TEXTILE COMPOSITE PROCESSING SCIENCE*

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ABSTRACT

A multi-dimensional model of the Resin Transfer Molding (RTM) process was developed for the prediction of the infiltration behavior of a resin into an anisotropic fiber preform. Frequency dependent electromagnetic sensing (FDEMS) has been developed for in-situ monitoring of the RTM process. Flow visualization and mold filling experiments were conducted to verify sensor measurements and model predictions. Test results indicated good agreement between model predictions, sensor readings, and experimental data.

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INTRODUCTION

Resin Transfer Molding (RTM) is of interest to the aircraft industry as a cost-effective method for the production of near-net shape primary aircraft structures. The RTM process also lends itself to the use of textile preforms manufactured through a variety of automated textile processes. Often, these preforms have through-the-thickness stitching for improved damage tolerance and delamination resistance. The challenge presently facing RTM for use in the aircraft industry is to refine the process to insure complete infiltration and cure of a geometrically complex shape preform with the high fiber volume fraction needed in the industry.

Towards this goal, a joint research program between NASA Langley Research Center, Virginia Polytechnic Institute and State University, and the College of William and Mary is designed to develop a science based understanding of RTM for aircraft composites. A necessary part of this project is to characterize the emerging resins and preforms used in the RTM process. Elements of the program include:

- Analytical modeling of the RTM process
- In-situ sensing of resin flow during the RTM process
- Mold filling and flow visualization experiments
- Preform and resin characterization
- Sensor/model intelligent process control

This paper will discuss the theoretical basis of the RTM process model and the characterization of the preforms used in the process. The use of Frequency Dependent Electromagnetic Sensing (FDEMS) for monitoring resin front position and cure will also be addressed. Results of two dimensional flow visualization and mold filling experiments performed to verify the process model will be presented.

RESIN PROCESS SIMULATION

The model, which is based on the finite element/control volume technique, was developed to predict the resin flow front position and pressure distribution inside the preform as a function of time. The following assumptions are made in the analysis: 1) the preform is a porous medium, 2) the preform permeability is heterogeneous and anisotropic, 3) the resin is incompressible and low Reynolds number flow is present, and 4) the injection is performed under isothermal conditions.

User defined variables such as the time/temperature/pressure profile along with the preform layup sequence and tooling assembly are input into the model. A flow diagram for the simulation model is given in Figure 1. The compaction and permeability behavior of the preform coupled with resin viscosity behavior are used by the model to predict the resin front position as a function of time. Once the preform is completely infiltrated, the degree of cure and total cure time are calculated by the model. The model outputs this data along with temperature as a function of time for later analysis. Panel thickness and the resulting final fiber volume fraction are also determined by the model.

PREFORM CHARACTERIZATION

In order for the model to correctly evaluate the infiltration behavior of the resin into the dry perform, it is necessary to characterize the porosity and permeability behavior of the perform. The porosity behavior is determined by measuring the compaction pressure necessary to achieve the desired level of fiber volume fraction. The fiber volume fraction is then related to the porosity and the preform thickness by the following equations:

$$\phi = (1 - v_f) = \left(1 - \frac{\xi}{t\rho_f}\right) \tag{1}$$

where ϕ is the porosity, v_f is the fiber volume fraction, t is the preform thickness, ρ_f is the fabric density, and ξ is the areal weight. This relationship is illustrated in Figure 2. The areal weight is the weight of the sample per unit area.

The steady state permeability behavior is determined by passing a fluid of known viscosity and volumetric flow rate through the preform and recording the pressure drop that occurs as the fluid passes through the fabric. Then, through the use of Darcy's Law,

$$Q = \frac{KA}{\mu}\frac{\Delta P}{\Delta x} \tag{2}$$

the permeability can be determined for each fiber volume fraction. The permeability is denoted as K, A is the flow area, the volumetric flow rate is Q, and μ is the viscosity of the fluid. The pressure difference is written as ΔP and the change in length is denoted as Δx. A diagram of the steady state permeability fixture is given in Figure 3.

EXPERIMENTAL

The set up for the flow visualization experiments conducted at Virginia Tech consisted of a 2 ft x 2 ft aluminum frame with a 1.5 inch thick poly (methyl methacrylate) top plate. The preform was composed of eleven (11) layers of Style 162 E-glass at a nominal fiber volume fraction of 43%. A dyed corn oil with a viscosity of 39.6 cps was injected into the mold at a constant pressure of 5.7 psi. The infiltration pattern was recorded through the use of a video camera. Frequency Dependent Electromagnetic Sensing (FDEMS) was used to determine the time at which the flow front passed a pre-selected point in the mold.

Two tests were conducted at NASA Langley Research Center to verify the simulation model. For these tests, a 1 ft x 1 ft stainless steel mold was used. The preform, composed of TTI IM7/8HS compressed to a fiber volume fraction of 60%, was injected at a constant flow rate of 10 cc/min with an epoxy resin. In one case, the viscosity of the epoxy was 58 cps while, in the second case, the viscosity was 165 cps. FDEMS were used to monitor the advancement of the flow front inside the closed mold. The total time required to fill the mold was also recorded.

The objectives of these tests were threefold:

1) To verify the flow-front and infiltration-time predictions of the RTM process simulation model
2) To verify permeability versus compaction measurements obtained from the preform characterization experiments
3) To demonstrate the ability of FDEMS sensing to detect the position of the flow front.

RESULTS

Preform Characterization

The compaction behavior for the TTI IM7/8HS preform is given in Figure 4. That of the Style 162 E-glass is shown in Figure 5. In both cases, the pressure needed to compress the preform is initially non-linear but then flattens out at the higher fiber volume fractions. The pressure required to compact the TTI IM7/8HS preform to an identical fiber volume fraction is less than that needed for the Style 162 E-glass preform.

The permeability behavior of the TTI preform is given in Figure 6 while that of the glass preform is provided in Figure 7. Experiments have shown that the permeability of both preforms decreases as the fiber volume fraction increases. This results from the available pore space in the preform being closed off at the higher fiber volume fractions, thereby restricting fluid flow.

Flow Visualization - Single Side Port Injection

The details for the flow visualization test are shown in Figure 8. The corn oil enters the mold through the single side port and flows around the preform in a quarter inch channel until the entire channel is filled. The corn oil then enters the preform from each side, fully saturates the preform, and exits through a centrally located port.

It was noticed that the pressure failed to remain constant at the early stages of injection. The pressure fell from the set injection pressure to almost zero as the channel was filling. Only after the preform was initially infiltrated did the pressure return to the pre-set position. Therefore, pressure was monitored as a function of time and this resulting curve was input into the model.

A comparison between experimental and model-predicted flow fronts are given in Figures 9-11. At each time, there is good correlation between the predicted and experimental flow fronts. The irregularly shaped experimental flow fronts were attributed to the wavy nature of the plexiglass lid which allowed for spatial variations in permeability not accounted for in the model predicted flow fronts.

A grid showing the FDEMS locations in the baseplate has been overlaid on Figures 9 and 11. The time at which some sensors wetted out has also been provided. Through these times, a comparison can be made between model predicted, experimental, and sensor measured flow front positions as a function of time. The sensor measured times were usually within a few seconds of both the experimental and model predicted values. The accuracy of the sensors can be improved by increasing the scanning rate used during the data acquisition.

Mold Filling Experiments - Single Side Port Injection

A schematic diagram for the RTM mold filling experiments is shown in Figure 12. The resin is transferred from the constant injection rate cylinder to the mold through plastic tubing. A shim is placed on top of the preform to insure that the desired fiber volume fraction is reached. A steel plate with a venting port is then placed on top of the shim. A vacuum is then applied to assist in the removal of air from the preform.

As mentioned earlier, the preform has a nominal fiber volume fraction of 60%

while an epoxy/diluent mixture was used to achieve different viscosity resins. The resin is injected at 10 cc/min into the single side port and proceeds to fill a 0.25" high by 0.25" wide channel. Then resin then infiltrates the preform until saturation is achieved. The resin then exits through the venting port.

FDEMS were used to measure the position of the flow front inside the mold cavity. Six (6) sensors were used: three (3) were placed on the edge of the preform, one (1) in the center of the preform. The remaining two (2) were placed approximately three inches from the center. Their locations are illustrated in Figure 13.

A comparison between model predicted and sensor measured flow front positions is given in Figure 14. The sensors located along the edge of the channel filled much faster than predicted. The two sensors located near the center of the mold agree fairly well with the model predicted times. This indicates that the permeability of the preform governs the infiltration behavior once the channel is completely filled.

The most important thing to note from Figure 14 is that the flow front passed the exit port (located above the center sensor) prior to complete infiltration of the preform. This is not desirable as this may result in a large region of entrapped air or many small voids. Both of these will result in a noticeable decrease in mechanical properties for the composite. Based on this observation, the model was used to simulate a dual port injection. The result of this simulation is shown in Figure 15. This figure shows the two resin fronts meeting at the center of the preform.

SUMMARY AND CONCLUSIONS

A multi-dimensional RTM process simulation model has been developed which can describe the infiltration of a resin into a dry textile preform along with the cure of the resulting saturated preform. This model is useful in predicting the total infiltration time needed along with the selection of optimal port locations in the mold. The model can also be used in determining the optimal cure cycle for a particular resin system. Frequency Dependent Electromagnetic Sensing (FDEMS) has been developed for use in the in-situ monitoring of the RTM process. These sensors were able to detect the resin front position as a function of time during the infiltration process. The sensors are also able to monitor the resin properties during the subsequent cure cycle.

A series of flow visualization and mold filling tests have been performed to verify the predictive capability of the model along with the ability of the sensors to monitor resin front position. Results from these tests indicated that the sensors were able to accurately monitor the front position during infiltration and that model predicted flow front positions agreed well with the experimental front positions.

Future work will concentrate on verifying the heat transfer analysis aspect of the model. Also, the sensor's ability to monitor resin properties during cure will be evaluated. The production of actual panels will be modeled and monitored with the sensors. The panels will be evaluated to determine possible manufacturing defects along with their mechanical properties.

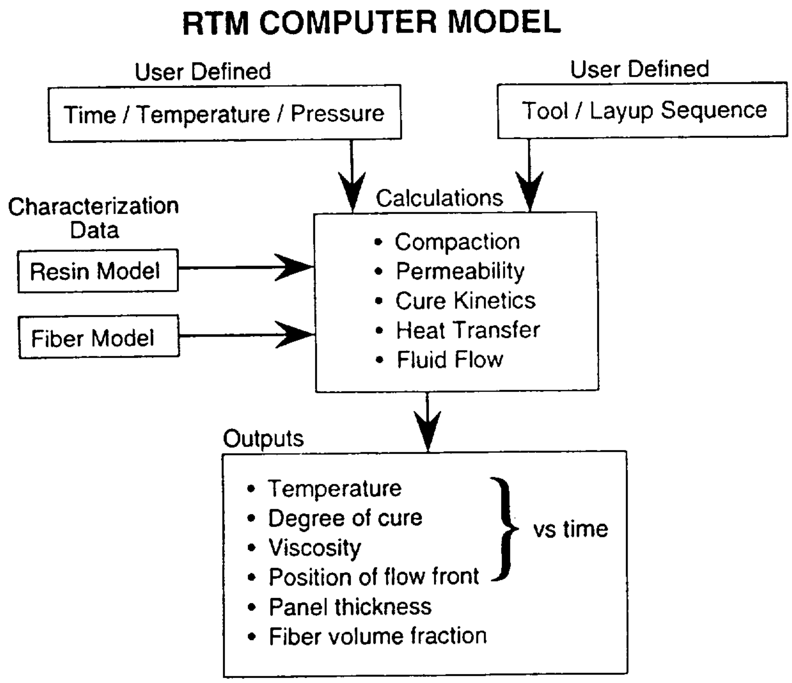
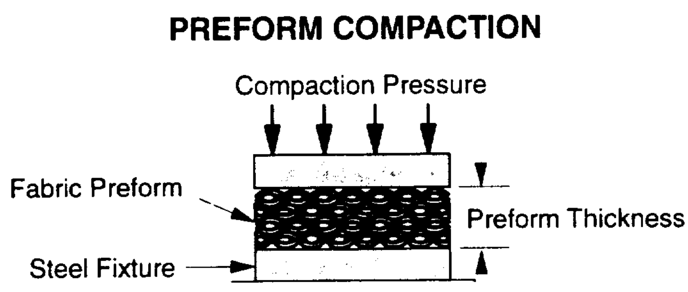


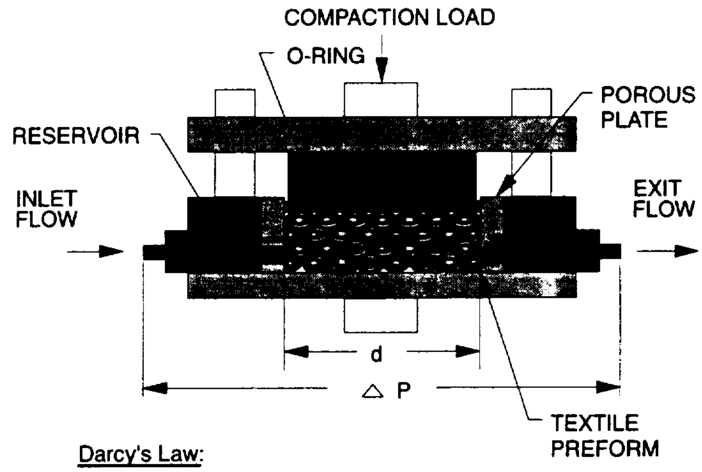
Figure 1: Flow chart of RTM simulation model.



$$\Phi = (1 - v_f) = (1 - \frac{\xi}{t \rho_f})$$

- Φ - porosity
- v_f - fiber volume fraction
- t - thickness
- ξ - areal weight
- ρ_f - fabric density

Figure 2: Schematic diagram relating preform thickness to porosity.



Darcy's Law:

$$Q = A \frac{K}{\mu} \frac{\triangle P}{d}$$

WHERE: Q = VOLUMETRIC FLOW RATE
K = PERMEABILITY CONSTANT
μ = VISCOSITY OF FLUID
$\triangle$ P/d = PRESSURE GRADIENT
A = AREA NORMAL TO FLOW

Figure 3: Diagram of steady state permeability fixture.

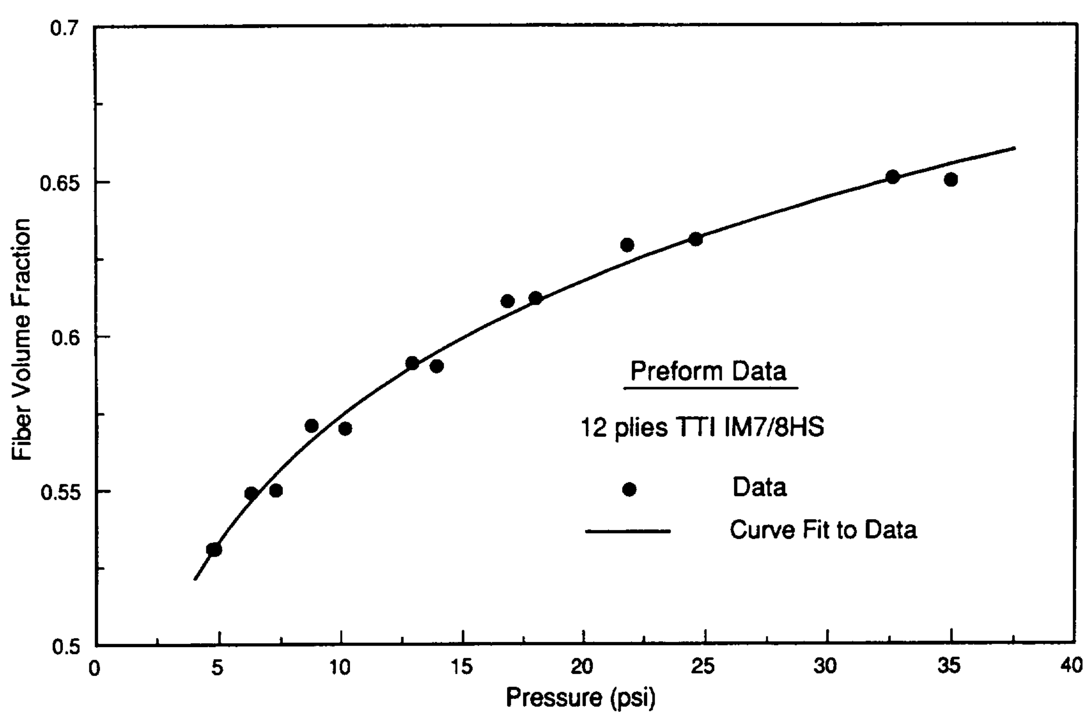


Figure 4: Compaction Behavior for the TTI IM7/8HS preform.

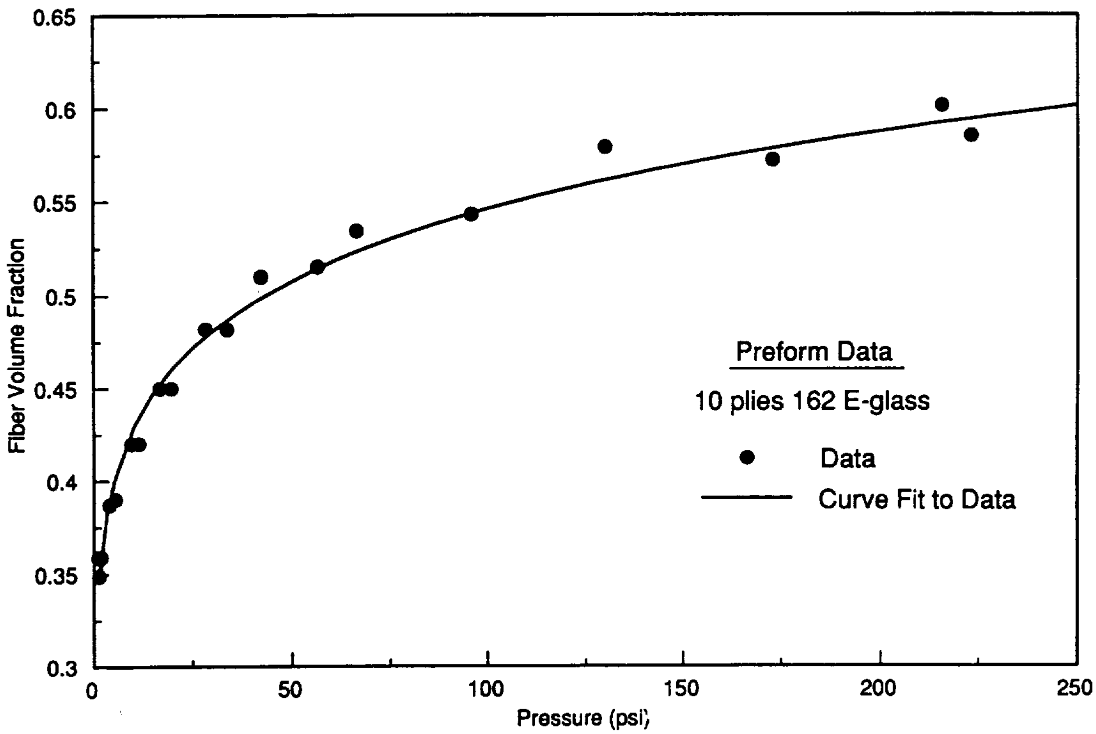


Figure 5: Compaction Behavior for the Style 162 E-glass preform.

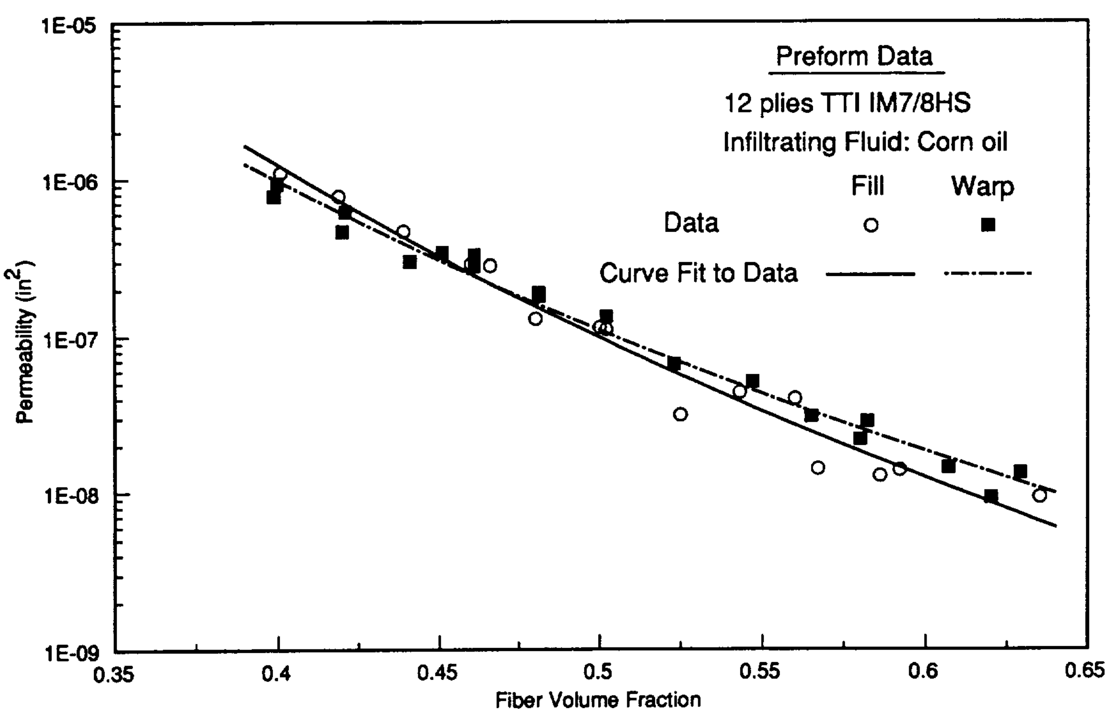


Figure 6: In plane permeability behavior for the TTI IM7/8HS preform.

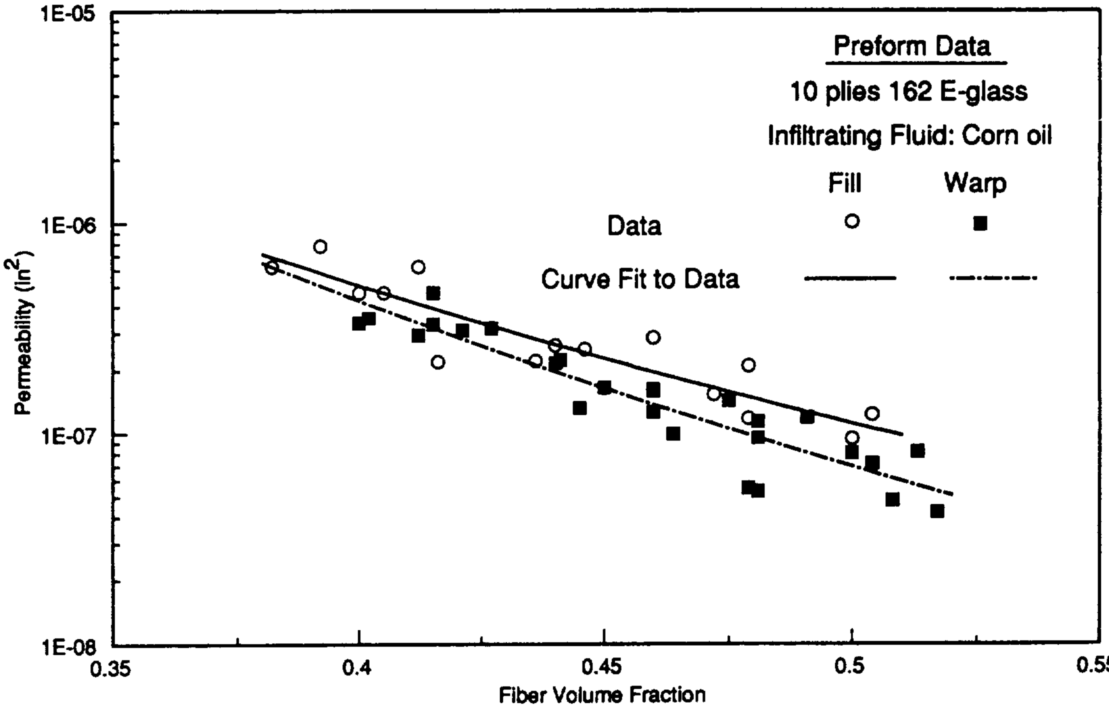


Figure 7: In plane permeability behavior for the 162 E-glass preform.

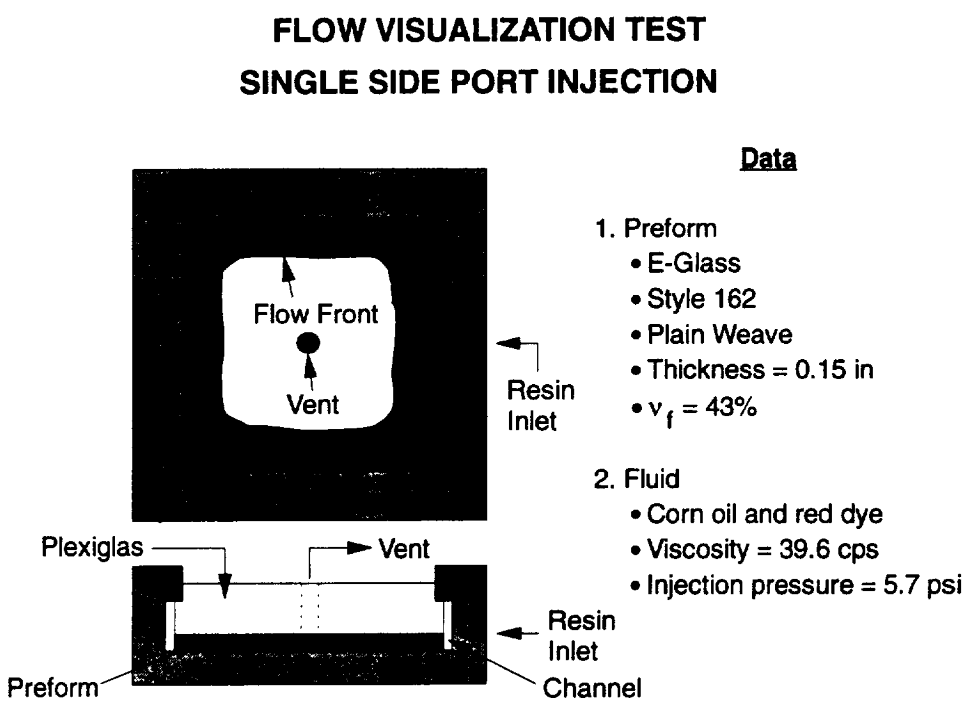


Figure 8: Details of single side port injection flow visualization test.

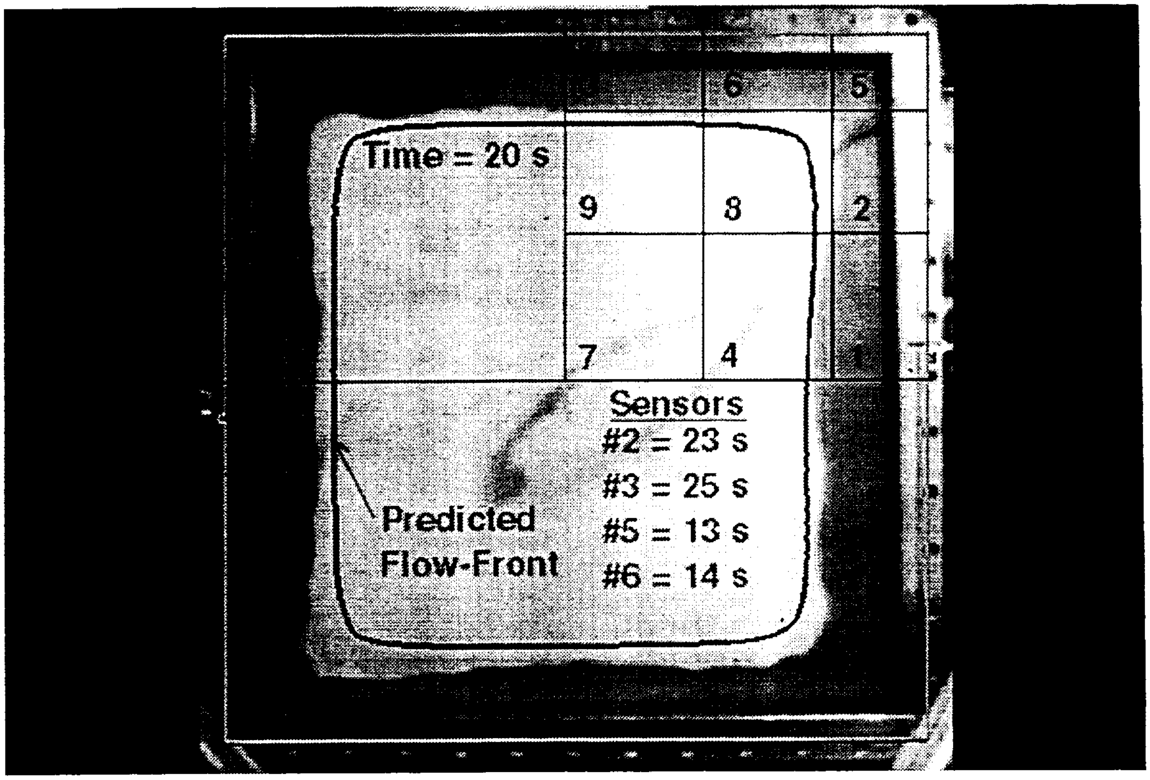


Figure 9: Comparison between model predicted and recorded flow fronts at an infiltration time of 20 seconds.

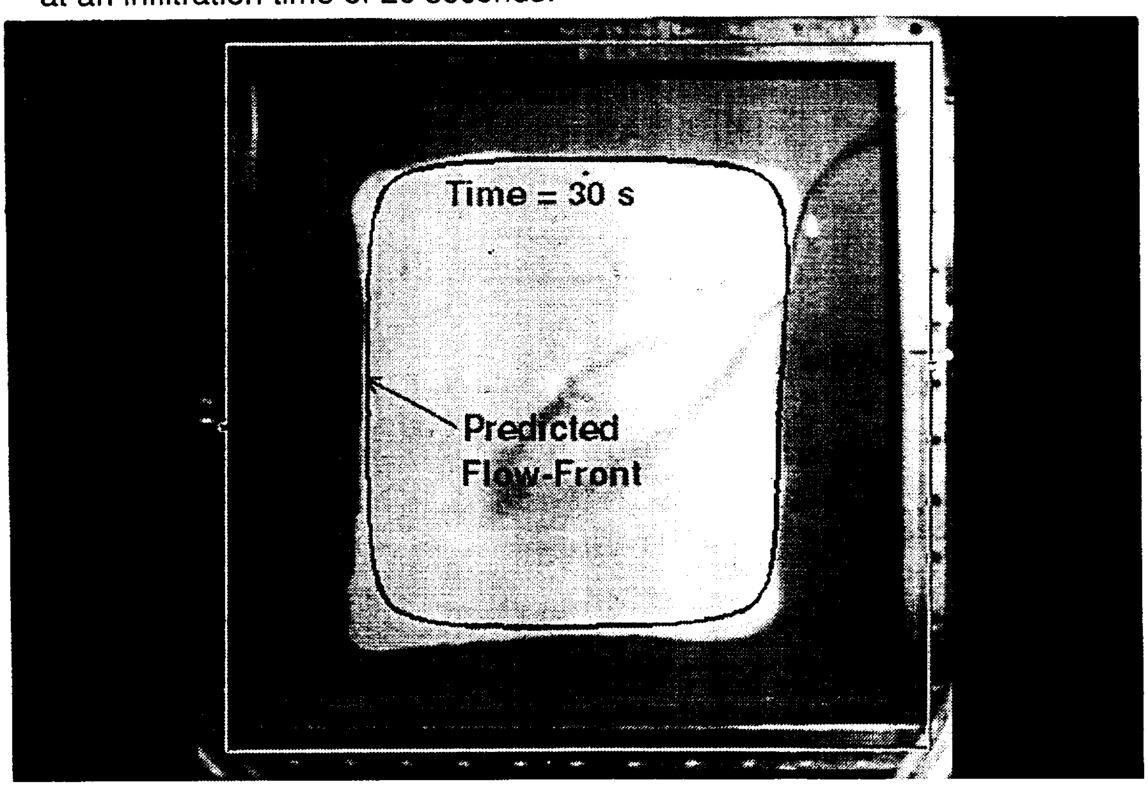


Figure 10: Comparison between model predicted and recorded flow fronts at an infiltration time of 30 seconds.

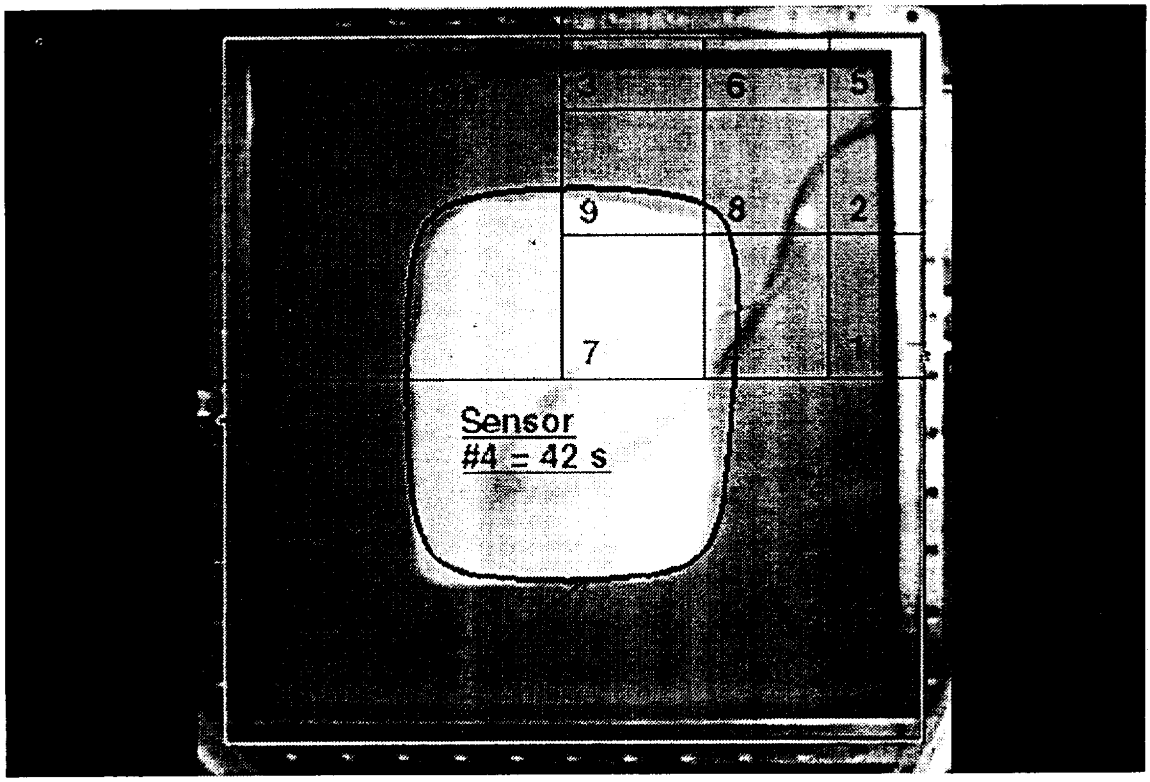
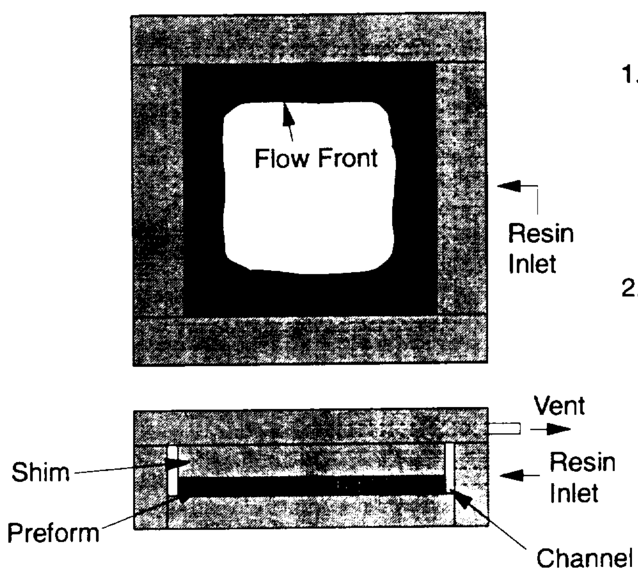


Figure 11: Comparison between model predicted and recorded flow fronts at an infiltration time of 45 seconds.

MOLD FILLING EXPERIMENTS

SINGLE SIDE PORT INJECTION



Data

1. Preform
   - IM7 graphite
   - 8-Harness satin
   - Thickness =0.25 in
   - v_f = 60%
2. Fluid
   - Epoxy and diluent
   - Viscosities = 58 and 165 cps
   - Injection flow rate = 10 cc/min

Figure 12: Details of single side port injection mold filling experiment.

Bottom Plate of RTM Mold

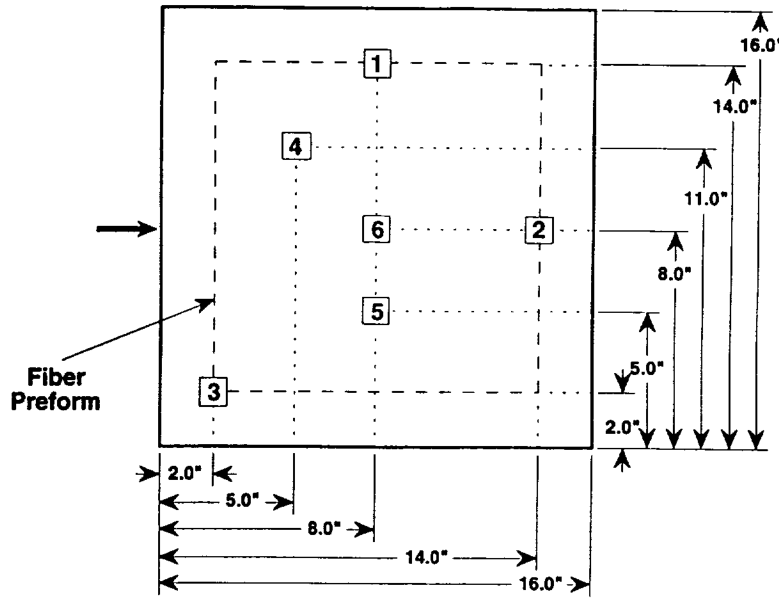


Figure 13: Location of FDEMS Sensor Array.

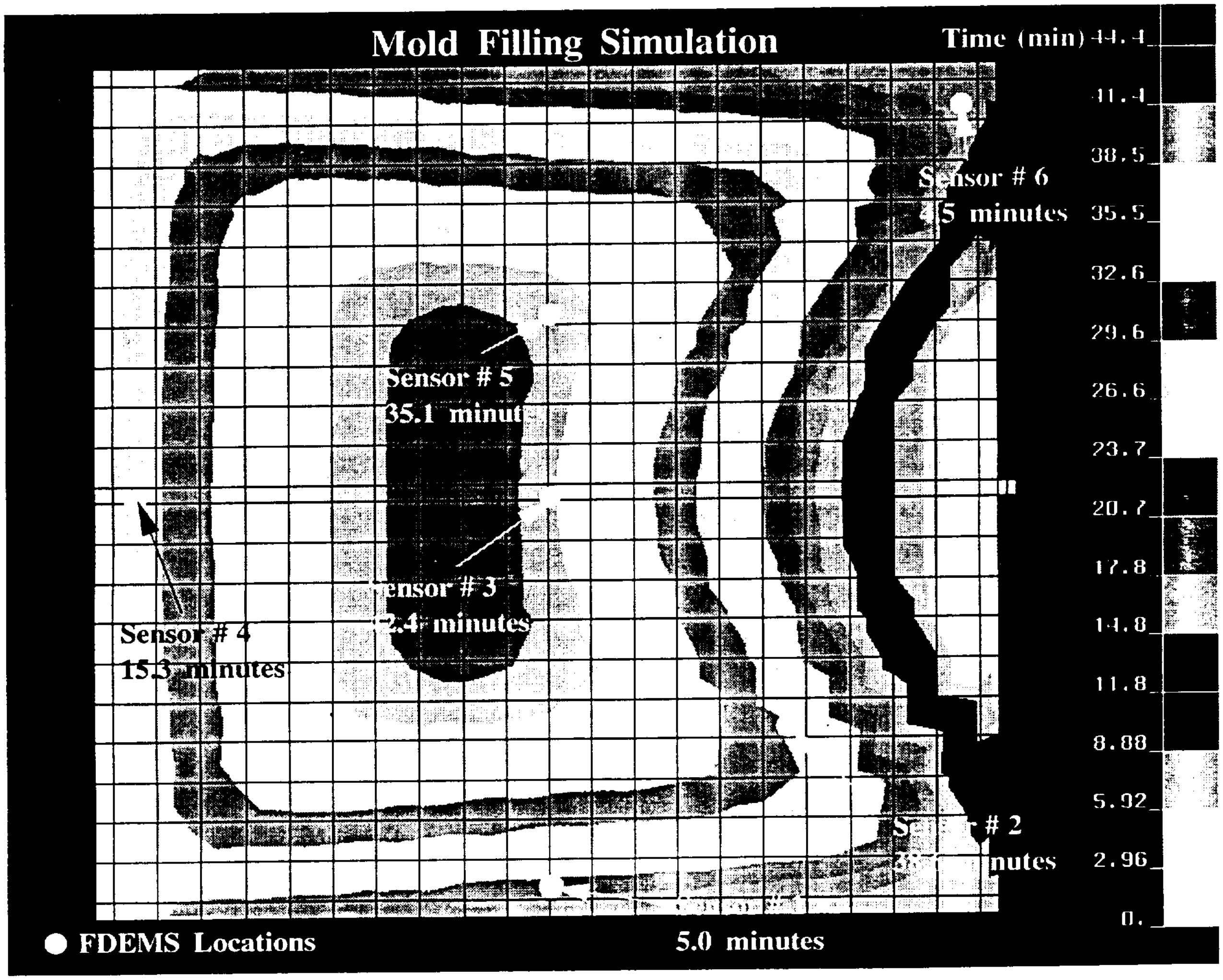


Figure 14: Comparison between model predicted and recorded flow fronts.

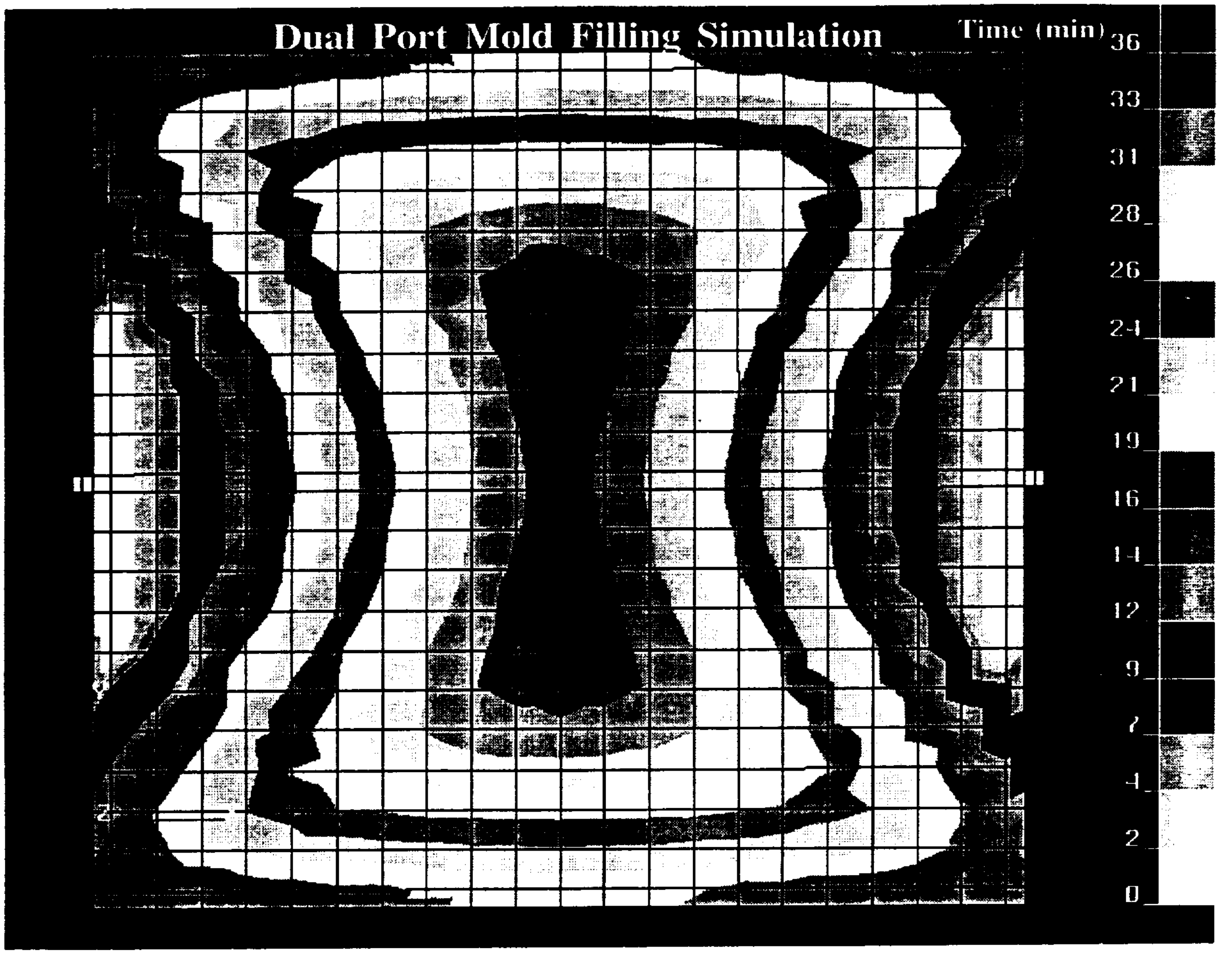


Figure 15: Predicted flow fronts for dual port injection.