

# Lineal Sensors for Liquid Injection Molding of Advanced Composite Materials

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## Abstract

This paper presents a lineal sensing concept for flow control in liquid injection molding. The sensor consists of a pair of parallel conductive wires and measures the resin flow front along its length continuously. The effect of different parameters on the sensor signal is studied. A sensor equation that relates the electrical resistance and the wetted length is postulated and validated by experimental results. The objective of this study is to create a finite number of sensors that can capture the global configuration of the flow front at any given time during molding within a reasonable error bound. A number of possible sensor configurations for a simple two dimensional mold is presented. The issue of accurate flow front reconstruction from the sensor data, which can be used for controlling the flow during molding and for updating a simulation program if needed, has also been addressed. A brief discussion is also presented on the formulation of nonlinear controls for regulating the resin flow in real-time by using the lineal sensor signals.

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# 1 Introduction

Polymer composite materials have been identified as some of the most promising materials in automotive, aircraft, marine and sports equipment industries. Liquid injection molding such as resin transfer molding (RTM) is a versatile and attractive process for high volume, high performance, and low cost manufacturing of polymer composites. However, at present, the processing costs are staggering as every new application or prototype requires many trial and correction cycles before one can manufacture a successful part within certain specifications. This has established an urgent need for improving the liquid injection molding technology. Automation will allow real-time adjustments to the molding process to account for part to part variability and to produce more uniform and better finished composite parts. It hence has a potential to reduce the manufacturing cycle time and cost. The study of controlling composite manufacturing processes with in-situ sensors is a first step toward automation. This paper presents studies of lineal flow sensors that will form a basis for the formulation of advanced control strategies.

Sensors for injection molding processes have been a topic of many research publications in recent years. Both embedded and non-embedded sensors have been developed for processes such as RTM, VARTM (Vacuum Assisted Resin Transfer Molding) and SCRIMP (Seemann Composite Resin Infusion Molding Process). Non-embedded sensors are placed outside the mold. These include laser ultrasonic sensing, photovoltaic sensing and even video recording. While they have the advantage of minimum interference with the molding process, almost all of them require visual access through the mold. This renders such techniques unsuitable for metal molds under high pressure and high temperature. Ultrasonics has been used to develop more powerful sensing techniques that do not suffer from this drawback. Thomas et al. have developed a solidification sensing system with two ultrasonic transducers placed on the mold to detect the arrival and solidification of the polymer [1]. Ultrasonics has also been used for cure monitoring [2,3]. The quantity measured by this sensor is averaged over the distance separating the ultrasonic transmitter and receiver or reflector surface.

Embedded sensors include pressure transducers, dielectric sensors, and fiber optic sensors. These sensors can be used to measure the flow front, the pressure profile, resin

viscosity and degree of cure. Since embedded sensors remain in the finished part, they have a potential of creating structural defects. This can cause safety concern with aerospace industry. It is preferable to place sensors on the inside surfaces of the mold whenever feasible. Many embedded sensors measure the molding condition at discrete points. A grid of such point sensors is usually needed to extrapolate the molding condition in the entire mold. SMARTweave is one of quite successful sensor systems [4{6]. This system consists of a rectangular grid of conducting wires placed inside the mold. As the resin fills the mold, gaps between transverse filaments at the flow front are bridged by the resin and an electrical circuit is closed producing a signal that the flow has reached that point. A modified version, called real-time embedded electronic sensing, RTEES, was also developed and tested by adding a DC-signal based circuitry and using the system for real-time process monitoring [7{9]. The sensor system needs a large number of channels required for complex molds. On the other hand, sensing the whole field in the mold interior with a high resolution by using techniques such as C-scanning can be expensive and requires high speed data acquisition systems.

Schwab et al. have developed a resin position sensor (RPS) for flow visualization and for cure monitoring by using DC conductometry [10]. The sensor makes use of the conductivity of the resin and consists of a matrix of small sensors embedded on the mold surface where each sensor is a pair of copper wires potted on a 1.6mm diameter ceramic sleeve. Since the resistance measured between the copper wires varies with viscosity, the sensor signal is also related to the viscosity of the resin and the curing process can be qualitatively described by the way the sensor voltage varies with time. It is claimed that the sensor voltage vs. time plot qualitatively describes the curing process. England et al. have done a similar study [6]. Day et al. have worked on a dielectric sensor of the viscosity by measuring the loss factor of the resin at 10Hz [11]. Shepard et al. have also developed a tool mounted dielectric sensor to monitor cure in-situ [12]. Kranbuehl et al. have developed a frequency dependent electromagnetic sensing system for measuring the viscosity and the degree of cure [13{20]. It is suggested that the sensor can be used for quality control to make sure that the resin has impregnated the preform and the curing has been completed. The sensor systems discussed up to now are all point sensing techniques. Rooney et al. have developed a capacitive sensor system capable of continuous sensing of

the resin flow front [21]. The effect of wetting by the resin on the sensor capacitance is used to sense the location of the resin front.

Fiber optic sensors are also gaining popularity lately. Fiber optics has been used in the implementation of evanescent wave spectroscopy in the UV, visible and infrared range, Raman spectroscopy, and fluorescent monitoring. Since optical fibers are usually of the same size as that of the preform fibers, they produce minimal adverse effect on the part quality, and they can be placed at any location inside the mold. Fluorescence monitoring has been used as a point sensor for flow as well as cure monitoring [22,23]. The fluorescence of a dye dissolved in the resin flowing past the tip of the optical fiber is detected and is used to register flow or to monitor the cure state of the resin. Evanescent wave fluorescence spectroscopy uses the entire length of the fiber as a sensor [24-28]. This sensor incurs the high cost and requires bulky hardware support. Fiber optic Raman spectroscopy has been used for cure monitoring of a neat epoxy/amine system using a distal mode optical fiber sensor [29]. This technique can directly measure the extent of cure, but has a low sensitivity and low signal-to-noise ratio. Another sensing technique, using optical time domain reflectometry (OTDR), was also employed to measure the degree of cure [30]. The sensors are suggested to be less expensive and also less intrusive.

The above review of sensing technologies indicates that with very few exceptions, most studies on sensors are not control oriented. Furthermore, many sensors are point-type, which deliver signals on the molding conditions at a set of discrete time instants. However, for the purpose of real-time control, continuous sensor signals are far more desirable than discrete time sensors. Motivated by the need of real-time control formulation, we present a lineal sensor concept for monitoring the resin flow. The effect of different parameters on the performance of the sensor has been investigated. The issue of accurate flow front reconstruction from the sensor data, which will be used for controlling the flow during the injection molding, has also been addressed. Initial tests bear out the feasibility of the sensor. Note that a similar study of lineal sensors can be found in [21].

## 2 Lineal Sensors

The proposed sensor consists of a pair of closely placed conductive wires with a small fixed gap between them. An electric circuit is shown in Figure 1 to illustrate how the

sensor works. As the resin infiltrates the space between the two wires, the two wires are connected by a conductive medium which is the resin. When there is no resin, the resistance between the wires,  $R_s$ , is infinite. As the wetted length of the wires increases,  $R_s$  decreases. Consequently, the voltage between points B and C in the circuit shown in Figure 1 goes up. The sensor voltage,  $V_s$ , is given by

$$V_s = \frac{R_b}{R_b + R_s} V_{ex}; \quad (1)$$

where  $R_b$  is a fixed resistance and  $V_{ex}$  is the constant excitation voltage. In order to use this signal to measure the precise location of the flow front, we need to calibrate the sensor. The calibration involves measurements of electric resistance across the sensor wires as a function of the wetted length for a given gap. Figure 2 shows a typical measurement of the resistance. By curve-fitting the experimental data, we find an approximate relationship between the electric resistance and the wetted length as

$$R_s = \frac{c}{x}; \quad (2)$$

where  $x$  is the wetted length and  $c$  is a constant whose value depends on the gap size and the material property of the resin. For the resin systems considered in this study, i.e. Vinyl Ester (411-C-50) and Epoxy (SC-15), and with  $R_b = 10M\Omega$ ,  $c$  ranges from 1000 to 1500  $M\Omega\text{-cm}$  for gap widths varying between 4mm and 8mm. The relationship between the wetted length and the sensor voltage is thus given by

$$V_s = \frac{R_b x}{R_b x + c} V_{ex}; \quad (3)$$

This relationship, referred to as the sensor equation hereafter, predicts that the sensor voltage  $V_s$  is nearly linear in  $x$  when  $x \ll c/R_b$ , and becomes nonlinear as  $x$  becomes larger. Experimental data presented later in the paper attest to this conclusion. With the knowledge of this sensor equation for the resin systems, one can readily compensate the nonlinear response of the sensor and develop a sensor with an accurate calibration.

Lineal sensors suitable for use inside the mold can be constructed in several ways. One way to make a lineal sensor is to deposit two parallel thin conductive metal strips onto a flexible plastic tape, similar to a printed circuit. The tape can then be bonded to the interior surface of the mold. Conductive painting can also be used to create various patterns of lineal sensors on the mold surface. Conductive coating can be applied to the preform fibers that are embedded in the preform to form lineal sensors in two or three dimensional configurations. In particular, the coated preform fibers can also provide the through-the-thickness sensing in the mold with thick sections.

Note that Figure 1 shows only one lineal sensor in the mold. To sense the whole flow front in the mold, one needs many sensors. How many sensors are needed and where to place them are active research issues. Section 4 presents a study of this kind. In general, one always looks for a smallest number of sensors placed in such a way that the flow front at any instant is sufficiently represented by the sensor readings.

### 3 Effect of Influencing Factors

The proposed lineal sensors make use of the conductivity of the resin as the sensing mechanism. There are two parameters that affect the sensor output, namely the gap width between the sensor wires and the resin conductivity. Resin conductivity varies with the ratio of resin, curing agent and accelerator, and also with the degree of cure. This section presents preliminary experimental results of the effect of all these influencing factors on the sensor output.

#### Gap Width

Experiments were conducted on lineal sensors with gap widths of 4, 6 and 8mm. The resin system is 411-C-50 vinyl ester (Dow Chemicals Company). The sensor voltage was recorded as a function of the wetted length of the sensor for the same resin system. The results are shown in Figure 4. The properties of the resin system and other parameters for this experiment are listed in Table 1. In each experiment, a fresh resin sample was used to nullify any effect of curing. All the readings were taken within 10 minutes of preparing the resin.

The results in Figure 4 show that as the gap width increases, the sensor signal decreases. This is due to the fact that the conduction path between the two wires of the sensor becomes larger, which leads to a higher resistance  $R_s$ . From Equation (1), a higher  $R_s$  leads to a lower sensor signal  $V_s$ . The variation of the sensor signal with the wetted length is linear when the wetted length is short, and becomes nonlinear when the wetted length is long, as predicted in Section 2. Figure 4 also shows a predicted sensor voltage signal as a function of the wetted length by using Equation (3). The excellent agreement between the prediction and the experimental data strongly supports the validity of the postulated relationship between the electric resistance and the wetted length given by Equation (2).

### Ratio of Resin, Curing Agent and Accelerator

In this part of the study, we have kept the same resin system as above, and all the experiments were conducted on a lineal sensor with a 6mm gap. The following ratios of the curing agent and accelerator were studied.

1. CoNap 0.2%, Triginox 2% (recommended ratio, Marked as case 1 in the figure)
2. CoNap 0.4%, Triginox 2% (Marked as case 2 in the figure)
3. CoNap 0.2%, Triginox 4% (Marked as case 3 in the figure)

The experimental results are presented in Figure 5. It can be seen from the figure that as the ratio of either the accelerator or the curing agent is increased, the sensor voltage readings go up. To obtain a quantitative relationship between the accelerator or the curing agent and the sensor voltage, one must conduct many more experiments with a wide range of ratios of the curing agent and accelerator. This is a task for future studies.

### Curing

Figure 6 shows the sensor signal variation with time as cure progresses for a sensor with a 6mm gap width,. The resin system is the same as before, namely, 411-C-50 Vinyl Ester. The ratio of the curing agent and accelerator as well as other conditions are the same as those in the case shown in Figure 4.

In the experiment, the sensor was wetted up to a length of 38cm. The resin was then allowed to cure at room temperature while the wetted length of the sensor was kept constant. The sensor voltage varies significantly as the cure progresses as shown in Figure 6. When one uses lineal sensors in a control system for regulating the resin flow, one would better finish the flow control tasks before curing begins. Otherwise, one has to take curing into consideration when calibrating the sensor. As the figure indicates, such a calibration is highly nonlinear and can be an extremely difficult task. Nevertheless, variations of the lineal sensor output as the resin cures provide a spatially averaged measure of the degree of curing along the sensor. Such an added function of flow sensors is very common. However, a rigorous calibration of flow sensor output with respect to the degree of curing is rare.

### Resin System

We tested two resin systems, namely 411-C-50 Vinyl Ester (Dow Chemical Company) and SC-15 Epoxy (Applied Poleramics Inc.), in order to examine the effect of the resin on the sensor output. The experiments were conducted with the lineal sensors of a 6mm gap. Figure 7 shows the sensor signals from the lineal sensors for both the resin systems. The sensor voltages are almost identical in both cases. However, this cannot be assumed to hold for other resins. More tests need to be done to establish an extensive database.

## 4 Applications of Lineal Sensors

As discussed earlier, our objective is to develop a sensor system that can provide a basis for control formulation. In particular, we are interested in regulating the resin flow in such a way that there will be no macroscopic dry spots formed in the finished parts. In addition to the necessary ability to control the resin flow, a minimum number of lineal sensors that can provide as much information about the entire flow front as possible is highly desirable. In this section, we briefly discuss the control formulation based a continuous time lineal sensor system. We then focus attention on the lineal system that can provide global information about the flow front.

## 4.1 Sensor Based Control Formulation

The main advantage of the lineal sensor is that the sensor signal is continuous in time. As mentioned earlier, it is far more desirable to have continuous sensor signals for the purpose of real-time feedback control. If the sensor system is point type, information on the resin flow is only available at certain instants when the flow front reaches the sensor. In between two sensors, no further information is available about the state of the flow, and the controller cannot update its actions. A continuous signal, as one provided by lineal sensors, allows the controller to update its action far more frequently. Here, we present a very brief discussion on how to make use of the continuous lineal sensor signals in formulating a real-time controller. A detailed study of this issue will be presented in a separate paper.

Let  $s(t)$  be a vector consisting of  $n$  sensor signals, and  $u(t)$  be a vector of  $m$  injection variables including flow rate and pressure. At any given time, there exists a nonlinear relationship such that

$$s(t) = f(u(t); t); \quad (4)$$

In general, this nonlinear function  $f(u; t)$  cannot be obtained in a closed form. We can linearize the function locally by using the Taylor expansion around the current sensor state  $s(t_0)$  at  $t = t_0$  [31].

$$s(t) = s(t_0) + [T(t_0) + G(t_0)\Phi u(t_0)](t - t_0); \quad t_0 \leq t \leq t_0 + \Phi t \quad (5)$$

$$T = \frac{\partial f}{\partial t}; \quad G = \frac{\partial^2 f}{\partial u \partial t}; \quad (6)$$

where the expansion coefficient  $T$  is an  $n \times 1$  vector and the expansion coefficient  $G$  is an  $n \times m$  matrix. This model is accurate upto second order terms involving  $\Phi t$  and  $\Phi u$  in the interval  $t_0 \leq t \leq t_0 + \Phi t$ . Using conventional system identification techniques, we can estimate and update  $T$  and  $G$ . Let  $s_{ref}(t)$  be a pre-designed reference signal that describes a desired flow front pattern in the mold. An optimal control problem can now be formulated as: find an optimal control  $\Phi u$  and an optimal time increment  $\Phi t$  at any time  $t_0$  such that the following performance index is minimized

$$J = \int_{t_0}^{t_f} j_s(t) - s_{ref}(t)j^2 dt: \quad (7)$$

This is one of many possible control formulations based on the lineal sensors. There is plenty of research opportunities along this direction.

## 4.2 Flow Front Reconstruction

In order for the control system to be effective in regulating the resin flow in the entire mold, lineal sensors need to be able to detect as much the flow front information as possible. In other words, the sensors should be placed inside a mold so that the flow front can be reconstructed simply based on the sensor measurements [32]. The ability to reconstruct the flow front is a good measure of the quality of the sensor system. Furthermore, such a global sensing capability also provides necessary information for updating simulation programs in real-time if the need arises. To this end, the performance of lineal sensors in 2-D molds has been investigated, and the results are presented below.

Flow in a simple rectangular mold was simulated using the program LIMS (Liquid Injection Molding Simulation) [33]. The flow front at any instant obtained in the simulation program is regarded as the actual flow front. Each lineal sensor is simulated as an array of densely spaced spatial points. The intersection point of the flow front with a lineal sensor can be computed by interpolation, and is taken as a sensor signal. The flow front is reconstructed by fitting a smooth spline through these points of intersection. A mean square error can be defined as follows

$$MSE(t) = \int_a^b (y_a - y_s)^2 dx \quad (8)$$

where  $y_a(x)$  represents the actual flow front, and  $y_s(x)$  is the reconstructed flow front based on a finite number of lineal sensors between the limits  $x = a$  and  $x = b$ . This error gives a quantitative measure of the global sensing performance of the lineal sensor system.

Note that depending on the orientation of the flow front, either  $y$  or  $x$  can be taken as the independent variable in different subregions. When  $y$  is taken as the independent variable, the integration in Equation (8) is then with respect to  $y$ . Having defined a figure of merit for the lineal sensors, we now examine several geometrical configurations of lineal sensors, and study their global sensing capability.

### 4.2.1 Streamline Configuration

Since the intersection of the lineal sensor with the flow front provides the sensing signal, an ideal configuration of lineal sensors is such that the sensor intersects the flow front at a right angle any time during the molding. By definition, this sensor line is the streamline of the flow. In our study, the streamlines of the flow are obtained from simulations. Figure 8 shows an example of flow front patterns and the streamlines in the simple rectangular mold with one injection port. It was assumed that no racetracking occurred along the edge of the mold. If racetracking occurs, i.e. the fluid races along the edge of the mold due to a higher permeability, the flow pattern changes drastically. Figure 9 shows the flow front patterns with racetracking and the corresponding streamlines.

We now place lineal sensors along the streamlines as shown in Figures 8 and 9. The sensor signals at any instant are used to reconstruct the entire flow front. Figure 10 shows the mean square error in the reconstruction of the flow front as the flow advances through the mold without racetracking. At any instant, there is an average of 25 lineal sensors intersecting with the flow front. The values of the mean square error are quite small indicating that the flow front reconstruction is sufficiently accurate. As the number of sensors increases, the error in flow front reconstruction decreases rapidly as shown in Figure 11. The trend of the error curve in Figure 11 shows that above a certain number of sensors, not much improvement can be brought about by adding more sensors. In this case, it seems that around 5-10 sensors will be sufficient.

Similar analysis is done for the flow with racetracking. Figure 12 shows the mean square error of reconstructing the flow front with 21 lineal sensors. Due to the nature of the flow in this case, the same number of sensors intersect the flow front at all time instants. It is observed that the order of the error in flow front reconstruction is the same as that in the case when there is no racetracking (see Table 2). Figure 13 shows the mean square error at a particular instant as a function of number of sensors. The same trend of the error curve as in the case without racetracking is observed.

It should be noted that the streamline configuration of lineal sensors is an ideal and mathematical implementation. There are many practical issues to be resolved in order to develop this configuration into a useful sensor system. There are many unavoidable

uncertainties in the process parameters such as the preform permeability as well as the unpredictable occurrence of racetracking that significantly affect the flow front and therefore the streamlines. How to design a robust streamline sensor system that can handle all these uncertainties is an issue that has to be addressed.

#### 4.2.2 Equal-segment Configuration

As can be seen in Figures 8 and 9, the streamlines are typically distributed in the mold very non-uniformly resulting in a different number of sensors being effective at different times. It is, however, desirable to employ the same number of sensors during the injection. To achieve this, we place the lineal sensor so that the flow front is divided into segments of equal curvelength by the sensors. Figure 14 shows an example of this placement of lineal sensors in the same rectangular mold previously considered. Figure 15 shows the mean square error in reconstructing the flow front with 21 lineal sensors as the flow advances through the mold. It is seen that the order of magnitude of the errors is the same as in the streamline configurations (see Table 2). Figure 16 shows the mean square error as a function of number of sensors. Again the same trend as in the streamline configuration is seen. The error reduces rapidly as the number of sensors is increased.

#### 4.2.3 Parallel Configuration

The previous two configurations depend on the way the flow is expected to behave. If the flow is drastically different from the nominal pattern one predicts using simulation programs, the sensor system cannot be expected to perform well. Another configuration is to have lineal sensors placed parallel to the boundaries of the mold along the direction of resin flow, irrespective of the flow behavior. In the rectangular mold, this reduces to just straight lineal sensors parallel to the top and bottom edges of the mold.

Figure 17 shows the performance of such a sensor configuration in the same mold without racetracking. Comparing it with the other two configurations (see Table 2), we see that the error in reconstruction is larger on average with a bigger standard deviation than the other previous configurations.

## 5 Concluding Remarks

A lineal sensor concept for sensing the resin flow front during impregnation in liquid injection molding has been investigated. A relationship between the electrical resistance and the wetted length of the sensor is postulated, and validated with experimental results. This relationship provides a foundation for calibrating the sensor and a prediction capability of the sensor output. The proposed sensor system can be made simple and rugged. Several geometrical configurations of lineal sensors for flow front sensing have been studied. The performance of the sensor configuration is quantitatively studied by considering the error of reconstructing the flow front based on the sensor signals. It has been found that with a good prior knowledge of flow front, streamline and equal-segment configurations can provide the global information about the flow front during the injection molding with a relatively small number of sensors. Without this prior knowledge, a parallel configuration can provide a comparable sensing performance with potentially a few more sensors. A nonlinear control formulation for regulating the resin flow in real-time has been also outlined in the paper by taking advantage of the continuous signal from the lineal sensors. More work along this line needs to be done.

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## List of Tables

1	The resin system and the experimental conditions. . . . .	20
2	Comparison of the global sensing performance of three different sensor configurations, when there is no racetracking. Since different number of sensors participate in case of the streamline configuration, the average number taking part in sensing at any instant is given. Average MSE is the mean square error values averaged over time. . . . .	20

## List of Figures

1	Circuit for measuring the sensor voltage $V_s$ . . . . .	21
2	Sensor resistance ( $R_s$ ) vs. the wetted length. The sensor gap width is 6mm. The resin is Vinyl Ester. . . . .	22
3	Comparison of experimental values of $V_s$ with the prediction based on the best fit curve of $R_s$ for sensors of different gap widths. The diamonds represent experimentally measured $V_s$ values, and the continuous lines represent the curve of predicted $V_s$ values. . . . .	22
4	Effect of gap width on the sensor signal. . . . .	23
5	Effect of resin-curing agent and accelerator ratio on the sensor signal. . . . .	23
6	Variation of the sensor signal with time as cure progresses. . . . .	24
7	Effect of resin systems on the sensor signals. . . . .	24
8	Flow fronts and streamlines in the simple rectangular mold with one injection port. No racetracking occurs. The lineal sensors are placed along the streamlines. . . . .	25
9	Flow fronts and streamlines in the simple rectangular mold with one injection port. Racetracking occurs. The lineal sensors are placed along the streamlines. . . . .	25
10	The mean square error of reconstructing the flow front as the flow advances through the mold by using the lineal sensors in a streamline configuration for the flow without racetracking. . . . .	26

11	The mean square error in flow front reconstruction as a function of number of lineal sensors in the streamline configuration for the flow without racetracking. . . . .	26
12	The mean square error of reconstructing the flow front as the flow advances through the mold by using the lineal sensors in a streamline configuration for the flow with racetracking. . . . .	27
13	The mean square error in flow front reconstruction as a function of number of lineal sensors in a streamline configuration for the flow with racetracking. . . . .	27
14	The placement of lineal sensors in the equal-segment configuration for the simple rectangular mold without racetracking. . . . .	28
15	The mean square error of reconstructing the flow front as the flow advances through the mold by using the lineal sensors in an equal-segment configuration for the flow without racetracking. . . . .	28
16	The mean square error in flow front reconstruction as a function of number of lineal sensors in an equal-segment configuration for the flow without racetracking. . . . .	29
17	The mean square error of reconstructing the flow front as the flow advances through the mold by using the lineal sensors in a parallel configuration for the flow without racetracking. . . . .	29

Resin	411-C-50 vinyl ester (Dow Chemicals Company)
Curing Agent	Trigonox 239 A (Akzo Nobel Industries)
Accelerator	Cobalt Napthenate 6% (Mehagony Company)
Composition (parts by weight)	resin=100, CoNap=0.2, Trigonox=2 (manufacturer recommended composition)
Temperature	Room temperature
$V_{ex}$	10V

Table 1: The resin system and the experimental conditions.

Con <sup>g</sup> uration Type	Streamline	Equal-segment	Parallel
Number of Sensors	25(average)	21	21
Average MSE	0.0034	0.0038	0.0049
Standard Deviation	0.0024	0.0033	0.0034

Table 2: Comparison of the global sensing performance of three di<sup>er</sup>ent sensor con<sup>g</sup>urations, when there is no racetracking. Since di<sup>er</sup>ent number of sensors participate in case of the streamline con<sup>g</sup>uration, the average number taking part in sensing at any instant is given. Average MSE is the mean square error values averaged over time.

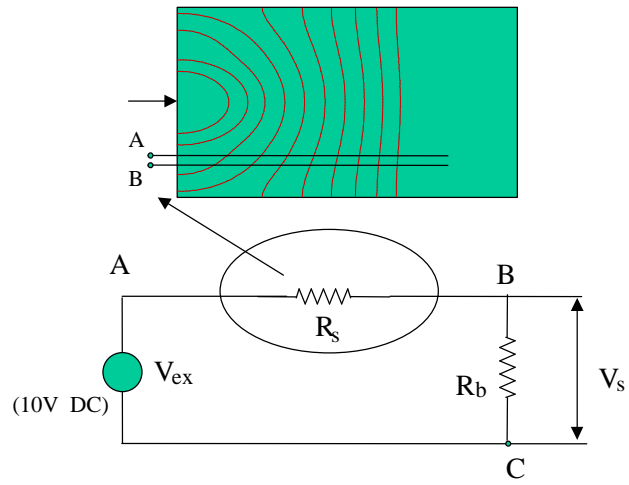


Figure 1: Circuit for measuring the sensor voltage  $V_s$ .

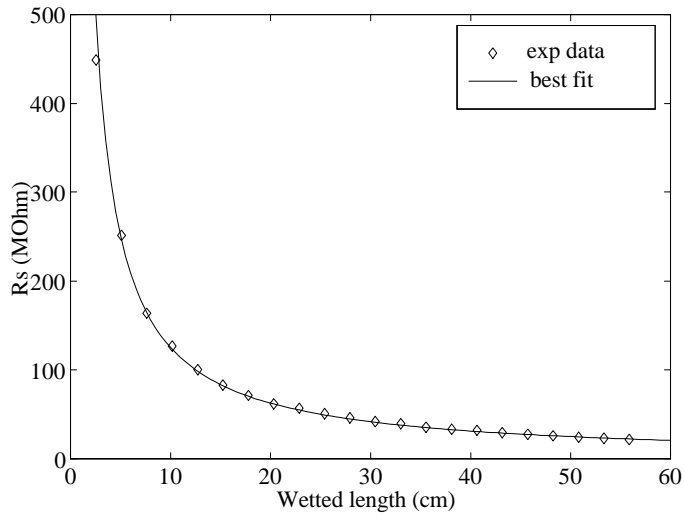


Figure 2: Sensor resistance ( $R_s$ ) vs. the wetted length. The sensor gap width is 6mm. The resin is Vinyl Ester.

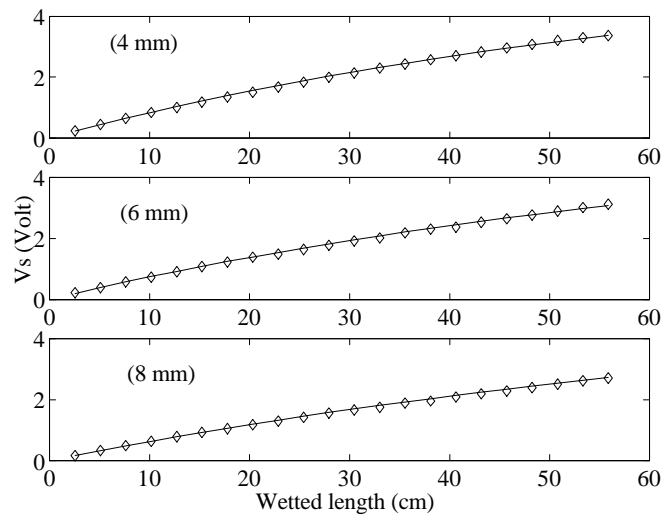


Figure 3: Comparison of experimental values of  $V_s$  with the prediction based on the best fit curve of  $R_s$  for sensors of different gap widths. The diamonds represent experimentally measured  $V_s$  values, and the continuous lines represent the curve of predicted  $V_s$  values.

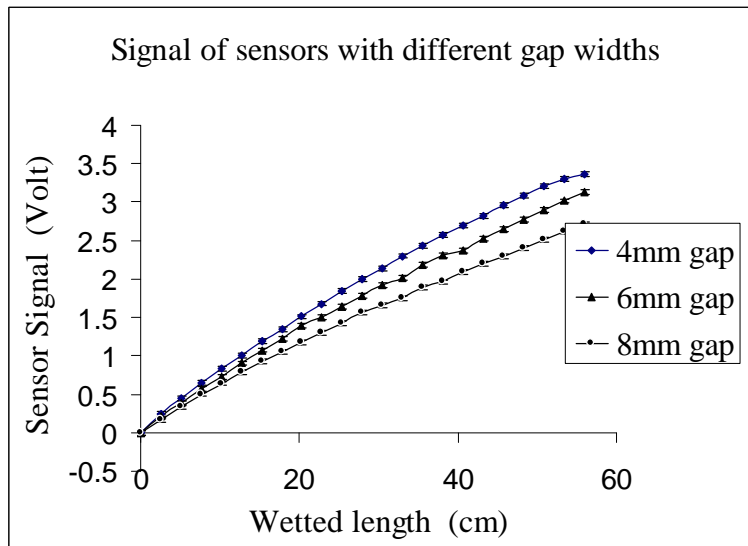


Figure 4: Effect of gap width on the sensor signal.

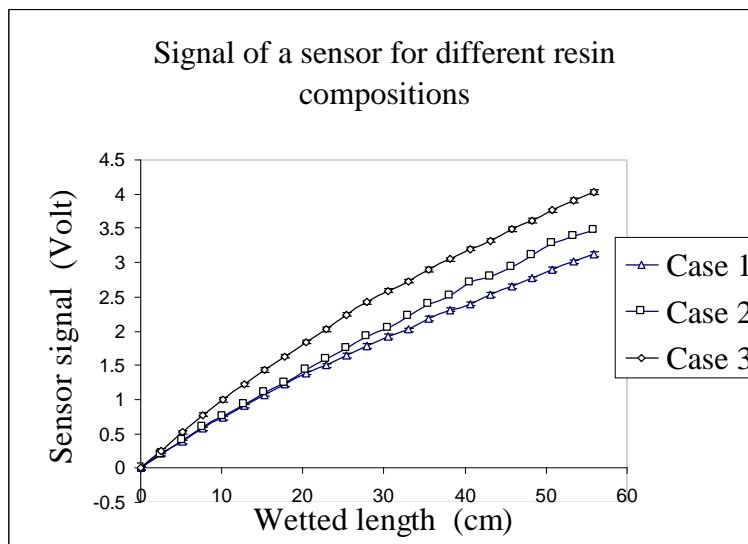


Figure 5: Effect of resin-curing agent and accelerator ratio on the sensor signal.

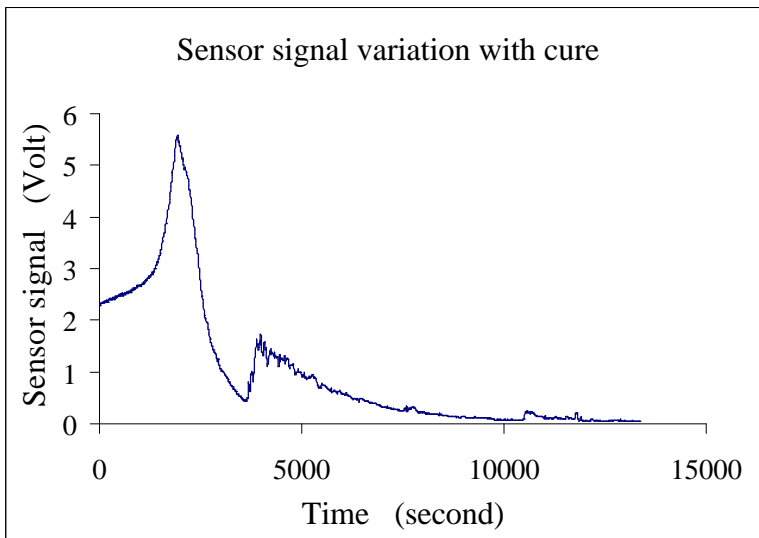


Figure 6: Variation of the sensor signal with time as cure progresses.

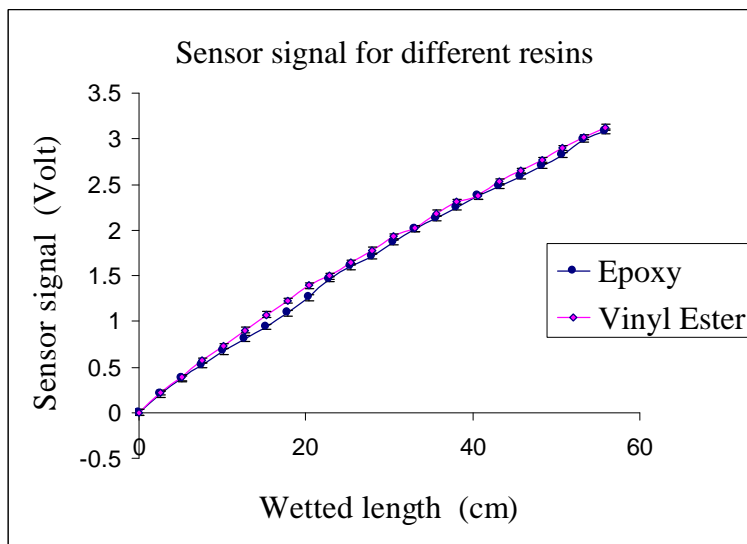


Figure 7: Effect of resin systems on the sensor signals.

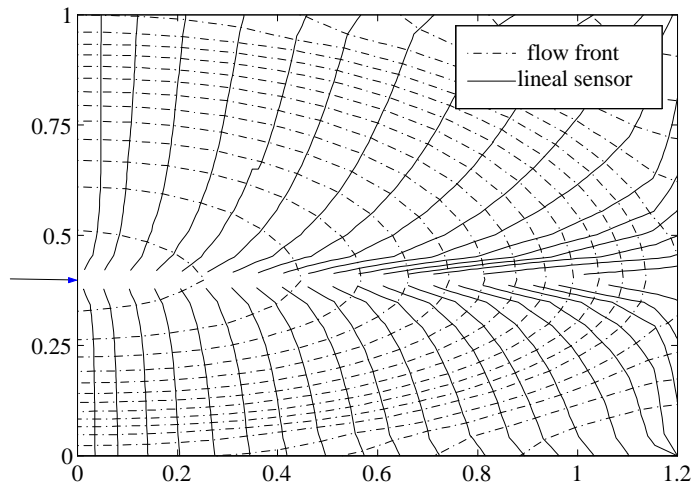


Figure 8: Flow fronts and streamlines in the simple rectangular mold with one injection port. No racetracking occurs. The lineal sensors are placed along the streamlines.

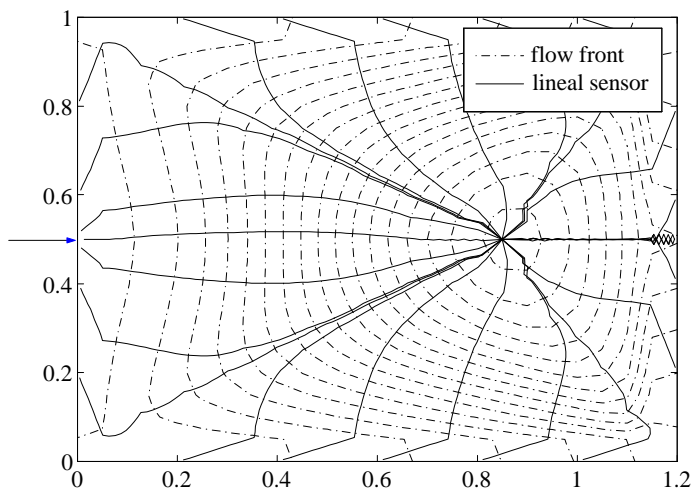


Figure 9: Flow fronts and streamlines in the simple rectangular mold with one injection port. Racetracking occurs. The lineal sensors are placed along the streamlines.

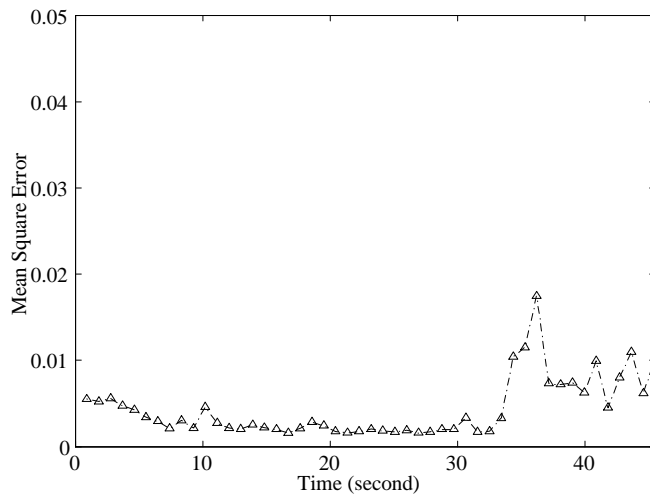


Figure 10: The mean square error of reconstructing the flow front as the flow advances through the mold by using the lineal sensors in a streamline configuration for the flow without racetracking.

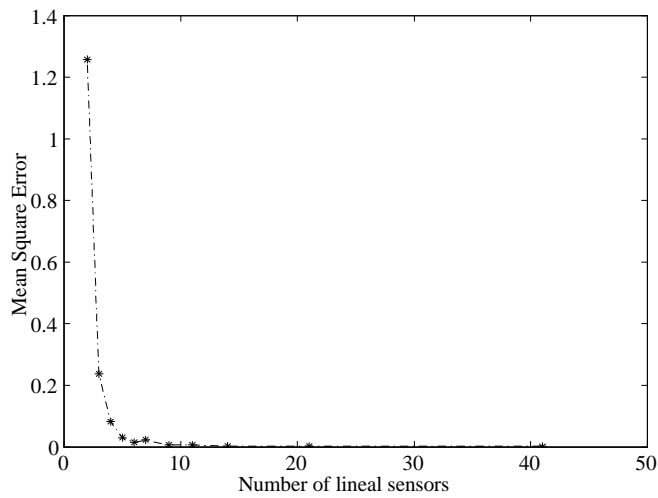


Figure 11: The mean square error in flow front reconstruction as a function of number of lineal sensors in the streamline configuration for the flow without racetracking.

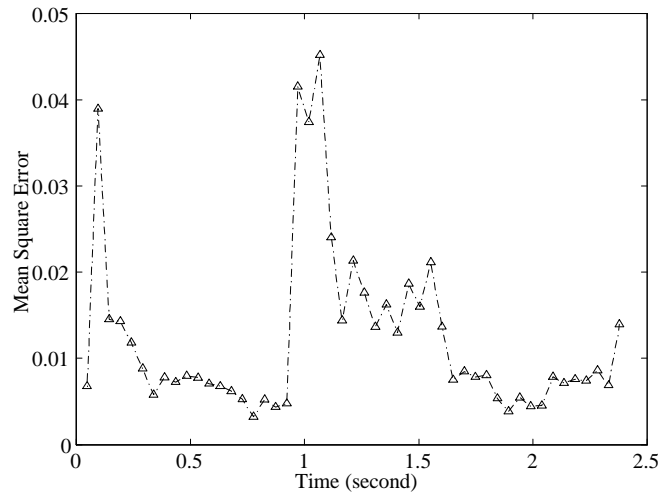


Figure 12: The mean square error of reconstructing the flow front as the flow advances through the mold by using the lineal sensors in a streamline configuration for the flow with racetracking.

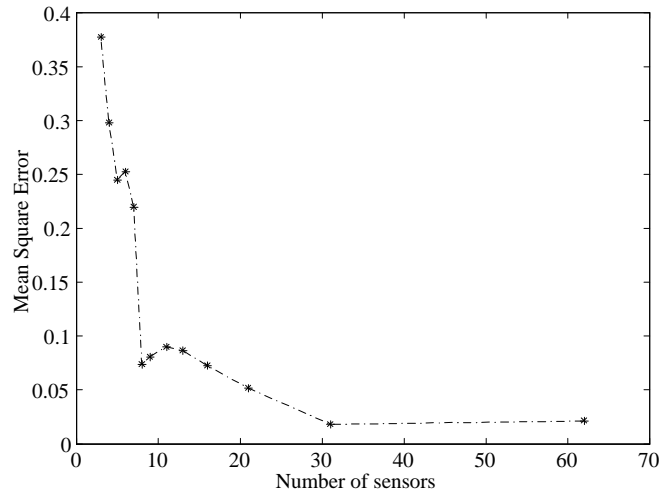


Figure 13: The mean square error in flow front reconstruction as a function of number of lineal sensors in a streamline configuration for the flow with racetracking.

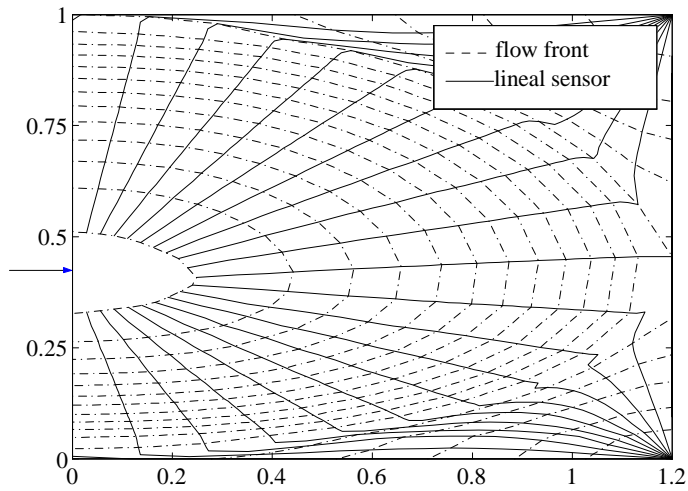


Figure 14: The placement of lineal sensors in the equal-segment configuration for the simple rectangular mold without racetracking.

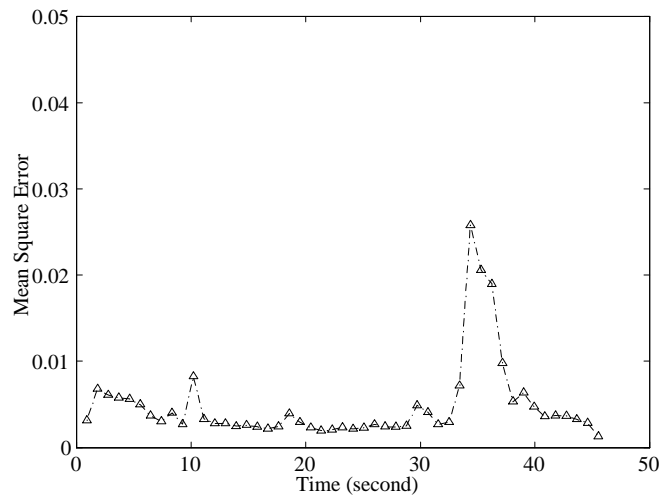


Figure 15: The mean square error of reconstructing the flow front as the flow advances through the mold by using the lineal sensors in an equal-segment configuration for the flow without racetracking.

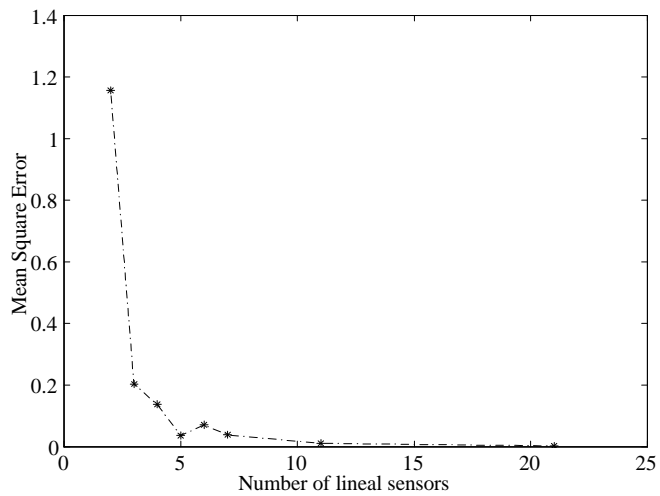


Figure 16: The mean square error in flow front reconstruction as a function of number of lineal sensors in an equal-segment configuration for the flow without racetracking.

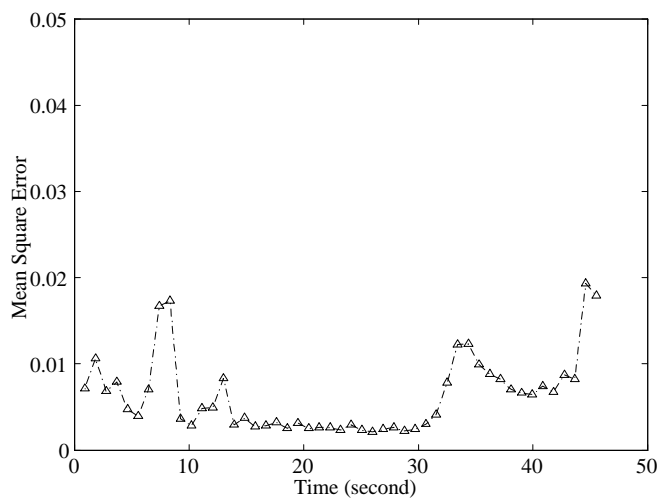


Figure 17: The mean square error of reconstructing the flow front as the flow advances through the mold by using the lineal sensors in a parallel configuration for the flow without racetracking.