MONITORING AND CONTROL FOR LIQUID COMPOSITE MOULDING

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ABSTRACT: A dielectric monitoring system has been developed for the real-time sensing of composite manufacturing processes. In addition, optimised durable non-intrusive interdigitated dielectric sensors have been designed and manufactured for the sensing of resin arrival, viscosity changes and resin cure. The cure sensors receive the appropriate AC stimuli from the monitoring system while the feedback is recorded and processed by the system providing real-time material state-based information (viscosity, degree of cure etc.). The flow sensors receive DC stimuli for fast and accurate location of resin arrival. A combination of neighbouring flow sensors is capable of providing the flow front direction and velocity, which is a valuable information for flow control. Furthermore the flow sensors can sense the viscosity variations providing a useful indication for the cure evolution until gelation.

KEYWORDS: Dielectric measurements, durable sensors, cure monitoring, flow sensing, control.

BACKGROUND

Several algorithms for the automatic control of the filling phase e.g. [1, 2, 3] and the curing phase e.g. [4, 5, 6] have been presented in liquid composite moulding. However, it seems that there is still a lack of intelligent sensors that could provide more information to the control algorithms. The development of the present flow sensor has been based on the existing platform of the dielectric cure monitoring system VI-DiAMon developed by Inasco Hellas.

The dielectric process monitoring system, as shown in Figure 1, has been successfully compared with an off-the-self high-quality dielectric analyser in static and dynamic tests. The static tests showed the excellent performance of the system over a wide range of impedances and at measurements over the frequency range 0.2 Hz to 100 kHz. The use of this system for room and high temperature cured epoxy resins for everyday production proved its robustness and capabilities to detect the major process milestones: resin arrival, minimum viscosity, gel point and end of cure, as shown in Figure 2.

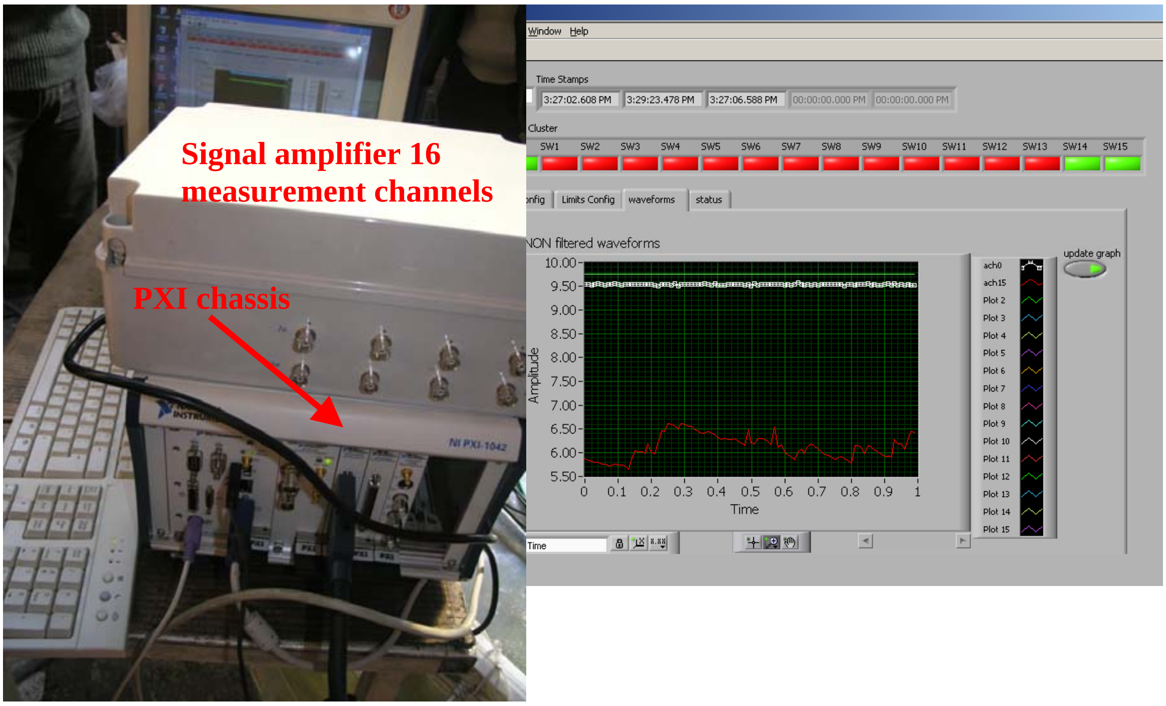

Fig. 1. Hardware and software for the VI-DiAMon process monitoring system

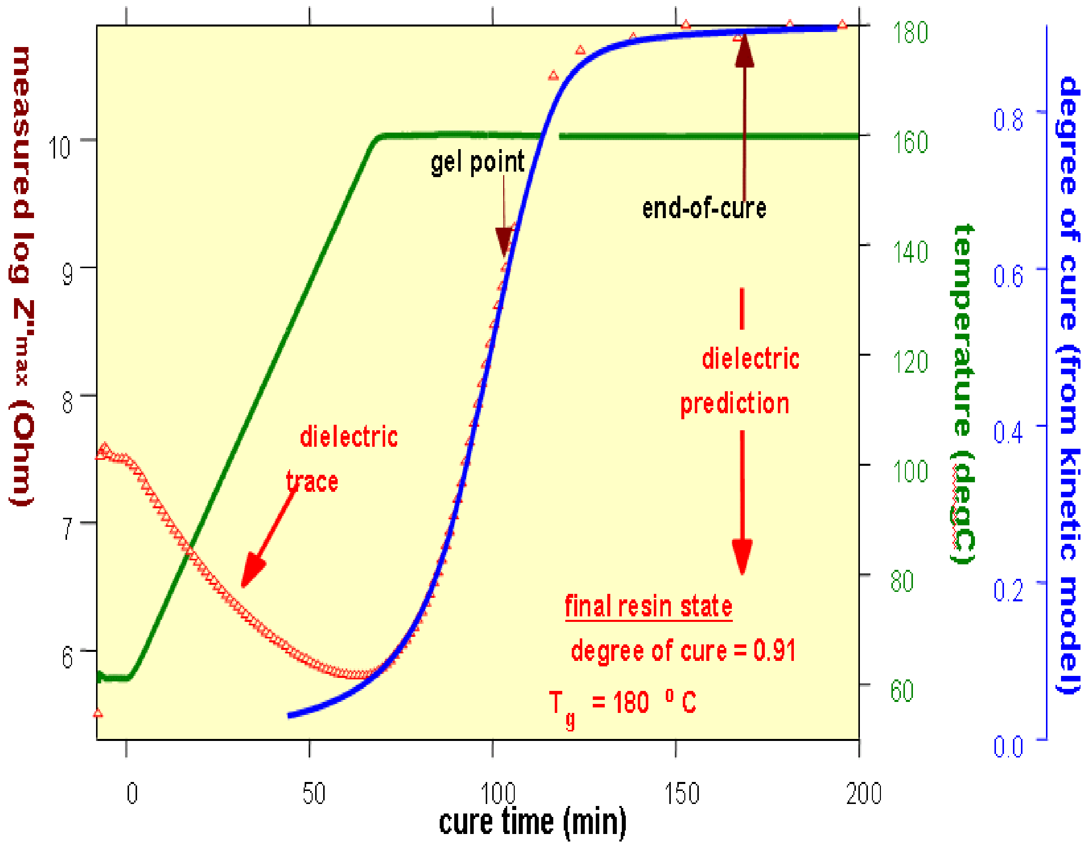

Fig. 2. Evolution of the VI-DiAMon dielectric signal (red line, left vertical axis), the kinetically estimated degree of cure (blue line, right vertical axis) for the RTM6 resin temperature profile (green line, right vertical axis).

In parallel, optimised durable dielectric sensors have been designed and manufactured as shown in Figure 3. Both the cure sensor (see Figure 3, left) and the integrated cure and flow sensor (see Figure 3, right) receive the appropriate (AC or DC) signals from the monitoring system and their feedback is recorded and post processed by the system providing real-time material state-based information.

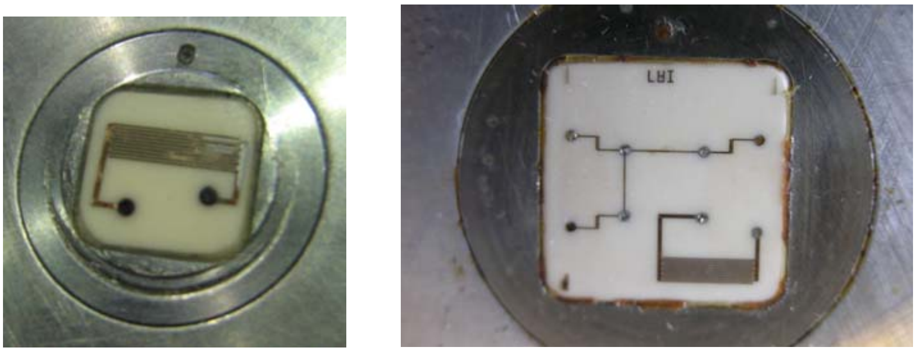

Fig. 3. A durable cure (left) and an integrated (right) dielectric sensors.

FLOW SENSING

In liquid composite moulding techniques there is a real need for sensors that not only inform the production supervisor with resin arrival at some location but also provide as much information as possible of what's happening inside the mould in order to use this information in a real-time control loop. As the installation of such sensors is not an easy task in real production environment, it is very important that one sensor can provide as much information as possible. So the new integrated sensor with flow and cure sensors shown in fig. 3 can provide information on:

- Resin arrival (flow sensor)
- Flow front velocity (flow sensor)
- Flow front direction (flow sensor)
- Viscosity changes (flow sensor)
- Gelation, Vitrification and end-of-cure (cure sensor)

The flow sensor comprises three couples of parallel contacts, which are fed with an appropriate DC signal and from the feedback of each couple resin arrival and viscosity changes can be detected. The hardware can scan the couples every 0.1 s so a very accurate time stamp of the resin arrival at the exact contact spot can be measured. As these contacts are very small the combination of three of them in an orthogonal triangle can provide the accurate calculation of the local velocity and the direction of the flow front using the formulae:

$$U = \sqrt{\frac{\left[(x_B - x_A)^2 + (y_B - y_A)^2\right]\left[(x_C - x_A)^2 + (y_C - y_A)^2\right]}{\left[(x_B - x_A)^2 + (y_B - y_A)^2\right](t_C - t_A)^2 + \left[(x_C - x_A)^2 + (y_C - y_A)^2\right](t_B - t_A)^2}} \quad (1)$$

$$\phi_x = 90^o - \tan^{-1}\left(\frac{(t_B - t_A)\sqrt{(x_C - x_A)^2 + (y_C - y_A)^2}}{(t_C - t_A)\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}}\right) \quad (2)$$

where *x* and *y* are the corresponding coordinates of each flow sensor's switches with respect to a common local (or global) coordinate system and t_i are the corresponding time stamps of resin arrival.

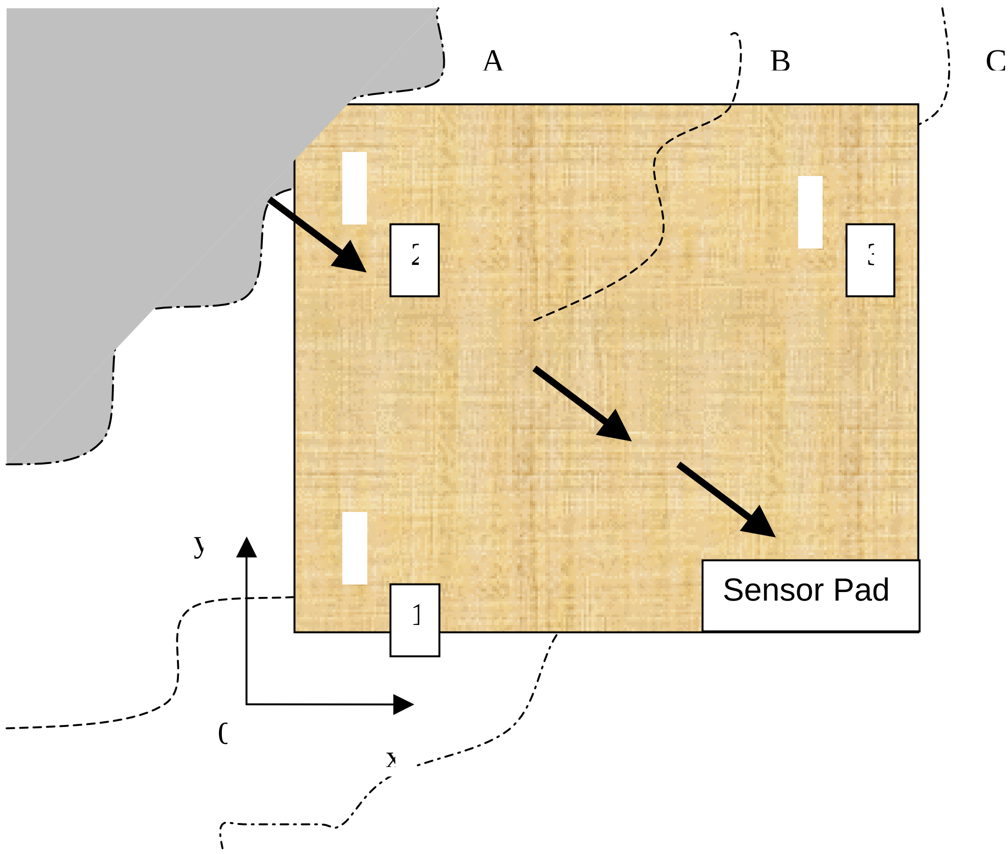

Fig. 4. Schematic of flow front advancement over the flow sensor. The resin arrival time stamps at flow couple locations 2, 1 and 3 are defined by instants A, B and C, respectively.

CONTROL ISSUES

The real-time availability of flow front velocity and direction can reveal valuable information for the current filling pattern and how fast the flow front evolves. Based on this information the supervisor or the automatic control software can make appropriate control actions if these are required. For example, if a dry spot area is expected at a specific region a flow sensor can be installed at an appropriate location in order to sense if there is an on-going formation of the dry-spot or it is a normal filling. In the case of dry-spot formation appropriate measures can be taken to restore the quality of the filling. For the model-based control which is under development for the automatic control of the filling process, the availability of such integrated information is very important for the performance of the control strategy.
Furthermore, the possibility of monitoring viscosity changes with the flow sensors provides a significant advantage as the cure measurements are particularly demanding of CPU and hardware requirements. In contrast, the use of DC-signal for flow sensing is much simpler and faster so various configurations are possible according to the production requirements.

RESULTS

In order to assess the robustness and the accuracy of the flow and cure sensors many trials have been executed with variable fibre volume fraction, type of fibres, type of fabrics and resins for the two main closed mould liquid moulding processes, RTM and vacuum infusion.

Flow Front Sensing

In the case of vacuum infusion a small composite part with 6 heavy biaxial NCF glass fabrics were infused. As shown in figure 5 the resin enters from a line feeder on the right of the part whereas vacuum was applied on the left. Although the resin flow front seems evident due to the transparent vacuum bag this represents only the flow front at distribution media. Based on the feedback signal from a four-switch flow sensor installed at the bottom of the tool there is a significant time lag between resin arrival at the top and the bottom of the part. In figure 6, the feedback signal of the integrated sensor is shown, while, based on the formulae (1) and (2) the local flow front velocity has a magnitude of 0.28 mm/s speed and an angle of 60^o with respect to the local x-axis. The difference on the signal levels over the sensor contact points is due to the variability in the distance of the contacts of the prototype sensor.

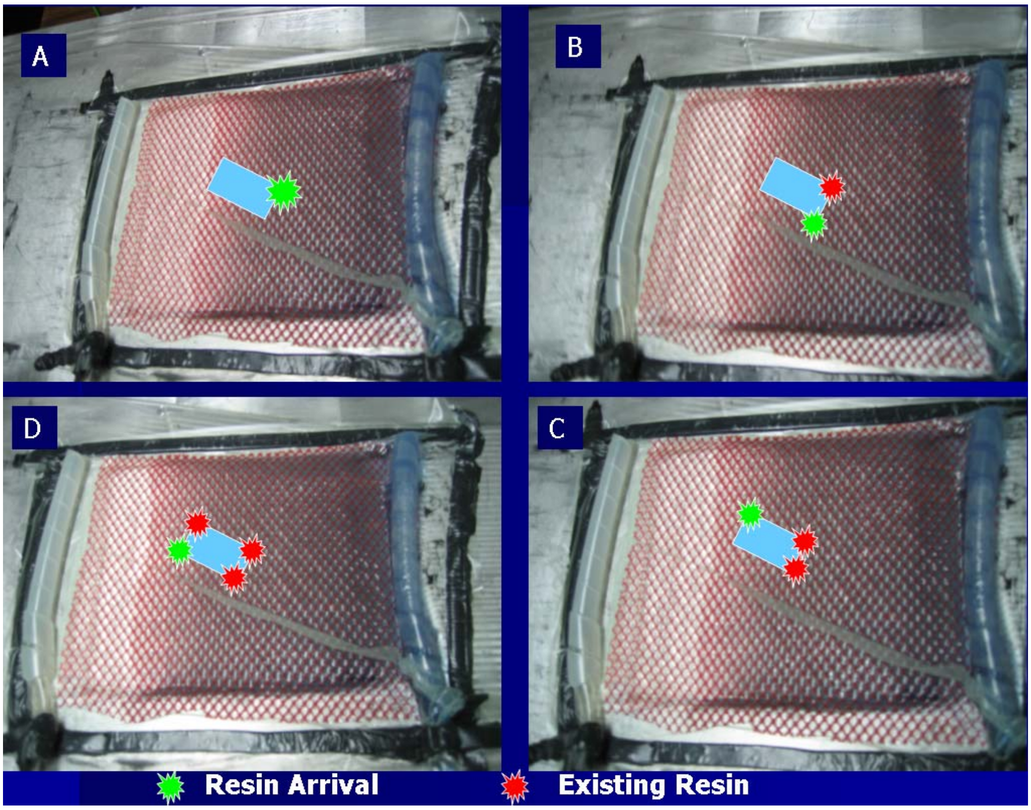

Fig. 5. A: Resin arrival at flow sensor point No 1, B: Resin arrival at flow sensor point No 4, C: Resin arrival at flow sensor point No 3, D: Resin arrival at flow sensor point No 2. The points are located on the sensor as indicated in Figure 6.

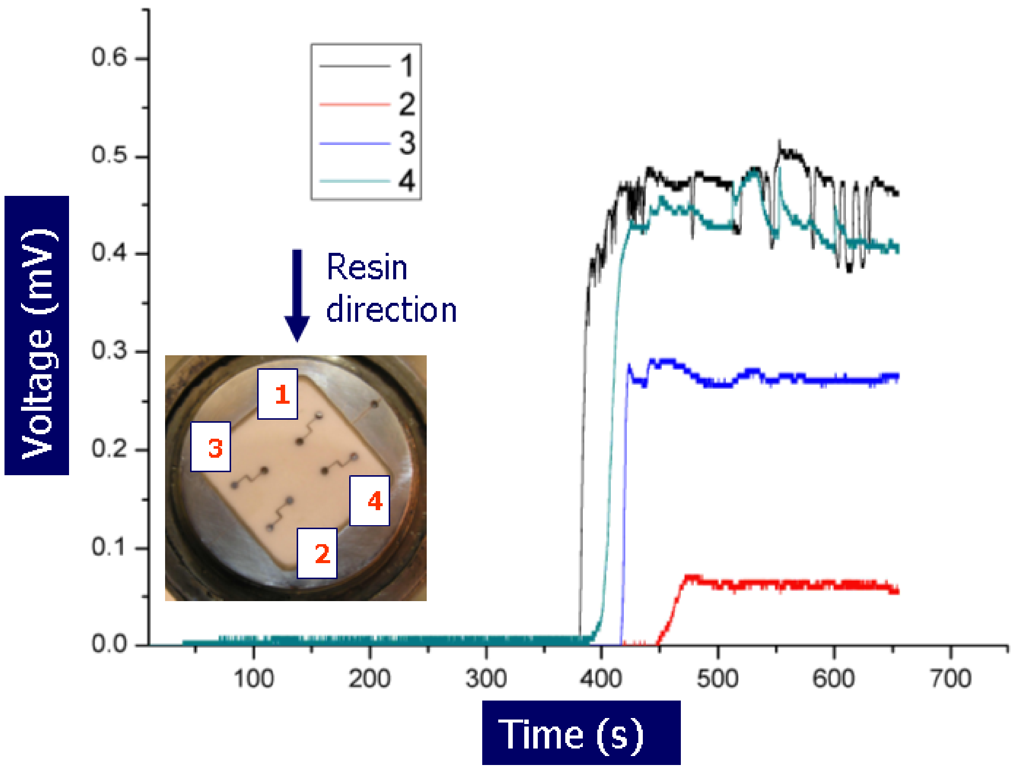

Fig. 6. DC feedback signal monitored at the four switches on a flow sensor during the resin injection.

Viscosity Changes

When the flow front has passed over the flow sensors, they continue supplying important information, such as the resin viscosity changes at the location of the sensor contact points. In case there is no cure sensor involved, this information is particularly useful as it provides a reliable indication of the hardening of the resin up to the gel point. This capability can be seen in fig. 7 at the monitoring the cure reaction of an epoxy single component system (Cycom 890 by Cytec) initially for 20 min at 80^{o}C and then a heating ramp with 1^{o}C/min. As the resin viscosity drops towards the maximum flow point the cure sensor shows a continuous drop of the max imaginary impedance whereas the three flow couples (switches 1, 2 and 3) show a continuous increase of the voltage measurement resulting from the reduction of the apparent resistance of the resin. After the maximum flow point the viscosity starts to rise again so the corresponding feedback signals from the flow sensor decrease while that of the cure sensor increase.

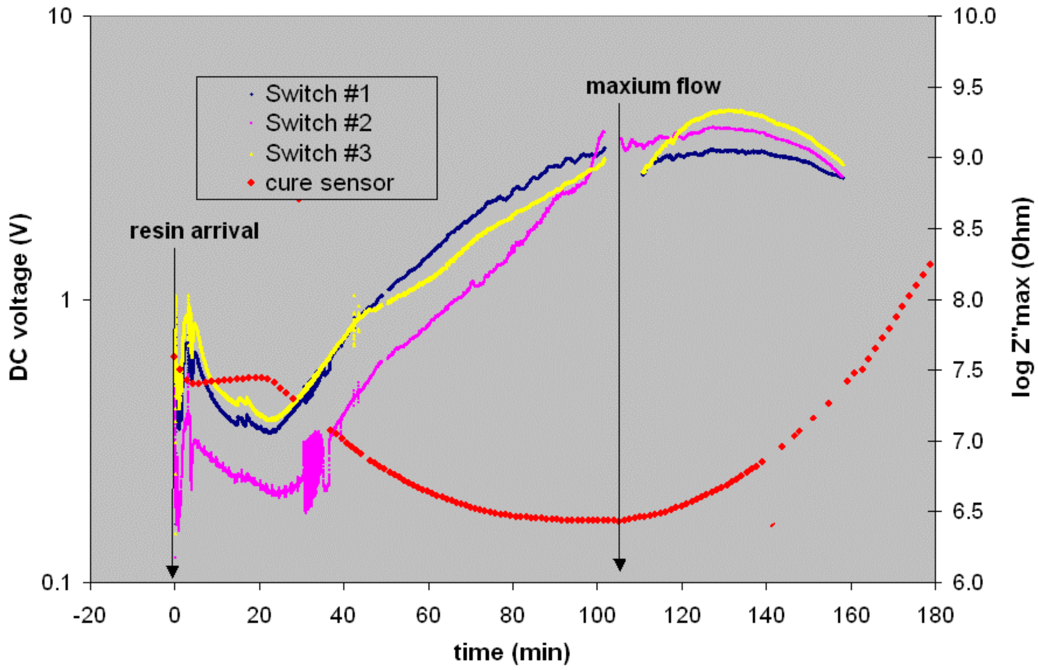

Fig. 7. Feedback signals at three flow sensing (left axis) and one cure sensing (right axis) locations on an integrated sensor during resin injection and isothermal curing of the Cycom 890 Cytec epoxy resin.

In fig. 8 a much faster epoxy resin has been tested using the same integrated sensor during injection and isothermal curing. In this case there is no maximum flow point observed but as the viscosity increases there is a steady decrease of the flow sensors signal in contrast to the continuous rise of the cure signal. As expected the flow sensors signal levels are nullified after gelation, so that vitrification and end-of-cure monitoring can be performed only by the cure sensor.

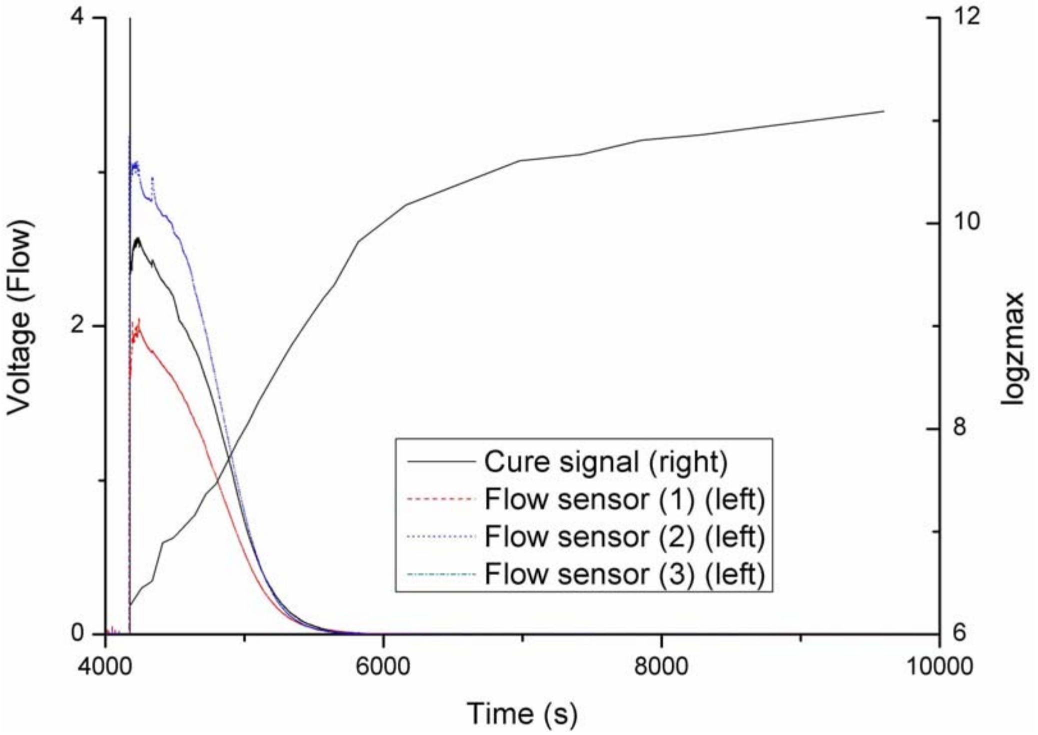

Fig. 8. Feedback signals at three flow sensing and one cure sensing locations on an integrated sensor during resin injection and curing for a fast-reactive two component epoxy system.

For the handling of carbon fibre parts, a non-conductive fabric of appropriate thickness should be used over the cure sensor to avoid short-circuit of the dielectric field. However, the flow sensor is not affected so much by the existence of carbon so a very thin non-conductive fabric is enough to provide robust measurements.

DISCUSSION

Valuable information of the processing status has been provided by the newly developed integrated flow and cure sensor with the relevant hardware and software. The sensor is robust, non-intrusive and durable providing a reliable basis for real-time control.

This information will be combined with a model-based control algorithm developed in parallel within the same project and will provide an intelligent system for the automatic and optimal processing of composite materials.

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