MODELING AND CONTROL
OF LIQUID COMPOSITE MOLD FILLING PROCESS

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ABSTRACT

Liquid Composite Molding (LCM) processes are gaining popularity in various composites industries, including aerospace, automotive, infrastructure and marine. LCM encompasses an increasing group of mold filling processes, which involve the injection of a resin into a mold cavity filled with a fibrous reinforcement preform. The goal is to understand the fiber fluid interactions at the microscopic level and to develop a macroscopic description to predict the movement of the free surface flow front of a thermosetting resin through a complex three-dimensional mold geometry. Practice has converged on use of Darcy's law to describe the impregnation process by treating the stationary fibers as an anisotropic porous media. A key to successful modeling is the permeability of the porous media which characterizes the resistance of the fibers to the flow of the infiltrating resin. The seminar will address modeling permeability for plain weave fabric, fabric deformation and its effect on flow, race tracking near the mold walls and edges, presence of fiber bundles with low permeabities as compared to the overall preform resistance and how to incorporate this knowledge in a numerical simulation of the LCM process. A promising approach to implement on-line control of LCM based on numerical simulations and in-situ sensors will also be discussed.

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

INTRODUCTION

All liquid molding processes involve impregnation of the resin into a bed of fibrous network. The goal in these processes is to saturate all the empty space (pores) between the fibers with the resin before the resin gels. Resin Transfer Molding (RTM), Resin Infusion Process (RIP) and Vacuum Assisted Resin Transfer Molding (VARTM) are some examples of liquid molding processes. In this paper, we will focus on RTM although many of the modeling and control concepts apply to this general class of manufacturing processes. The steps in the RTM process are shown in Figure 1. A preform is draped over a tool surface, the mold is closed and a thermoset resin is injected to fill the empty spaces between the fibers. After the resin cures the part is demolded [1]. The mold filling is a key step in ensuring the quality of the part, hence it became the focus of the RTM modeling and simulations [2-9]. For complicated mold shapes, the manufacturing engineer has to make decisions about injection pressure, flow rate, location of gates and vents, etc. to achieve a high-quality composite part which is free of dry spots and takes minimum amount of time for the resin impregnation process.

Several sophisticated computer simulations [2-9] of the liquid molding process have been developed based on the physics of flow through porous media over the last two decades. By having robust mold filling simulation codes available to manufacturing and design engineers, prototype development will save money and time, which usually involves many trial and error iterations of the mold configuration and boundary conditions. During prototype development, the engineers can combine their manufacturing experience with simulations to decide if RTM is a viable manufacturing process for the selected part, select the locations for the injection gates and vents to avoid dry spots and minimize fill time.

All mold filling simulations require the information regarding the permeability of the preform, which is resistance to flow at every spatial location in the mold. The accuracy of the flow simulation is directly tied to the specification or prediction of the permeability. Permeability is a function of the fabric architecture, type of preform, fiber volume fraction and deformation the preform undergoes during placement, especially in molds that have corners and double curvatures [10-13]. Moreover, the permeability will change due to inconsistent fabric cutting, stacking and placement into the mold. Sometimes this will cause unintentional race tracking (channels of fiber free regions through which the resin can flow with ease due to much higher permeability) [14-17]. The uncertainties in preform permeability due to compaction, deformation and improper placement of the preform inside a mold around ribs and corners do significantly change the flow impregnation patterns as compared with simulations that do not account for these effects. Hence if the simulations are to be of value in manufacturing practice, one cannot ignore their influence.

One can definitely model deformation of the fabric as it is a deterministic to some extent. However, when the preform is stacked correctly or incorrectly, although an unavoidable event, is a function of how the placement is carried out and may result in one part with proper stacking and the next one with a race tracking channel. One approach to overcome some of these hurdles is to use sensing and on-line control. A point sensor or a probe inside the mold placed at a strategic location can distinguish between a situation of whether there is race tracking along a certain edge or not. It can do this by noting the time for resin arrival. From simulations, we can pre-calculate the time it takes for the resin to reach that location if there was no race tracking along the edge as compared to when the race-tracking is present. The flow detector or probe can compare this time of resin arrival with the predicted times and decide which of the two situation is occurring for that particular manufacturing run and use on-line control of the processing conditions to drive the process towards a successful completion.

In this paper, we present the building blocks and their integration and interaction in moving towards development of an on-line control framework of the RTM process using our previous work of modeling and simulation of the resin flow impregnation process. It has the potential of enabling manufacturing of composite parts with the RTM technique that were previously not possible without on-line control.

MODELING MODULES FOR FLOW SIMULATION

Three different codes developed at the University of Delaware simulate different stages of RTM process. DRAPE [18] is used to predict the fabric deformation on the preform due to draping over the tool surface. PERM [18,19] is a preform permeability predictor for a fabric mat. LIMS ("Liquid Injection Molding Simulation") [2,18] is a robust code to design and control the mold filling process. The schematic of the interface between the codes and the data transfer between them are shown in Figure 2. These three codes work in coordination with each other and are sufficient for a complete numerical simulation and control of the mold filling of the RTM process. The unique feature in our LIMS code is the introduction of command line programming. As part of the input file the user can write independent script files in visual basic that enables placement of virtual sensors anywhere in the mold for feed-back control, on-line control of the process and execution of different control actions by varying the boundary conditions during the simulation.

Draping Model: DRAPE

The fabric structure undergoes a deformation during the draping stage of RTM. DRAPE considers the shearing deformation and neglects the fiber tow slip. A fabric is draped over a fairly general tool surface, and the resulting shearing angle and fiber volume fraction are predicted. As shown in Figure 3a, a kinematic model is used in DRAPE where the real fabric is replaced with a yarn net. The net is draped over the tool surface in the user's specified directions. Yarns are assumed intextensible and pinned at their original intersection point. At the end of the simulation, the deformed paths of the yarn net can be viewed as well as the shearing angle and fiber volume fraction distributions. An example of this is shown in Figure 3b. A different example is shown in Figure 4 for the draping simulation of a braided tube of preform over an axisymmetrical tool. The deformed preform, resulting shearing angles and the fiber volume fraction are shown in the same figure.

Permeability Prediction Model for a Fabric Preform: PERM

As shown in Figure 5, preform permeability will depend on the final fabric structure, which is a function of fabric type, shearing deformation due to draping, degree of compaction, and corners in the mold. One-dimensional or radial experiments can be performed to find the permeabilities of the preform under different amount of compaction and/or shearing deformation. A database of permeability values for undeformed fabrics has been created by Parnas [20]. But, experiments are expensive and difficult to do. Alternatively, PERM can be used to predict the permeability tensor. The preform is divided into resin channel and fabric sub-domains. Two-dimensional (in-plane) resin flow in the empty space between the fabric layers (resin channel sub-domains) satisfies the lubrication flow (see Figure 6 for a single layer preform case). Resin can pass from one resin channel to another through the fabric layers in transverse direction satisfying one-dimensional Darcy's flow. Macroscopic architecture of a unit cell and the bundle permeability are used as input to the model. In-plane permeability components of the mat are predicted. Alternatively, one could create the unit cell geometry in detail and analyze the Stokes flow inside it [21-23]. However, the creation of complicated geometry is non-trivial and has to be modified with compaction and the results are not that different from the approximate solution of lubrication theory used in PERM. Moreover the error in prediction caused due to random nesting of the fabrics is much higher than the accuracy obtained by using the complete solution by use of Stokes equations.

Mold Filling Simulation Model: LIMS

LIMS (Liquid Injection Molding Simulation) is a RTM mold filling simulation code. Salient features of LIMS are ability to handle molds of complicated shapes, racetracking, void handling, non-uniform preform properties, changing injection gate/vent conditions and locations. In addition, one can investigate different injection scenarios in series for design purposes and on-line control of the process. The simulation is based on a finite element/control volume approach. Two-dimensional Darcy's law is used to relate the in-plane resin velocity to the resin pressure gradient within a mold geometry which is represented by shell-type elements in a three-dimensional space. First, resin pressure distribution in the mold is solved at each time step using the finite element method. Then, the flow front is advanced using the control volume method. The unique feature in LIMS is it allows one to introduce virtual sensors and monitor feed-back information regarding the pressure or the resin arrival at any location and introduce decision aspect in the process. Thus creating a framework for development of strategic controller that can execute changes in the injection conditions during the process. This allows one to use the simulation not only as a design tool but also as on-line control tool for development of control strategies as it will be shown here with a case study with experimental validation. First, we will describe our experimental set-up before the discussion of on-line control. The details of modeling of DRAPE, PERM and LIMS can be found in [2,18,19,24,25] and will not be discussed here.

EXPERIMENTAL SET-UP

Mold

For validation studies of active control of the resin flow in a lab-scale experiment, a relatively simple mold was selected. The aluminum flat mold has dimensions of 0.91m by 0.46m. An aluminum spacer frame of 6.4 mm thick was used between the top and bottom plates to create the mold thickness. The aluminum bottom plate of the mold has 17 insert locations which can be used as gates, vents, sensors, or, plugs. The transparent acrylic top plate enables to validate the flow pattern, sensor responses, and control strategies. To change mold thickness, a spacer frame with different thickness can be used. By placing rubber inserts inside the mold, complicated mold geometries can be created.

Injection System

The available injection systems usually 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, such as diluted corn syrup, a sophisticated multiple line injection system was developed [15,26]. This system can inject simultaneously into three injection locations under a specified pressure or an independent specified flow rate for each injection line. It can change the flow rates and pressures on-line in a few seconds. The schematic of the 3-line injection system is shown in Figure 7. The resin in the reservoir is maintained at a constant pressure of 690 kPa. Each copper tubing connecting the reservoir and the flow visualization mold, 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 [15].

DEVELOPMENT AND IMPLEMENTATION OF STRATEGIC CONTROLLER

An on-line strategic controller can help influence the flow front pattern during mold filling and drive the process towards successful completion. The key ingredients for design of such a controller are (i) a numerical simulation that can predict flow front patterns for a selected set of possible variations in the process and material properties, (ii) embedded sensors and their placement in the mold to identify which situation of the selected set is happening, (iii) an appropriate intervention such as increase or decrease of the flow rate or closing or opening of a gate to avoid dry spots or excessive fill times, (iv) a data acquisition software that can collect the sensor data and implement the control action. In our case we used LIMS as the mold filling simulation and LabView as the data acquisition software [15,26].

First, for each possible variation in the preform such as racetracking and non-uniformity of the permeability, off-line LIMS simulations were carried out to calculate the pressure distribution and the flow front locations as a function of time. A decision tree was constructed to detect each of the possible variation uniquely, based on the numerical sensors used in the simulations. The cases in which the parameter variations may cause possible dry spots or require excessive time to fill the mold, possible control actions were explored with the simulations using the command line programming feature to eliminate these undesired results. From the several numerical control-actions (opening and/or closing of gates or vents or changes in the inlet flow rates or pressures after the situation was uniquely identified by the sensor) the best control-action is selected and attached to the corresponding branch of the decision tree.

After the complete decision tree was constructed, a PC with the LabView card is integrated with the embedded sensors and the injection and vent locations within the mold. LabView can implement the commands of the controller by specifying the set points to the actuators of the injection system. Thus, the entire RTM process can be automated and controlled by the PC.

Part Geometry

A complex part geometry was created by placing rubber inserts of different thickness inside the mold cavity as shown in Figure 8. Two gates and four vent locations were selected among the 17 predrilled locations. The transparent top mold plate and dyed corn syrup as the impregnating resin permitted us to validate the experimental results by comparing the flow front positions with simulations and also evaluating the effectiveness of the sensor responses and the control strategies.

Among many possible variations in the RTM parameters, racetracking was chosen as one of the uncertain parameters during mold filling for this paper. Depending on how the preform is trimmed and how it is placed into the mold, four different cases may occur: (i) no racetracking, (ii) racetracking along the top edge, (iii) racetracking along the bottom edge, and (iv) racetracking along both edges. In the racetracking cases, the edges of the preform were trimmed such that there was a 3.1 mm gap between the fabric and the mold wall. 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.

Off-Line Mold Filling Simulations without Control Action

To simulate the mold filling, a uniform finite element mesh with 7800 elements was created. By taking the no racetracking case as the basis, only the first gate in the left air channel, and the vents 1, 2 and 4 were opened. Vents closed automatically upon the arrival of the resin. Mold filling under four different racetracking cases (cases i through iv) were simulated using LIMS. Although, it is an optimization task to design the locations of the sensors, we limited the number of sensors to four and used a simple logic to decide on the locations. Our criteria was that the sensors should be located such that the resin arrival times to those four sensors must be distinct enough to uniquely identify which one of the scenarios from cases i through iv is taking place just from the numerical sensor data. Another important criteria was to locate the sensors as close as possible to the first gate to detect which case is in progression early enough so that there was sufficient time to take control action that would be effective enough to influence the flow front pattern to avoid dry spot formation.

Using the sensors A, B, C and D as shown in Figure 9, the simulations show that for cases i through iv the order of the sensor signals as triggered by resin arrival is ABCD, DACB, ABDC, and DABC, respectively. Thus, this uniquely detects among the four cases as illustrated in the decision tree shown in Figure 10. The simulations are shown in the left column of Figure 11. Of course, here the assumption is that the preform variation elsewhere is minimal.

Off-Line Mold Filling Simulations with Control Action to Eliminate the Dry Spots

As seen in cases (iii) and (iv), a dry spot is predicted in the preform at the end of the filling if no control action is taken. In order to eliminate this flaw, different control actions were explored and the first action that gave us a successful completion was used. In case (i), no control action was necessary. In case (ii), after the sensor C was 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 all race-tracking cases with the control actions described above. The flow front locations at various times for each of the race-tracking cases are shown in the right column of Figure 11. 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.

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, that was determined by exploring different possible ones from simulations, to the actuators.

Mold Filling Experiments with On-line Controller

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. Although all four scenarios were validated experimentally [10], only results from one case will be presented here to depict the advantage of active control during mold filling in RTM. For case (iv), two experiments were conducted: one without any control and one where the control decisions were triggered. A significant dry spot on the right side of the mold was formed at the end of the filling without control. This part would have to be rejected due to this defect. In the experiment with controlled injection, 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. With the help of the active control, the formation of the dry spot was avoided. The flow front locations at several time steps are shown in Figure 12.

Effect of Variations in the Preform and Degree of Race-tracking

Usually, it is difficult to characterize quantitatively the degree of race-tracking. In manufacturing practice the degree may vary with the placement and egde condition of the preforms. To explore the influence of this, we introduced three more cases with weak race-tracking where the racetracking channels along the two sides were created with a gap of 1.6 mm (cases v-vii). We also introduced a case (viii) where we have strong racetracking along both edges as in case (iv) but with a 20% variability in the permeability of the preform in a selected region where the permeability of the bulk material with Vf = 6.4 % is reduced by 20 % assuming that the value used in predictions was off from the one in the actual part). All cases are tabulated in Table 1. Although, in reality the possible variations are not limited to the ones considered in this section, this is our first attempt at exploring the sensitivity of our control action to uncertainities in characterization of permeability values and the strength of the race-tracking phenomena.

Table 1. Different racetracking cases investigated in the mold injections.

Case	Racetracking gap [mm]	
	Top edge	Bottom edge
i	0	0
ii	3.1	0
iii	0	3.1
iv	3.1	3.1
v	1.6	0
vi	0	1.6
vii	1.6	1.6
viii	Same as case (iv) except that the permability of preform in the Vf = 6.4 region was reduced by 20%.	

The simulations with and without control are shown in Figures 13 and 14. In cases (v)-(vii), the flow front patterns are affected significantly as compared with cases (ii)-(iv). The decision tree detects cases (v), (vi), (vii), and (viii) as being cases (ii), (iii), (iv) and (iv), respectively. The controller excecutes the control actions of the decision tree created for cases (i-iv). Nevertheless, the control action eliminates the dry spots confirming that it is not very sensitive to the strength of race-tracking or variation in the permeability value. Of course, as the degree and the number of variations increase, the originally determined decision tree will not be adequate to take all contengencies into account. The decision tree will need to be extended by considering the new additional variations. A methodoly to develop a decision tree is underway.

CONCLUSIONS

Although, mold filling simulations have helped in reducing the number of trial and error experiments in manufacturing practice when developing a prototype part to be made by Liquid Composite Molding process, the inherint variablity in the process and the possible error bars in characterization of material properties continue to challenge the manfacturing engineer to reduce the number of unacceptable parts. To address this issue, our approach has been to focus on some of these variabilities and introduce sensors inside the mold to identify the variabilities and take corrective action to avoid failure. To accomplish this, we re-wrote our mold filling simulation to allow command language programming that can detect resin arrival at nodes, introduce new gate and vent locations and change boundary conditions during the process based on the feed-back from the sensors. This created the foundation for development of a strategic controller by mimicing the variations that may occur on the shop floor, detecting them early enough with sensors and exploring various control actions that could be taken to correct the problem. All this was casted in a form of a decision tree. The approach was described with an example case study and experimental validation to prove the usefulness and implementation of the concept and move liquid composite molding processes towards automation.

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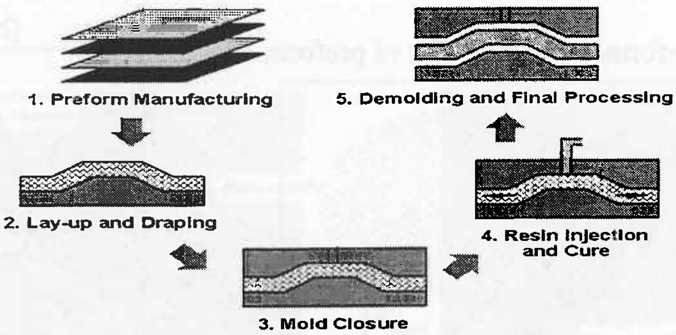

Figure 1. The schematic of the RTM process.

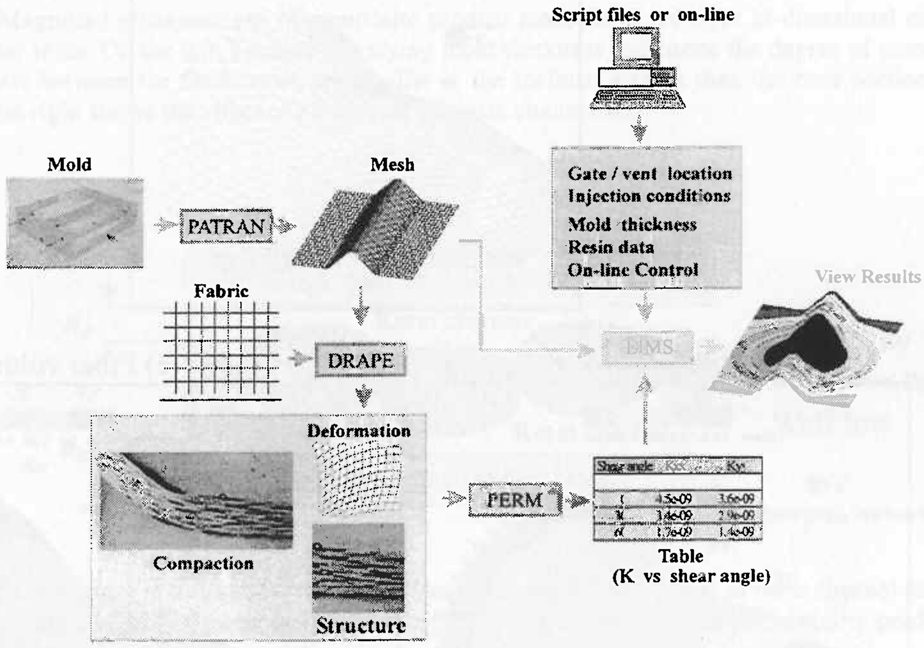

Figure 2. Interface between the codes DRAPE, PERM and LIMS for the draping, permeability prediction, and the mold filling stages of RTM process, respectively.

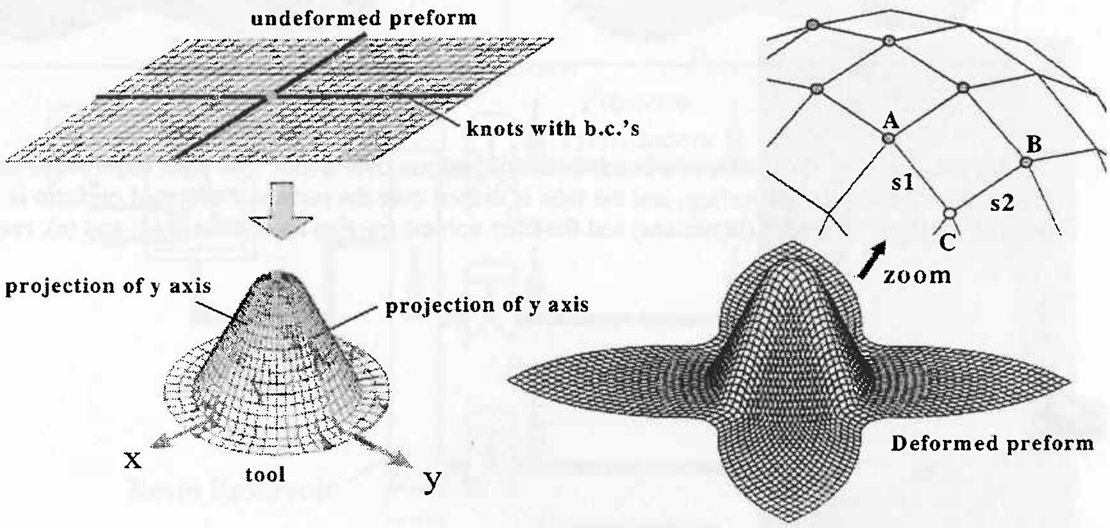

Figure 3. Draping model. The fabric undergoes a structural deformation while it is draped over the tool surface.

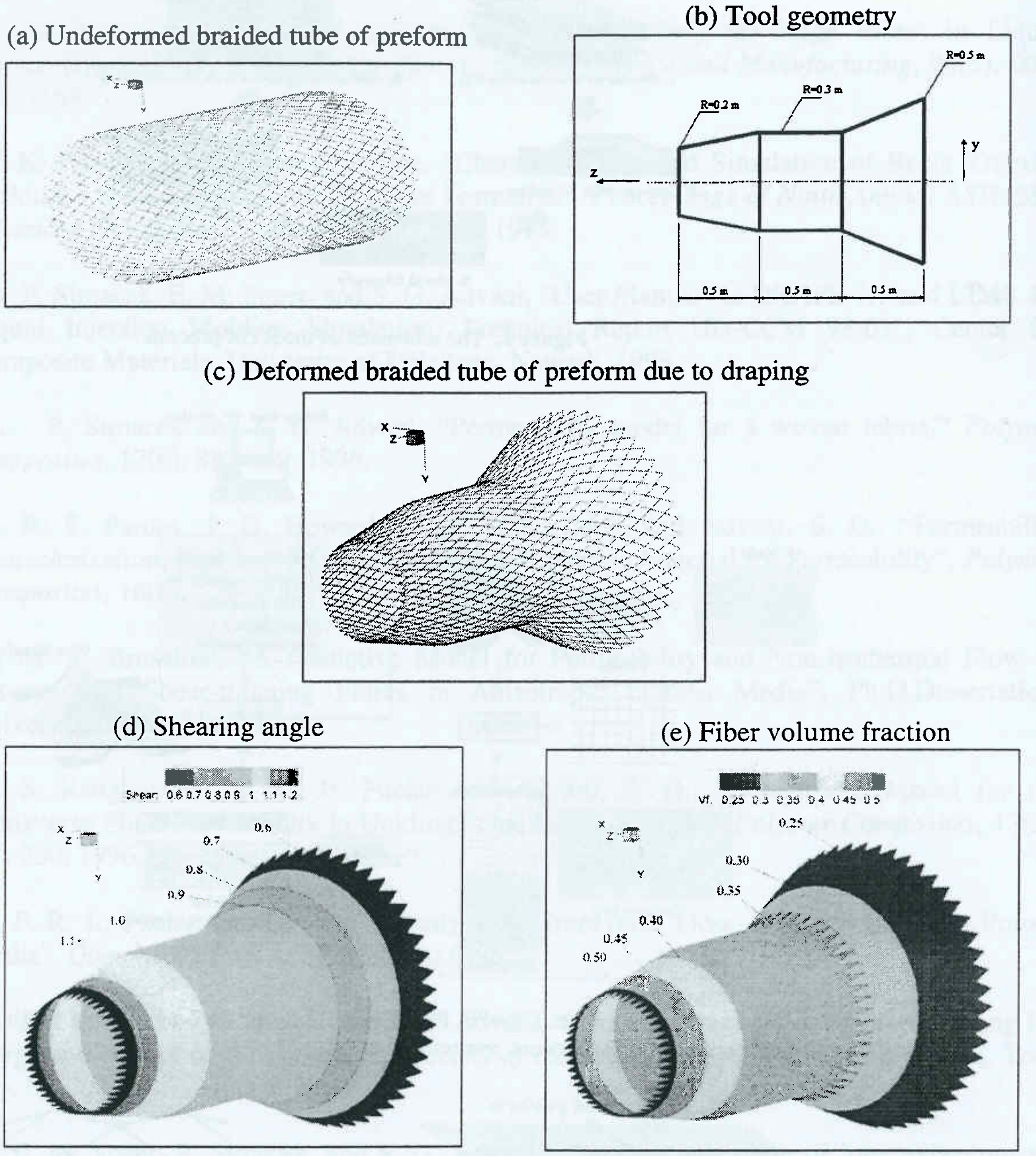

Figure 4. Draping simulation of a braided tube of preform over a tool. The right edge of the tube is fixed at the right edge of the tool surface, and the tube is draped over the surface. Deformed preform is shown in (c). Resulting shearing angles (in radians) and the fiber volume fraction are shown in (d) and (e), respectively.

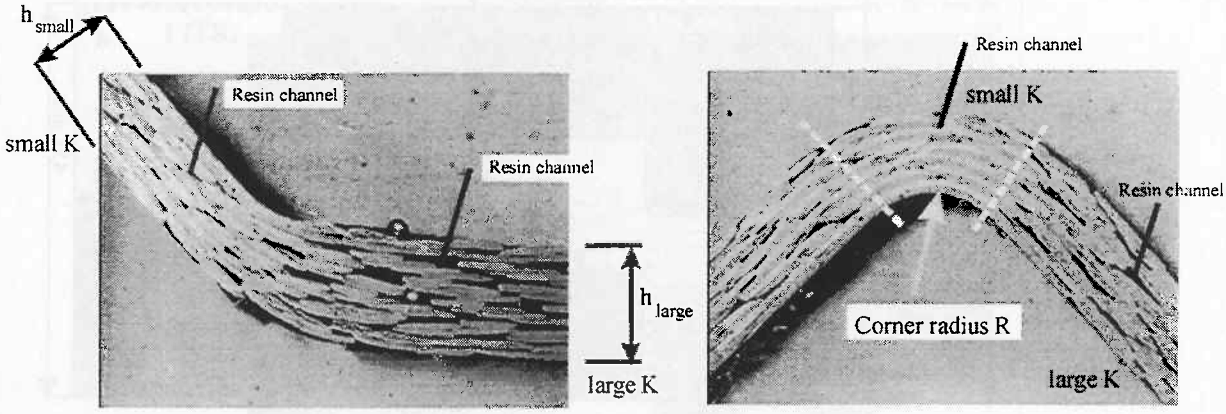

Figure 5. Magnified cross-sections of composite product made from six-layer bi-directional carbon fabric and vinylester resin. On the left, because of varying mold thickness and hence the degree of compaction, the resin channels between the fabric tows are smaller in the inclined section than the base section. The cross section on the right shows the effect of corners on the resin channel size.

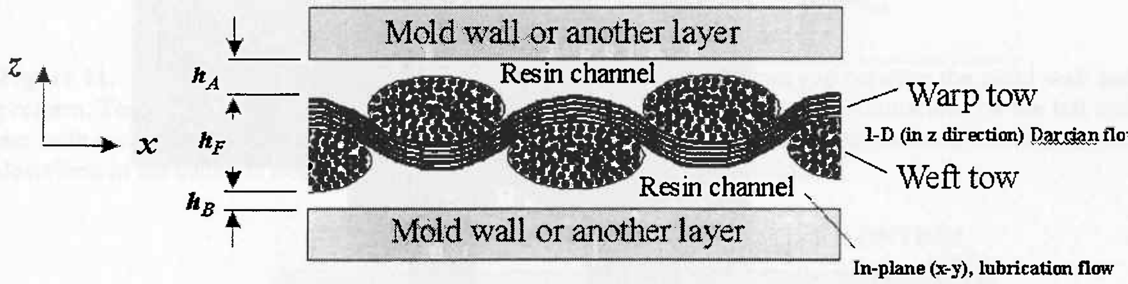

Figure 6. Flow regions in a single layer of plain weave preform. Stokes flow in resin channel sub-domains, and one-dimensional Darcy flow in the fabric sub-domain are assumed in the permeability predictor model PERM [18,19].

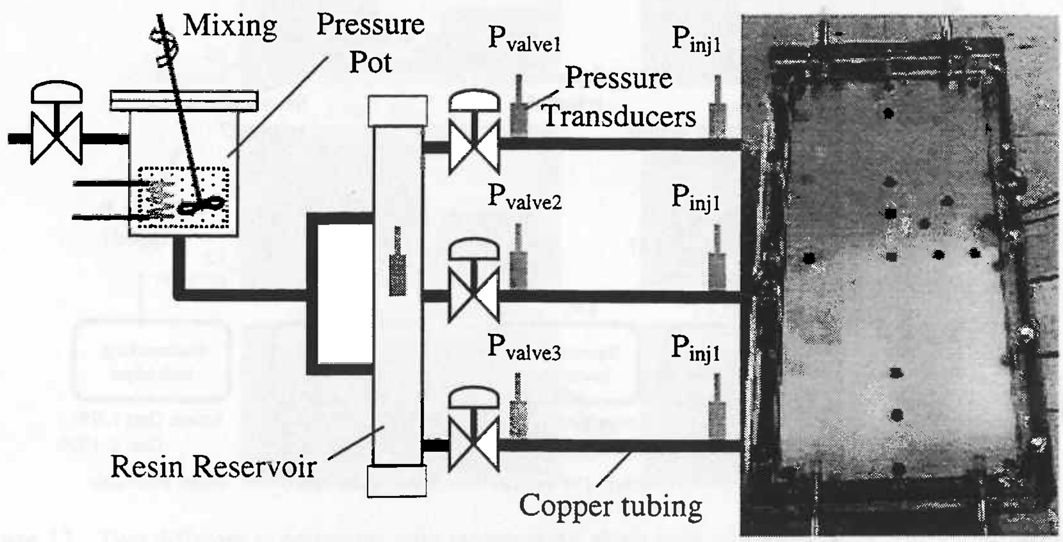

Figure 7. Multi-line injection system connected with the flow visualization mold.

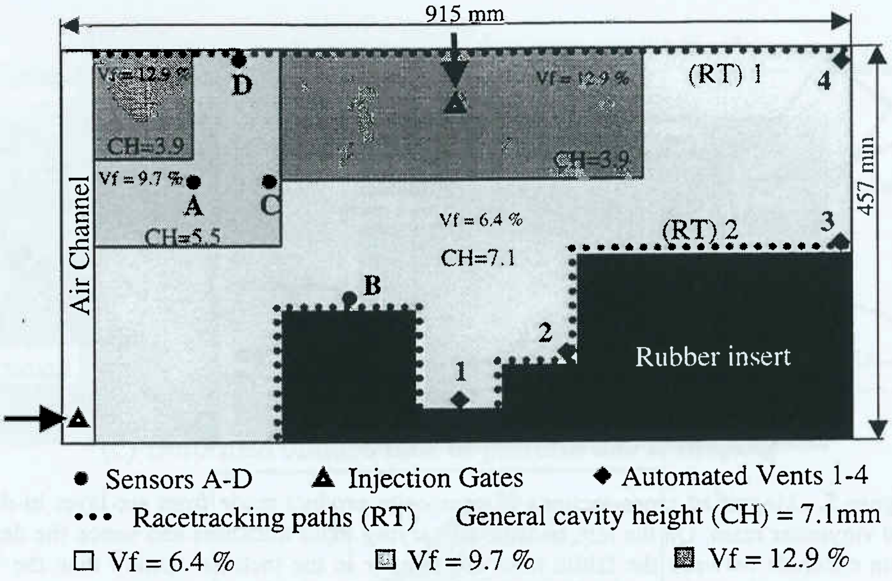

Figure 8. Schematic of selected mold cavity for experimental validation.

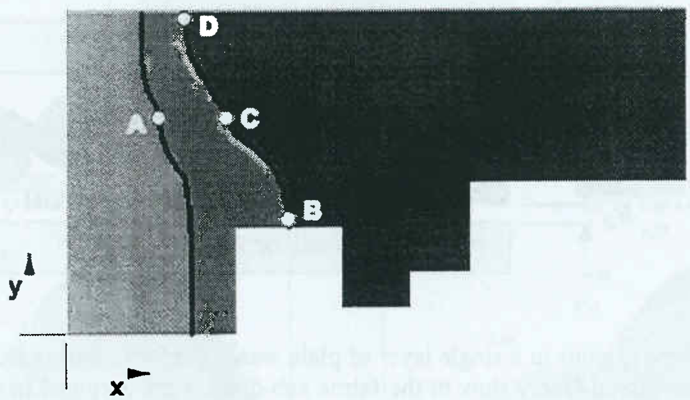

Figure 9. Locations of four flow front sensors in the mold. The two curves show the location of the flow front at two different time steps under no-racetracking condition.

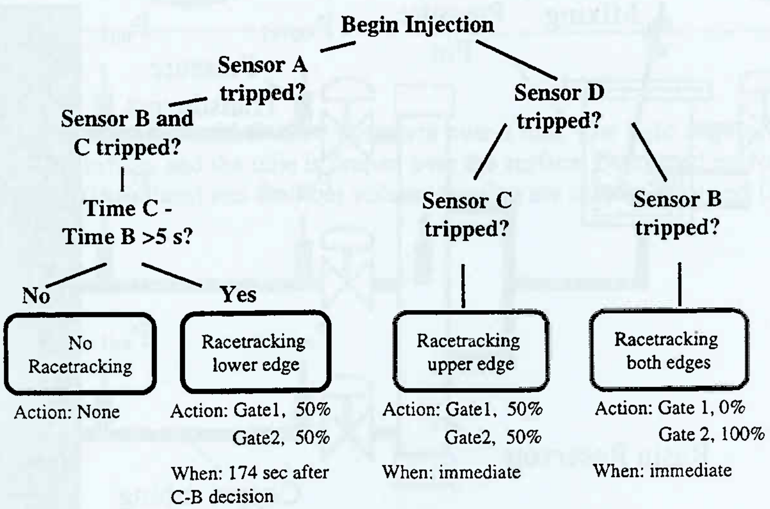

Figure 10. Decision tree for the controlled mold injection.

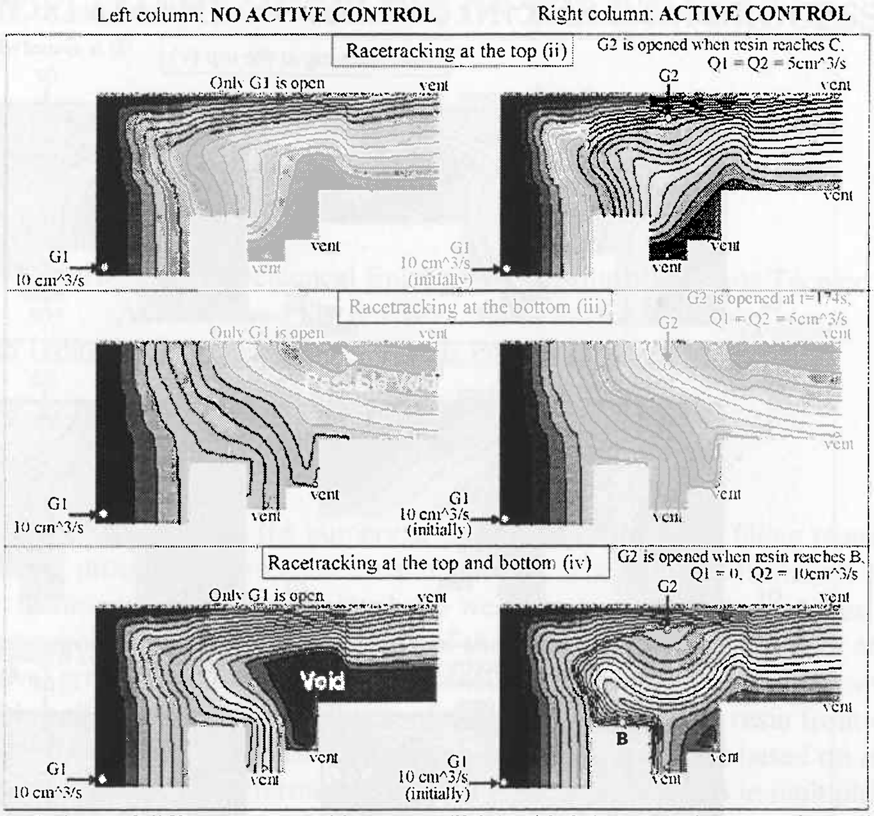

Figure 11. Simulations of different racetracking cases (ii-iv) with 3.1mm gap between the mold wall and the preform. The curves show the location of the flow front at different times. The simulations on the left column are with no active control whereas the ones on the right column are with the necessary active control as described in the decision tree section to eliminate the dry spot (void) problem.

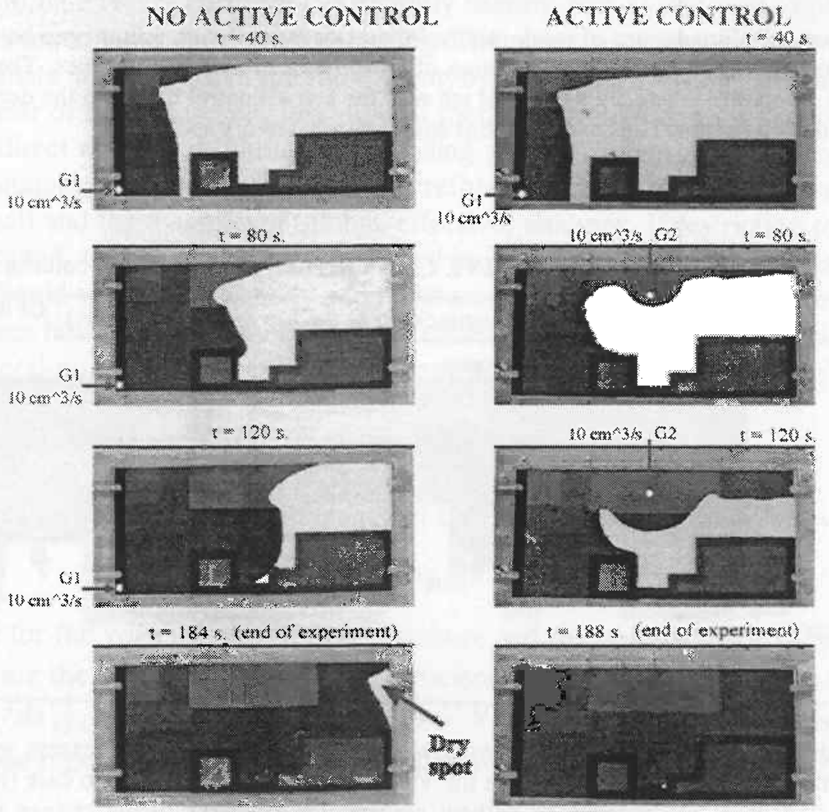

Figure 12. Two different experiments with racetracking along both edges (case iv). The experiment shown in the left column is without active control in which a dry spot remains in the mold at the end of filling. The experiment in the right column features active control which eliminates the dry spot.

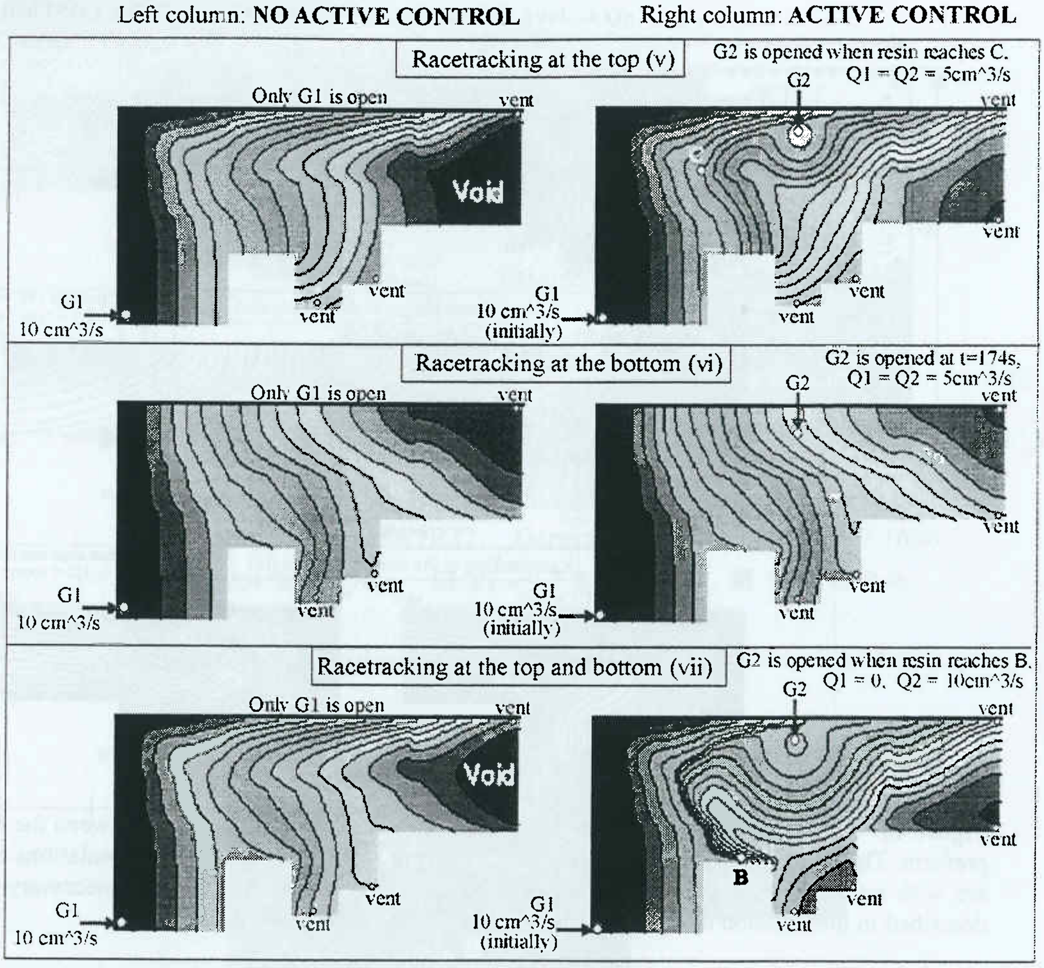

Figure 13. Simulations of weak racetracking cases (v -vii) with 1.6mm gap between the mold wall and the preform. The curves show the location of the flow front at different times. The simulations on the left are with no control whereas on the right are with the active control based on the decision tree created for strong racetracking cases. The control-actions still eliminate the dry spots.

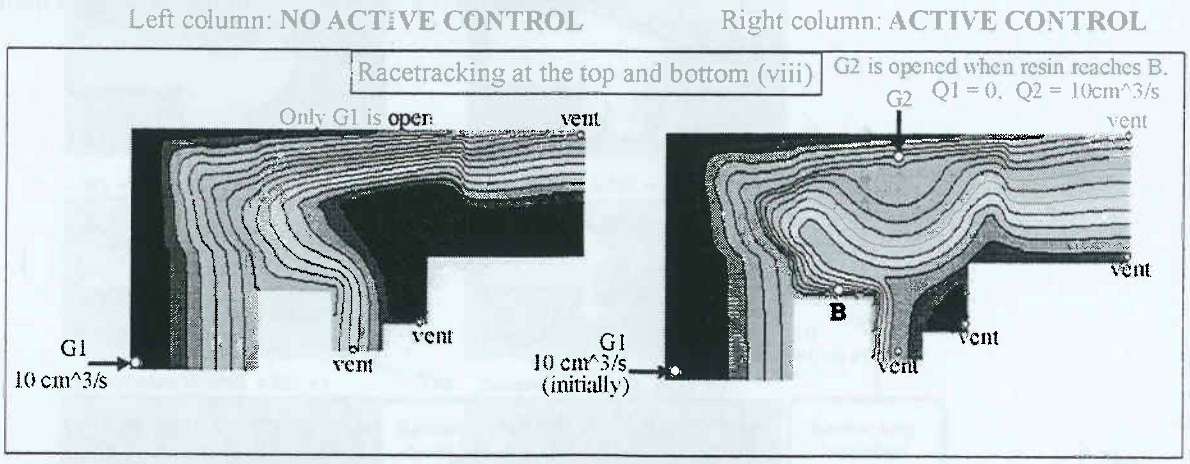

Figure 14. Simulations of case (viii) which is identical to case (iv) except with a 20 % reduction in the permeability of the bulk preform in the Vf = 6.4% section. Compared to case (iv), there is no big change in the flow front pattern with or without control. The only significant change is that the total filling time increased due to possible unexpected variation in the preform permeability.