.

2. SPECIFIC NUMERICAL APPROACH OF INFUSION

A complete model for the study of a non-isothermal fluid flow through highly compressible porous media such as fibrous preforms has been proposed by Celle *et al.* [5]. This approach opens the way to the development of refine numerical simulations of real infusion process, taking account of large variations of the preform thickness during the process. The model has shown its ability to deal with the non-linear deformations of fibrous preforms during the compaction step.

In such infusion-based process, liquid resin is supposed to flow through the compressed preform thickness, as a result of the difference between the permeability of the draining ply and the preform. From the modeling point of view, problems of this multi-physical analysis are two fold. Firstly, one faces ill-posed boundary conditions regarding the coupling of liquid regions, where a Stokes flow prevails, with the fibrous preform regions modeled as porous media governed by the Darcy’s law and a non-linear mechanical response. Secondly, the interaction phenomena due to the resin flow in the highly compressible preform are not classical.

A first application of the model is presented in Figure 2 in the case of the Vacuum Assisted Resin Infusion (VARI) of a T-shaped composite beam with permeability orientation and which is one particular manufacturing challenge of aircraft industry. In this case, the resin layer model is not employed. A non linear finite strains behavior is considered and an iterative scheme between Darcy equations and the Lagrangian based-method developed in this study is employed to get the solution for the current time increment.

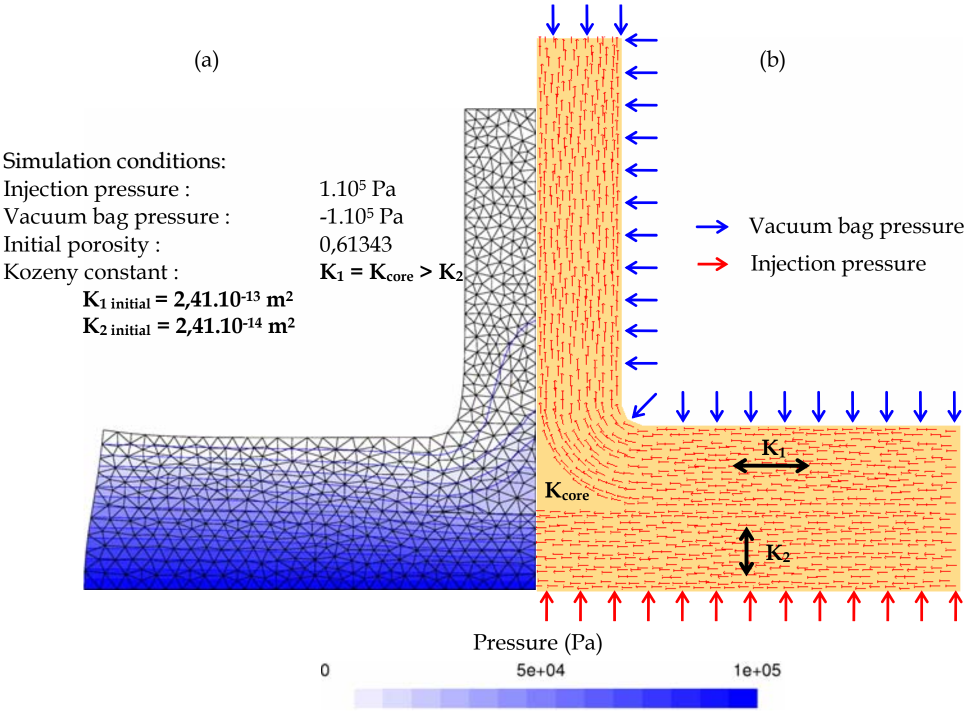

Figure 2: Infusion of a T-shape: (a) pressure distribution - (b) permeability orientation on the original configuration.

The vacuum pressure applied on the stacking is the pressure needed to overcome the constant injected pressure on the lower side. The dilatation of the element near the injected side of the part can be noticed. This is a consequence of the Terzaghi assumption [6]. The fluid flows across the transverse direction and the permeability orientations controls its direction. Two steps have been revealed in this simulation. Firstly, the high decrease of the porosity during the initial compression stage, followed by the porosity increase during the resin infusion.

3. EXPERIMENTAL CHARACTERISATION OF THE FILLING STAGE

It is clear that from such a numerical model, new information can be derived. But the filling process of a preform undergoing compaction cannot be grasped properly without experimental evidence of the phenomena encountered. The aim of this physical model consists in predicting the resin flow front that obviously cannot be followed visually. Few techniques permit to achieve this goal, they usually rely on distributed sensor grids of electrical sensors [3] or optical fibres [4] which lead to complex systems. In the present case, this has been achieved by two complementary techniques: thermocouple sensors distributed within the preform, and a full-field optical measurement method: the fringe projection technique, which permits to measure the thickness changes.

These techniques were both applied on the same experiments conducted using $[90_6/0_6]_S$ composite plates, made of G1157 E01 UD fabric produced by Hexcel Corp. The plates are 6 mm thick, balanced and symmetrical, with in-plane dimensions of 335 mm × 335 mm. For the resin, a HexFlow© RTM-6 epoxy resin has been used. Before infusion, the resin is preheated to 80°C in a heating chamber, and drawn into the draining fabric and the preforms because of the vacuum applied in the vacuum bag connected to the resin inlet (Figure 1).

Experiments presented here were performed by using a heating plate with a lid to maintain a homogeneous temperature field. However, when the optical set up was used, the lid remained open. During the filling stage, a temperature of 120°C is enforced on the heating plate. A curing temperature of 180°C is maintained subsequently for two hours.

3.1 Flow detection using thermocouple sensors

The basic idea of using micro-thermocouples to detect the flow front is that the resin tends to cool down during the flow since it is maintained at 90-100 °C while 120 °C is prescribed to the dry preform. Micro-thermocouples of type-K were used. They are widely used in industry and well suited to harsh environment. The temperature ranges from –75 °C to 250 °C. This type of sensor is composed of 2 wires of 79µm diameter limiting the intrusivity. Data is acquired by a 20 channels 34970A Agilent acquisition unit. The maximum frequency acquisition is 20 values/sec and the resolution 0.1°C. The calibration of the measurement system has been achieved in an oven during 3 isothermal conditions and compared with a platinum probe (PT100). The resolution of this calibration is closed to 0.1°C.

Results presented here illustrate the principle of detection of the resin front. It is expected to be composed of two stages. The first one is the filling of the draining fabric and the second one the filling of the preform across the thickness. The aim of this test was to detect those two types of flow. The composite plate was equipped with 7 thermo-couples, 1 below the draining fabric, 5 in the preform mid-plane, and 1 in the first ply, in contact with the heating plate (Figures 3 and 4).

Time 0 is the beginning of the infusion process and the temperature is first equal to the one of the dry preform. Then, the measured temperatures decrease which confirms the presence of the resin which tends to cool down the preforms. After some time the temperatures rise again to reach a plateau. Assuming, as it will be confirmed by fringe projection measurements (next section), that the minimum of the temperature is linked to the resin arrival, it is noticed that the resin reaches the mid-plane at time 120 s, although a delay of 50s is observed for TC2 (centre of the plate). This delay might be due to race-tracking effects which favour resin flow along the contours first.

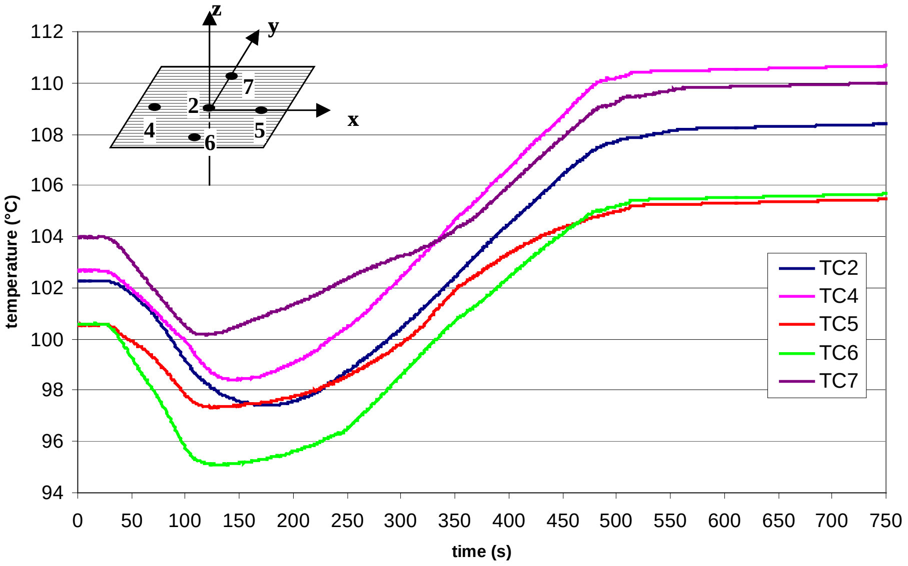

Figure 3: Response *vs* time of the thermo-couple sensors located in the mid-plane.

It is established that the resin infusion is homogeneous through the laminate thickness. Figure 5 shows results across the thickness by using thermocouples along a vertical line going through the centre of the plate. The resin first reaches TC3 at 97s, on ply 24 underneath the distribution layer, and then TC2 in the mid-plane, at 180s. As for TC1, the temperature measured may not be so reliable since the sensor is placed over ply 1, close to the heating plate. But considering TC1 response before and after the critical period, it could be inferred that this response might be of the same form as TC2 and TC3 responses but shifted in time. This point will receive a particular attention in future experiments.

The thermocouple measurements permit to verify that the scenario retained for the numerical model is founded: resin first fills in the draining fabric and then infuses across the preform thickness, filling the plies homogeneously.

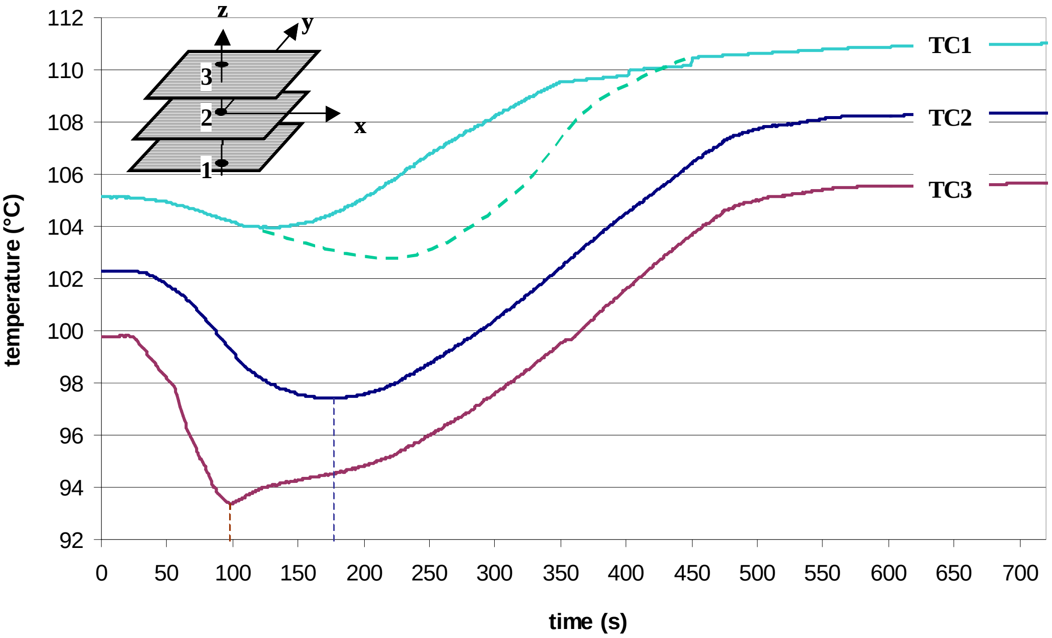

Figure 5: Response *vs* time of the thermo-couple sensors located across the thickness.

3.2 Fringe projection to assess the preform thickness variation during infusion.

The measurement of out-of-plane displacements during the manufacturing process has been performed by using the fringe projection method. The physical principle of the fringe projection method is straightforward: a periodic pattern of white and black lines is projected on an object; the light is diffused by the object and captured by a CCD video-camera. The deformation of the fringes, recorded as phase maps, has a known dependency to the out-of-plane displacements of the illuminated object.

Only a brief summary of the optical set-up is given here [1, 4]. Fringes are projected using a classical video-projector (Figure 6). The images diffused by the plate are captured by a CCD camera connected to a personal computer. Spatial phase extraction is performed using a wavelet repeating 3 times a 12 pixels sine wave. Then, the displacements are estimated by using a local calibration table.

An estimation of the resolution based on a repeatability test gives a value of 0.8 % of one fringe pitch, i.e. a noise level of 36 µm [2]. The spatial resolution, i.e. the mean distance between two statistically independent data, has been determined by using the noise autocorrelation function, with a cut-off set to 0.5. The value is 25 pixels, or 5.7 mm.

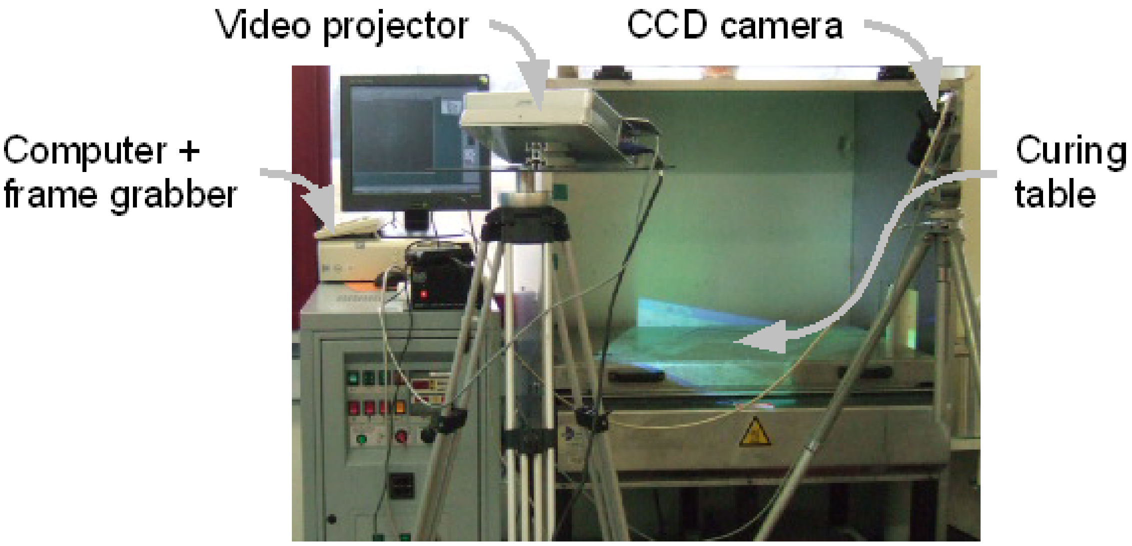

Figure 6. Experimental testing device

The thickness variations are recorded versus time for the whole field. The measured displacements are the sum of all the changes which occur during the process, including shape variations due to temperature variations. In this second experiment 5 areas were selected to follow the thickness change versus time: the four corners, and the middle of the cured plate (Figure 7).

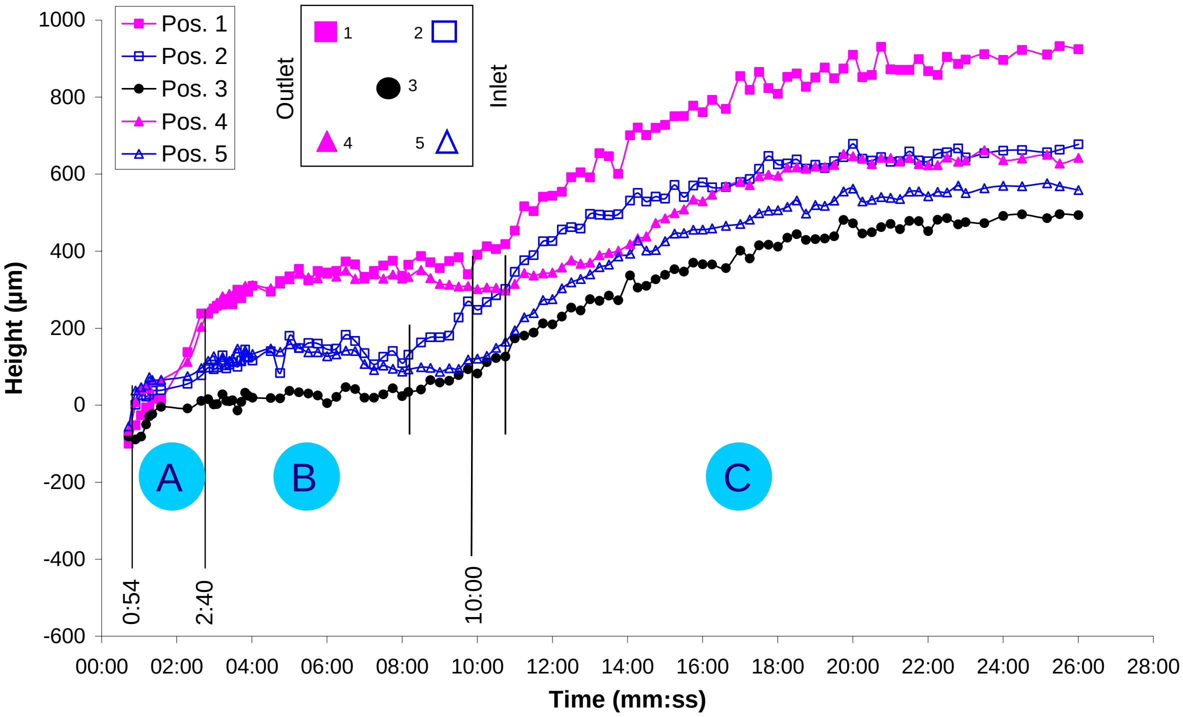

Figure 7. Resin propagation in the draining blanket

The process could be split in 3 parts. Firstly, the resin flows through the draining ply (Zone A), reaching the opposite side after 2min40s. Point 5, the nearest from the inlet pipe, moves first, then point 2 and 4, point 1 and point 3 finally. The resin flows along the preform boundaries first, then through the central part. Secondly, the thickness is more or less stable for the following 8 minutes, zone B. This means that the resin impregnates the system without any significant volume variation. Anyway, resin is still injected in the system, and no resin flow could be observed in the outlet tube. During all the period, resin is filling the voids between the fibre reinforcement.

Then another increase is clearly identified. It begins in the vicinity of the inlet and of the central part of the plate (points 2, 3 and 5) simultaneously, and afterward at the outlet (points 1 and 4). This increase as well as the previous one is almost simultaneous over the plate, referring to the total filling time.

Lastly, the whole preform is filled in (Phase C). Points 1 and 2 and points 3 and 5 underwent similar variations, the increase being less significant at point 4, close to the outlet pipe. From that time, all the voids, *ie* spaces between fibres, should be filled in and the resin excess separates the fibres, giving the final resin volume fraction. The process ends when the resin flows through the outlet pipe (28 min).

Finally, the total thickness increases from 600 to 1006 µm, depending on the zone, when filling in the preform. Spatial variations are about 400 µm, related to the first swelling (from phase A to phase B) and to the second swelling (from phase B to phase C).

4. DISCUSSION

The thermocouples and fringe projection technique results were compared during the same test cases. Consider the case presented in Figures 6 and 7, where fringes projection has been used along with three thermocouples placed in the preform, on the 3rd ply from the bottom, respectively close to the resin inlet, at the centre, and at the resin outlet (Figure 8).

The response of the thermocouple located at the resin outlet exhibits a minimum at 650 s, while the slope of the thickness variation changes at 630 s (Figure 8). One can figure out that these responses are related to the same phenomenon, the arrival of the resin at the bottom of the plate. Indeed, the resin should induce a temperature decrease, for the reasons reported below. Meanwhile, the thickness increases once the resin reaches the bottom of the plate, *i.e.* the swelling takes place when resin has filled in the voids. This corresponds to the change from phase B to phase C in Figure 7.

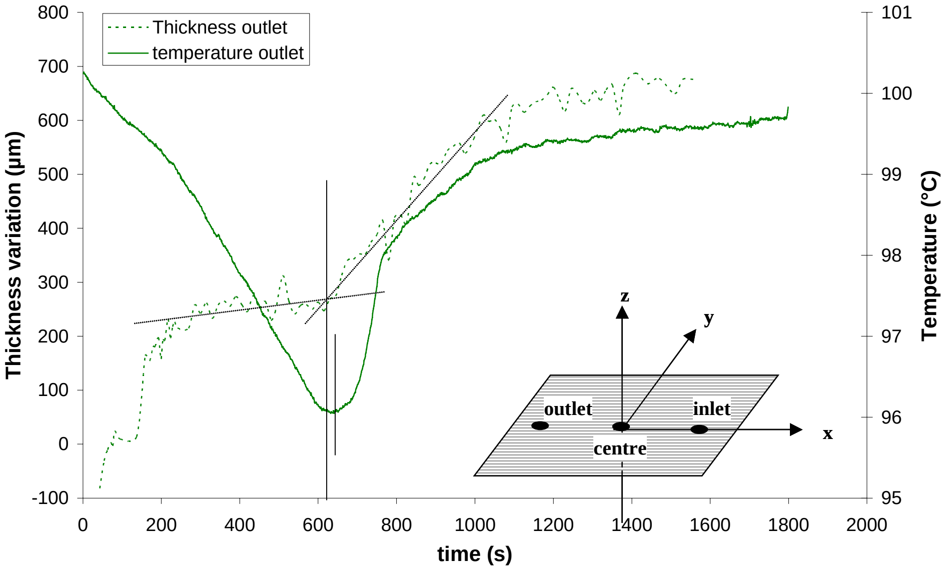

Figure 8. Thermocouple and thickness variation at the resin outlet

This correlation in the thermocouple response and thickness variation is verified for the two other thermocouples (Figure 9). The minima of the temperatures measured by the thermocouples coincide with the thickness change at the vicinity of the inlet and plate central part, although the thickness variation cannot be identified properly. A slight delay is observed regarding the thermocouple minima, at 444s for the inlet, and 470s for the centre. As stated, the outlet is reached 3 minutes later.

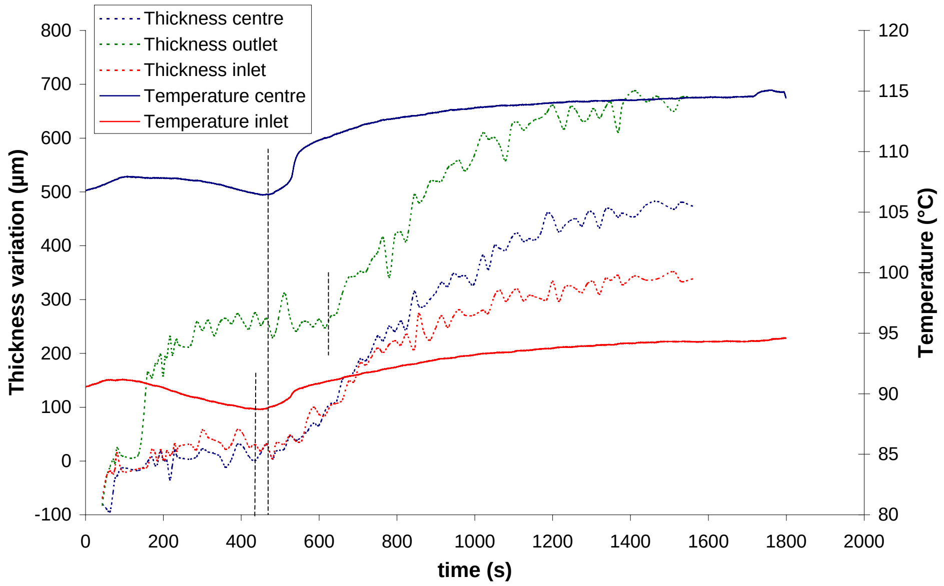

Figure 9. Thermocouple and thickness variation for the 3 locations along the resin flow.

From these two last figures, it can be concluded that thermocouples can detect the resin flow, this is confirmed by thickness variations measurements. In the first test, the lid was maintained closed because no fringe projection was used. From the thermocouple measurements, in that test it seems that resin first fills in the draining fabric before infusing ply by ply across the laminate thickness. However, the lid was opened all along the second test, thermocouples as well as fringe projection technique show that the resin reaches the bottom of the plate at the inlet and centre before reaching the outlet 3 min later. Refined experimental approaches are going on to clarify that point. Especially uncertainties should be characterised.

Eventually, a comparison can be made between experiments and simulations of the filling stage for the last case studied here. Simulations were achieved with 1150 triangle mixed velocity-pressure elements, considering a constant resin viscosity, and representing as precisely as possible the boundary conditions. Starting from the initial thickness measured, 9.8 mm, computations yield a thickness after compaction of 6.17 mm while measurements give 6.18 mm. After the filling stage, computations show a 0.63 mm expansion while a mean value of 0.74 mm is assessed experimentally with the fringe projection. The mass of resin received by the system (plate + distribution layer + pipes …) is 470g experimentally and 410 g numerically for the plate. Regarding the filling times, there is an order of magnitude between measurements and simulations. This is a critical issue of simulations, since it is related at the same time to simulations (mesh dependency, filling algorithm, macroscopical approach, boundary conditions representation, …) and experiments (permeability measurements, temperature control, boundary conditions controlled, …). To sum up, the predictions correlate well both types of experimental measurements regarding the complexity and large number of mechanisms encountered. Only a global numerical framework associated with proper experiments permits to get a deep insight into the mechanisms controlling the filling stage of composite preforms.

5. CONCLUSIONS

The paper referring to new advances in process numerical modelling emphasises the need for advanced experimental characterisation to serve as references to benchmark new simulation tools. Experiments performed in close cooperation with industry are necessary to set up relevant experimental conditions. In the present case, two experiments have been carried out to have a first glimpse into the complex mechanisms occurring during LRI process. Two different measurement techniques have been utilised : micro-thermocouples, with low intrusivity and friendly-user, and fringe projection technique which gives a direct quantitative measurement of the thickness variations. It has been shown that thermocouples are a promising technique to detect the resin flow inside the preform and so to deliver information which can be compared to numerical predictions. However, the full-field measurement technique required some special conditions whose possible parasitic effects should be controlled. Finally, the two techniques point out that the assumption of a uniform transverse resin flow through the preform is reasonable. This is a first support to the numerical model previously developed which demonstrated here its ability to grasp the main physical issues of the filling stage of composites.

Let us note that these measurements were achieved in an industrial framework, and repeatability, especially the boundary conditions have to be mastered. These were some first tests which have to be confirmed by further experiments under progress.

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