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ANALYTICAL MODELING AND SENSOR MONITORING FOR OPTIMAL PROCESSING OF ADVANCED TEXTILE STRUCTURAL COMPOSITES BY RESIN TRANSFER MOLDING*

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ABSTRACT

A two-dimensional model of the resin transfer molding (RTM) process was developed which can be used to simulate the infiltration of resin into an anisotropic fibrous preform. Frequency dependent electromagnetic sensing (FDEMS) has been developed for in situ monitoring of the RTM process. Flow visualization tests were performed to obtain data which can be used to verify the sensor measurements and the model predictions. Results of the tests showed that FDEMS can accurately detect the position of the resin flow-front during mold filling, and that the model predicted flow-front patterns agreed well with the measured flow-front patterns.

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INTRODUCTION

Resin transfer molding (RTM) is seen as a cost-effective method of fabricating primary aircraft structures. It also enables the use of a variety of automated textile processes for making the dry fiber preforms, several of which offer through-the-thickness reinforcement. RTM has been used for decades in various industries for less critical structures having low fiber volumes and readily processed resins. The challenge in adapting RTM to primary aircraft structures lies in ensuring successful injection and cure for high fiber volumes, limited resin processing windows and geometrically complex shapes.

A joint research program between NASA Langley Research Center, Virginia Polytechnic Institute and State University, The College of William and Mary, and Douglas Aircraft Company is underway to develop a science-based understanding of the RTM process in order to minimize costly trial-and-error steps during process development of a structure, and to ensure quality during production. This involves characterizing the processing behavior of the fibers and resins, developing mathematical models of the RTM process, and monitoring significant process variables in real time. The ultimate goals of this program are to develop a comprehensive three-dimensional RTM model for complex shape fiber architectures and to incorporate the model into an intelligent process control system which uses frequency dependent electromagnetic sensing (FDEMS) for sensing the process variables in real-time.

The first result of this collaborative research program was the development of a mathematical model of the resin film infusion process [1,2]. The model can be used to simulate one-dimensional, through-the-thickness infiltration of resin into a fabric preform and cure of the resin saturated preform. Compaction and permeability characteristics of the fabric preform along with the kinetic and viscosity characteristics of the thermosetting resin are incorporated into the model to predict, as a function of applied temperature and pressure boundary conditions, the following parameters: a) initial resin mass; b) resin front position and time required for preform infiltration; c) preform temperature distribution; d) resin viscosity and degree of cure; and e) final part thickness and fiber volume fraction. Basic features of the RTM computer model are shown in Fig. 1.

Verification of the one-dimensional resin film infusion model has been accomplished for two types of textile preforms, Hercules 3501-6 resin, and several thermal cycles. Frequency dependent electromagnetic sensors (FDEMS) were used for in situ measurements of the infiltration time, resin viscosity, and resin degree of cure. The physical arrangement of the FDEMS sensors and measuring system is shown in Fig. 2. The results of the one-dimensional model verification and utilization studies were reported at the first and second NASA Advanced Technology Conferences [3,4].

Recent research has focused on extending the model to two-dimensional anisotropic geometries. Specific applications include in-plane injection of liquid resin into a flat preform (Fig. 3) and resin infiltration of a complex shape preform by the resin film infusion process (Fig. 4).

The purpose of this paper is to discuss experimental and analytical techniques that are being used in the development of the two-dimensional RTM flow model. Specifically, a series of flow visualization experiments were performed to verify the flow-front and infiltration-time predictions of the RTM process simulation model, to verify the permeability versus compaction measurements obtained from preform characterization experiments, and to demonstrate the ability of FDEMS sensing to detect the position of the flow-front.

RESIN INFILTRATION MODEL

The two-dimensional resin flow model was developed to determine the position of the resin flow-front and the pressure distribution inside the preform. In development of the flow model the following assumptions are made: 1) the textile preform is a porous medium; 2) the preform permeability is heterogeneous and anisotropic; and 3) the resin is incompressible, and capillary and inertia effects are neglected (low Reynolds number flow).

For flow through porous media, the momentum equation can be replaced by Darcy's Law which relates the flow rate to the pressure gradient. Darcy's Law for an anisotropic porous medium can be written as

$$\begin{Bmatrix} q_x \\ q_y \end{Bmatrix} = -\frac{1}{\mu}\begin{bmatrix} S_{xx} & S_{xy} \\ S_{xy} & S_{yy} \end{bmatrix}\begin{Bmatrix} \frac{\partial P}{\partial x} \\ \frac{\partial P}{\partial y} \end{Bmatrix} \tag{1}$$

where q_x and q_y are the flow rates per unit area (superficial velocities) in the x- and y-coordinate directions, S_{xx}, S_{xy}, and S_{yy} are the components of the permeability tensor for the textile preform, μ is the viscosity of the resin, and $\frac{\partial P}{\partial x}$ and $\frac{\partial P}{\partial y}$ are the pressure gradients.

The continuity equation of two-dimensional, incompressible flow is written as

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \tag{2}$$

The combination of Darcy's Law and the continuity equation yields the governing equation for resin infiltration into a textile preform:

$$\frac{\partial}{\partial x}\left[\frac{-S_{xx}}{\mu}\frac{\partial P}{\partial x} + \frac{-S_{xy}}{\mu}\frac{\partial P}{\partial y}\right] + \frac{\partial}{\partial y}\left[\frac{-S_{xy}}{\mu}\frac{\partial P}{\partial x} + \frac{-S_{yy}}{\mu}\frac{\partial P}{\partial y}\right] = 0 \tag{3}$$

Solution of Eq. (3) gives the pressure distribution $P(x, y)$ within the region of the textile preform where the resin has infiltrated. Once the pressure distribution is determined, the resin velocity at any point inside the preform can be calculated from Darcy's Law.

Solution of the governing equations requires specification of the boundary conditions. At any instant of time, the pressure or flow rate must be specified at each resin inlet port (gate).

If the wetting force due to the resin advancing through the dry fiber preform is neglected, the pressure at the flow front is

$$P = 0 \tag{4}$$

The final boundary condition requires that there be no flow across the surfaces of the mold wall which for an anisotropic material can be expressed as

$$q_n = -\frac{1}{\mu}\left(S_{nn}\frac{\partial P}{\partial n} + S_{nt}\frac{\partial P}{\partial t}\right) = 0 \tag{5}$$

where n and t represent the directions normal and tangent to the mold wall, respectively.

The flow area (area of the pores) is less than the cross-sectional area of a porous material. The relationship between the superficial velocities (q_x and q_y) and the interstitial resin velocities (v_x and v_y) is given as

$$q_x = v_x(1 - \nu_f) = v_x\phi$$

$$q_y = v_y(1 - \nu_f) = v_y\phi \tag{6}$$

where ν_f is the fiber volume fraction and ϕ is the porosity of the fabric preform. The interstitial resin velocity is calculated at the front and is used to determine the advancement of the flow-front during infiltration.

Numerical Solution Procedure

Many methods of modeling free boundary movement have been explored over the past decade [5]. The modeling of the RTM process presents several challenges. A method must be chosen that will allow for the variation in permeability of the media into which resin is being injected. Perhaps as important is that the method chosen must be computationally efficient. Due to the complexity of the part geometry and manufacturing conditions, a typical model of the RTM process can be quite large. For these reasons the finite element/control volume technique was chosen for use in this investigation.

The finite element/control volume approach has several advantages. The use of finite elements allows for the inclusion of variation in material properties throughout the domain with little difficulty. Also, the control volume approach allows for the use of a fixed mesh which eliminates the need to do computationally expensive remeshing to track the flow front movement.

The Finite Element model used is based on a 2-D model developed by Reddy [6]. At present, the model uses a fixed mesh of isoparametric quadrilateral elements. Each element has constant properties. Also, for convenience, the local Cartesian coordinate system of each element is aligned with the global coordinate system. This allows for the global stiffness matrix to be formulated without any transformations. PATRAN is used as a pre and post processor for the simulation model. The boundary conditions and the material properties are input into the processing model via PATRAN. PATRAN also is used to plot the results after the simulation is completed.

The governing equations describing fluid flow through a porous medium are coupled to a technique which is used to determine the flow front position within the preform. The control volume approach consists of constructing a region around each node in a fixed finite element mesh. These regions, called control volumes, can then be either empty, full, or partially full depending on whether the resin flow front has reached that point in the computational domain. The resin flow front is then tracked from one time step to the next by locating all the positions where the nodal control volumes are partially filled. A nodal fill factor is used to keep track of the state of each node. A fill factor of 0 represents an empty nodal control volume (no resin); whereas, a fill factor of 1.0 means that the nodal control volume is filled. A detailed explanation of the control volume technique and flow front advancement is given in Ref. 7.

Preform Characterization

The preform permeability must be specified in order to obtain a numerical solution of the resin infiltration model. Textile preforms are deformable and anisotropic porous materials. Hence, the permeability depends not only on direction but on the amount of deformation or compression of the preform.

Presently, analytical models that can be used to calculate the permeabilities of advanced architecture preforms do not exist. Thus, the compaction characteristics and the permeabilities in the principal material directions must be measured for each textile preform.

Compaction characteristics of preforms are quantified by mounting a sample between rigid plates, applying a compaction load, and measuring the resulting thickness. Data are commonly reported by constructing plots of fiber volume fraction (ν_f) or porosity (ϕ) versus applied pressure. The fiber volume fraction and porosity can be calculated using the following expression

$$\nu_f = 1 - \phi = \frac{\xi}{d\rho_s} \tag{7}$$

where ξ is the preform areal weight, d is the preform thickness and ρ_s represents the preform density.

Permeability is also a nonlinear function of preform compaction pressure. For the two-dimensional resin infiltration model, the three components of the permeability tensor (S_{xx}, S_{xy}, S_{yy}) must be determined. If the preform is orthotropic, permeability versus compaction pressure measurements are performed in each of the two principal material directions to obtain S_{xx} and S_{yy}. The cross term permeability, S_{xy}, can be calculated using the principal permeabilities in a second order tensor transformation.

Two techniques are commonly used to measure preform permeability. The first method, denoted the steady-state technique, measures the permeability of a fluid saturated preform under constant flow rate conditions. In the second method, denoted the advancing front technique, the permeability is determined by measuring the velocity of the advancing resin front into the dry preform [8]. The steady-state technique was used in the present investigation to measure the permeability. A schematic diagram of the test fixture used to measure in-plane permeability is shown in Fig. 5. To measure the permeability of the preform the following procedure is followed. The sample is placed inside the test chamber and compressed to the specified thickness. A fluid with a known viscosity is allowed to pass through the preform at a constant flow rate and the pressure drop across the preform is measured. The permeability is calculated using the one-dimensional form of Darcy's Law.

EXPERIMENTAL

The three major components used in the flow visualization experiments are shown in Fig. 6. These include the visualization fixture, the video camera and high resolution tape recorder, and the air pressurized resin pot.

The fixture consisted of a square aluminum frame with a 1.5 inch thick poly (methyl methacrylate) top plate. The dimensions of the test cavity are $2ft \times 2ft$. A total of nine FDEMS sensors were mounted in the aluminum bottom plate of the mold. The locations of the sensors in the bottom plate are shown in Fig. 7. The FDEMS sensors were installed into aluminum mounting plugs and the mounting plugs were inserted into cavities that were machined into the bottom plate, as shown in Fig. 8. A $1/4in.$ diameter by $3/8in.$ deep hole was drilled into the center of each cavity which allows resin at the flow-front to enter the cavity and wet-out the sensor. The output leads from the sensors were connected to a multiplexer as shown in Fig. 2.

Fluid was transferred from the pressure pot to the visualization fixture using $1/4in.$ inner diameter plastic hoses. Pressure was monitored during the experiment using gages installed at the exit of the resin pot and at the visualization fixture resin inlet ports. Resin injection pressure was controlled by an air pressure regulator mounted on the resin pot.

At the beginning of each experiment, the video camera was mounted above the visualization fixture. The flow patterns from the experiments were recorded using the high resolution video tape recorder. The video tape was used to determine the infiltration times and to provide a means of correlating the measured flow patterns with the predictions of the resin infiltration model. A total of fourteen images were captured from each taped sequence and stored in 32 bit form on a computer disk for later retrieval.

The textile preform used in the visualization experiments was a style 162, plain weave, E-glass fabric. Eleven layers of the fabric were stacked into the fixture and compressed to the cavity thickness of 0.15 in. The fluid used in the experiments was corn oil. A small amount of red dye was added to the oil. The viscosity of the oil and dye mixture was measured to be 40 cp.

RESULTS

Preform Characterization

Compaction characteristics of the E-glass fabric are shown in Fig. 9. Note that the fiber volume fraction is calculated from the preform thickness measurements using Eq. (7). The fiber volume fraction of the eleven ply stack of E-glass fabric compressed to fit into the 0.15 in. thick cavity was calculated to be 43%. Based on the fabric compaction data, a pressure of 10.3 psi is required to compress the E-glass preform to a 43% fiber volume fraction.

The permeabilities of the E-glass fabric were measured in the warp and fill directions using the fixture shown in Fig. 5. Data from the permeability experiments are plotted on Fig. 10. The solid and dashed lines are power law regression fits to the warp and fill direction data, respectively. Results of the measurements show that the permeabilities in the warp and fill directions are nearly the same. Hence, a center port injection experiment should result in circular flow-front patterns.

Single Side Port Injection

A schematic diagram of the single side port injection experiment along with pertinent preform and fluid data are shown in Fig. 11. Resin enters the cavity through a single side port and flows along the $1/8in.$ channel around the perimeter of the fabric. Resin then begins to infiltrate through the edges of the preform, saturates the preform, and exits through the center port.

The finite element mesh for the resin infiltration model consisted of 2707 quad elements and a total of 2816 nodes. Since the coordinate axes coincide with principal material directions of the fabric the elements are orthotropic. The measured E-glass fabric warp and fill direction permeabilities at 43% fiber volume fraction were input for each element.

One difficulty in modeling the side port injection experiment was that at the beginning of the test, the resin pressure at the fixture inlet port drops below the specified injection pressure. The pressure at inlet port remains low until the channel is completely filled with resin. As resin begins to infiltrate the fabric, the inlet port pressure increases to the specified injection pressure. Thus, the inlet port pressure was monitored as a function of time during the experiment and the data input into the model as boundary conditions.

The influence of the channel was considered in the model by adjusting the permeability of the elements representing the channel until the model predicted inlet port and channel pressures matched the measured values. This technique gave a reasonably good representation of the resin channel in the simulation.

Comparisons between the model predicted and recorded flow-fronts are shown in Figs. 12-14. The time that the image was captured on the video tape is denoted on each figure. The dark shaded area is the resin saturated region of preform, the whitish area is the dry preform and the solid line represents the model predicted flow-front. The images of the model predicted flow-fronts were taken at times corresponding to the images stored to disk from the video tape. Each model predicted flow pattern was overlaid on top of the appropriate video image taken from the experiments.

As can be seen from the figures the model matched the experimental results at the three different infiltration times very well. Note that measured flow front is somewhat wavy during infiltration. This may be due to the waviness of the plastic top plate.

A grid showing the positions of the FDEMS sensors, which are located underneath the glass fabric, has been overlaid on Figs. 12 and 14. The grid was helpful in comparing the FDEMS sensor response to the flow-front position. The sensor locations and measured wet-out times are denoted on each figure. The sensors are numbered in the order that they are scanned by the computer measuring system. As can be seen from the figures, the FDEMS sensors can detect the location of the resin flow-front to within $5s$ of the measured infiltration time. The accuracy of the FDEMS measurements can be improved by increasing the scanning rate of the data acquisition system.

Center Port Injection

A schematic diagram of the center port injection experiment along with the preform and fluid data are shown in Fig. 15. Resin enters the cavity through a port in the center of the plastic top plate, infiltrates the preform, and exits through the vents in the sides of the mold.

The same finite element mesh that was generated for the single side port resin infiltration model was used for the center port model. On the first attempt at modeling the center port injection experiment, the measured E-glass fabric warp and fill direction permeabilities at 43% fiber volume fraction were input for each element. The resulting model predicted flow-fronts were considerably slower than the recorded flow-fronts. After an examination of the data and the flow fixture, we concluded that when the resin entered the mold under pressure the plastic top plate was deflecting. This caused an increase in the cavity depth, a decrease in the fiber volume fraction and a corresponding increase in the fabric permeabilities. Considering both the deflection and the nonuniform thickness of the plastic top plate, it was estimated that the depth of the cavity at the center of the fixture was about 12% greater than the designed cavity depth of 0.15 in. This resulted in a decrease in the fabric fiber volume fraction to 38%. When the model was rerun using the E-glass fabric warp and fill direction permeabilities at 38% fiber volume fraction, the predicted flow-fronts agreed well with the recorded flow-fronts.

Comparisons between the model predicted and recorded flow-fronts are shown in Figs. 16-18. Again, the time that the image was captured on video tape is denoted on each figure. As can been seen from the figures, the model predicted flow-fronts with the adjusted fabric permeabilities agreed well with the recorded flow-fronts at the three infiltration times. Note that the flow patterns are circular due to the nearly equal permeabilities in the fabric warp and fill directions.

Grids showing the positions of the FDEMS sensors have been overlaid on Figs. 17 and 18. The locations and wet-out times of the sensors at the flow-front are denoted on each figure. As was shown in the side port experiments, the FDEMS sensors can accurately detect the location of the resin flow-front.

SUMMARY AND CONCLUSIONS

A two-dimensional RTM process simulation model was developed which can be used to describe the infiltration of resin into a dry textile preform, and cure of the resin saturated preform. The model can be utilized in the development of optimal cure cycles and in mold design by specifying the location of resin injection parts which result in complete wet-out of a complex shape preform. Frequency dependent electromagnetic sensors (FDEMS) have been developed for in situ monitoring of the RTM process. FDEMS sensing can be used to detect the position of the resin front inside the mold during infiltration and to measure the resin properties during cure.

A series of flow visualization experiments were performed to obtain data which can be used to verify the sensor and the model. The results of these tests showed that FDEMS can accurately detect the location of the flow-front in the mold during infiltration, and that the model predicted flow-front patterns agreed well with the recorded flow-front patterns.

In-plane fabric permeabilities were measured using the steady-state technique. When the warp and fill direction permeabilities at the measured fiber volume fraction of the E-glass preform were input into the RTM simulation model, agreement between the model predicted and measured flow patterns was good. However, in the center port injection experiment, the permeabilities were adjusted due to excessive deflection of the plastic top plate. The center port injection experiments will be repeated using auxiliary supports to minimize the deflection of the top plate.

In future studies, the visualization experiments will be repeated using different fabric preforms and epoxy resin as the infiltrating fluid. Once the two-dimensional model has been verified, the model will be extended to simulate resin transfer molding of three-dimensional complex shape preforms.

REFERENCES

1. Loos, Alfred C.; and Weideman, Mark H.: RTM Process Modeling for Advanced Fiber Architectures. Advanced Composite Materials: New Developments and Applications Conference Proceedings, ASM International, 1991, pp. 209-216.

2. Weideman, Mark H.; Loos, Alfred C.; Dexter, H. Benson; and Hasko, Gregory H.: An Infiltration/Cure Model for Manufacture of Fabric Composites by the Resin Infusion Process. Virginia Tech Center for Composite Materials and Structures, Report no. CCMS-92-05, Virginia Tech, February, 1992.

3. Loos, Alfred C.; Weideman, Mark H.; Long, Edward R., Jr.; Kranbuehl, David E.; Kinsley, Philip J.; and Hart, Sean M.: Infiltration/Cure Modeling of Resin Transfer Molded Composite Materials Using Advanced Fiber Architectures. First NASA Advanced Composite Technology Conference, Seattle, WA, Oct. 29 - Nov. 1, 1990, NASA Conference Publication 3104, pp. 425-441.

4. Hasko, Gregory H.; Dexter, H. Benson; and Weideman, Mark H.: Resin Transfer Molding of Textile Preforms for Aircraft Structural Applications. Proceedings of the 9th DOD/NASA/FAA Conference on Fibrous Composites in Structural Design, Lake Tahoe, CA, Nov. 4-7, 1991 (in print).

5. Wang, H. P.; and Lee, H. S.: Numerical Techniques for Free and Moving Boundary Problems. Fundamentals of Computer Modeling for Polymer Processing, C. L. Tucker, ed., Hanover Publishers, New York, 1989, pp. 369-401.

6. Reddy, J. N.: An Introduction to the Finite Element Method. McGraw-Hill, Inc., 1984.

7. Fracchia, Carlos, A.; Castro, Jose; and Tucker, Charles L.: A Finite Element/Control Volume Simulation of Resin Transfer Mold Filling. Proceedings of the American Society for Composites, Fourth Technical Conference, Oct. 1989, pp. 157-166.

8. Foley, Michael, F.; and Gutowski; Timothy G.: The Effect of Process Variables on Permeability in the Flexible Resin Transfer Molding (FRTM) Process. 23rd International SAMPE Technical Conference, Oct. 1991, pp. 326-340.

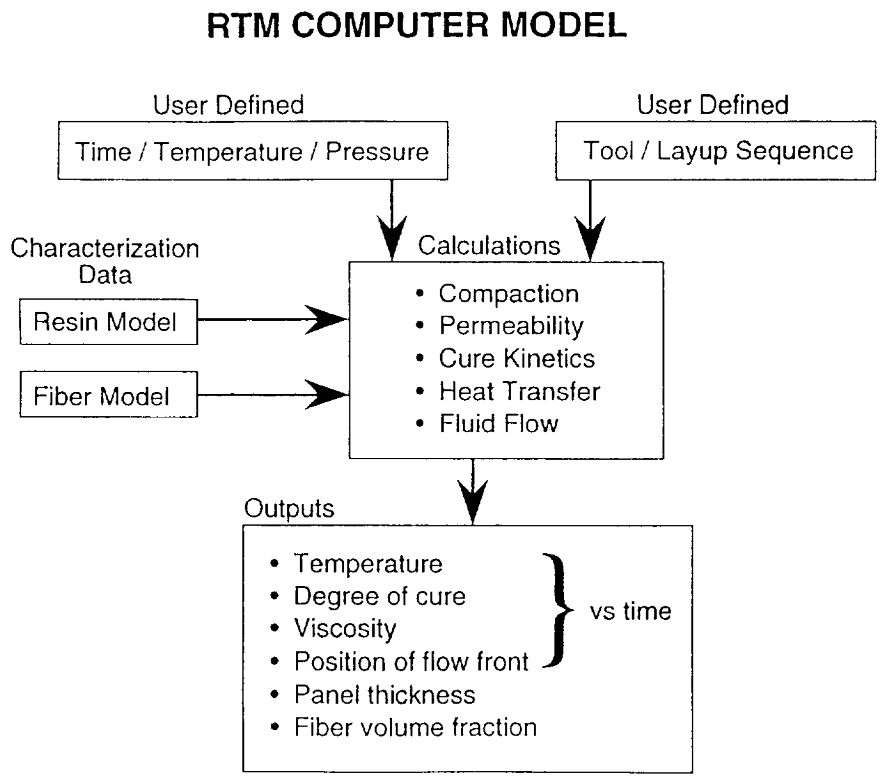

Figure 1. Schematic diagram of the RTM computer model.

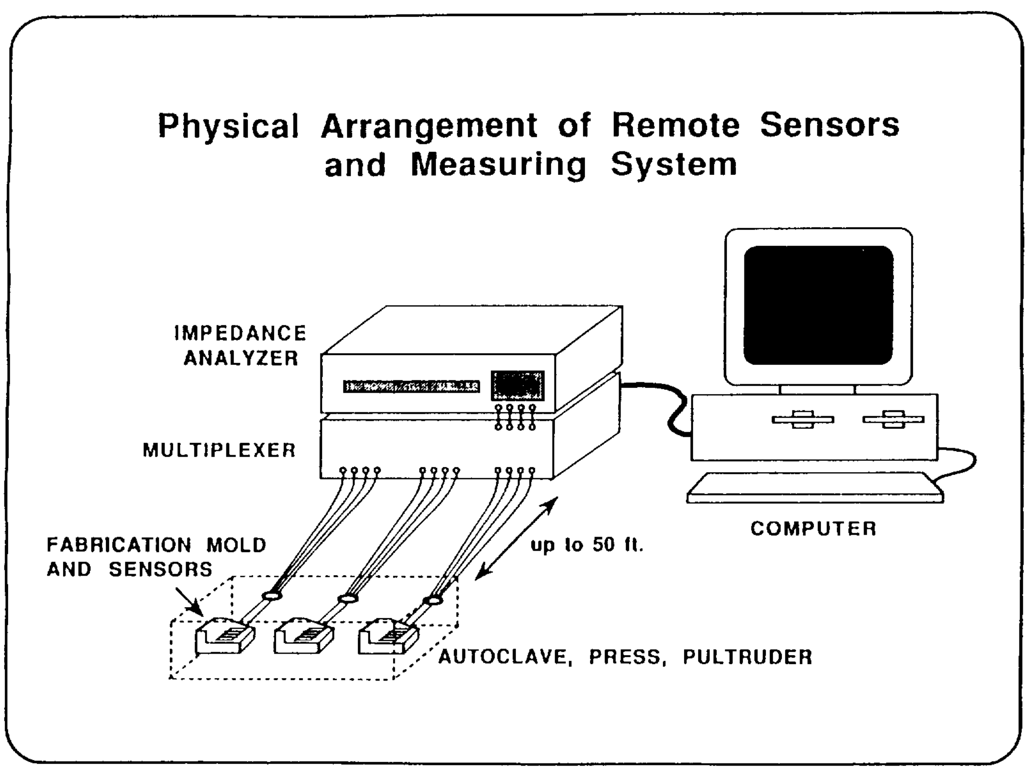

Figure 2. Physical arrangement of the FDEMS sensors and measuring system.

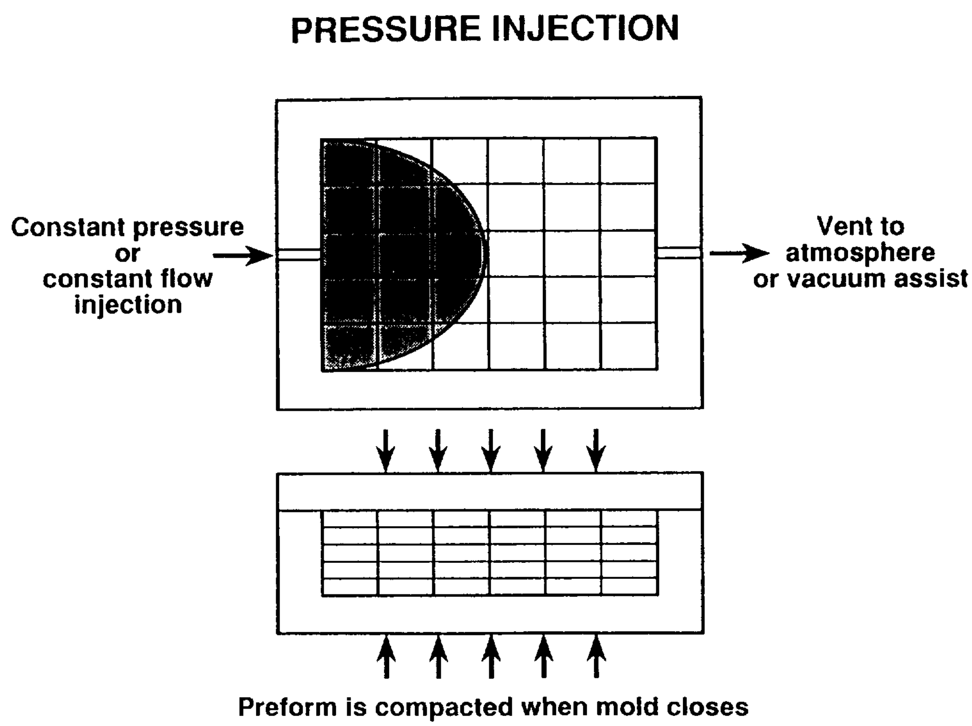

Figure 3. Pressure injection of liquid resin into a flat preform.

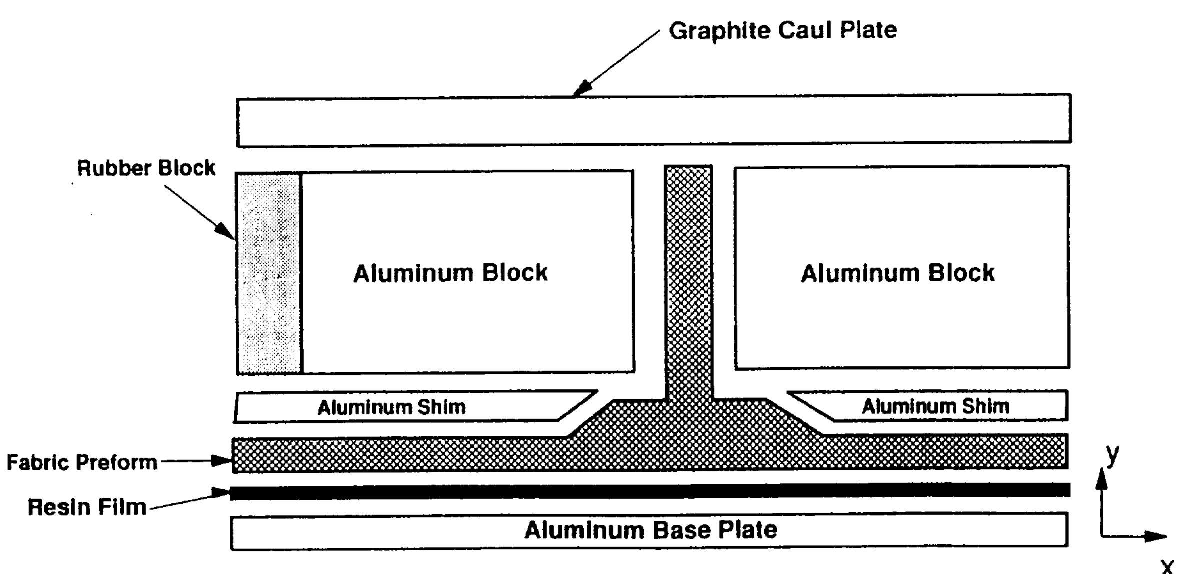

Figure 4. Resin infiltration of a complex shape preform by the resin film infusion process.

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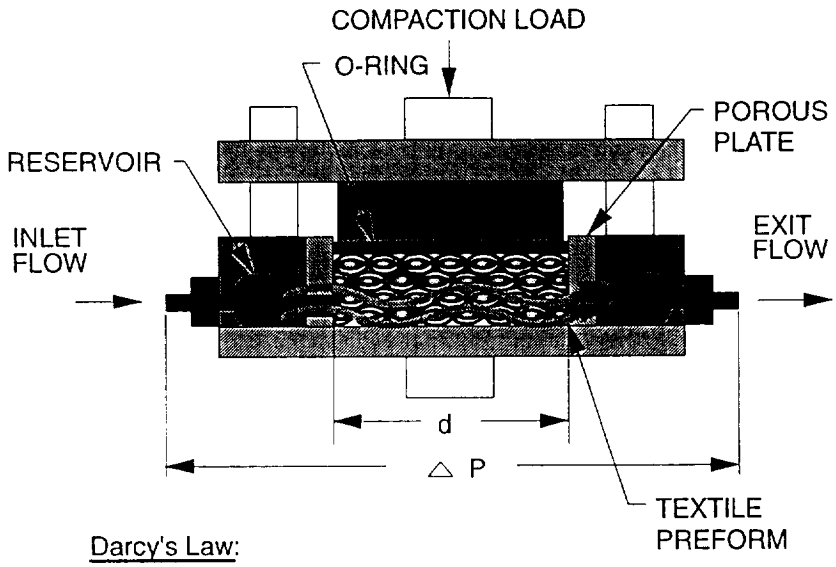


Darcy's Law:

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

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

Figure 5. Permeability test fixture.

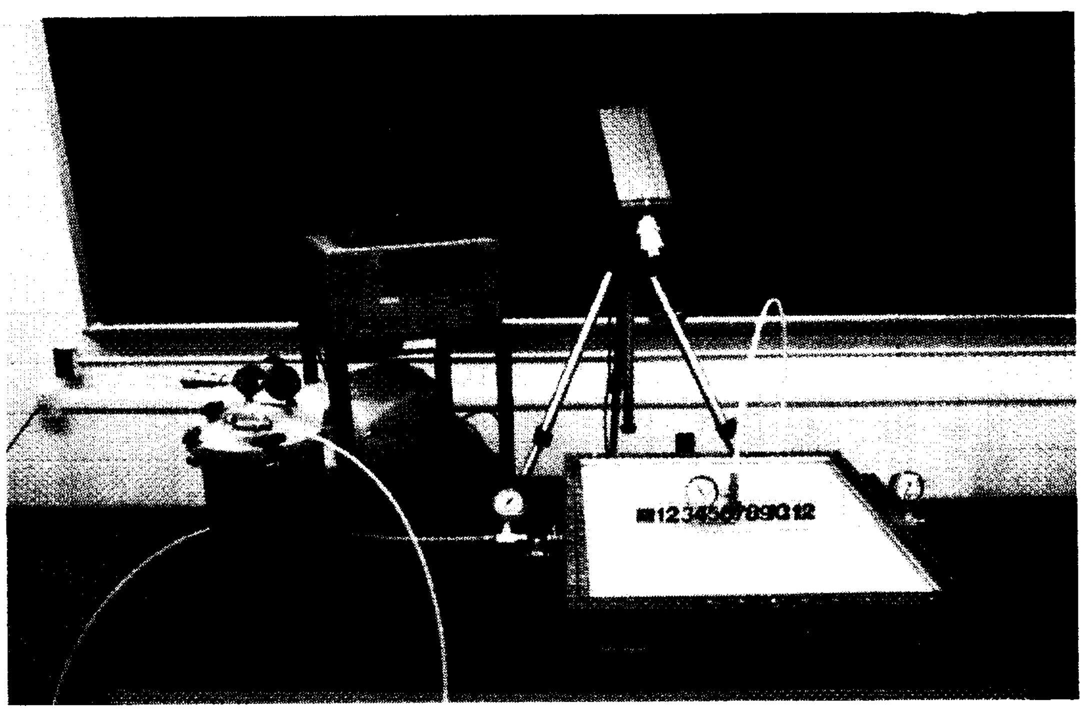


Figure 6. Equipment used in the flow visualization experiments.

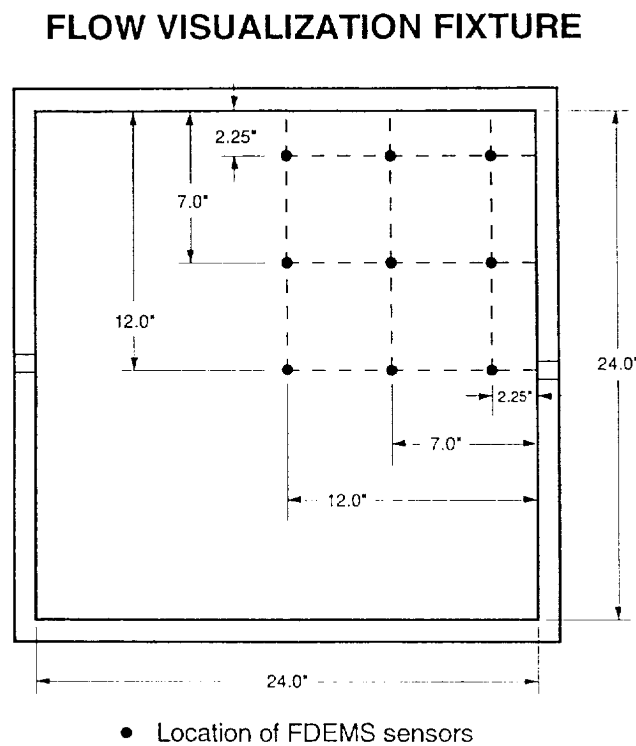


Figure 7. Location of the FDEMS sensor array in the visualization fixture.

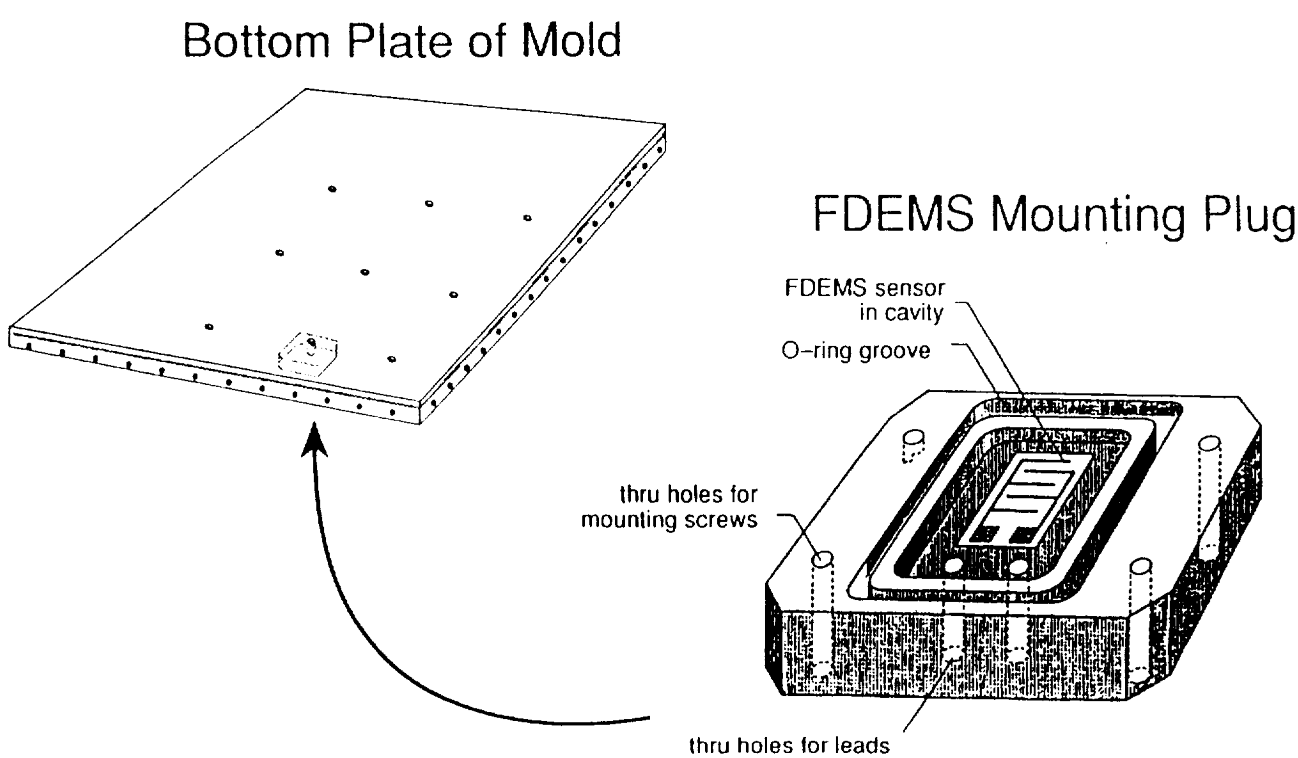


Figure 8. Installation of FDEMS mounting plugs into the bottom plate of the mold.

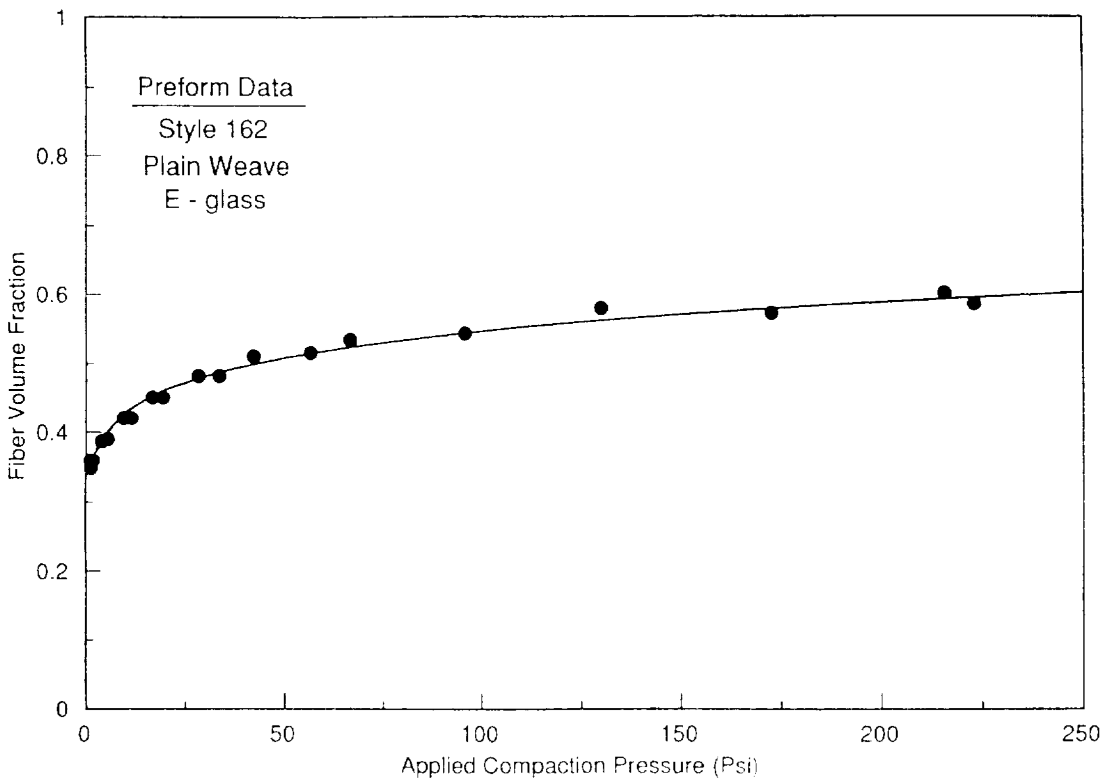


Figure 9. Compaction characteristics of style 162, plain weave, E-glass fabric.

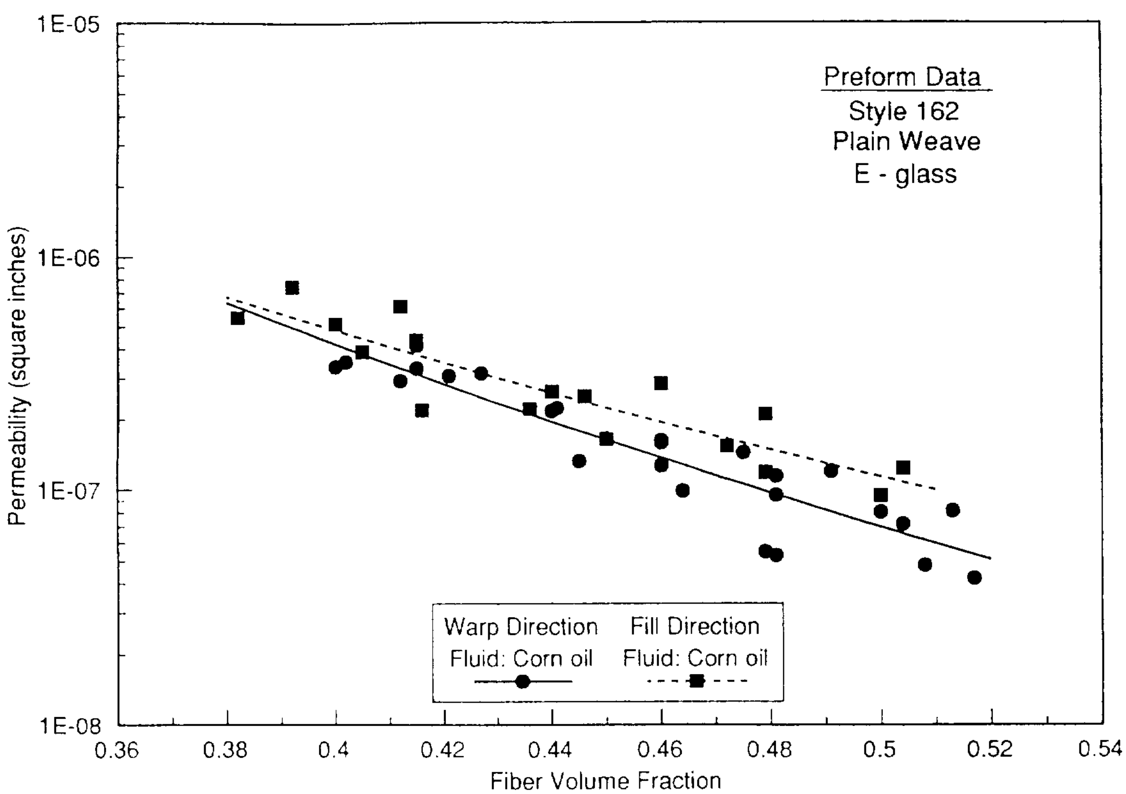


Figure 10. Permeability of style 162, plain weave, E-glass fabric.

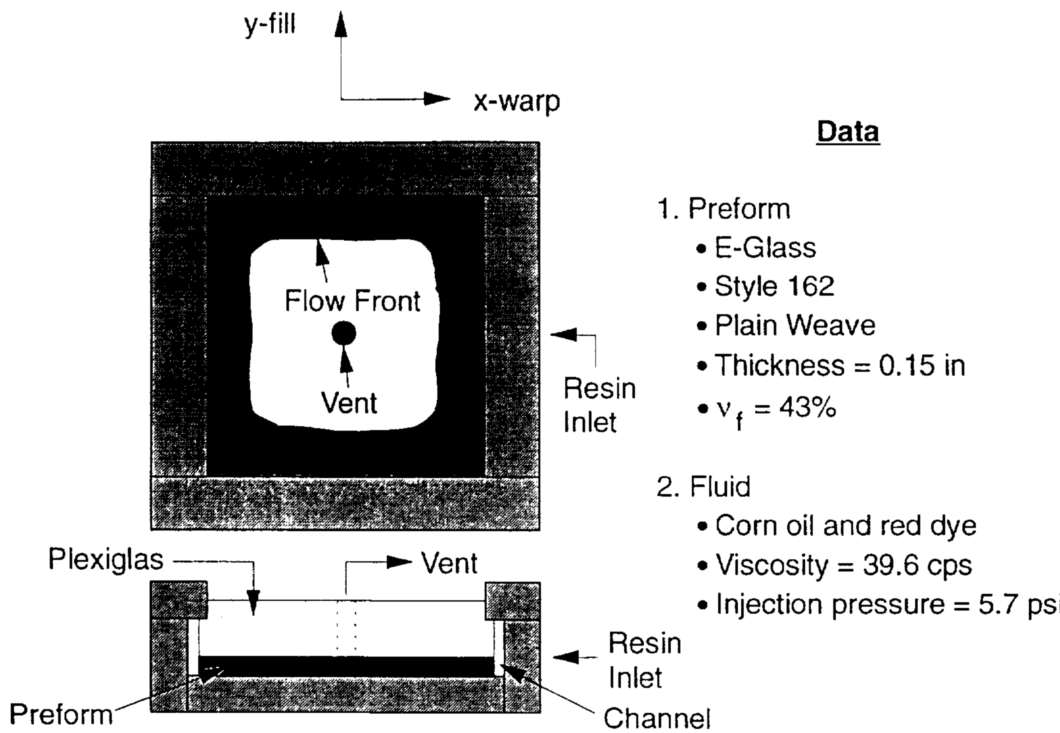


Figure 11. Single side port injection experiment.

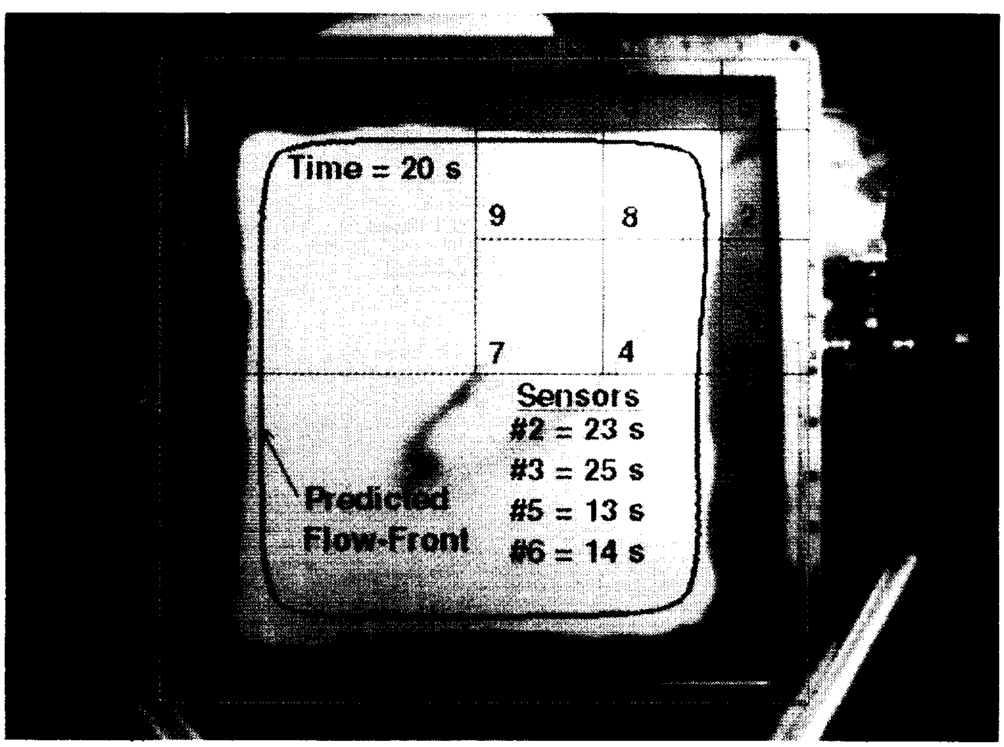


Figure 12. Comparison between the model predicted and recorded flow-front at an infiltration time of 20s.

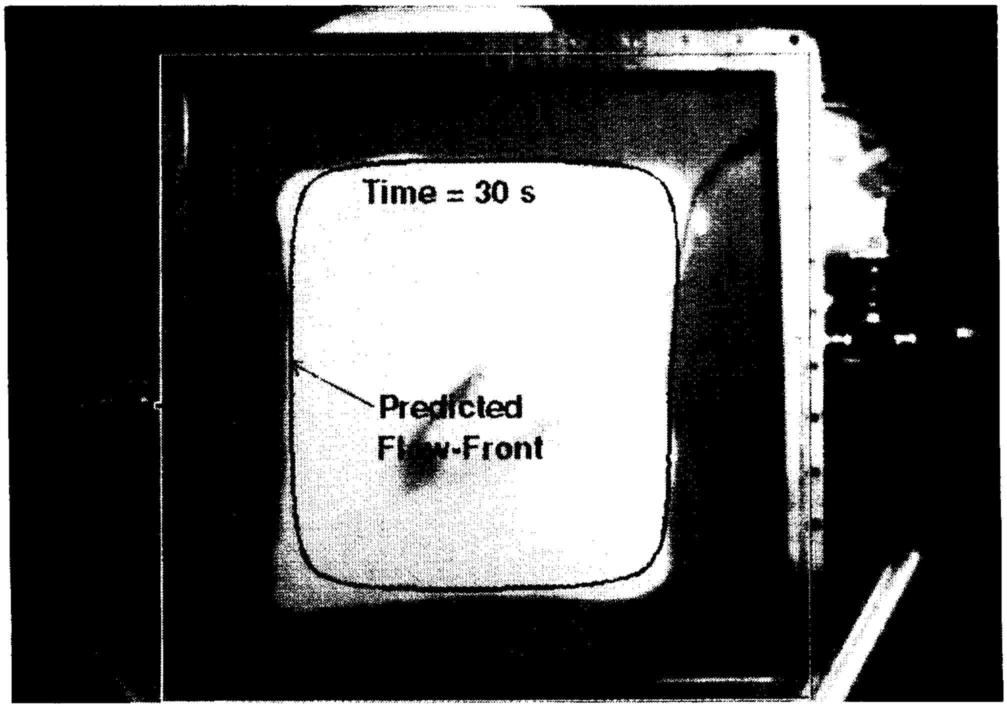


Figure 13. Comparison between the model predicted and recorded flow-front at an infiltration time of 30s.

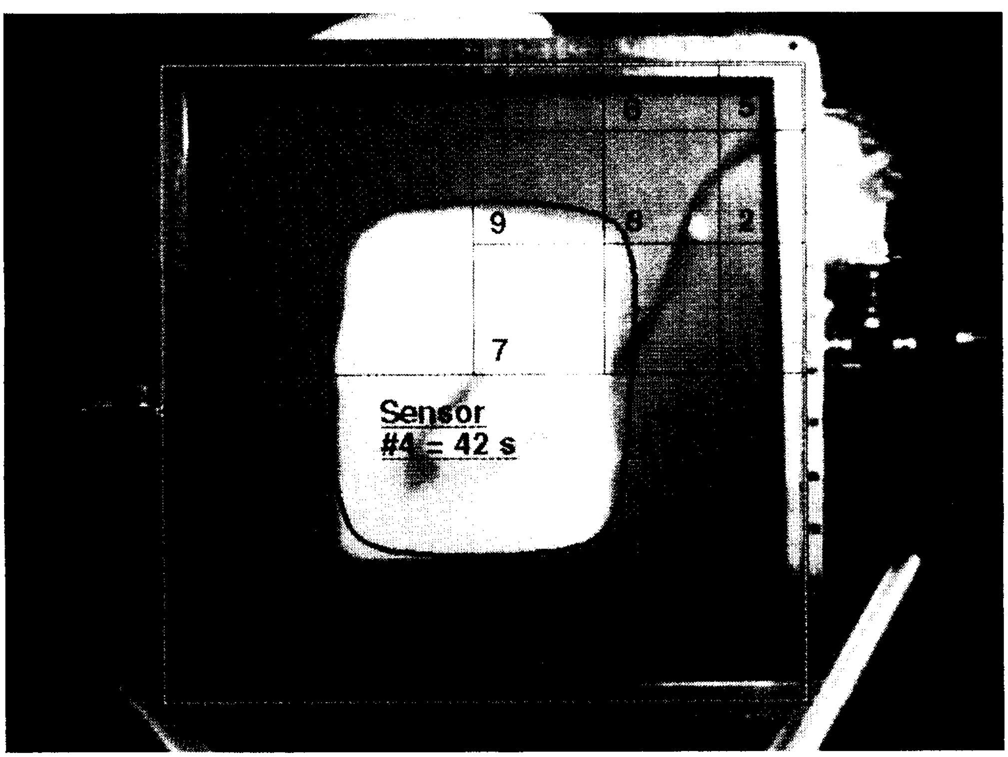
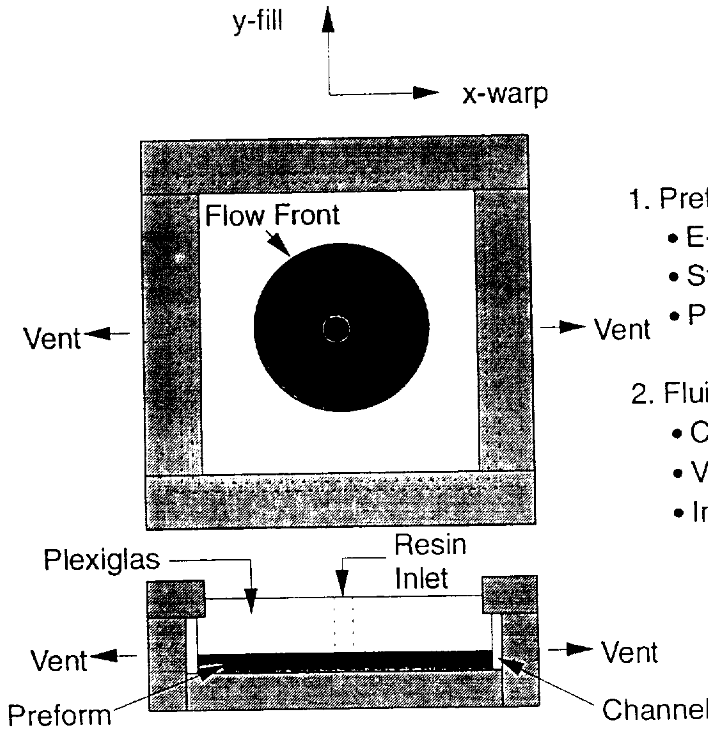


Figure 14. Comparison between the model predicted and recorded flow-front at an infiltration time of 45s.



Data

1. Preform
   - E-Glass
   - Style 162
   - Plain Weave
2. Fluid
   - Corn oil and red dye
   - Viscosity = 40.2 cps
   - Injection pressure = 12.7 psi

Figure 15. Center port injection experiment.

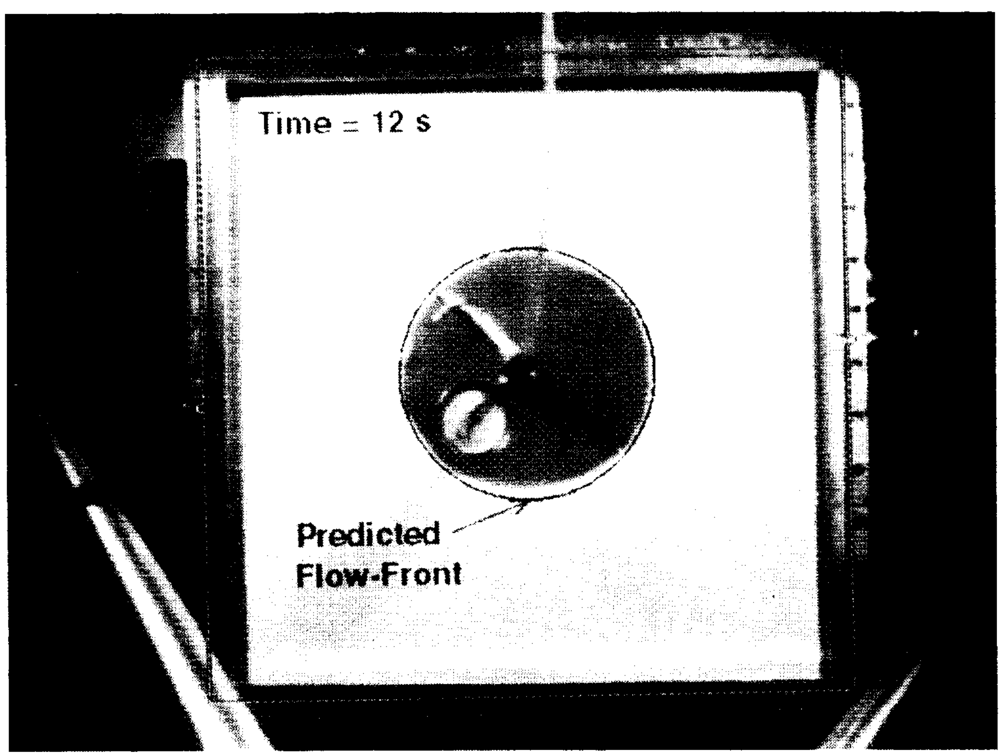


Figure 16. Comparison between the model predicted and recorded flow-front at an infiltration time of 12s.

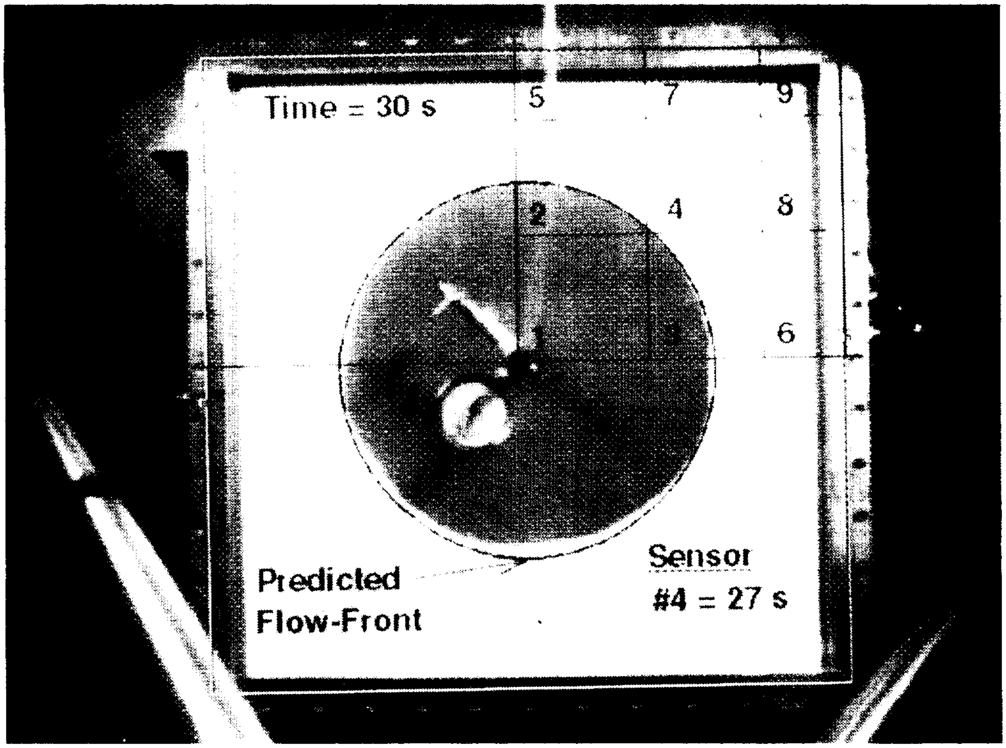


Figure 17. Comparison between the model predicted and recorded flow-front at an infiltration time of 30s.

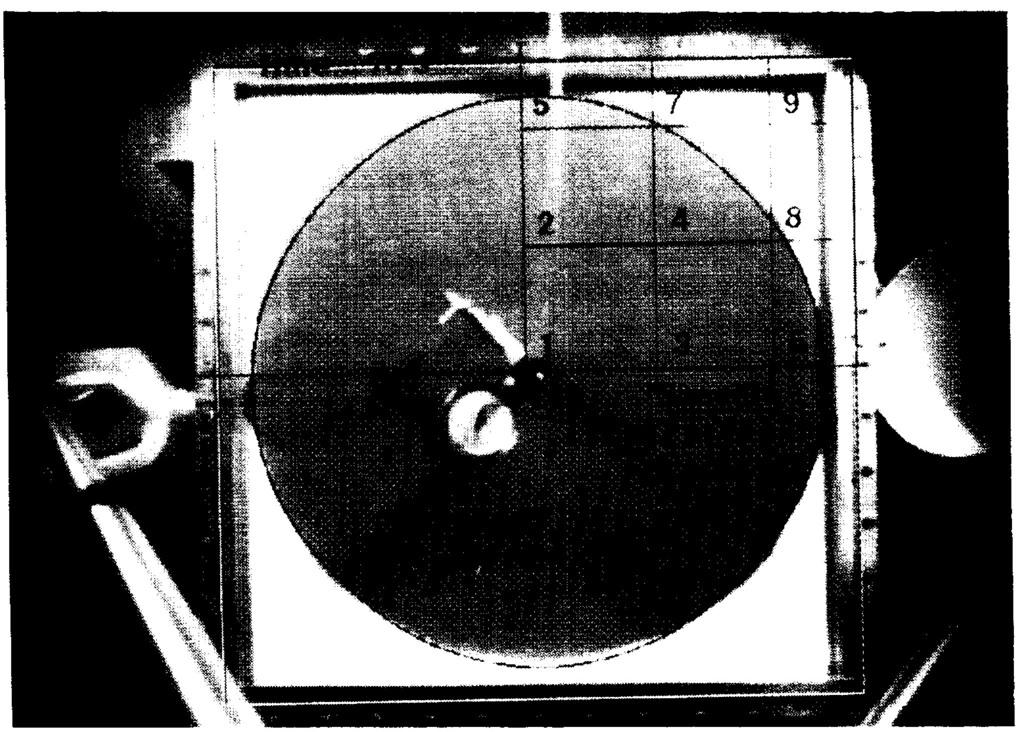


Figure 18. Comparison between the model predicted and recorded flow-front at an infiltration time of 78s.