USE OF SENSORS AND SIMULATIONS TO MOVE TOWARDS AUTOMATION OF THE RESIN TRANSFER MOLDING PROCESS

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SUMMARY

Resin Transfer Molding (RTM) has the potential to manufacture high-quality, geometrically complex composite parts. Inherent variability in the process can cause problems if moderately complex parts are to be produced on a very consistent basis. On-line control of mold filling provides an opportunity to manipulate the process by changing the inlet gate pressure or flow rate and/or by adding or deleting new injection locations, based upon feed back from relevant sensor data. This methodology will bring RTM a step closer towards process automation and lead to cost avoidance by reducing prototype development cost, rejection rate, and trial and error manufacturing practice. For active control of mold filling to be effective, the resin injection system employed should be versatile. This paper explores the feasibility of such intelligent resin injection systems, and presents results obtained by using an injection system with three individually controllable lines which provides continuous feed back control of either injection flow rate or injection pressure. Several flow visualization studies are presented, the goal being to demonstrate the advantages of RTM filling with active control. Reductions can be made in size of dry spots and in void content, time to fill, and also in the amount of resin wasted. Numerical simulation of the mold filling process is a valuable tool for the design of mold filling strategies. Simulations are used to identify the parameters to be sensed and those to be actuated. The main parameters to be sensed are pressure and the arrival of the resin. The actuators that can be invoked are location of the injection gates, vents, inlet pressure and flow rates at the injection location. Strategic controllers that describe the decision process based on sensor feedback are developed using the simulations. The sensor signal travels to a LabView controller which in turn implements the decisions on a lab-scale RTM mold by invoking the actuators which will switch gates/vents or change pressure/flow rates. An experimental case study is conducted to demonstrate the methodology.

KEYWORDS: Resin transfer molding, mold filling simulation, permeability, flow sensors, model based control, on-line control, automation, composites, decision-tree.

INTRODUCTION

Resin Transfer Molding (RTM) process is widely used to manufacture high-performance composite parts and also for high-volume secondary structures in the transportation industry. Conventional RTM tool design and processing on the shop floor is mostly based on experience and not on scientific fundamentals of the process. The process can roughly be divided into five steps as shown in Figure 1. First, several layers of fabric are stacked to create the preform and then draped over the mold surface. After the mold is closed, a thermoset resin is injected into the mold to fill the empty spaces between the fibers. The composite part is demolded after the resin is cured.
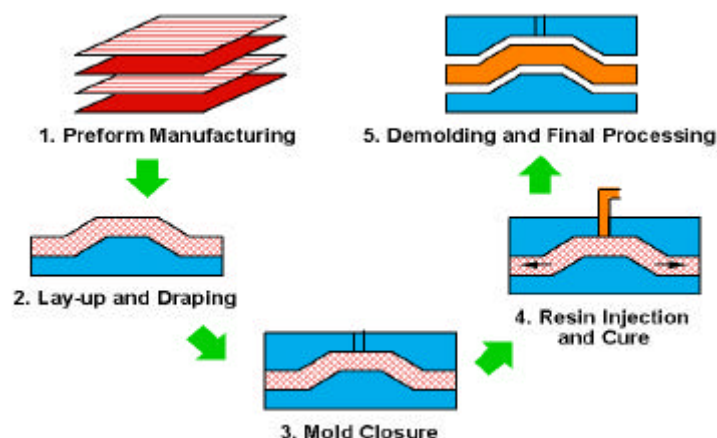

Figure 1. The schematic of the RTM process.

Over the last two decades several sophisticated computer simulations [1-6] of the liquid molding process have been developed based on the physics of flow through porous media. During prototype development, the engineers now routinely combine experience with simulations to decide if RTM is a viable manufacturing process for the selected part, and to decide on the locations for the injection gates and vents to avoid dry spots and minimize fill time. This has been marginally better but there are still many hurdles that cause high rejection rate and huge premiums in prototype development cost and time. For example, improper placement of preforms in the mold can result in race-tracking [7,8] that will drastically change the flow patterns and result in a part with dry spots. Other issues such as uncertainties in permeability values due to compaction and/or deformation inside a mold around ribs and corners can significantly divert the flow patterns compared to those predicted by simulations and result in unexpected impregnation dynamics that will increase the rejection rate. Also, the RTM injection equipment is frequently rather primitive and can either inject under constant pressure or sometimes under a constant flow rate.

One approach to overcome some of these hurdles is to use the simulation of the process with sensors to detect and/or to estimate the uncertainties in the mold and use on-line control to drive the process towards a successful completion. In this paper, we present the building blocks and their integration and interaction in moving towards developing an on-line control of the RTM process. It has the potential of enabling manufacturing of composite parts with the RTM technique that were previously not possible without on-line control.

APPROACH

The objective in any manufacturing process is to improve part quality and reduce rejection rate. In RTM, we can do this by using the simulation tool for mold design, gate, and vent locations,

by introducing sensors for feed back to strategic controllers for decisions and actuators for on-line control of the process.

Composite parts are manufactured in shapes from simple geometries to complex near-net shaped structures. As our goal was to first show that we can take the tools of simulations, sensors and actuators and integrate them in an intelligent fashion for on-line control, we decided to keep the mold geometry relatively simple. We selected a flat plate mold of 0.91m. by 0.46m. which could have inserts and different thicknesses.

In this paper, we will focus on the demonstration of active control of the resin flow in a lab-scale experiment. A transparent mold was utilized so the flow pattern, sensor responses, and control strategies could be validated. Before we discuss the details of control strategies, we will first describe the various components needed to perform on-line control in the lab-scale experiments.

LAB-SCALE EXPERIMENTS

The important components for lab-scale experiments are the mold with locations for gates and vents and sensors, the injection system with valves to open and close gates and vents, and the sensors that can detect flow rate, pressure, and resin arrival.

Mold

A lab-scale mold, shown in Figure 2, was fabricated to investigate the interaction of the sensors and actuators within the mold. The cavity width and length was 0.91m. by 0.46m. This enables us to investigate our control strategy on reasonable sized parts. In order to investigate the influence of the part thickness, a spacer plate of any thickness may be inserted, however, a spacer plate of 6.4 mm. thickness was used since most composite parts are usually of that thickness.

The mold was made from aluminum with a transparent lid to enable us to monitor the flow behavior of the resin and validate the data obtained from the resin arrival sensor. The lid was an acrylic slab of 10.2 cm thickness that could withstand 690 kPa. internal pressure with minimal deflection.

Multi-purpose inserts were designed for implementation in the mold. They are bolts that fit in threaded holes in the bottom part of the mold. The outer shape of the bolts remains the same while the inside can be machined to fit to a vent, an injection gate, a pressure sensor, or an on/off switch. This concept enables us to expand the scope of the control strategies we can execute. There are 17 locations in the mold that can hold a multi-purpose insert. This allows for flexibility in the mold and control scheme design.

Injection System

The available injection systems usually use a pressurized pot for resin injection. This system cannot accommodate sophisticated on-line control where one can control the flow rate and/or switch between pressure control and flow rate control. For model fluids, we have developed a sophisticated multiple line injection system that can inject simultaneously into three injection locations under a specified pressure or a specified flow rate and can change the flow rates and pressures on-line in a few seconds. In the future, the goal is to modify this system for use with

real resins. However, currently this flow visualization set-up permits us to evaluate our sensors and our control strategies.

17 multi-purpose insert locations

Type : • **Plug**
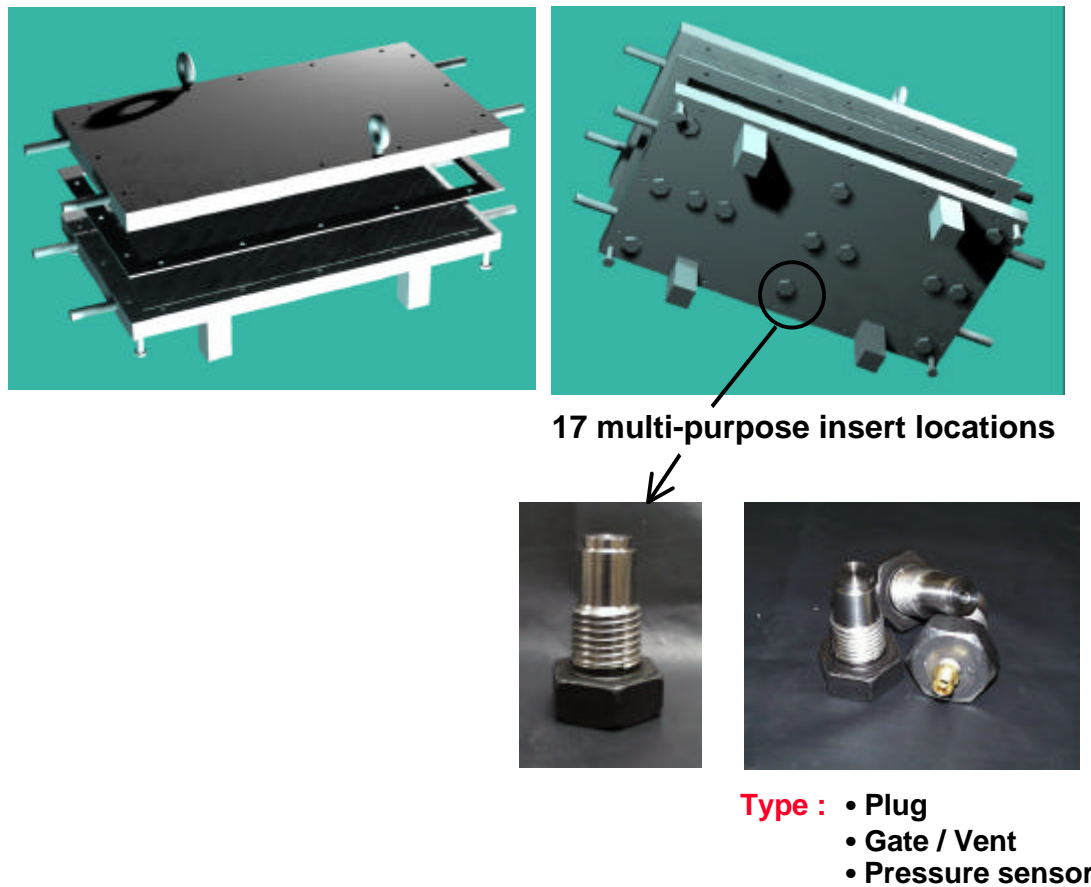• **Gate / Vent**
• **Pressure sensor**

Figure 2. The mold for lab-scale experiments. There are 17 locations in the mold that can accomodate multi-purpose inserts.
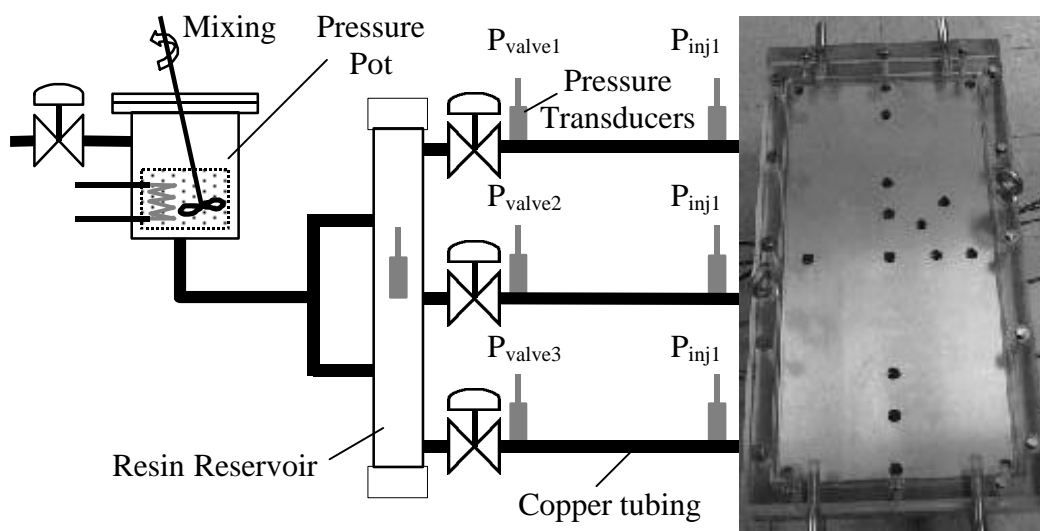

Figure 3. Multi-line injection system connected with the flow visualization mold.

A versatile but also simple injection system was designed [8,9], and used in this set-up. As shown in Figure 3, the resin is kept in the reservoir, which is driven from the pressure pot. The resin in the reservoir is maintained at a constant pressure of 690 kPa. Three copper tubings are connected between the reservoir and the flow visualization mold. Each tubing has a pneumatically actuated globe valve to individually control the flow of the resin through the lines. Two pressure transducers are attached to each tube right after the valve and right before the mold entrance. The pressure drop between these two transducers is proportional to the resin flow rate within the tube. By evaluating the data from these transducers, the valve is adjusted to achieve the desired flow rate. Dilluted corn syrup was used as model resin. The viscosity of the model resin could be easily varied between 0.1 and 0.35 Pa.s (the usual viscosity range of the real resin used in RTM manufacturing) by varying the mixing ratio. Flow rate and pressure control of the injection is detailed in [8].

Strategic Controller

To implement an on-line control strategy for the RTM process based on process model simulations and in-situ sensors providing instantaneous feedback, a "strategic" controller is necessary. It will have to make decisions to influence the flow front pattern during mold filling and drive the process towards successful completion. These decisions are based on in-mold sensors providing the necessary feedback and are conveyed to the resin injection system by specifying the set points for the actuators (opening and/or closing of gates or vents or changes in the inlet flow rates or pressures).

Design of a strategic controller and development of an injection system to implement the strategy is very crucial for active control of mold filling of composite structures.

There are two important components of a strategic controller. First is the creation of a control strategy that dictates which set points to activate at what time. We use a numerical simulation software, LIMS [10], which can calculate the pressure field and the position of the flow front at each time step using input data of resin and preform properties, mold geometry, and boundary conditions. By use of a script, one can invoke numerical sensors and change boundary conditions based on feedback from the numerical sensors. Thus, LIMS allows us to develop such a strategy in the form of a decision tree by conducting various possible mold-filling scenarios. The second component is how the decision is conveyed to the hardware. We use the data acquisition software LabView for this purpose. All the data input and output from and to the sensors and actuators is physically connected to a PC. Through the use of a data acquisition board, LabView can implement the commands of the controller by specifying the set points to the actuators of the injection system that is also operated by LabView. Thus, the entire RTM process is controlled by the PC.

Experiments with a Model Liquid

Once all the components of an intelligent RTM workcell are evaluated and tested they need to be integrated and their interactions evaluated. Figure 3 shows a schematic of the experimental set-up. The experiments were conducted with corn syrup as the model liquid with a viscosity that is very close to actual resin viscosity. This simplifies the cleaning while using the transparent mold. This permits one to validate the experimental results by comparing the flow front positions with simulations and also evaluate the sensor responses and the control strategies.

Although the lab-scale mold is a simple one, a complex cavity was designed by using rubber inserts with different thicknesses as shown in Figure 4. Among many variations in the RTM parameters, racetracking was chosen to be studied for this paper. For the base case of no racetracking, the fabric was cut very carefully so that it fits into the mold without any gaps between the fabric and the mold wall. In the racetracking cases, the edges of the preform (felt) were trimmed such that there was a 3.1 mm gap between the fabric and the mold wall. For a more detailed study where the racetracking gap can also vary, see [8]. Depending on how the preform is trimmed and how it is placed into the mold, four different cases can occur: (i) no racetracking, (ii) racetracking along the top, (iii) racetracking along the bottom edge, and (iv) racetracking along both edges. To limit the variations of the RTM parameters to only the racetracking effects, a preform of felt material was chosen in this study. This material has an isotropic permeability, and the relationship between permeability and the fiber volume fraction is well defined.
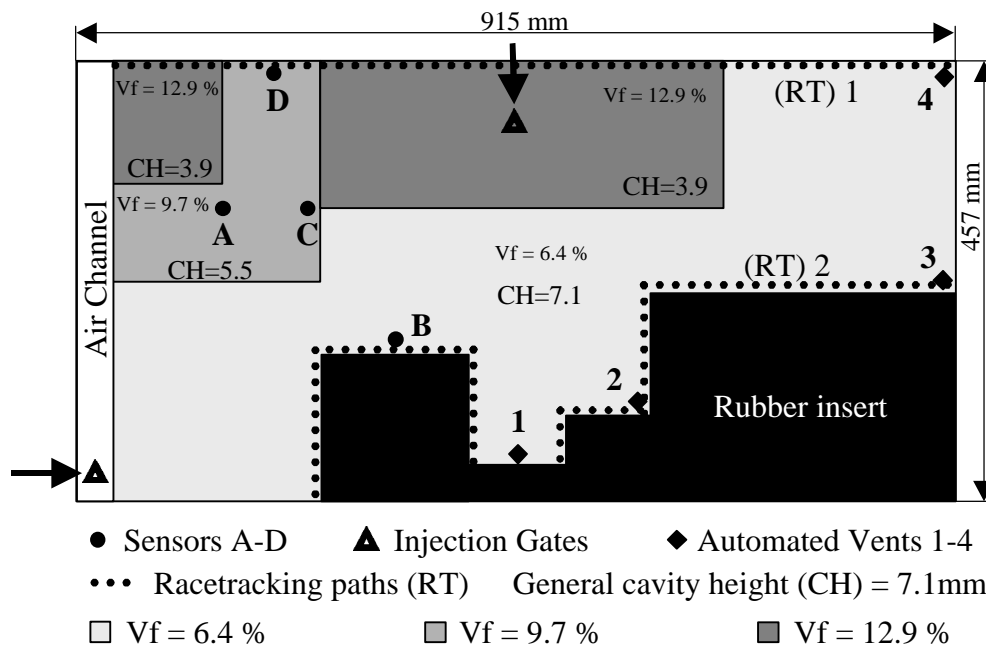

Figure 4. Schematic of selected mold cavity for experimental validation.

A finite element mesh of the mold was created and used in the mold filling simulation LIMS. Simulating the four different racetracking cases, two gates and four automated vents (where the vent is closed with a delay of 5 seconds after the resin arrival [8,9]) were chosen from the 17 predrilled locations as shown in Figure 4. Here, the goal is to show the importance of on-line control during mold filling once the gate/vent/sensor locations are chosen. However, the choice of the locations of the gates/vents will also influence the control strategy. It would be beneficial if one could optimize these locations by considering various scenarios using LIMS as the simulation tool [11].

In this paper, we focus on one possible scenario for the selection of the number and location of the point flow front sensors (also called resin arrival sensors) which is another optimization task. Here, the number of sensors is limited to four to minimize the hardware used in the mold. The sensors should be located close to the first gate to detect the flow front progression early enough so that the necessary control actions can be taken to avoid dry spot formation. A dry spot area is the region in which no resin has impregnated to saturate the empty pores between the fibers. The simulation for the no-racetracking case is shown in Figure 5 with the

contour of the flow front at two different time steps. The sensors were located along these flow fronts.
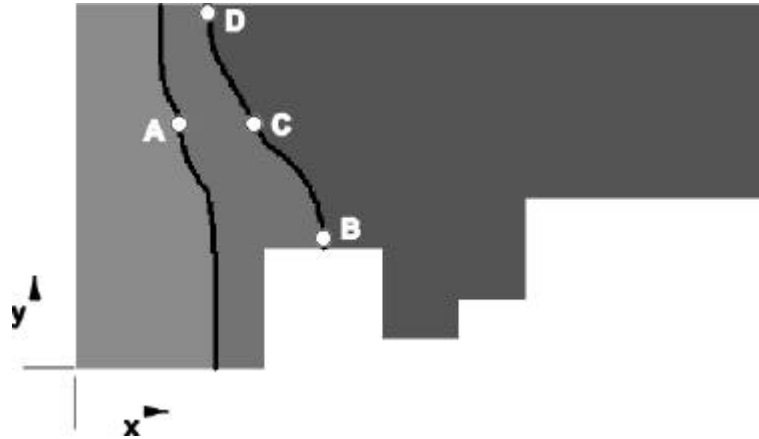

Figure 5. Locations of four flow front sensors in the mold. The two curves show the location of the flow front at two different time steps under no-racetracking condition.

Of the four sensors used, two of them (B and D) were located at the two ends of the second flow front, one of them (C) at the mid point, and the remaining one (A) was on the first flow front at the same level as C. During the experiments, if resin flow trips the sensors B, C, and D at almost the same time, then that will be recognized as the no-racetracking case (i). On the other hand, if there is a time delay between the sensor signals, the controller will be able to interpret the type of racetracking depending on the order of the sensor signals received. For example, the simulations show that for cases (ii), (iii), and (iv) the order of the sensor signals is DACB, ABDC, and DABC, respectively. The problem of constructing the decision tree gets more complicated if one has to include the variation of the racetracking gap as well [8], which will require the controller to check the time delay of the sensor signals carefully to distinguish between the cases. Since each of the four cases has a unique sensor signal order, the chosen sensor locations were found to be adequate for use in the active control of the resin injection experiments. Here, we do not claim that these are the optimized locations for the four sensors, but they represent one of the configurations that can distinguish between the different racetracking cases.

The flow front locations at different time steps are shown in the left column of Figure 6 for different racetracking cases without active control with the first gate injecting resin at 10 cm^3/s until the three vents (1, 2 and 4) are shut off. As seen in the two cases where the racetracking is along the bottom and along both edges, a dry spot is predicted in the preform at the end of the filling. In order to eliminate this problem, different control actions were applied. In controlled injections, vent 3 was also opened initially. In case (i), no control action was necessary. In case (ii), after the sensor C is tripped, the flow rate at the first gate was reduced from 10 cm^3/s to 5 cm^3/s and the second gate was opened and resin was injected from this gates at a flow rate of 5 cm^3/s. In case (iii), the second gate was opened toward the end of the filling and resin was injected from both the first and the second gate at a flow rate of 5 cm^3/s each. In case (iv), resin was injected from only the second gate at a flow rate of 10 cm^3/s after sensor B was tripped. Simulations were run for the above race-tracking cases with the control actions described earlier. The flow front locations at various times for each of the race-tracking cases are shown in the right column of Figure 6. These control actions were able to reshape the flow front towards the vents and avoid creation of a dry spot. This end result could have been achieved in many different ways. Our intent here was to show that if race-tracking does occur unexpectedly, one can use the on-line control strategy and take corrective action.
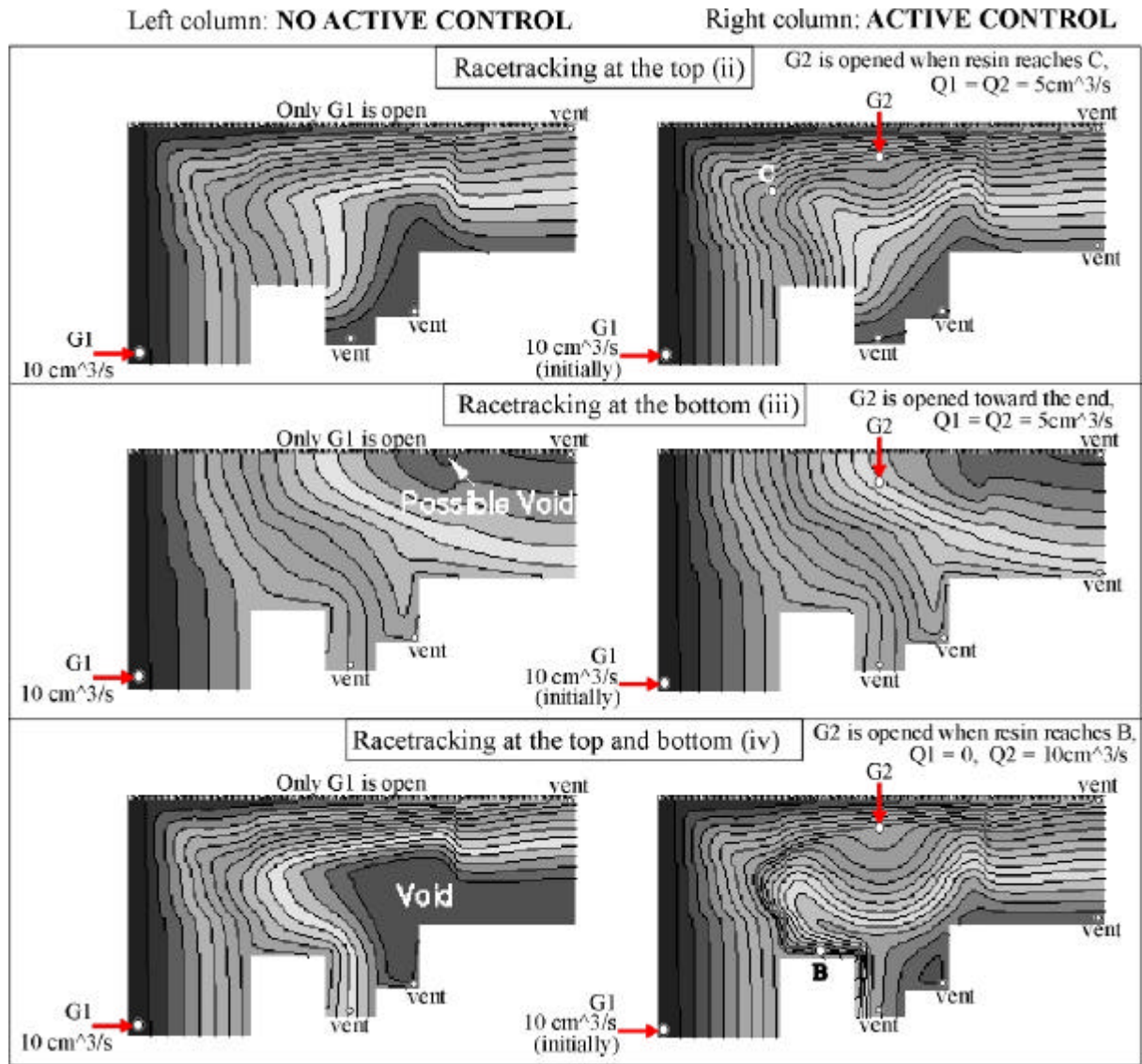
Figure 6. Simulations of different racetracking cases. The curves show the location of the flow front at different times. The simulations on the left column are with no active control whereas the ones in the right column are with the necessary active control as described in the decision tree section to eliminate the dry spot (void) problem.

Thus, our strategic controller is a decision tree that will sense the difference between the four scenarios of no race-tracking, race-tracking at the top, race-tracking at the bottom and race-tracking along both edges and issue the corrective action to the actuators. The next step is to interface the sensors, the strategic controller, the injection system with the mold using LabView and validate experimentally what was created in the virtual environment.

Experimental results

Although all four scenerios were validated [8], only results from one case will be presented to depict the advantage of active control during mold filling in RTM. A preform of felt material was used in the mold shown in Figure 4. As model fluid, dilluted corn syrup with a viscosity of 0.128 Pa.s was used. Flow visualization was enabled by using a black clothing dye in the resin and an acrylic lid for the mold.

Two experiments were conducted for each case study. One without any control and one where the control decisions were triggered. In both experiments for case (iv), racetracking channels of 3.1 mm width were introduced both at the upper and the lower edges. In the first experiment no active control was applied. Under constant flow rate of 10 cm^3/s from the first injection gate on the left, the flow front propagation is shown in the left column of Figure 7. A significant dry spot on the right side of the mold was formed at the end of the filling. This part would have to be rejected due to this defect.
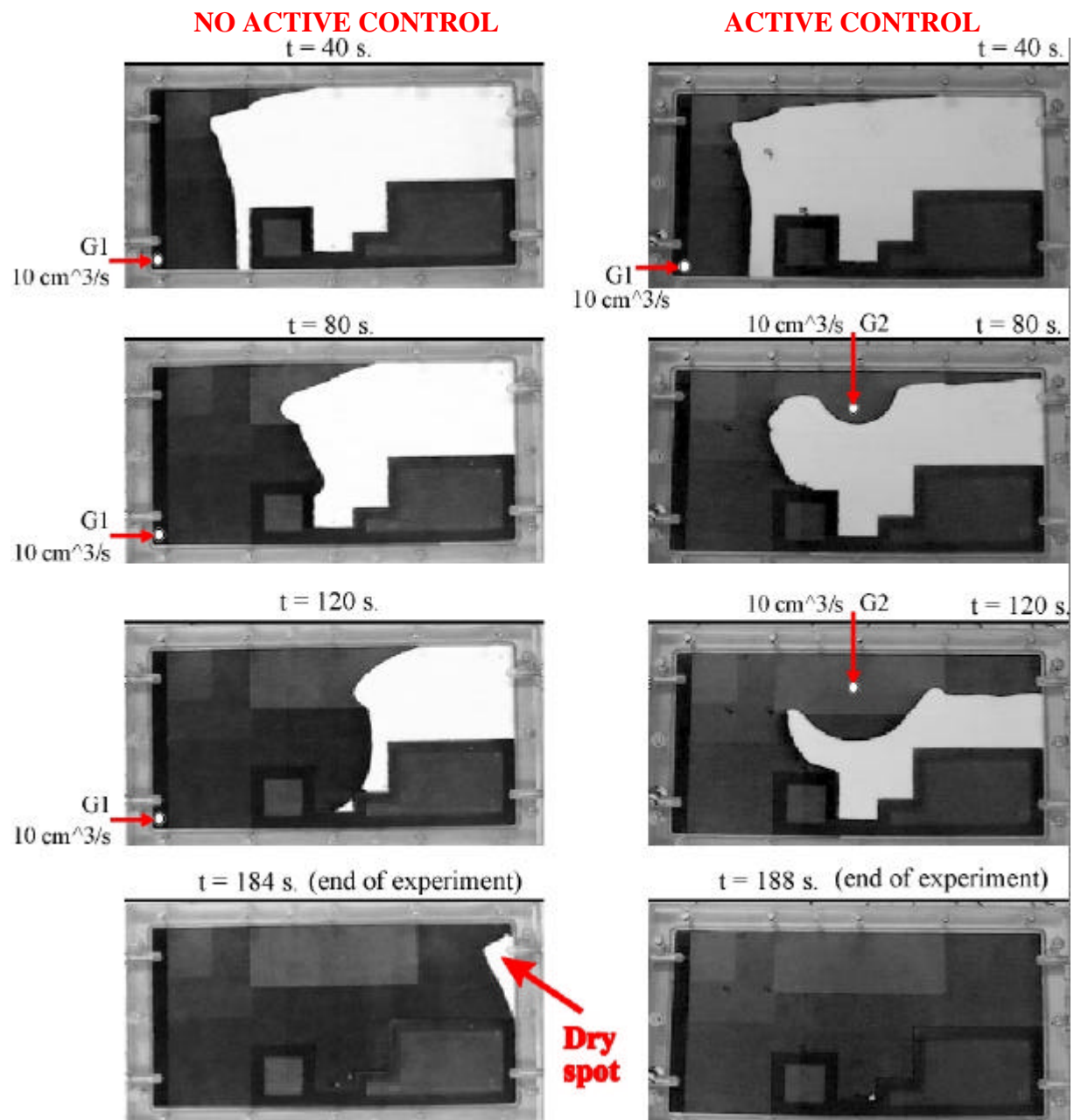

Figure 7. Video stills of the resin flow in the mold in two different experiments. The experiment shown in the left column is without active control, whereas the one in the right column features active control. A dry spot or void remained in the mold in the no active control case.

In the second experiment, an active control was applied. Sensor D tripped at 3.4 seconds, A at 29.7 seconds, B at 64.0 seconds and C at 80.3 seconds. This sequence of the sensor tripping events is recognized by the strategic controller as "the racetracking along both edges" branch of the decision tree. Without any manual interaction, LabView automatically closes the first gate and opens the second one at the flow rate of 10 cm^3/s. The flow fronts are shown at 40, 80, 120, and 188 seconds in the right column of Figure 7. With the help of the active control, the formation of the dry spot was avoided.

CONCLUSIONS

The objective in mold filling strategy with on-line control is to detect the significant variations in the RTM process, such as racetracking and nonuniformity of the perform, from one mold filling case to another and be able to take the required control action to drive the impregnation front to saturate the preform without any dry spots. Mold filling simulations are valuable tools that can be used for tool design as well as for mold filling strategy design. If there is no variation of the parameters from one experiment to the next, the task of the mold filling simulation is reduced to finding the optimum locations of the gates and vents under repeatable conditions. Racetracking effects, which are the only variation considered in this study, and the others due to non-uniform compaction, deformation around ribs and corners can be simulated to create a decision tree to be used in the mold filling strategy. Actuators can be invoked (by opening/closing gates/vents, or changing the inlet flow rate or pressure) by a data acquisition software, such as LabView, after reading and evaluating the data from the sensors used in the mold. LabView will automatically interpret the sensor data and decide which branch of the decision tree fits the current mold filling scenario, and then send the switching signals to the actuators to achieve the mold filling goals such as elimination of dry spots. A mold filling simulation (LIMS), a lab-scale RTM mold with 17 potential locations for gates/vents/sensors, an injection system with three individually controlled lines, resin arrival sensors, valves, and LabView software were integrated to built an on-line control RTM injection system. The system was tested for a part geometry with patches of different fiber volume fractions and racetracking effects along different edges of the mold. Two flow visualization experiments were performed by using diluted corn syrup as a model fluid and a thick acrylic lid for the top half of the mold. The vents were adjusted such that they were closed with a five-second delay after the model fluid reached them. In both experiments, the fabric was cut short to generate a gap between the preform and the mold wall along the bottom and top edges. In the first experiment, the automated injection control system was intentionally turned off and the initial injection conditions for the case of no racetracking were maintained. Hence, at the end of the filling, there was a significant dry spot in the mold, which would cause rejection of the composite part. In the second experiment, the automated injection control system was turned on. Vent # 3 was opened initially. The sensors correctly sensed the arrival of the mold fluid and signaled this information to the LabView. The related branch in the decision tree was found, and the corresponding action, which is to close the first gate and to open the second one, was taken automatically. In this case, the mold filling was completed successfully without any dry spot formation. The importance of the injection control system was demonstrated by comparing two mold fillings under the same internal condition but with and without external control actions. As the mold geometry gets increasingly complicated and variations in the preform increase, the gain by use of an intelligent RTM injection system will be tremendous and will lead to savings in prototype development costs. This work is been extended into mold filling with real resin systems [9].

ACKNOWLEDGEMENTS

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