MEASUREMENT OF PERMEABILITY AND CURE USING THERMOCOUPLES IN THE VACUUM ASSISTED RESIN INFUSION PROCESS TO AID SIMULATION

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Abstract

This study investigates permeability measurements and cure monitoring in the context of the vacuum assisted resin infusion (VARI) process using a polyester resin system (Crystic 701PA) and non-crimp triaxial glass reinforcement fabrics. An experimental setup has been designed by considering the parameters of the permeability such as flow front advancement, flow rate, pressure gradient, and porosity. In the current work, a multi-thermocouple system is presented and used to monitor the flow front advancement in the VARI process. The thermocouples are low-cost and durable; and demonstrated their ability to detect the flow front position inside the layers of the laminate. Also, the thermocouples provided an in-built monitor of the cure period of the resin after the infusion process. The results of the experimental study were used to inform the PAM-RTM simulations of flow and cure for a typical application case.

1 Introduction

The vacuum assisted resin infusion (VARI) process is a cost-effective method for the manufacture of high-quality composite structures and widely used in the composites industry. The VARI process offers advantages over traditional resin transfer moulding (RTM), such as lower tooling costs, large scale composite manufacturing and room temperature processing [1]. The process exhibits similarities with RTM. However, the important difference is that two-part rigid moulds used in RTM are replaced with a one-part rigid mould sealed with a vacuum bag, as shown in Figure 1. The preform is placed on the rigid mould with a layer of peel ply and a layer of flow-enhancement medium which is used to reduce fill time. After locating inlets and vents, the vacuum bag is sealed to the rigid mould using a sealing tape. Air is extracted by means of a vacuum pump to compact the preform between the vacuum bag and the mould. A pressure differential drives the resin through the compacted preform. The flexibility of, and the resin pressure field beneath, the vacuum bag affect the compaction state of the preform and also alter permeability [2].

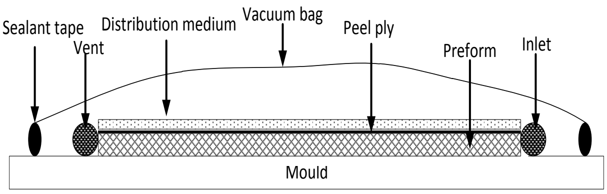


Figure 1. Schematic illustration of VARI method

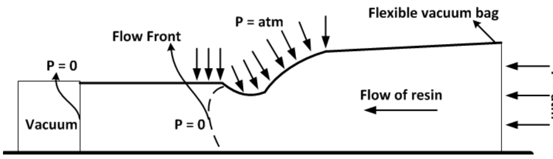


Figure 2. Representation of the resin flow front under a flexible cover

A more complex flow mechanism (Figure 2) is involved in VARI than RTM because of the presence of the flexible bagging film. In the VARI process, the maximum compaction pressure is 1 bar which limits the maximum achievable fibre volume fraction. Also, a pressure gradient occurs between the inlet and vent during infusion that results in a thickness gradient in the flow direction. The thickness gradient results in fibre volume fraction variations. It is important to properly locate the inlets and vents to fully wet out the laminate, avoid creating resin-rich zones (especially near the vents after the inlet is closed), and reduce excessive resin bleeding to minimize waste [3].

The aim of this study is to investigate the processability of the selected resin system with the glass fibre reinforcement in VARI process. PAM-RTM simulation software has been used to compute the experimental results for validation.

2 Theoretical background

2.1 Resin flow through the textile preform

The infusion of the fibrous preform with resin is typically described using Darcy`s law [4], which is formulated as

$$\boldsymbol{v} = -\frac{\boldsymbol{K}}{\boldsymbol{\eta}}\nabla \boldsymbol{p} \qquad (1)$$

where $\boldsymbol{v}$ is the phase averaged (resin + fibres) flow velocity, $\boldsymbol{K}$ is the permeability of the textile material, $\boldsymbol{\eta}$ is the viscosity of the resin and $\nabla \boldsymbol{p}$ is the gradient of the pore-averaged pressure inside the mould. Based on Eq.1, the process parameters for production of composite components can be optimized to achieve complete high quality impregnation, and the cycle times can be predicted [5].

2.2 Compaction of the preform

Because of the flexible nature of the vacuum bag, there is no direct control of the fibre volume fraction of the composite during VARI. It is well accepted that during resin infusion, the total compaction pressure ($\boldsymbol{P_{total}} \approx \boldsymbol{1\ atm}$) is shared between the resin pressure ($\boldsymbol{P_{resin}}$) and the pressure supported by the reinforcement ($\boldsymbol{P_{reinforcement}}$).

$$\boldsymbol{P_{total}} = \boldsymbol{P_{resin}} + \boldsymbol{P_{reinforcement}} \qquad (2)$$

2.3 Fibre volume fraction

The fibre volume fraction can be calculated according to

$$\boldsymbol{V_f} = \frac{\boldsymbol{NW_f}}{\boldsymbol{h\rho}} \qquad (3)$$

V_f is the fibre volume fraction, W_f is the weight per unit area of the fabric, h is the thickness, ρ is the density of the fibres.

3 VARI process monitoring methodology

Process monitoring plays a crucial role in the VARI process as it significantly affects the repeatability of the process cycle and the quality of the resulting composite. Monitoring the resin flow helps to detect the flow front propagation and dry spots and to sure the manufacture of fully cured high quality composites. The most frequently used sensors for these purposes are thermocouples, dielectrics, ultrasonics, fibreoptics, point and lineal voltage sensors and SMARTweave [6].

In this study, one camera on each side (top and bottom) and thermocouples (between the layers of the preform) were used to monitor the resin flow. A transparent mould (glass) was chosen to monitor the resin flow beneath the preform. The in-built thermocouples inside the preform also measured the cure period of the resin. In order to calculate the porosity ($\varphi = 1 - V_f$) by using Eq.3, variation of the thickness (h) along the preform was measured by means of LVDTs. Compaction experiments on the preform and the resin pressure distributions in PAM-RTM simulations helped to obtain the preform compaction and the resin pressure data.

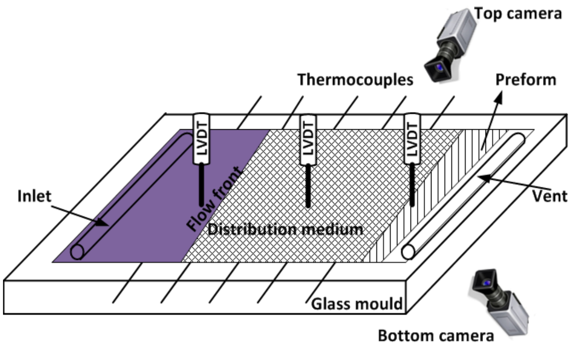
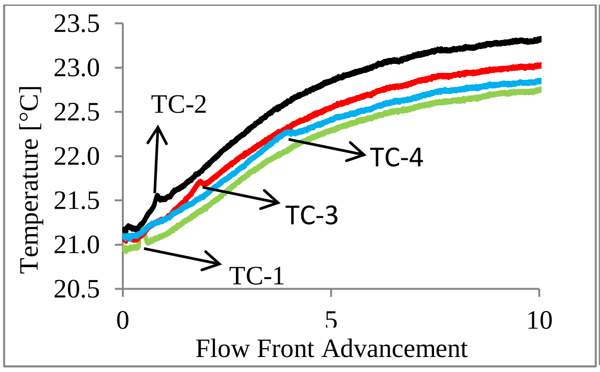
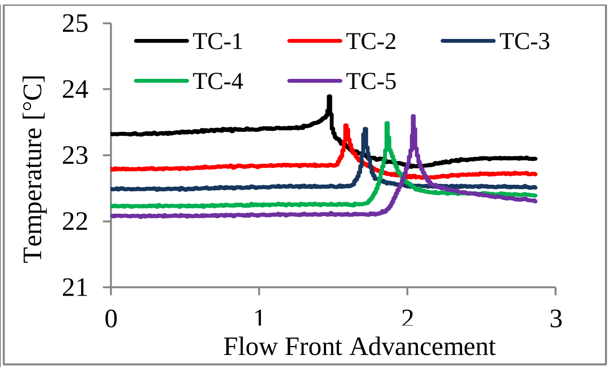


Figure 3. Monitoring methodology of the VARI process

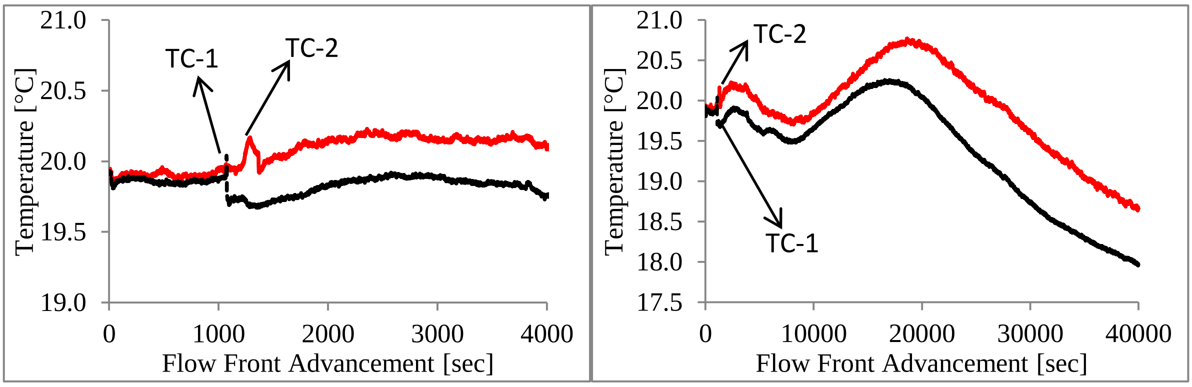
The in-built thermocouples detected flow front advancement without needing any temperature difference. A preliminary study with 6 layers of glass fabric reinforcement was conducted to observe the repeatability of the measurements with thermocouples placed between the inlet and vent. Peaks or spikes in the thermocouple data indicate the presence of the infusion fluid. This behaviour was repeatable for different viscosity fluids (corn syrup-Figure 4a, machine oil-Figure 4b, and polyester resin-Figure 4 c and d). However, it was noted that the nature of the curves varies depending on the viscosity of the fluid.



a) Corn Syrup (η=3.5 Pa*s)



b) Machine oil



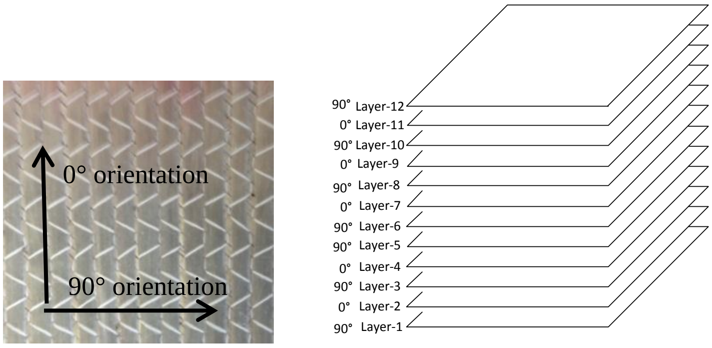
c) Flow front detection of polyester resin (η=0.2 Pa*s) d) Polyester resin curing for 11 hours

Figure 4. Flow front detection by the help of thermocouples (representative data)

4 Experimental work and simulation

4.1 Experimental

Flat panels (45cm x 15 cm) were fabricated by the VARI process using Devold triaxial non-crimp E-glass fibre reinforcement (817 g/m^2) and Crystic 701 PA polyester resin supplied by Scott Bader. Low processing temperatures and extended pot life at room temperature were the main characteristics of this low viscosity resin system. The pot life of the resin with 1.5% Catalyst M (Butanox M50) is given as 158 mins. Thermocouples with a diameter of 0.2 mm were chosen to minimize the flow distortion inside the laminate. The thermocouples (Figure 6) were only used in the multi-layer preform infusion experiments.



a) b)

Figure 5. Orientation (a: single layer, b: multilayer preform)

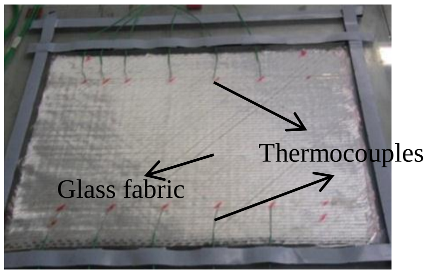
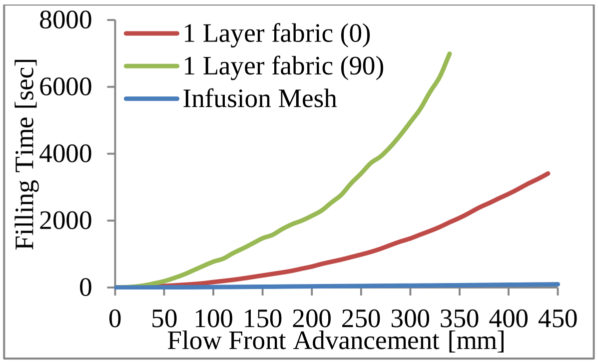
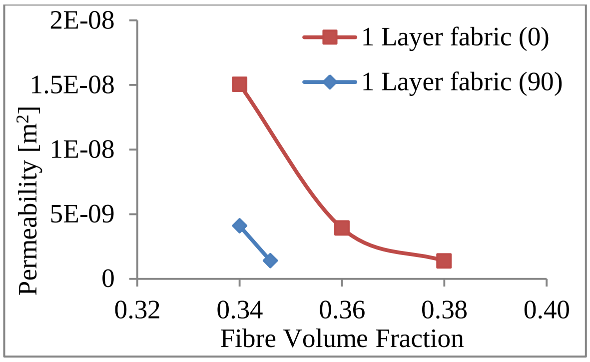


Figure 6. Location of thermocouples between layers of reinforcement

Due to the inhomogeneity of the triaxial fabric, two orientations were defined (Figure 5a). Single layer infusions without infusion mesh were carried out to examine the permeabilities in the 0° and 90° orientations of this triaxial fabric. The flow front stopped after wetting 75% (350mm) of the 90° orientation fabric (Figure 7a). This test was carried out twice and the results were similar. The complete filling time was noted as 3252 seconds for the 0° orientation fabric and 98 seconds for the infusion mesh. 0° orientation fabric was completely infused with higher permeability values (Figure 7b). This result is expected as the orientation of the fibres parallel to the flow direction would aid the infusion process.



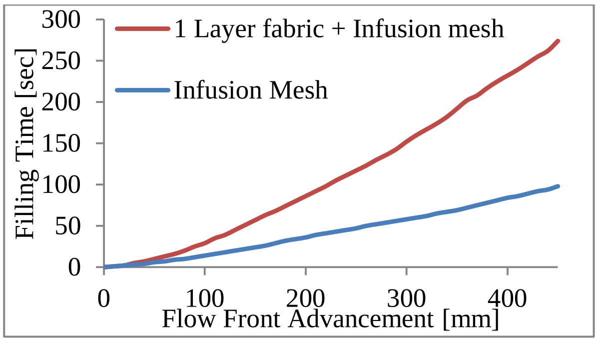
a) Flow front



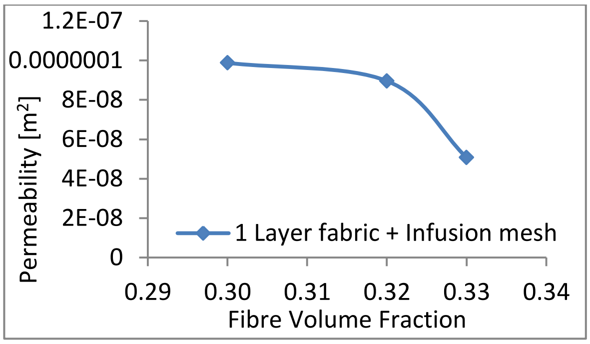
b) Permeability

Figure 7. 1 layer fabric infusion analysis

Single layer tests were also carried out incorporating the distribution mesh. The filling time was noted as 280 seconds with the single layer preform (Figure 8a). As expected the permeability was much higher in comparison to one layer fabric infusions without the distribution mesh (Figure 8b).



a) Flow front



b) Permeability

Figure 8. 1 layer fabric with infusion mesh

Because of the variations in permeability and filling time in two different directions, multi-layer (12 layers) infusion experiments were conducted by placing the fabrics as shown in Figure 5b to obtain a homogenous structure. Infusion experiments were carried out with and without infusion mesh. Thermocouples were located between layers 4 and 5, and layers 8 and 9. Figure 9 shows the filling time versus flow front advancement for the 12 layer preform without infusion mesh. Top and bottom represents the camera measurements of resin front position. Thermocouple measurement results are also shown in Figure 9.

In this case, two different catalyst contents were used to evaluate the processing times of the polyester resin. The flow front stopped after filling 55% of the mould when infusing with polyester resin with 2% catalyst. However, the preform was fully impregnated with 1% catalyst content with higher permeability values (Figure 10).

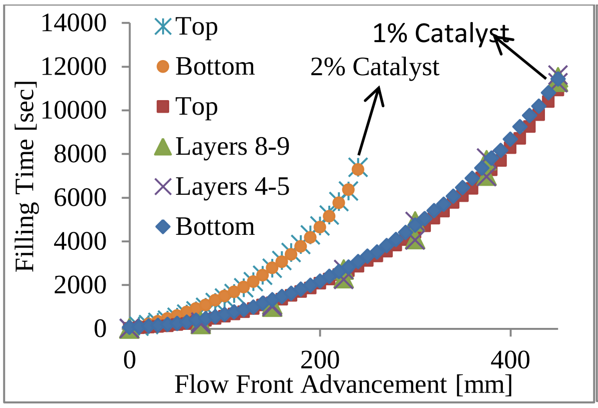


Figure 9. 12 layers preform infusion

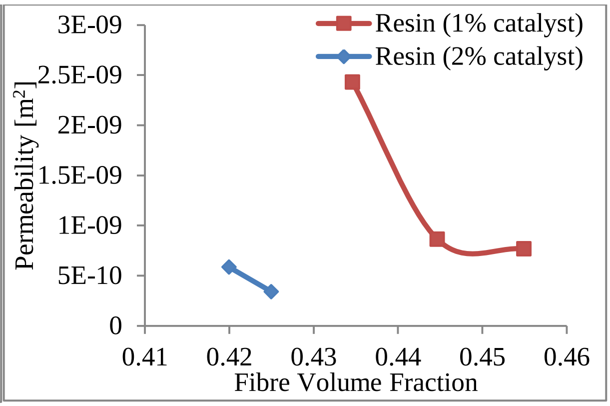


Figure 10. Permeability vs fibre volume fraction for 12 layers fabric infusion with 1% and 2% catalyst contents

The higher permeability of the infusion mesh reduced the total filling time (Figure 11). Because of the significant differences between the permeability of the infusion mesh and the permeability of 12 layers preform, the flow front advances first through the infusion mesh and lags in the reinforcement. This lead-lag effect can be seen in Figure 11 and Figure 12a where the filling time observed for the bottom of the mould is much greater than the top where the distribution mesh is located. The pressure variation is shown in Figure 12b.

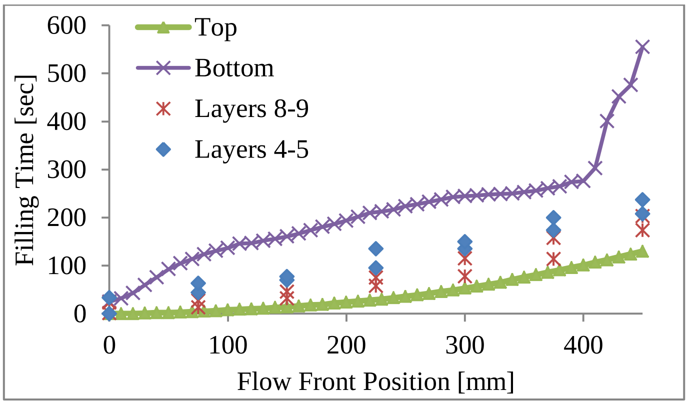
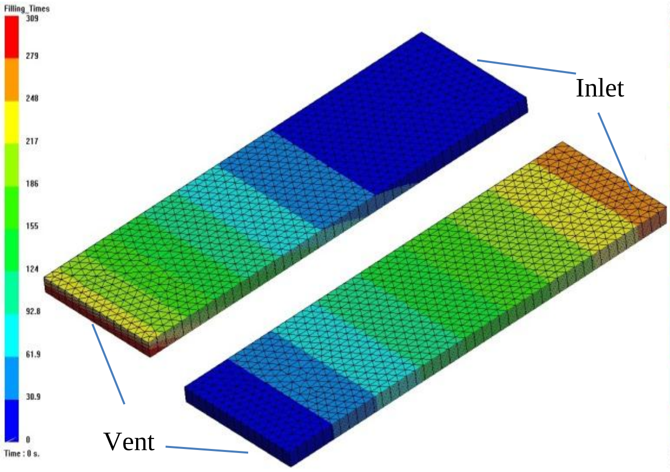


Figure 11. Flow front position for 12 layers fabric with infusion mesh

4.2 PAM-RTM simulations

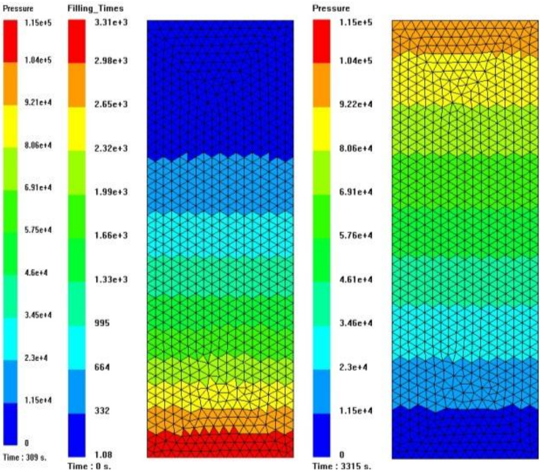
PAM-RTM 2011 is a simulation software package developed by ESI Group and was used for the simulation of resin flow and cure. The VARI module was selected because of the interaction between compaction pressure and fluid pressure which results in thickness variation. The required inputs were: i) density and viscosity of resin, and ii) thickness, porosity, and permeability of reinforcement. The outputs are: i) location of flow front with respect to time, ii) resin pressure with respect to time and location and iii) fill time.

Experimental data was used to inform the PAM-RTM simulations. The preform was represented by shell elements (450mm x 150 mm) with two groups of nodes representing inlet and vent. Visual Environment 7.5 software (from ESI group) was used to mesh the structures. Also, the RTM module was used by taking average permeability and porosity results from the experimental data for 3D flow simulations (Figure 12).



a) Filling time (seconds) b) Pressure (Pa)

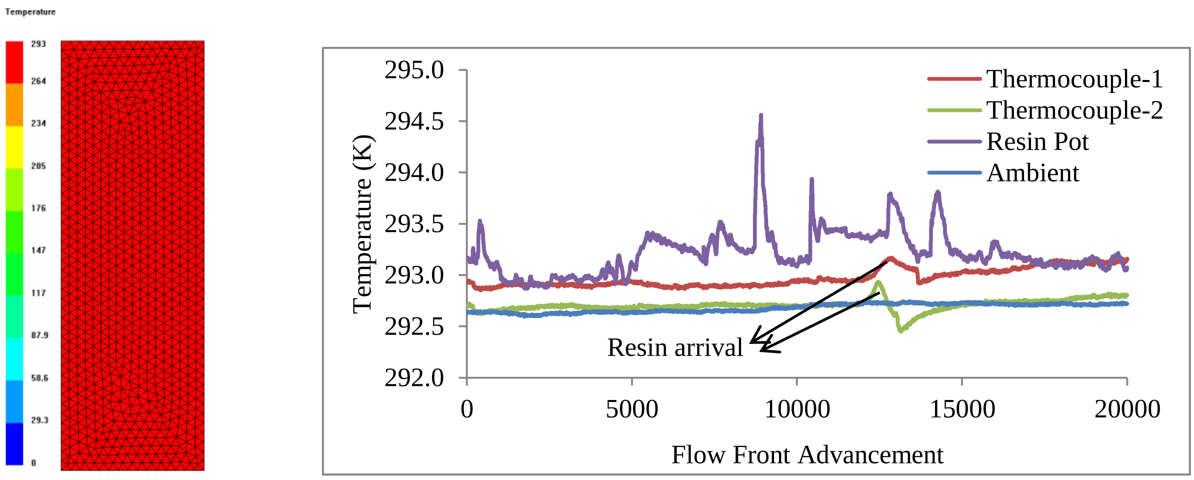
Figure 12. Resin flow analysis in PAM-RTM with solid elements (12 layer fabric)



a) Filling (seconds) b) Pressure (Pa)

Figure 13. Resin flow analysis in PAM-RTM with shell elements (1 layer fabric, 0° orientation)

PAM-RTM simulations helped to validate the experimental results (Figure 12a and 13a). Also, the pressure profiles shown in Figure 12b and 13b were obtained and used in the experimental data to plot the permeability graphs. The simulation of the experiment plotted in Figure 7 for the 0° orientation single layer fabric is shown in Figure 13. The filling time in the experiment was measured as 3252 seconds and it was 3310 seconds in PAM-RTM simulations. The total filling time was around 500 seconds for the 12 layer fabric with an infusion mesh (Figure 11), and it was simulated as 309 seconds in the simulations (Figure 12a). The difference between the different filling time between the experiment and the simulation can be attributed to the specification of the meshing of the 3D structure or the use of RTM module instead of the VARI module for the simulation of the VARI experiment.



a) PAM-RTM simulation with solid elements (Kelvin) b) Experimental

Figure 14. Temperature-cure monitoring

By using the specifications of the resin (viscosity versus temperature, density, specific heat, and thermal conductivity), reinforcement and the process Figure 14a was simulated in Kelvin. In the experimental results, the resin temperature was similarly around 293K (Figure 4d and 14b) during its cure period.

5 Conclusion and discussion

Since this is an ongoing project, the following points can be concluded based on the preliminary results with polyester resin:

- Development of novel fire retardant resin systems is a part of this EPSRC project and their processability with the glass fabric reinforcements is the scope of the current work, which will be followed by fire performance tests (combined with loading) of glass fibre composites impregnated with new resins.
- In order to ensure the quality of the test panels before the fire testing, the permeability and the cure monitoring methods have been studied in this work.
- An experimental setup has been developed and flow simulation software developed by ESI group has been chosen for the simulations.
- In PAM-RTM, the VARI module supports shell elements and can be used for 2D simulations. The RTM module supports both shell and solid elements and the flow front through the thickness can be simulated by using solid elements. In order to use the RTM module, average data from experiments have been used for the simulation of 3D flow.
- In the experiments, a multi-thermocouple system was chosen as a sensing method of flow front and temperature. Thermocouples are cost effective and demonstrated their ability to detect the flow front without needing temperature difference.
- Polyester resin, corn syrup and machine oil have been examined in this study to get some preliminary results. This study will be extended further by using new resin systems as a future work.

Acknowledgement

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