RESIN TRANSFER MOLDING PROCESS MONITORING AND CONTROL

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ABSTRACT

Resin Transfer Molding (RTM) offers the opportunity for significant cost savings in the fabrication of polymer matrix composite aerospace structures. However, the realization of this cost savings has been restricted by quality problems, such as voids, poor fiber volume control, etc., that are inherent to the RTM process. Similar quality issues in autoclave processes have benefited from the use of advanced process control systems such as the Air Force developed "Qualitative Process Automation" (QPA) and Aerospace Service and Control's "Composite Processing Control" (CPC) systems. These advanced systems utilize sensor feedback and a knowledge base to make control decisions and manage the process in real-time with the goal of improved end-product quality. An intelligent RTM control system based on the QPA approach has been developed. This paper presents the feasibility demonstration of its implementation on the CPC control system. A dc-resistance sensor grid was used to monitor the flow front in real-time from discrete measurements of sensor wet-out time. The CPC system was able to predict the flow front progression and alter the shape of the flow front either by zoned temperature control or by controlling resin feed rates through multiple injection ports. The same sensor grid was also capable of monitoring the cure state of the resin.

KEY WORDS: Composites, Cure Monitoring, Equipment and Machinery, Process Control, Resin Transfer Molding

1. INTRODUCTION

Resin Transfer Molding is a process where resin is injected into a closed cavity mold that is filled with a fiber reinforcement (referred to as a preform). Historically, RTM processes were the domain of manufacturers that specialized in low fiber volume (< 45%) and low performance resin systems. The aerospace industry considers RTM a process that can significantly reduce the cost of composite structures. However, aerospace structures need to have a fiber volume greater than 50% and high performance resins must be used. Both these two requirements create problems for the RTM process. Voids, lack of fiber wet-out and dry spots are some of the more common problems that are encountered. Although higher performance components have been fabricated, these processes have used very high pressures which require expensive equipment and tooling.

Considerable effort is being put into understanding the transport phenomenon of resin flow through a high fiber volume preform (>50%) and the factors associated with the successful injection of resin. Most studies center around modeling of the flow of resin through the fiber preform. The results are used to select locations of injection ports, vent ports and secondary injection/vacuum ports. Although the modeling of flow has been successful for well defined conditions, it is difficult to model the local variations in permeability, temperature, and resin state that can give rise to quality problems. The limitations of the models typically lie in the assumptions of constant permeability of the preform and isothermal condition with constant viscosity of the resin. In reality, permeability is not soley determined by the fiber volume of the preform but is also affected to a significantly extent by fiber orientation and the geometric shape of the preform. Preforms of the type used in aerospace structures are complex and frequently involve non-uniform permeability. It is very difficult and expensive to determine the permeability distribution throughout a preform. It is even more difficult, and impractical, to ensure that every preform has the same permeability distribution. For many processes, the resin viscosity can vary not only due to temperature variations, but also as a result of curing of the resin. Therefore, while modeling gives a first approximation of the mold filling process that provides insights to mold design and selection of port locations, it does not directly lend itself to solving the product quality problems.

The QPA approach of self-directed control has been implemented on the CPC system for resin transfer molding. This system utilizes a grid of discrete dc-resistance sensors to detect the resin flow front. A simple approach to predict the flow front progression in real-time is used by the system to compare to a specified desired shape of the flow front. The controller then controls either the temperatures of the various zones in the mold or the resin feed rates through multiple injection ports to alter the shape of the flow front. The results of these two demonstrations are reported in this paper although the system is capable of concurrent control of temperature, feed rates through multiple ports, vacuum application, and feed line pressure control. The dc-resistance sensor grid is also capable of monitoring the cure state of the resin.

2. EXPERIMENTAL

An experimental RTM system, designed with the capability to both monitor and control the resin flow front in real-time, was built with the following features: 1) a screw driven piston pump which can control resin flow based on volumetric flow rate and/or pressure, 2) multi-port gating control, 3) multi-zone temperature control from resin pot to the part, with 18 individual temperature zones on the tool arranged in a 6×3 grid, 3) multiple discrete dc-resistance sensors which are capable of detecting sensor wet-out by resin and monitoring resin viscosity.

2.1 Tooling The design of the tooling allowed for an extended flow path length (time) in which various control actions could be tested. It was decided to use a uniform thickness for which additional preform plies could be placed in arbitrary locations to create regions of lower permeability. It was further decided to have 18 individual heat zones and five inlet/outlet ports which could be independently controlled to affect the flow front. The tooling had overall dimensions of 61 cm × 30.5 cm (24"×12"). A 6×3 grid of heater pads, with dc-resistance sensors located at the centers of the pads, were placed as shown in Figure 1. The tooling consisted of a top plate, a bottom plate, and a clamping frame. The top tool plate was made from a 2.5-cm thick clear Lexan (polycarbonate) plate. Clear Lexan was used so that the flow front monitoring and control capabilities could be visually validated. The top tool had 18 individual point sensors, simply brass screws, centered over the heater zones. The top tool also had multiple 1/4" NPT inlets used as resin injection and vacuum ports. The top tool was fabricated to be placed over a 1.3-cm thick aluminum lower plate, which held the eighteen 7.6 cm × 7.6 cm (3"×3") heater pads and acted as the ground for the point sensors. Eighteen thermocouples, for temperature feedback control, were placed between the heaters and the lower plate. Two 1/4" steel clamping frame plates held the tooling together through the use of twelve 3/8" bolts.

2.2 Flow Front Detection Very simple electrodes fabricated from thermocouple wire can be used for dc-resistance measurement which provides a very low cost method for detecting bleeder wet-out or mold filling. As the resin completes the circuit between the two electrodes, a large decrease in resistance is sensed. Such dc-resistance sensors can be plugged into existing thermocouple ports; so no special wiring of equipment is required. In addition, most control systems are readily capable of voltage measurement, which is the signal that one measures with the use of a reference resistor. In many cases, useful information of resin cure state can also be obtained by simple dc-resistance measurement instead of using more costly dielectric sensor and instrumentation. The measured dc-resistance is effectively the same quantity as what is frequently referred to as the dielectric “ion viscosity” [1]. Figure 2 demonstrates this for the cure of a graphite/epoxy composite.

A sensor system based on dc-resistance can consist of two primary forms. One is the SMART (Sensors Mounted As Roving Threads) Weave system developed by Walsh [2], which consists of a grid of orthogonal conductive strands separated by a non-conducting medium such as a glass preform. When a conductive medium (liquid resin) wets out two strands that form a node, the voltage drops and the presence of the medium is noted. The advantage of this approach is that m+n channels are required to monitor m×n points. The disadvantages of this technique include low sensor contact area (a problem if the resin has low conductivity), inability to monitor viscosity, the need to lay-up a sensor grid for each part, and false readings caused by electrical shorts. The second arrangement can consist of discrete sensors that are tool mounted. This arrangement requires the use of one data acquisition channel for each sensor. However, the discrete dc-resistance sensors offer advantages which include the ability to monitor both wet-out state and resin state (viscosity), as well as the ability to use permanent tool mounted sensors in a production environment.

2.3 Flow Front Control While the use of sensors to monitor the flow front has been used to verify flow models and aid in tool and preform design, little has been reported on the application of this data toward on-line process control. Because slight variations in preforms can lead to local variations in permeability, it is probable that the resin flow front will vary somewhat in a production process. This variability can lead to dry spots and thus poor quality parts. Once a tool and preform have been “optimized” there are only two process variables which can be altered to affect the resin flow front. Darcy’s Law describing flow through a porous medium states:

$$V = -\frac{k}{\mu}\,\nabla P \tag{1}$$

where V is the flow velocity, μ is the resin viscosity, k is the preform permeability and ∇P is the pressure gradient. Equation (1) shows that the flow front velocity can be controlled by altering either the resin viscosity or the pressure gradient. For the cases presented in this paper, the pressure gradient developed as a consequence of the flow driven by a positive displacement pump and the resin viscosity was altered by altering the local temperature on the tool through individual control of the eighteen heater pads. Figure 3 illustrates that a temperature increase from 50°C to 100°C will result in an order of magnitude decrease in the viscosity of the resin used in this study.

2.4 Material System 3M's PR520 epoxy resin system was chosen for this study because it is a premixed resin system which has a very long out-time at room temperature [3]. This system and PR500, a similar system, are currently being used for RTM processing in aerospace applications. The viscosity and dc-resistance of the resin were measured simultaneously in a Rheometrics Dynamic Spectrometer with parallel plate fixtures. Using this technique the aluminum parallel plates acted as the sensing electrodes without compromising the viscosity measurement. The data shown in Figure 4, indicate that the resin's dc-resistance is nearly directly proportional to its viscosity.

The preforms used in this study were constructed from a plain weave glass cloth and were approximately 4 mm thick. Local variations in preform permeability were created by placing additional strips of cloth, typically 7.6 cm (3") wide, at selected locations in the preform.

3. RESULTS AND DISCUSSION

A 6×3 dc-resistance sensor grid, as shown in Figure 1, was used to obtain sensor wet-out times. We will first show that the method used for post-run processing of sensor wet-out time data allows accurate reconstruction of flow front progression. This method was used to determine the flow front progression for all experiments. We will then show two different methods for estimating the flow front locations in real-time for control purposes. The results of flow front control experiments by zoned temperature control of the mold and by feed rate control will then be presented.

3.1 Flow Front Reconstruction One can construct three imaginary paths for resin flow from the three injection ports at one end of the mold (1" below station 1) towards the exit at the other end of the mold. The sensor grid monitors the flow front along these three imaginary paths at six stations. As the flow front reaches a sensor, the resistance between the sensor electrodes decreases. The time of sensor "wet-out" is recorded. At the end of a run these 18 sensor wet-out times can be used to construct constant-time curves through interpolation. A constant-time curve over the grid represents the flow front at that time. Figure 5 shows these constant-time curves at 2-minute intervals superimposed on video clips of the flow fronts at these times. It can be seen that the reconstructed flow fronts are accurate representations of the actual flow fronts; even with such a small number of sensors and sensor data.

3.2 Real Time Estimation of Flow Front It is necessary to know the flow front location in order to perform feedback control on the flow front progression. With the 6×3 sensor grid arrangement, there are at most 18 updates of the flow front location during the course of filling the mold. For the current system running at a feed rate of about 20 cc/min, the update rate is about one per minute. Since typically only one sensor gets wetted out at a time, it is necessary to infer the shape of the flow front from past data. We tested two methods of estimating the flow front: one method updates flow front information only upon new sensor wet-out while the second method continuously updates flow front information at 5-second intervals. It should be noted that, in either case, no reliable information is available until at least one of the three station-1 sensors is wetted out.

3.2.1 Update on New Sensor Wet-Out Only When a sensor at station j on path i is wetted out, the time is recorded and the flow front velocity along this particular path is calculated by the sensor location from the inlet ($L_{j_{max}, i}$) and the wet-out time ($W_{j_{max}, i}$). The sub-subscript *max* indicates that these are the most recent values. This velocity is used for predicting the flow front location (F_i) on this particular path until the next sensor wet-out on this path occurs:

$$F_i = V_i \cdot t = \left[\frac{L_{j_{max},i}}{W_{j_{max},i}} \right] \cdot t \tag{2}$$

This is a very simple approach that works well for constant injection rate. A comparison of the resulting estimated flow fronts to the reconstructed actual flow fronts is shown in Figure 6. Note that the estimated flow fronts are not equally spaced in time but depends on the successive sensor wet-outs. An additional condition

$$F_i \le L_{j_{max}+1,i} \quad \text{(the predicted front must not exceed the next unwetted sensor location)} \tag{3}$$

was added to the algorithm to correct for the over-prediction of flow front (in Figure 6, where predicted flow fronts cross).

3.2.2 Continuous Update at Constant Time Intervals In this method, the prediction uses the most current estimate of the flow front velocity:

$$F_i = V_i \cdot \left(t - W_{j_{max},i}\right) + L_{j_{max},i} = \left[\frac{L_{j_{max},i} - L_{j_{max}-1,i}}{W_{j_{max},i} - W_{j_{max}-1,i}} \right] \cdot \left(t - W_{j_{max},i}\right) + L_{j_{max},i} \text{ and} \tag{4}$$

$$F_i \le L_{j_{max}+1,i} \tag{5}$$

where t is the time since the start of the run. A comparison of the resulting estimated flow fronts to the reconstructed actual flow fronts is shown in Figure 7. The estimated flow fronts are calculated at 5-second intervals and plotted in Figure 7 at 2-minute intervals. Note that the first estimated flow front curve shown is that at 4-minutes which is in error compared to the reconstructed actual fronts. At 4 minutes, none of the sensors at station 2 had been wetted out and the lack of information resulted in the large error in prediction.

3.3 Flow Front Control The results of flow front control experiments by zoned temperature control of the mold and by feed rate control are presented in this section. The control objective for both experiments was to achieve a flat flow front.

3.3.1 Flow Front Control by Altering Resin Viscosity Through Temperature Control

According to Darcy's law for flow through a porous medium, the fluid velocity is inversely proportional to the viscosity of the fluid. Since the resin viscosity can decrease by an order of magnitude or more, it is possible to alter the flow front during mold filling by altering the resin viscosity through temperature control. To demonstrate the feasibility of this approach, we tested to see whether the controller could detect the lagging flow front along a low permeability path and compensate for it by heating that part of the resin to bring the flow front up to meet the control objective of a flat flow front. A lower permeability region in the mold cavity was created by adding extra layers of preform cloth to path 3. The controller compared the estimated flow front and heated the zones where the flow front was behind the average value through proportional control of zone temperatures. Only one injection port at one inch before station 1 of the center path was used.

An open-loop experiment at a uniform temperature of 32°C shows that the lower permeability along path 3 resulted in lower flow velocity along that path and skewed flow fronts as shown in Figure 8(a). When proportional control was applied, heaters along path 3 were set by the controller to the maximum permitted temperature (79°C) during most of the run in order to increase the flow front velocity along path 3. The resulting flow fronts, as shown in Figure 8(b), although not quite flat, were more symmetrical and had lower curvature than those of the open-loop run in Figure 8(a). It should be pointed out that although the center path temperature was set to 32°C, it reached about 54°C because of the lack of active cooling.

3.3.2 Flow Front Control by Varying Feed Rates Through Multiple Injection Ports

Flow front control by controlling injection rate was tested by using three injection ports, one for each flow path at one inch before station 1. For a limited length along a flow path, increasing feed rate to one path can cause the flow front of that path to lead. Paths 1 and 3 have pneumatically controlled on-off valves and path 2 has a manual valve. The flow rates through the on-off valves on paths 1 and 3 are controlled by valve-opening time (30% controller output causes the valve to stay open 30% of the time) such that at open-loop conditions, the flow rates through the three valves are the same.

The control strategy was to manipulate flow rates (by increasing valve opening time) to path 1 and/or path 3 depending on whether the flow fronts on these paths were lagging or leading the flow front of the center path. This was done because there was no control for the center path injection valve. The control objective was to achieve a flat flow front with proportional and integral gains applied to the lead or lag distance between the flow front locations on the paths. The flow front locations were estimated and control actions were taken at 5-second intervals.

For the case shown in Figure 9, nine layers of preform cloth were used. The mold was kept at a constant temperature of 57°C. It can be seen that at about 5 minutes the controller called for a decrease in feed rate to path 1 to below the baseline value of 33% because the flow front of path 1 was leading. Flow front of path 3 started to lead at about 10 minutes which caused the feed rate to path 1 to increase. The feed rate to path 1 was kept high throughout the run because of a slight lead in path 3.

4. SUMMARY & CONCLUSIONS

A 6×3 dc-resistance sensor grid has been successfully used for flow front monitoring in resin transfer molding process. A simple 2-dimensional interpolation of sensor wet-out times allows reconstruction of flow front progression accurately. Algorithms have been developed for the control software to predict flow front locations in real-time for control purposes.

Control of flow front progression has been demonstrated with proportional temperature control and proportional-integral feed rate control through multiple injections ports. Temperature control did alter the flow front but not to the extent desired. This was because it was not possible to maintain large temperature differentials over such a small tool area without active cooling. Greater control of flow front was achieved by controlling feed rates through multiple injection ports.

Using multiple injection ports along each path with feed rate control may improve the system performance. Such arrangement will require proper gating of injection ports. The current control system can be adapted to accomplish this easily.

We have demonstrated that self-directed control of flow front in resin transfer molding process is feasible. The methodology developed under this project is generally applicable to mold filling processes.

5. REFERENCES

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2. Walsh, S., "Artificial Intelligence: Its Application to Composite Processing", Proc. of the 35th International SAMPE Symposium, April 2-5, 1990, pp. 1280-1291.

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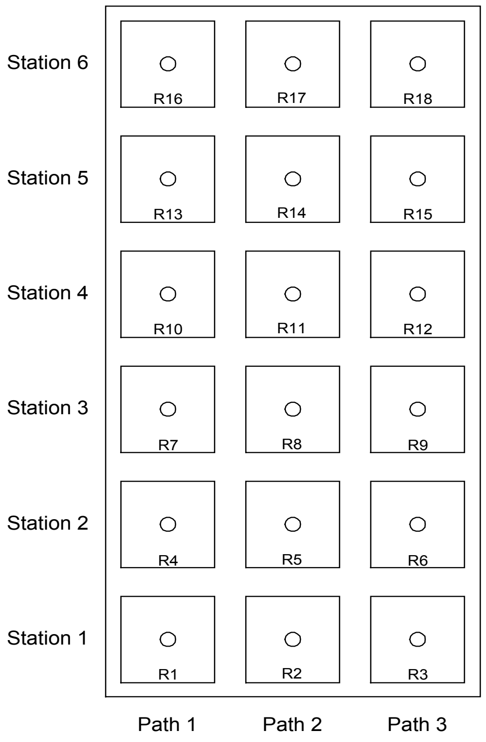


Figure 1: Sensor grid, heater pads, and flow path designations for tooling.

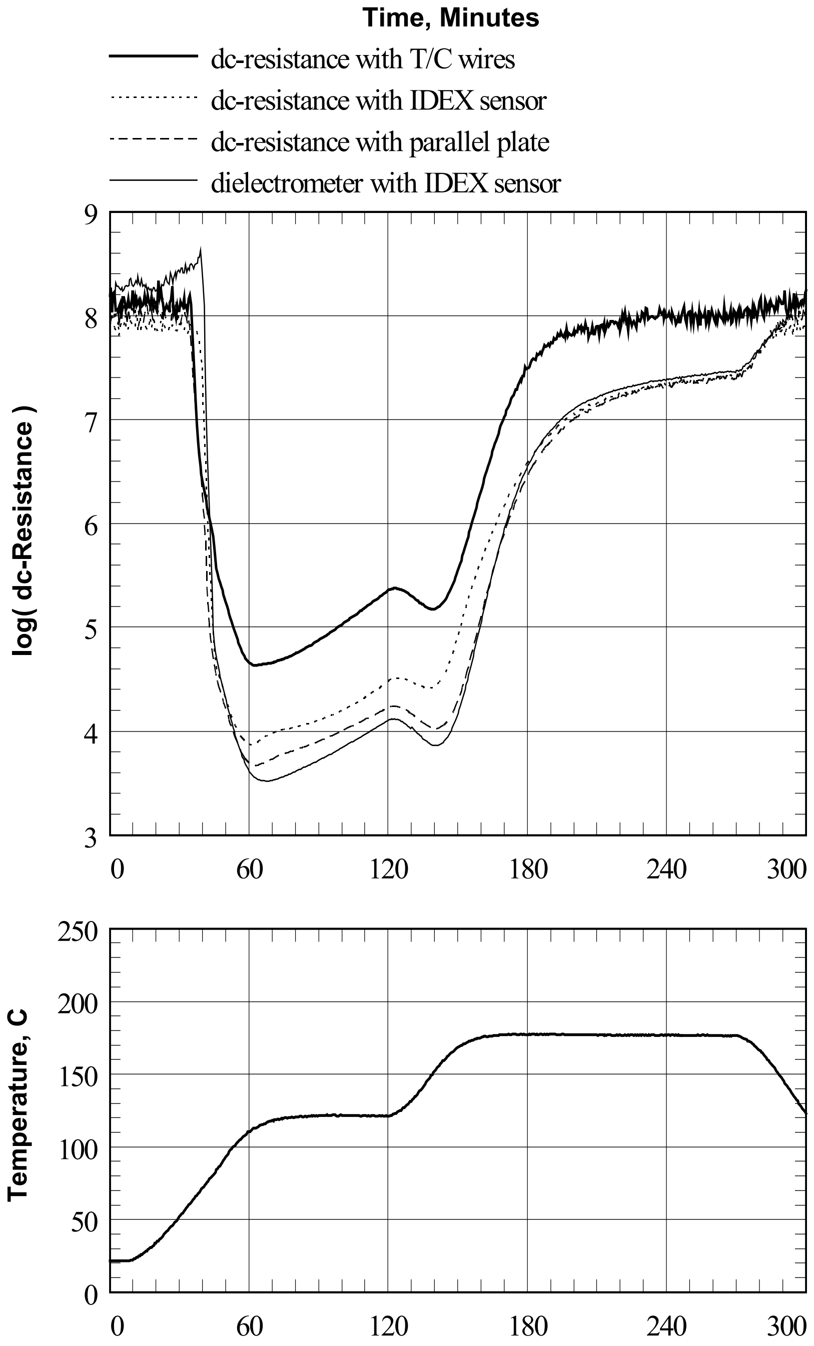
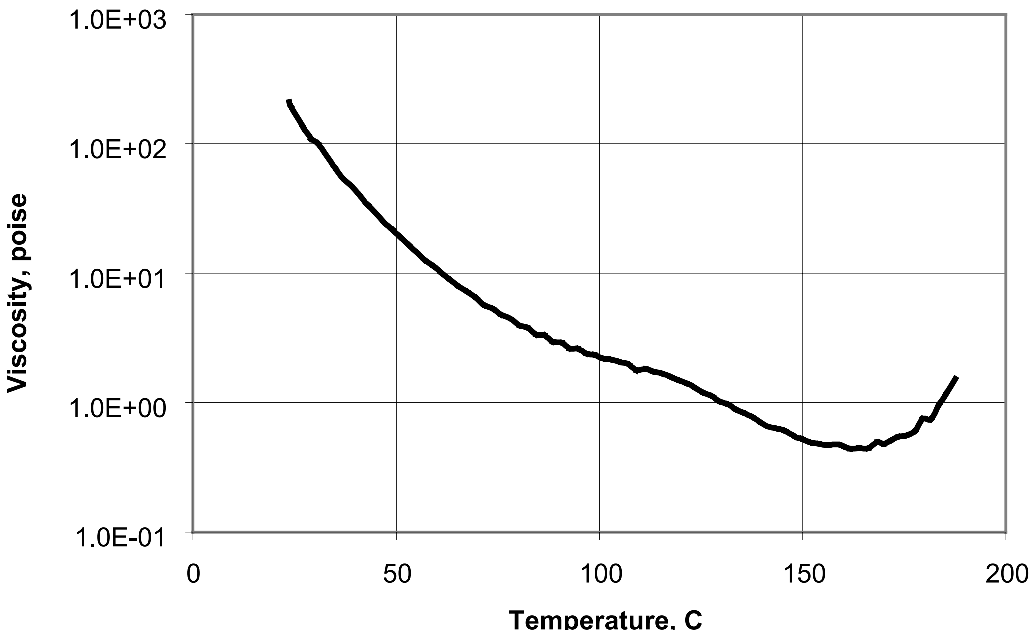


Figure 2: Comparison of dc-resistance and dielectric measurements on an 3501-6 epoxy composite [1].

Figure 3: Viscosity profile of PR520 during a heating rate of 2°C/min.



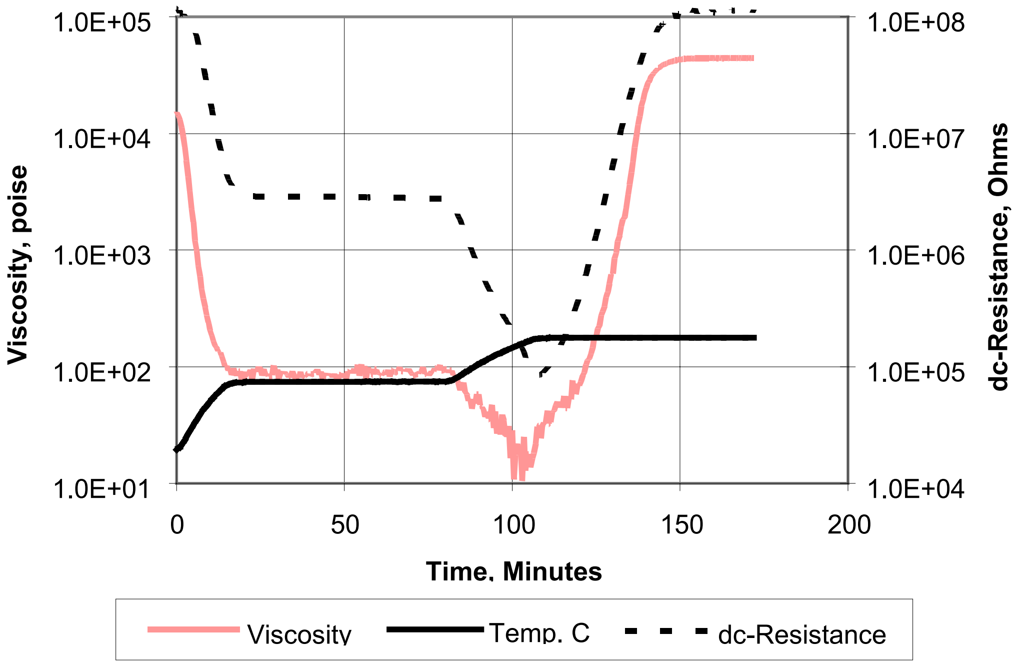
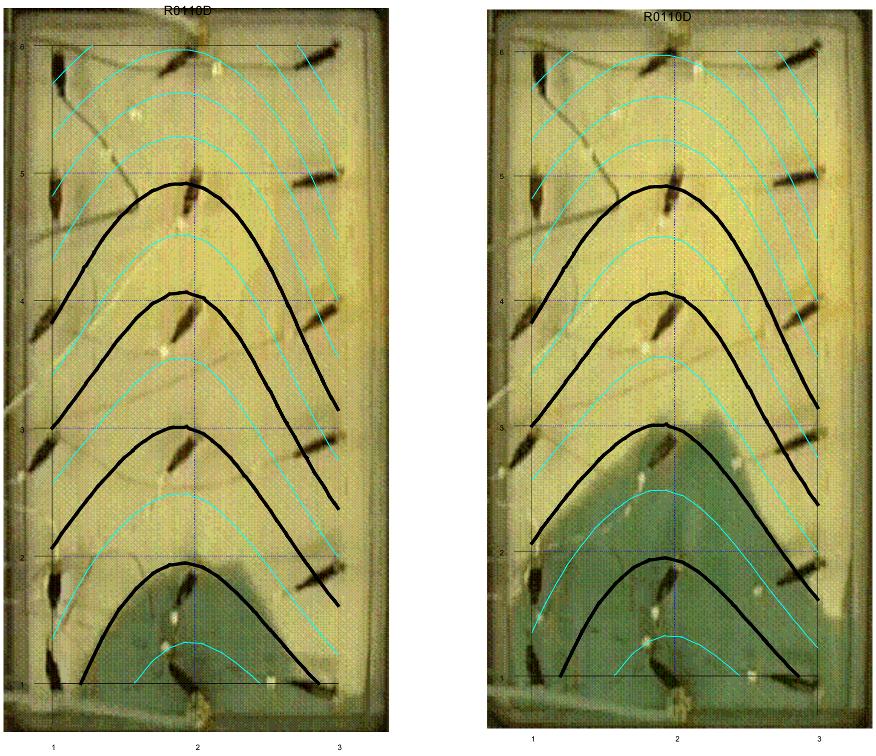
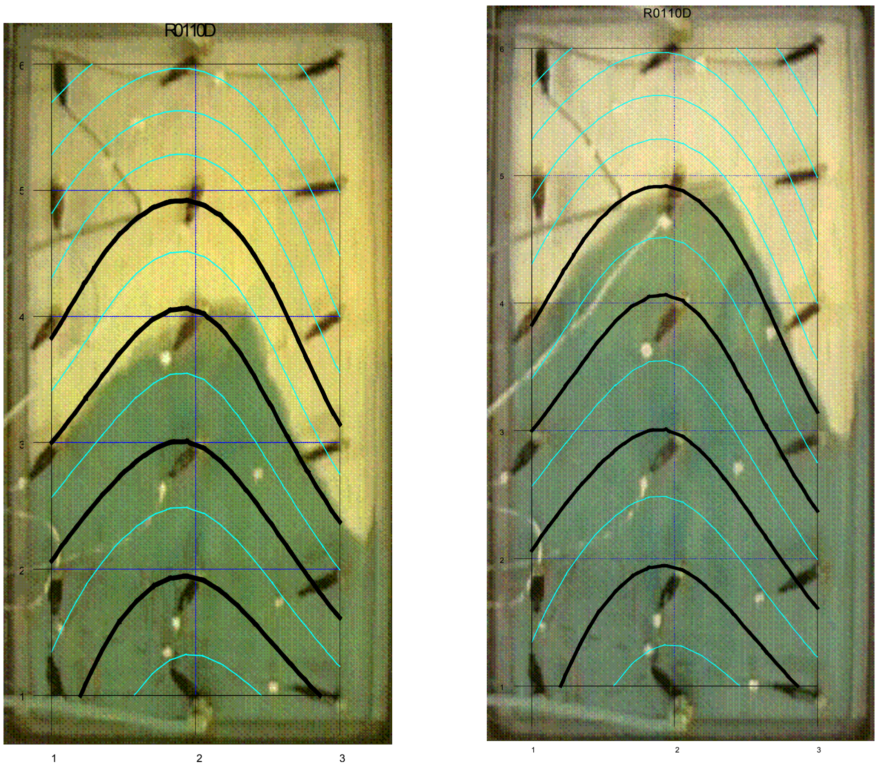


Figure 4: Simultaneous viscosity/dc-resistance measurement of PR520 using parallel-plate method.



Flow front at 4 minutes

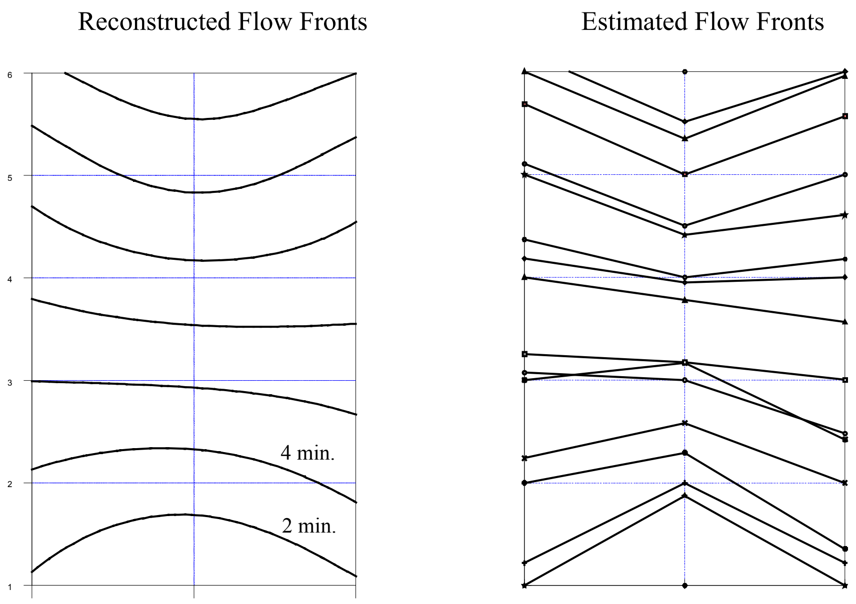
at 8 minutes



at 12 minutes

at 16 minutes

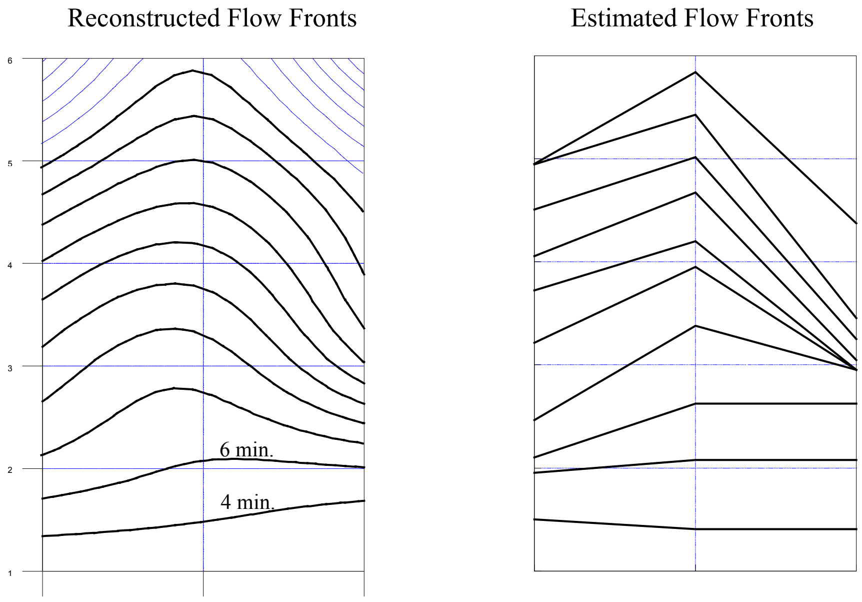
Figure 5: Comparison of actual and reconstructed flow front progression.



Reconstructed Flow Fronts

Estimated Flow Fronts

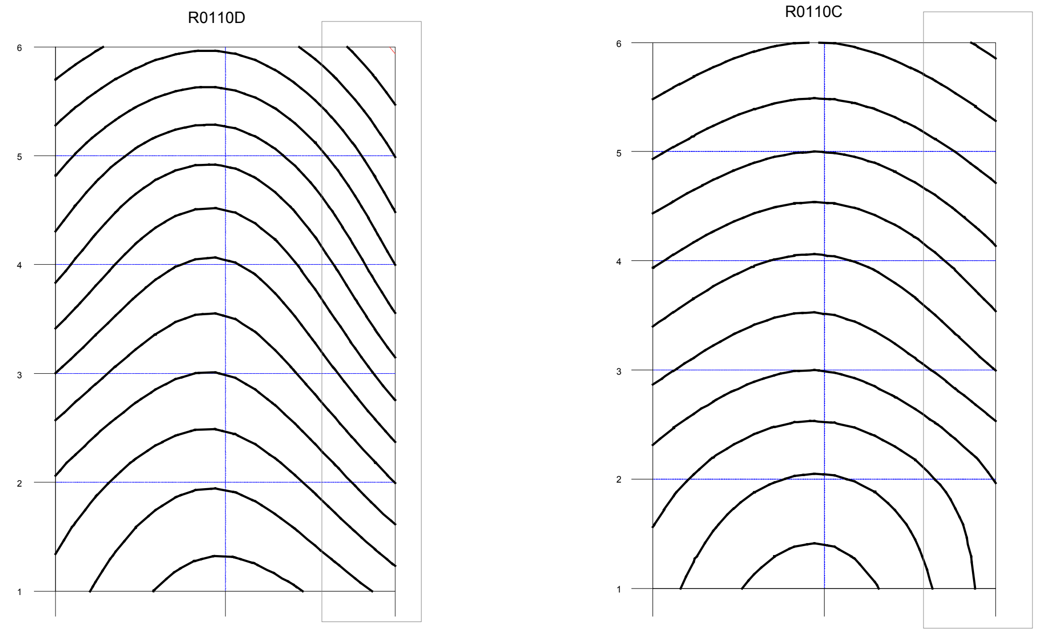
Figure 6: Estimated flow fronts at times of new sensor wet-out.



Reconstructed Flow Fronts

Estimated Flow Fronts

Figure 7: Estimated flow fronts based on most current flow front velocity, continuously updated at 5-second intervals. Plotted at 2-minute intervals.



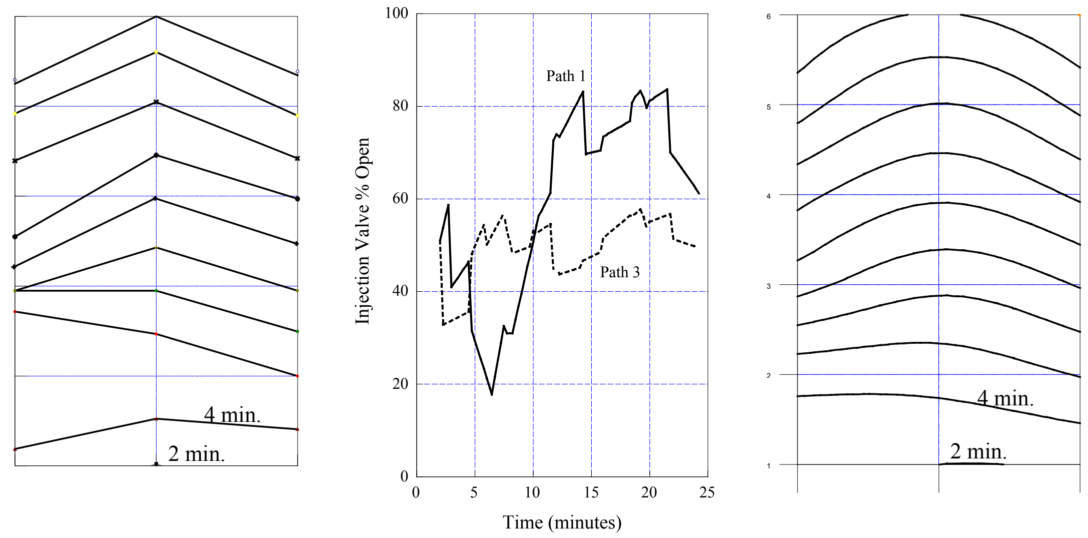
Open-Loop
Uniform Temp @ 32°C

(a)

Proportional Control
G = 14, 32°C - 79°C

(b)

Figure 8: Proportional temperature control, update on new sensor wet-out only. Nine layers of cloth preform with three additional layers for path 3.



Real-Time
Estimated Flow Fronts

Controller Output

Flow Front Progression

Figure 9: Control of flow front through PI control of feed rates to paths 1 and 3.