

MONITORING OF RESIN FLOW AND CURE IN RESIN TRANSFER MOLDING (RTM) PROCESS

by

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This is to certify that I have examined this copy of a master's thesis by

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and have found that it is complete and satisfactory in all respects,
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ABSTRACT

Manufacturing processes of composite materials have not been completely automated yet due to the variations in material used and preparation of it. In this study, Resin Transfer Molding (RTM) process is controlled by using two alternative sensor systems integrated with a mold, injection machine, data acquisition system, and mold filling simulations. Since mechanical properties of finished part and its protection against ambient conditions are affected by entrapped air in it, the mold must be completely filled with polymer. A sensor system is needed to monitor both mold filling and resin cure, so that it is ensured that the mold cavity is filled completely, and to decide when to end the cycle of manufacturing by opening the mold. First, thermocouple sensor system was applied with some limitations on usage. The major drawback of this system was high conductive heat loss from polymer to mold wall such that when polymer arrived at sensor locations under typical RTM injection conditions, its temperature was not high enough to detect a significant temperature rise. However, by using water as dummy resin, and increasing flow rate, it was illustrated that thermocouple sensors can be used to monitor mold filling. As a second alternative for sensor system, lineal and point voltage sensors were studied. Considering the disadvantages of lineal systems, we developed point voltage sensors after eliminating some of the drawbacks observed in earlier usage. These sensors are low-cost, reliable, durable, and easy to manufacture.

Another element of a robust control system is mold filling simulations. Accurate simulation results can be obtained only if the input data for material is accurate. Permeability of fabric preform, which is one the most crucial material data that affects the results, can be measured by using one-dimensional injection experiments, or predicted by mathematical models. When race-tracking air channels exist along the mold edges and corners, they need to be taken into account. A model was applied based on Stokes flow through the channel with no-slip boundary condition. The model was solved by using finite difference method for different channel geometries.

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NOMENCLATURE

a	ratio of race-tracking permeability over bulk permeability
C	electrical capacitance, [F]
E	modulus of elasticity, [Pa]
h	height of race-tracking channel, [m]
K	permeability tensor of fabric preform
K_{xx}	permeability components in different directions, [m ²]
L	length of mold cavity, [m]
m	resin viscosity, [Pa.s]
P	resin pressure, [Pa]
R	electrical resistance, [ohm]
R_{sens}	electrical resistance of media between the two wires of a lineal sensor, [ohm]
S	spacing between two parallel wires of a linear sensor
t	time, [s]
T	temperature, [°C]
$\bar{u}_x$	averaged resin velocity in x direction, [m/s]
$\bar{u}_y$	averaged resin velocity in y direction, [m/s]
$\bar{u}_z$	averaged resin velocity in z direction, [m/s]
UTS	ultimate tensile strength, [Pa]
V	electrical voltage, [V]
V_{sens}	electrical voltage difference of media between two wires of lineal sensor [V]
V_{exc}	excitation voltage supplied to a lineal or voltage point sensor, [V]
w	width of race-tracking channel, [m]
W	width of mold cavity, [m]

Chapter 1

LITERATURE REVIEW

Superior properties of composite structures over other materials such as high specific strength (ratio of strength over density) and resistance to corrosion made them become one of the most commonly used materials in engineering applications. A typical polymer composite is basically a combination of polymer and a reinforcing material such as glass fabric. Modern composites have been used since the 1940s, but the manufacture of most composite products is still very labor intensive. This limits production rates and keeps costs high. Parts produced might show significant variations in dimensions and mechanical properties. This brings quality control problems. New methods are currently being applied to standardize, simplify and automate manufacturing of composite parts. Resin Transfer Molding (RTM) process is one of these processes which is classified in advanced thermoset composite manufacturing methods, and it belongs to the subgroup of liquid composite molding (LCM) processes [1]. By controlling the process parameters in LCM processes, engineers can eliminate the drawbacks of traditional composite manufacturing techniques and automate the manufacturing of high quality parts with complex shapes.

RTM is a technique for manufacturing high quality composite parts. In this process, a fabric preform is placed inside a mold cavity and then the mold is sealed and closed. Thermoset resin is injected into the mold cavity to saturate the fabric preform. After the resin cures, the mold is opened and the composite part is taken out. Today, many industries such as automotive, aerospace, construction and marine make use of the RTM process.

The first use of RTM appeared in a US navy contract for the development of 28 feet long personnel boats in 1946 [2]. Boats were manufactured by using the vacuum injection method in which the reinforcement was held between two mold halves and the resin was poured into the lower one and drawn up by vacuum from the top of the tool. RTM was described in a series of British patents between years 1952 and 1956 [2], by Harold John Pollard and John Rees from Bristol Aircraft Limited. These patents covered many issues of RTM.

Molded-in metal inserts were used in the production of integrally stiffened wing skins. The patent to cover this, was applied in 1952 [2]. In 1953, another patent was applied for the manufacturing of an airfoil just in one shot from reinforced phenolic or polyester resin [2]. The basic RTM process was described as the high pressure injection of phenolic resin over felts of preimpregnated asbestos. This patent also discussed the use of polyester resin at low injection pressure and the use of woven reinforcements rather than felts.

The early RTM process techniques were suitable only for manufacturing of small shell parts. Further improvements in the process were necessary to manufacture larger and more complex parts. In October 1955, an injector mechanism mixing two part resins in a controllable way prior to injection was developed [2]. Most importantly, in 1956 a patent described the idea that automation might be possible by utilizing devices that were attached to each outlet point of a mold such that they automatically shut off the outlet valves when a predetermined amount of resin has passed through them [2]. However, it was not before 1960 that modern RTM techniques were introduced [2].

Throughout the literature, the focus has always been to understand the physics of RTM process and to model it properly. Thus, many studies were made for modeling and simulating the RTM process. Monitoring of resin flow and cure constitutes a significant portion of these studies. By this way, researchers and engineers aimed to overcome some potential problems commonly encountered during the RTM process and tried to fully automate the process for the sake of manufacturing high quality composite parts, and increasing the production rates.

The major problems of the RTM process that can occur during preparation and placement of the fiber preform or during the injection process can be listed as follows: (i) '*race-tracking*' channels between preform and mold wall, sometimes also called '*edge effect*' or '*edge flow*', (ii) presence of '*dry spots*' due to air entrapped in the mold, and (iii) '*wash*' of fabric due to high pressure and improper preform compaction.

Race-tracking channels are one of the most important phenomena that is to be considered in modeling of the RTM process. Gaps between fiber mats and mold edges form small air channels that are called race-tracking channels. These low resistant (high permeable) channels, through which resin can flow easily, may seriously alter the flow front propagation.

Bickerton et al. [3] and Hammami et al. [4] emphasized the importance of modeling race-tracking channels. They used the 'equivalent permeabilities' approach. Equivalent permeability for an air channel was calculated using a rectangular duct model based on Stokes flow equations and one-dimensional Darcy's Law. The calculations were repeated for different preform types, mold cavity thicknesses and air channel widths. Then, results were compared and verified with two dimensional numerical filling simulations.

Sometimes, race-tracking channels may be intentionally introduced to enhance the mold filling process. Mohan et al. [5] demonstrated this by using a mold with grooves (empty spaces in the grooves generate race-tracking channels) to reduce injection pressure and to increase resin impregnation. Being able to keep injection pressure at tolerable levels, they increased injection flow rate and reduced process cycle time. However, race-tracking channels are usually undesirable and accepted as a disturbance to flow.

Macrovoid formation in the composite part is a significant problem. If there is significant amount of air left inside the mold and cannot be replaced with incoming resin, then these voids which are also called '*dry spots*' occur [6]. They may occur due to the effects of race-tracking channels. Parts with dry spots lack the desired mechanical properties such as strength, and cannot be protected against ambient conditions. Hence, these parts are defective

and they fail to fulfill the necessary requirements. The issues of RTM process will be discussed in more detail in the following chapter.

The RTM process parameters such as injection pressure, injection flow rate, position of gates and vents should be set in such a way that the disturbances just mentioned above are avoided and composite parts with the desired quality and specifications can be manufactured. Process monitoring by sensors, data acquisition (DAQ), numerical simulations of mold filling and controlling the process parameters are the key factors to launch control systems, which will drive and influence RTM process to a successful completion.

Nielsen and Pitchumani [7] developed a close-loop flow control methodology, which uses a finite difference based numerical solution which they call “on-the-fly finite difference method” to optimize the injection flow rates using multiple gates in real time. On-the-fly finite-difference method is based on the numerical solution of the partial differential equations governing the mold filling process. Their control schemes were based on the use of multiple injection ports and adjusting parameters such as flow rates or pressures at inlet. They emphasized the importance of using a real time process controller, which optimizes the injection parameters at multiple ports.

Lawrence et al. [8] introduced the concept of on-line strategic control for manipulating the resin flow to compensate for the disturbances caused due to the inherent variabilities in the process. This on-line strategic controller influences the flow front pattern by registering the arrival of resin at several discrete sensor points, and tries to finish the process free of dry spots by adjusting process parameters. Embedded point sensors were placed at critical positions and three control gates were set. A genetic algorithm solver [9] was used to set the optimum flow rates at these gates (compensating for race-tracking effects) to minimize the size of dry spot formation.

Similarly, Bickerton et al. [10] and Sozer et al. [11,12] used actively controlled injection schemes for producing dry spot free parts. They demonstrated a methodology for design of RTM injection schemes including flow front sensors and a control system. Figures 1.1 and

1.2 show the mold cavity, actively controlled gates and vents, sensors and the decision-tree applied by their strategic controller. In Figure 1.1, sensors A, B, C and D are located in such a way that previously considered mold filling scenarios (due to different disturbances) will be detected. Then, the boundary conditions will be adjusted to fill the mold cavity completely. Corresponding control actions to be taken are noted below the decision tree in Figure 1.2.

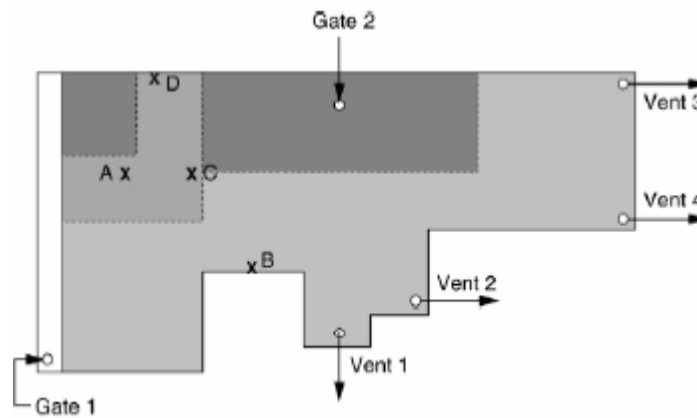


Figure 1.1 Schematic for the mold cavity and actively controlled gates and vents [10,11,12].

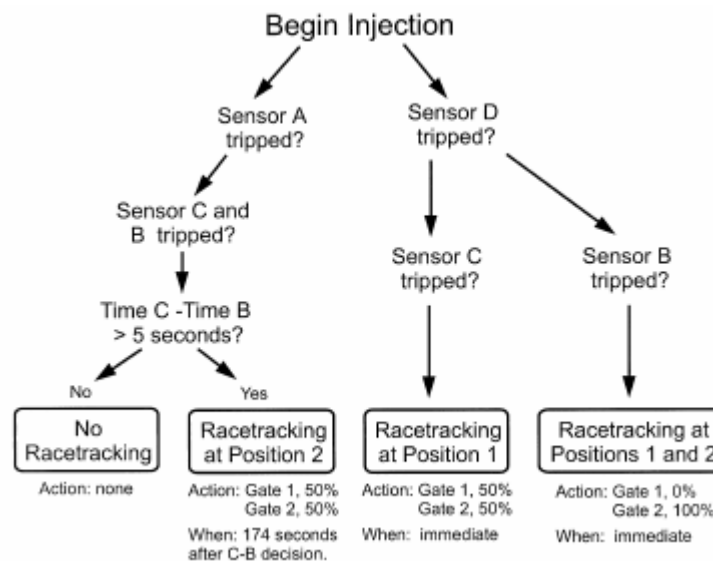


Figure 1.2 Decision tree applied for the actively controlled injection scheme [10,11,12].

In the studies that have been just cited [10,11,12], *numerical simulations* were used in the design of the actively controlled injection schemes. In general, numerical simulations of mold filling can be used for the following purposes:

- *Design of mold and process parameters:*

If the user knows material properties of resin and reinforcing fabric (viscosity of resin, fiber volume fraction and permeability tensor of fabric), then simulations will be very valuable tool to design the followings:

- (i) where to locate the injection gates and ventilation ports,
- (ii) what boundary condition (pressure or flow rate) should be used,
- (iii) when to open or close these gates and ports

so that the mold cavity can be filled completely.

- *A part of control system for an automated manufacturing process:*

Any disturbance (such as race-tracking channel or non-uniformity of fabric preform) will be detected by the sensors for a corresponding potential scenario. The outcome of this scenario will be predicted by using mold filling simulations. However, it is difficult to make on-line simulations which can propose a set of proper control actions to affect resin flow so that mold can be filled completely. The difficulty with on-line simulations is the time limitation during an actual experiment since most RTM injections are completed in several minutes. Current researches are based on off-line simulations of potential scenarios that are needed to be predicted before actual injections.

- *When experimental injection pressure data is available to measure the permeability of fabric preform (as it will be demonstrated later in this study):*

In order to use analytical formulations of Darcy Law, the flow must be perfectly one-dimensional (1D). However, it is a very difficult task to create this 1D flow. By using mold filling simulations, a correction factor will be determined once the value of disturbance is determined. This way, experimental results of quasi-1D flows can be used to calculate approximate permeability values.

Three different simulation codes were developed at the University of Delaware for the RTM process [11,12]: (i) DRAPE [66] is used to predict the fabric deformation due to draping over the tool surface, (ii) PERM [66] is used to predict preform permeability, and (iii) LIMS [53] is used to simulate the mold filling process.

LIMS (Liquid Injection Molding Simulation) is extensively used for simulating the filling stage of the RTM process. It uses a finite element method (FEM) for the solution of resin pressure, and a control volume method for flow front progression with time [12]. LIMS is able to make simulations for mold cavities with complex shapes, handle non-uniform permeability distribution, race-tracking, and multi-port injection and ventilation. It can be used as a major design tool for placing sensors, gates and vents and setting proper boundary conditions in an on-line control system. LIMS is used in this study as well.

Sozer et al. [11,12] used LIMS and other supplementary codes (mentioned above) in their strategic on-line controller and demonstrated the usefulness of these codes. Besides mold filling simulations (LIMS), they emphasized the importance of using simulations accounting for fabric draping and permeability (by using DRAPE and PERM) for a complete analysis of the RTM process.

Apart from these simulation codes, Shojaei et al. [13,14,15] developed a three-dimensional flow and cure simulation for thick and complex shaped parts where the resin flow can no longer be considered as two-dimensional. These simulations were done for non-isothermal mold filling processes and by considering both filling and curing stages for more accurate analysis. Solution model was based upon control volume/finite element method (CV/FEM). The code provided various data on injection (pressure field, velocity field and etc.) and flow front progression. It is adaptable for different injection schemes (multiple gates and vents), varying mold thickness and resin temperature. Figure 1.3 shows simulated pressure distribution of a complex shaped part using this simulation code.

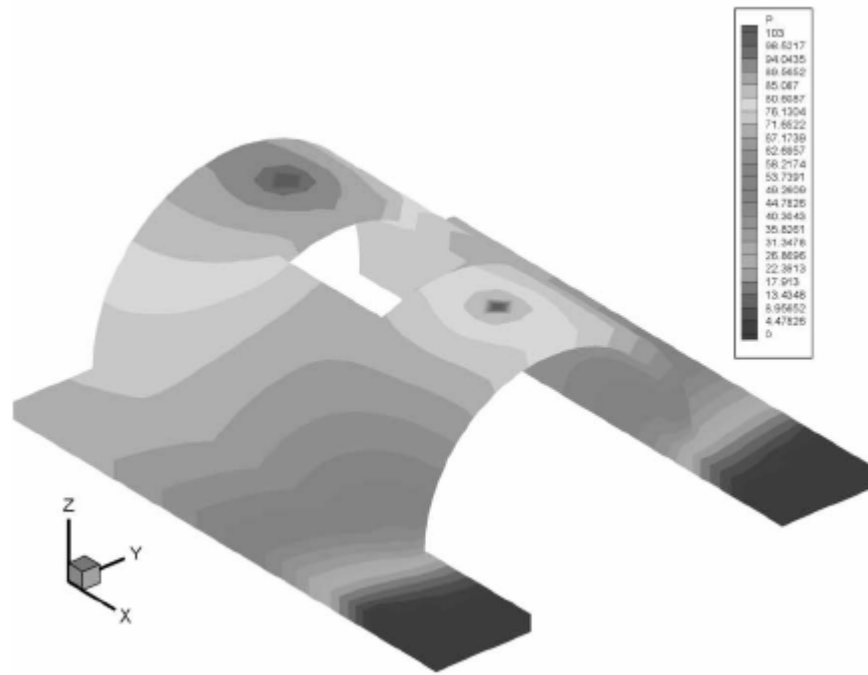


Figure 1.3 Simulated pressure distribution of a three dimensional complex part [13].

As previously mentioned, process monitoring plays a crucial role in RTM process as it significantly affects the repeatability of the process and the quality of parts produced. Monitoring resin flow allows engineers to detect whether the flow front propagates as it was designed or not, and hence if any void remains within the mold cavity. Monitoring the cure of polymer allows engineers to decide when to de-mold the part (open the mold and take the part out). If we have a closer look at the various types of sensors and monitoring systems that are being used for these monitoring purposes, the most frequently used sensors are thermocouples, pressure transducers, SMARTweave, dielectric, ultrasonic, fiberoptic and lineal sensors [16].

Thermocouples provide an easy and efficient way of measuring temperature. A thermocouple consists of a pair of two dissimilar metal wires connected together at one junction. When the junction is heated, a small voltage difference due to emf (electromotive

force) occurs between these two wires. This voltage (e_{AB} shown in Figure 1.4) is a linear function of temperature and can be easily converted to a temperature value [17].

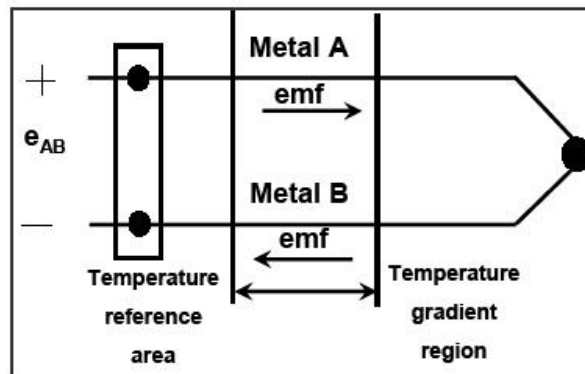


Figure 1.4 Inside a thermocouple sensor [17].

Thermocouples are widely used in cure monitoring investigations such as the ones at the Stanford University and most other universities. To predict the degree of resin cure by using thermocouples, one has to know the temperature history of the resin [18]. Besides being used for cure monitoring, thermocouples are used for resin flow monitoring as in our study. However, it is important that there should be a considerable amount of temperature difference between the mold (usually at room temperature) and the resin so that resin arrival can be detected by using thermocouple sensors. Hence, thermocouple sensors are not applicable when both resin and mold are at the same temperature. In our study, although general purpose room-temperature polyester was used (no heating required), it is heated such that its temperature is above the room temperature by about 20 °C.

A pressure transducer is a device that converts pressure into an electrical signal. Most commonly used one is the strain-gage type. Pressure is converted into an electrical signal by the physical deformation of strain gages which are bonded to the diaphragm of the pressure transducer. The diaphragm deflects when pressure is applied and the strain will produce an electrical resistance difference proportional to the pressure [19]. Melt pressure transducers as

shown in Figure 1.5 [20] are designed specifically for measuring polymer pressure. They are widely used for storing resin injection pressure data as in most of the studies cited here. They are not generally used for flow monitoring purposes or sometimes used together with other sensor systems since placing pressure sensors at many discrete positions inside the mold would be very costly.



Figure 1.5 Melt pressure transducer [20].

SMARTweave was developed by the U.S. Army Research Laboratory for the sake of monitoring resin flow front progression and providing data for control of resin flow in large RTM fiberglass parts [16]. It consists of a grid of conducting wires, half of which are located between two plies in one orientation and the other half between two other plies oriented orthogonally (Figure 1.6) [25]. When resin flows over the grid of wires, some portion of these electrical circuits are closed and voltage readings indicate if resin has arrived or not. The SMARTweave system has been successfully used to monitor the resin flow and cure in resin transfer molding (RTM), Seeman composites resin infusion molding process (SCRIMP) and vacuum assisted RTM processes (VARTM). It provides an effective continuous real-time assessment of the RTM impregnation process [21]. However, the wires remain in the final part produced and this may cause structural defects in the part. From the mold filling point of view, another disadvantage of this sensor is that the presence of the sensor within the mold cavity behaves as an obstacle to the resin flow. Fink et al. [22],

Bradley et al. [23], and Don et al. [24] used SMARTweave in their resin flow and cure monitoring studies.

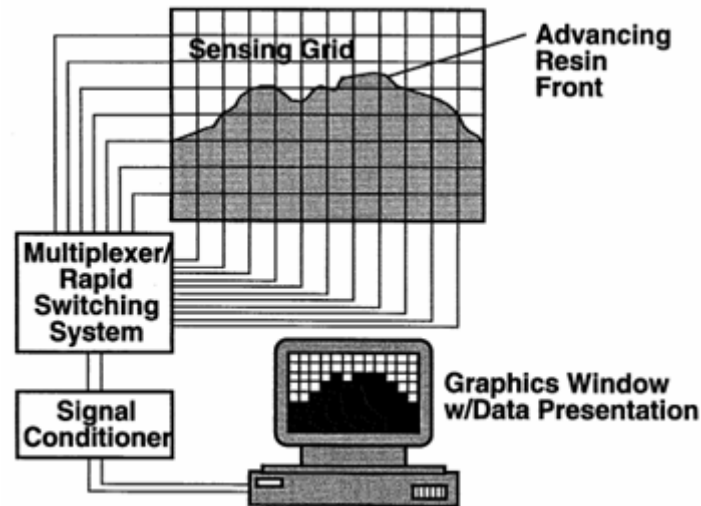


Figure 1.6 Schematic for the Smartweave system [25].

Recently, dielectric analysis (DEA) has become one of the most promising methods for especially monitoring resin cure. Dielectric measurements provide information that is strongly correlated with various parameters such as molecular mobility, dynamic moduli, extent of crystallization, viscosity, the build up of glass transition temperature and the extent of cure [16]. Thus, dielectrometry is commonly preferred for cure monitoring purposes. Parallel plate or comb (in the shape of a comb) electrodes are used to measure capacitive properties and they are embedded in the bulk material. One of the major disadvantages of dielectric sensors is the disturbance of resin flow. The sensors will change the open channel structure of porous mold cavity and hence the flow propagation will be affected [16].

A. McIlhagger, D. Brown and B. Hill [26] used dielectric analysis (DEA) to identify the key stages in the curing process and to estimate the values of the resin properties at these stages. By using DEA, they measured electrical characteristics of the material such as the conductance and the capacitance as a function of time, temperature and signal frequency.

They showed that these electrical properties are significant when correlated to activities on a molecular level. They used ionic conductivity to directly make a correlation to viscosity and gelation point which are key parameters for resin cure. The results were shown to be useful in terms of monitoring and optimizing the RTM cure cycle.

Bang et al. [27] showed that dielectric characteristics of glass fiber epoxy composites are dependent on the viscosity of the epoxy matrix. They measured dissipation factors of glass fiber epoxy composites by using a dielectric sensor with a sensing area of 3 mm x 3 mm, which was manufactured by etching a thin copper plate bonded onto an epoxy substrate as shown in Figure 1.7. Sensors were placed between layers of fabric preform. Resistance-capacitance type of Wheatstone bridge circuit was used for enhanced sensitivity and for measuring dissipation factor. With the collected data, they calculated the isothermal degrees of cure. They also measured electrical resistance, capacitance and internal temperature of the composite material. They compared and verified their results with another cure monitoring method called differential scanning calorimetry (DSC).

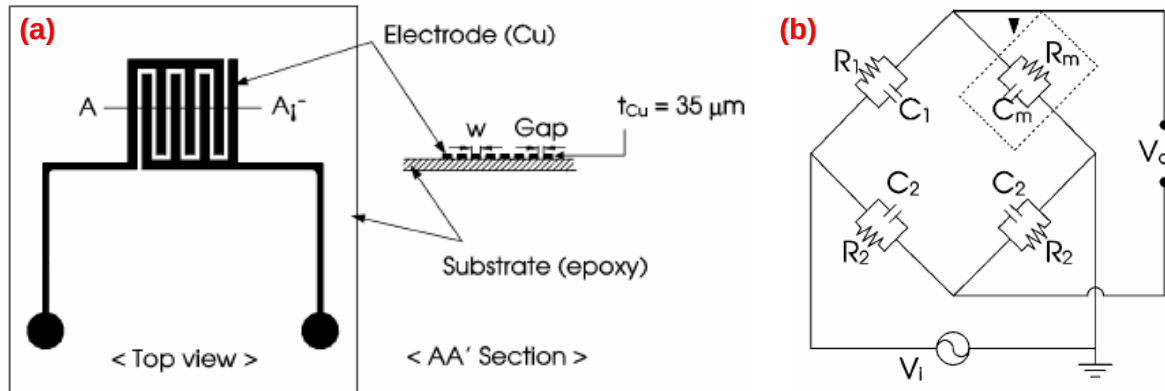


Figure 1.7 (a) The dielectric sensor (t_{Cu} = thickness of copper), (b) Wheatstone bridge circuit (R_m and C_m are the resistance and the capacitance of fiber-epoxy composite, respectively) [27].

Kim et al. [28] developed a new method to measure the degree of cure during on-line cure monitoring for S-glass/polyester composites by employing a combined function of temperature and dissipation factor. The temperature signal was measured with a K-type thermocouple, and the dissipation factor signal was measured with a dielectric sensor during the curing process. Degree of cure was calculated from the experimental data using dielectrometry and it was compared with the differential scanning calorimetry (DSC) method. The two results were in good agreement, and it was stated that the new method could be applicable for the measurement of degree of cure.

Schmachtenberg et al. [29] used ultrasonic built-in sensors in the mold with on-line process control for monitoring both resin flow and cure. Figure 1.8 shows the schematic for the experimental set-up. They claim that ultrasonic sensors are advantageous compared to other sensors since the ultrasound is transmitted indirectly and there is no contact between sensor and fabric. This means they don't create any defects on the part. With the help of an impulse generator, an ultrasonic sensor gives an acoustic signal that is detected by a second ultrasonic sensor just opposite to it and the second sensor sends an electrical signal which can be repeated and analyzed. These signals have two elements of information: the sound velocity and the attenuation. The arrival of the flow front is detected by any change in these parameters. During the curing process, an increasing sound velocity is detected by the ultrasonic receiver, which reaches a maximum value at the end of curing.

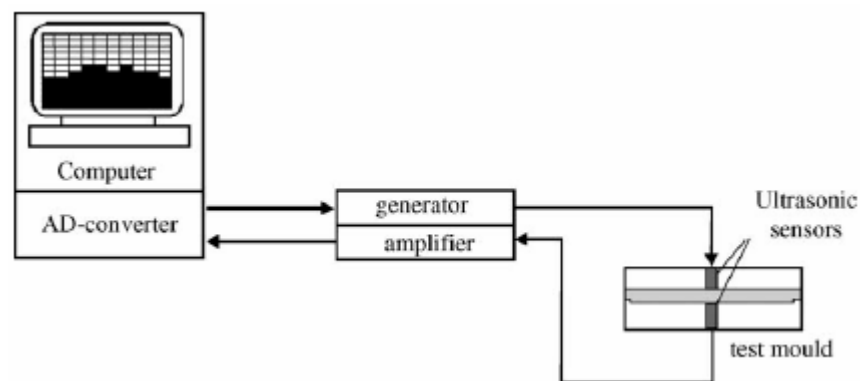


Figure 1.8 Use of ultrasonic sensors [29].

Rath et al. [30] also used the ultrasonic technique for monitoring the cure process. They investigated the effects of various material parameters, such as chemical composition, filler content, artificial thermal weathering, moisture content and hardener amount on the cure process. For this purpose, they made sound velocity and attenuation measurements similar to Schmachtenberg's approach.

Lim and Lee [31] used fiber-optic sensing to monitor the three dimensional resin front location as a function of time. They compared their results with numerical simulations done by using control volume/finite element method (CV/FEM). An optical fiber consists of core and cladding. The core is the path of light and the cladding is the mechanical protection. Lim and Lee used a halogen lamp as the infrared light source. The infrared light signal was transmitted through the optical fiber from one end, and the intensity of the light signal was monitored on the other end. Before the resin reaches the sensing spot, light can be transmitted through the optical fiber, but it refracts as soon as the resin reaches the spot. Thus, by placing fiber-optic sensors in between fiber layers as shown in Figure 1.9, it is possible to monitor the resin flow front.

Dunkers et al. [32] made use of fiber-optic sensors for resin cure monitoring as well.

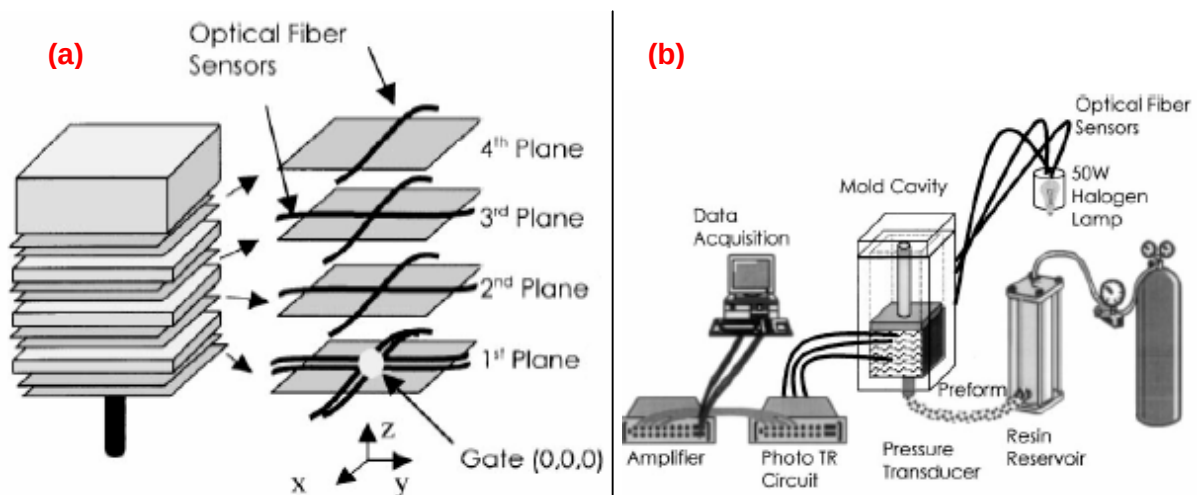


Figure 1.9 (a) Fiber-optic sensors in between fiber layers, (b) experimental set-up [31].

Ultrasonic and fiber-optic sensors usually require usage of either transparent or thinner mold parts for the transmission of signals and light. This means that the mold might bend significantly during compaction since it has less stiffness. This also makes it inconvenient to make the injection process under high pressures and temperatures.

Lineal sensor systems developed by Barooah et al. [33] are practical systems consisting of two electrically conductive wires and an electrical circuit. These conductive wires are placed at a distance (on the order of a few millimeters) to each other on an electrically insulated film and attached to the mold surface. The simple circuit used for lineal sensors is composed of two resistance elements: a high value resistance used as a voltage divider (not shown in Figure 1.10(a)) and a resistance generated by the polymer-fabric media between the wires (as shown in Figure 1.10(a)). Separate couples of wires can be placed at desired locations of the mold. A certain voltage is applied to each circuit's beginning (between points A and B) as shown in Figure 1.10(a). As resin advances in the longitudinal direction over the gap between these wires, the resistance of the media between the wires changes. Consequently, the voltage reading over this resistance changes, and the position of the resin flow front can be recognized. A detailed analysis for lineal sensors is given in Chapter 5.

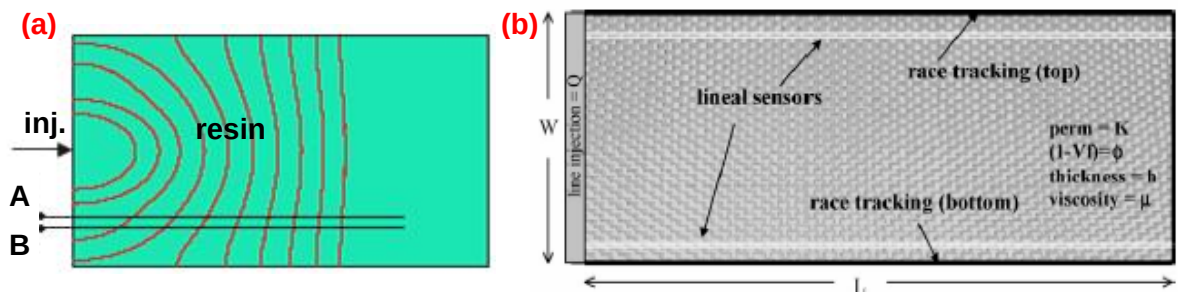


Figure 1.10 Lineal sensors: (a) a schematic for a single lineal sensor [33], (b) lineal sensors placed along mold edges [34].

Lawrence et al. [34] developed a method to calculate the bulk permeability of fiber preforms by using lineal sensors. They placed lineal sensors along the mold edges where race-tracking may occur (Figure 1.10(b)), and conducted several mold filling simulations by using LIMS. They gathered lineal sensor data that gives wetted length information along the two edges of the mold as a function of time. By comparing and matching the experimental and simulated results they introduced correction factors to calculate the bulk permeability in the presence of race-tracking channels.

Similar to the operation of lineal sensors, flow monitoring sensors based on DC (Direct Current) voltage measurements were also used by Lawrence et al. [8], Bickerton et al. [10] and Sozer et al. [11] as part of their control systems. These are used as embedded point sensors which can detect resin when the two poles of a sensor are wetted by resin.

Organization of the thesis:

In this study, we tried to monitor resin flow and cure in RTM process via different type of sensors. The organization of the chapters can be given as follows: A general introduction to composite materials is given, and the experimental set-up used for RTM manufacturing is described in Chapter 2. In Chapter 3, the problems of RTM process and the necessity for a control system are discussed; the data acquisition system is described. Use of thermocouple sensors for monitoring resin flow and cure, and the problems associated with them are discussed in Chapter 4. As an alternative to thermocouple sensors, the application of voltage lineal and point sensors is described in Chapter 5. Equivalent permeability calculations for race-tracking channels with different geometries are made in Chapter 6. The use of non-perfect one-dimensional injection experiments to measure the bulk permeability of a fabric preform is discussed in Chapter 7. The conclusions of this study are summarized in Chapter 8.

Chapter 2

INTRODUCTION AND EXPERIMENTAL SET-UP

2.1 Composite Materials

Composite materials are preferred to traditional engineering materials because of their properties of high specific strength, high stiffness, high energy absorption upon impact and high corrosion resistance. Today, composite materials are used in industries including aerospace, marine, construction, automotive, military and sport goods (Figure 2.1).



Figure 2.1 Use of composite materials in different industries.

Composite materials have a vast variety of usage area. They are used in aircraft components, auto parts, turbine blades, construction of bridges and similar structures, in the main body of ships and boats, sport goods such as racquet frames, bicycle bodies and hockey clubs.

A typical composite material is a combination of polymer and a reinforcing material such as a fabric. “Advanced” composite materials have continuous fibers (usually in the form of stitched or woven fabrics) and a surrounding matrix which is usually a thermosetting polymer.

2.1.1 Fabric

Fabrics carry structural loads on composite parts, and provide stiffness and strength to the part. Fabrics for composite manufacturing are generally made of either glass or carbon fibers. They are available in different structures as shown in Figure 2.2. Different types of fabric show different draping (being able to lay up over a tool surface) and mechanical properties. Fiber volume fraction ($V_f = 1 - f$, where f is the porosity) is the ratio of fiber volume to the total mold cavity volume. As fiber volume fraction of the part increases, the strength of the part increases. However, during resin injection, it is more difficult to impregnate a fabric with a higher fiber volume fraction.

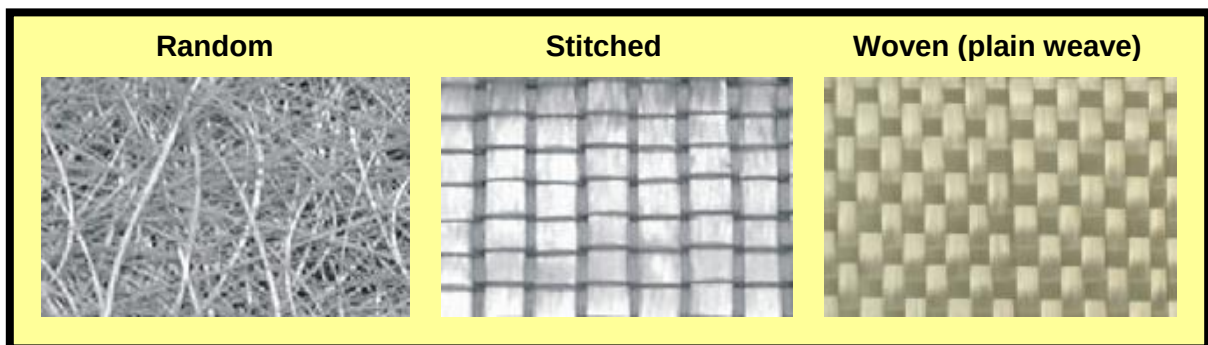


Figure 2.2 Different types of glass fabric [37].

In this study, both random and plain woven e-glass fabrics were used in the experiments. The thickness of glass fabric before compaction is about 1-2 mm. Woven glass fabric is made up of orthogonal fiber bundles which are called tows or, wefts and warps as shown in Figure 2.3. These bundles are usually 1-5 mm wide. Number of wefts and warps per unit length might not be the same, and vary according to the type of fabric. Each of these bundles is composed of 100 to 48000 fibers [35].

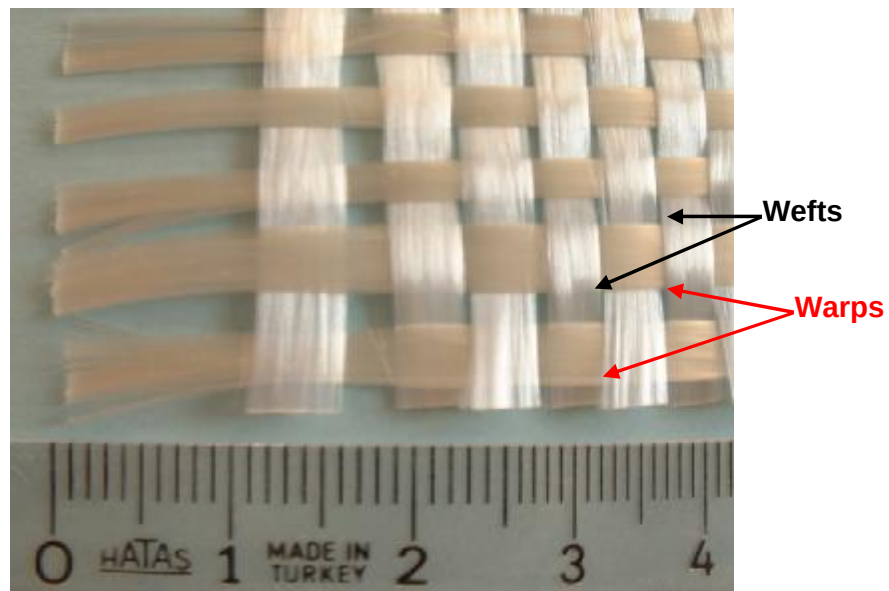


Figure 2.3 Plain weave glass fiber bundles called wefts and warps.

The distances between two consecutive warp bundles, and between two weft bundles are usually different. Bundle widths vary as well. Thus, fabrics are generally non-isotropic and their mechanical properties differ in both weft and warp directions. This also affects the flow front propagation of polymer through fabric preforms. For example, if an internal point injection gate is used, the flow profile of polymer will be circular for an isotropic fabric, whereas it will be elliptical in the case of a non-isotropic fabric [35].

A single glass fiber has a tensile strength of about 4000 MPa which is much higher than that of typical steels which is about 1000 MPa [36]. However, due to the weave structures and empty spaces between fibers, the fabric strength is either smaller or on the same order of magnitude compared to steels [35]. The overall strength of composite part will be dependent on the fiber volume fraction and structure of fabric. In Table 2.1, a comparison of modulus of elasticity and ultimate tensile strength for different materials is given [36].

Composite materials are indispensable for industries such as aerospace and marine where lightweight structures with considerable strength are needed. High corrosion resistance of composite materials is also very useful and advantageous for especially marine industry.

Table 2.1 Modulus of elasticity and ultimate tensile strength for different materials [36].

Material	Modulus of Elasticity, E [GPa]	Ultimate Tensile Strength, UTS [MPa]
Aluminum	69 - 79	90 – 600
Steel	190 - 200	415 – 1750
Thermoplastic polymer	1.4 - 3.4	2 – 70
Thermoplastic polymer (reinforced with short fibers)	2 - 50	20 – 120
Thermoset polymer	3.5 - 17	35-170
Glass fiber (unidirectional)	73 - 85	3500 – 4600
Carbon fiber	275 - 415	2000 – 3000
Kevlar (DuPont)	62 - 117	2800

2.1.2 Resin

Resin, which is the second major component, is any polymer that acts as a matrix covering the fabric and keeping the fibers in place. It protects the fabric against environmental conditions such as moisture and chemical effects, and transmits external forces to the fibers. Polymers have low tensile strengths of about 35-170 MPa which is much lower than that of steels (Table 2.1).

There are two types of polymers used in composite materials manufacturing: thermoset and thermoplastic resins. Thermoset resins have low viscosity and they require a stage in which a chemical reaction of cross linking between polymer molecules takes place. This stage is called *curing* and it is irreversible. For most of the thermoset systems, it is necessary to add chemical agents to initiate and accelerate the curing process; for some other systems heat may also be applied. Thermoset resins are generally in liquid phase at room temperature. With the curing process, gelation starts and their viscosity increases considerably. As the process comes to an end, they solidify. Due to their low viscosity, they have the advantage of easy processing. Before the curing process starts, it is possible to impregnate fabric preform with polymer and wet it completely without working under high temperatures and pressures.

In contrast to thermoset resins, thermoplastic resins have higher viscosity and they do not go under the curing process. They are generally in solid phase at room temperature. When external heat and friction are applied, they melt and can be injected into a mold. By heat conduction to mold walls, they solidify again. This process is reversible. That means, they can be reheated and then reshaped. However, due to their high viscosity at the processing temperatures, it is hard to get them flow through tiny empty spaces between fibers. They also show non-Newtonian flow characteristics. For a comparison, Table 2.2 shows some viscosity values for different materials [37].

Table 2.2 Some viscosity values for different materials [37].

Material	Viscosity [Pa.s]
Air	10^{-5}
Water	10^{-3}
Glycerin	1
Thermosets	0.05 to 0.5
Molten thermoplastics at processing temperature	10^2 to 10^6
Glass	10^{21}

2.2 Composite Materials Manufacturing Techniques

As stated before, composite materials containing continuous fibers are called advanced composites. They are used in structural parts requiring high mechanical strength and stiffness. Parts with lower strength requirements might be manufactured with discontinuous fibers which are less costly and easier to manufacture than continuous fibers. Discontinuous fibers may be in the form of cut or chopped fibers compacted in random orientation.

Composite materials manufacturing techniques can be classified as short (discontinuous) fiber composite manufacturing, and advanced composite manufacturing techniques [37]. Advanced composite manufacturing techniques can be classified into two: thermoset and thermoplastic composite manufacturing.

In advanced *thermoplastic* composite manufacturing, heat and pressure are applied to have the highly viscous resin system and the fibers move together. In these processes, resin and fibers deform together and take the shape of the final part. Thermoplastic sheet forming, thermoplastic pultrusion and fiber tape laying methods can be classified in this group.

Advanced *thermoset* composite manufacturing processes involve the impregnation of a preform fabric with thermoset resin. Since thermoset resin is used, curing takes place. The processes that fall into this class are autoclave processing, filament winding and all liquid composite molding (LCM) processes such as resin transfer molding (RTM), vacuum assisted RTM (VARTM), and wet-hand lay-up.

2.3 Resin Transfer Molding (RTM) Process

In this study, our focus will be on RTM process which belongs to the group of LCM processes [37]. In LCM processes, the basic principle is to inject resin into stationary fabric preform and saturate all gaps between the fibers with resin before the curing (gelation) starts.

RTM process is one of the most commonly used composite materials manufacturing methods. It enables the production of composite parts with:

- Low costs and low cycle time compared to many other methods,
- High fiber volume fraction (V_f) which means parts with higher strength,
- Dimensional accuracy (low tolerances),
- Large size and having complex shapes,
- Good surface quality.

With RTM, near net-shape manufacturing (little further processing is needed on parts) is possible. Parts with varying properties can also be produced. For instance, some sections can be made stronger and stiffer by adding more fabric layers and, hence increasing the fiber volume fraction.

As illustrated in Figure 2.4, there are five major stages of RTM process:

1. *Preform Manufacturing*: Fabric layers with certain dimensions are cut from rolls of fabric. These dimensions should match the size of mold cavity.

2. *Lay-Up and Draping*: Fabric layers are placed over the lower part of the mold. Many layers might be necessary depending on the thickness of the part.
3. *Mold Closure*: Mold is closed by compacting the fabric preform between upper and lower mold parts. Fiber volume fraction may be increased up to 65-70% if high strength is needed.
4. *Resin Injection and Cure*: Resin is injected into the mold cavity using injection machines. Injections are done at either constant injection flow rate or constant injection pressure. Resin cures (cross-linking of polymer) and the part solidifies.
5. *Demolding and Final Processing*: Mold is opened and the part is taken out. If needed, the excess parts are trimmed and holes are drilled.

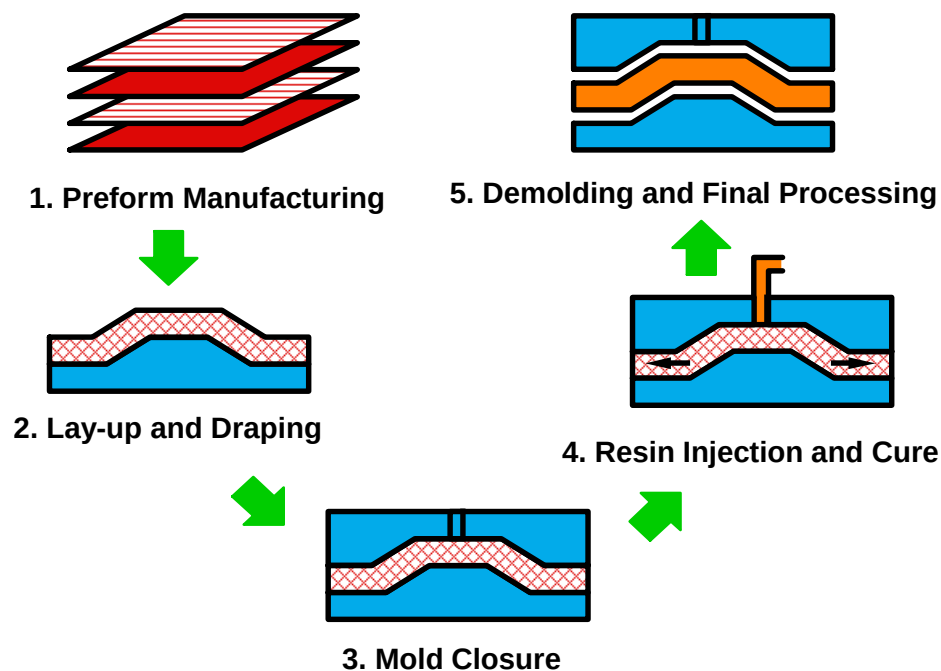


Figure 2.4 Process stages of RTM process [12].

2.4 Experimental Set-up and Mold Design

The modular RTM mold used in this study was designed and manufactured in TUBITAK, MISAG project [35]. A similar modular mold was originally used by Sozer et. al [11,12]. The mold enables the production of different parts in the form of rectangular panels with different dimensions. It is a general purpose mold that enables testing of different injection and control schemes. Figure 2.5 shows the major components of this RTM mold. The functions of mold parts can be described as follows:

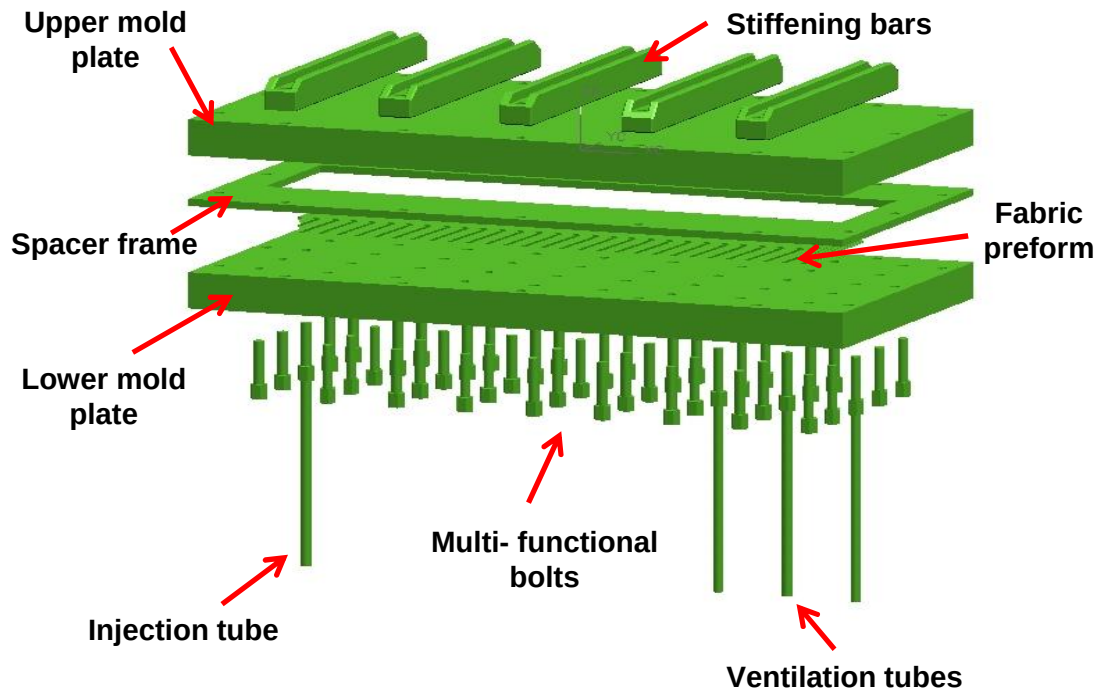


Figure 2.5 Modular RTM mold and its components.

1. Upper and Lower Mold Plates: Mold parts should be fixed to each other so that during the injection process, leakage of polymer is prevented. Considering that the injections can be made under high pressure and/or high temperatures, the mold parts should be chosen from

materials having high strength and stiffness. This ensures the necessary compaction of mold parts and prevents bending. This is especially true if composite parts with high fiber volume fraction are to be produced and many layers of fabric are to be compacted.

In this study, compaction of mold is performed by screwing 16 bolts around the mold manually. The lower part of the mold is made of aluminum and fixed to a wheeled steel cart as shown in Figure 2.6. Silicon O-ring is used on both plates of the mold to prevent polymer leakage. Two alternative upper parts are used: metal (aluminum) part, or transparent acrylic part. While upper aluminum part provides higher stiffness and hence better compaction, transparent acrylic part provides a visual access to the system and flow front propagation can be observed. The thickness of the aluminum part is 5 cm. In general, a set of three acrylic parts are used (for better compaction), each having a thickness of 3 cm. Figure 2.7 shows the RTM mold closed with two different upper parts.

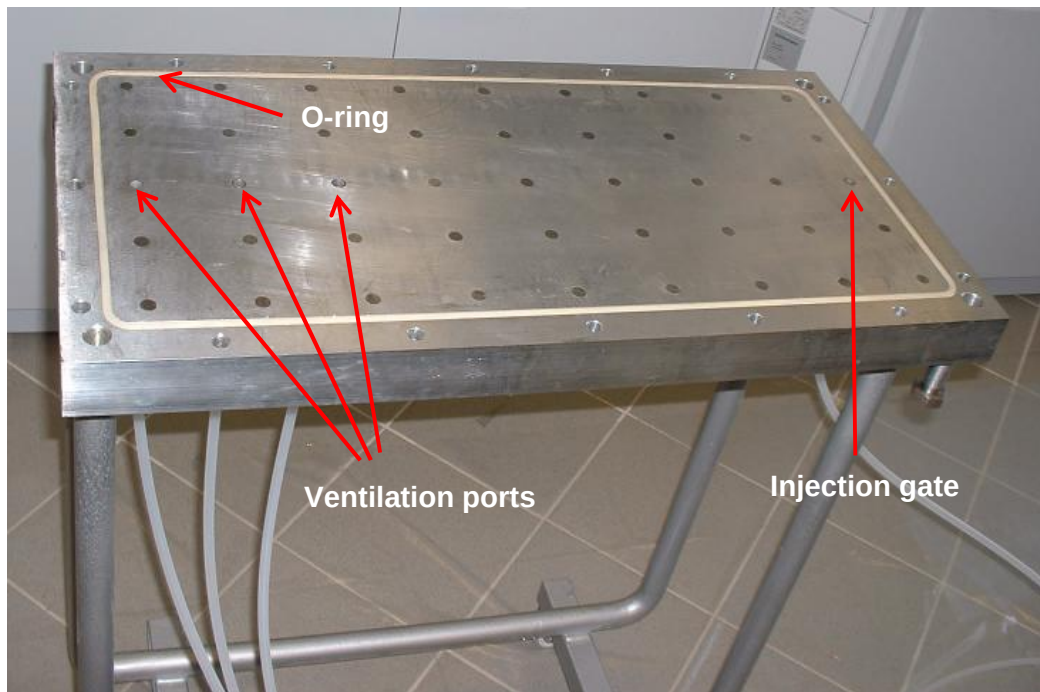


Figure 2.6 The lower part of RTM mold and wheeled steel table fixed to that.

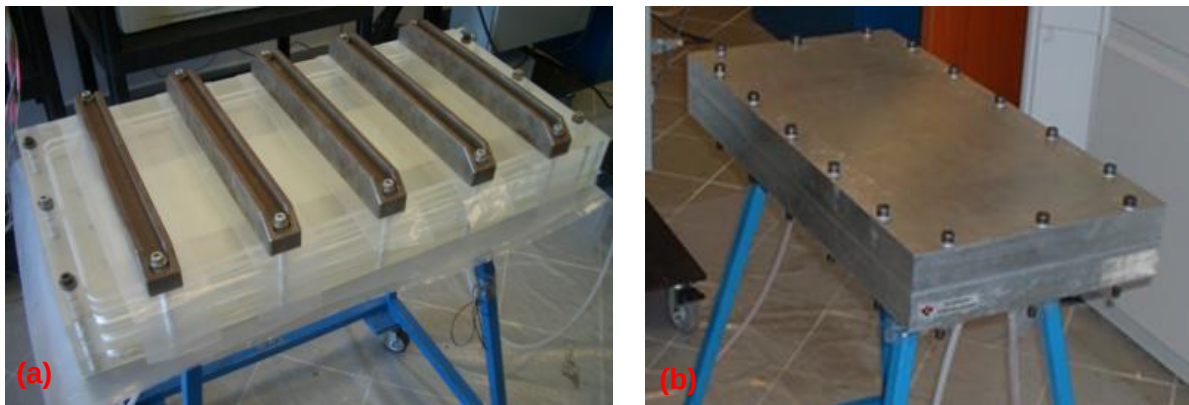


Figure 2.7 Two different upper parts: (a) acrylic part (3 pieces), and (b) aluminum metal part of the RTM mold.

2. *Spacer Frame*: Spacer frame determines the dimensions of the mold cavity, and thus the dimensions of the part to be manufactured. There are six spacer frames which are made of aluminum and they are used to manufacture parts with different dimensions. Length and width of the composite part to be manufactured depend on the dimensions of the specific spacer frame used. With these frames, composite parts with either 3 mm or 5 mm thickness can be manufactured. In Figure 2.8, sample spacer frames are shown.

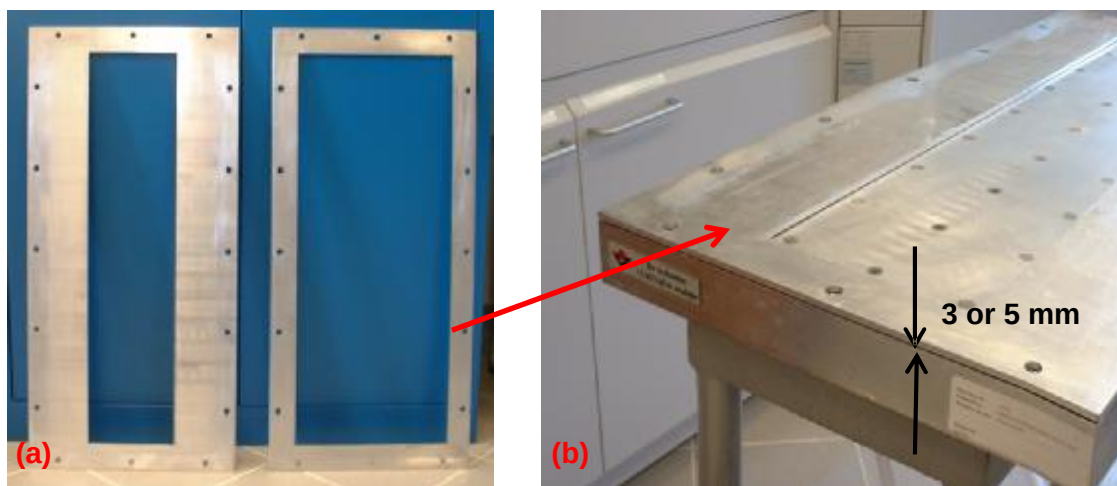


Figure 2.8 (a) Two of the six spacer frames, and (b) a spacer frame placed on lower mold part.

3. *Stiffening Bars*: They are used to ensure stiffness of mold plates against bending and, hence for better compaction of preform. They are especially used together with acrylic transparent upper plate as it has less stiffness than the metal upper part.

4. *Fabric Preform*: Fabric is cut from rolls to fit the interior dimensions of the spacer frame used. Figure 2.9 shows layers of fabric cut from a fabric roll and placed into the mold cavity.

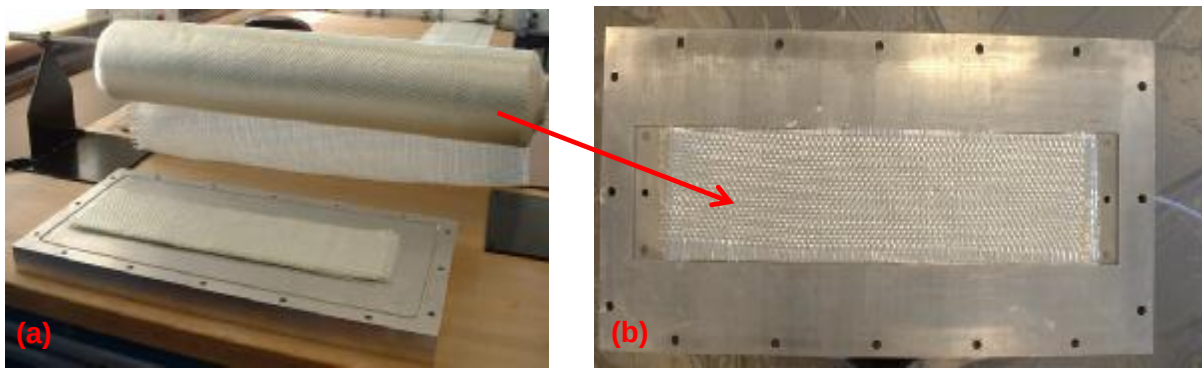


Figure 2.9 (a) Roll of fabric, and (b) fabric preform placed into mold cavity (top view of mold).

5. *Injection and Ventilation Tubes*: Resin is transferred from the injection machine to the mold through polyethylene injection tube(s) [39], (see Appendix A). Resin enters into the mold cavity through injection port(s). As the resin advances, air inside the mold and excess resin leave the mold through ventilation port(s). The number of injection and ventilation ports can be one or more. Expendable injection and ventilation tubes are used for inlet or outlet of resin through these ports.

6. *Multi-function bolts*: There are 45 multi-function bolts as shown in Figure 2.10(a). These bolts can be used for different purposes. Solid ones do not have any function (just fitting the holes in the mold); the one in the middle in Figure 2.10(b), is used for either

ventilation or injection; and the one on the rightmost has a sensor placed in it for resin flow monitoring.

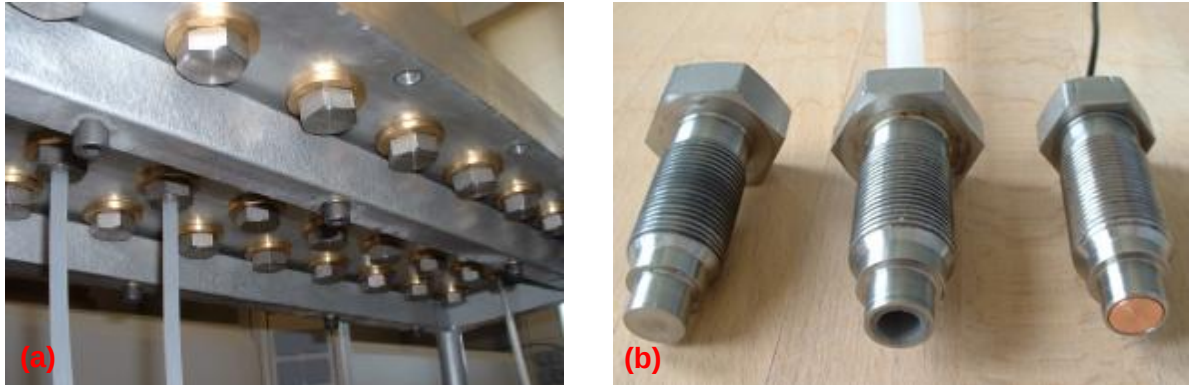


Figure 2.10 (a) Bottom view of the mold with 45 multi-function bolts, and (b) the bolts.

Resin is injected into the mold through injection tubes from the injection machines (Figure 2.11(a)). Two injection machines are available in the laboratory and they are from Radius Engineering Inc [38]. They are computer controlled by a software called Floware. By using Floware, injection parameters such as pressure and flow rate can be set and the injection process can be automated. One of the advantages of using Floware is that a pressure set point can be defined. In a constant flow rate injection, if the pressure reaches a critically high value, flow rate is decreased automatically. Afterwards, the injection pressure is set constant at the previously selected critical value. The process can be followed from the Floware display as shown in Figure 2.11(b). In this study, constant flow rate injections were done. The injection machines have built-in heating systems so that resin can be heated prior to injection. Technical specifications of the injection machines can be found in Appendix A. In the case of multi-port injection, one or more injection machines together with T-junctions (Figure 2.12) are used. Using T-junctions, resin flow coming from one injection tube can be switched off (manually) and directed to another tube going to another injection port, or both sides are kept open or closed at the same time.

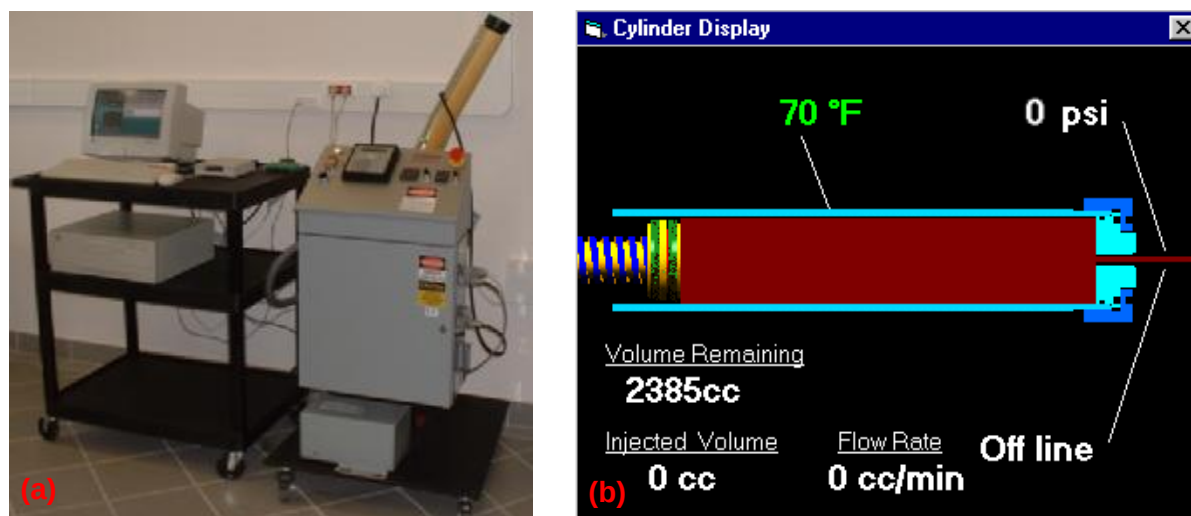


Figure 2.11 (a) Injection machine, and (b) display of Floware software.

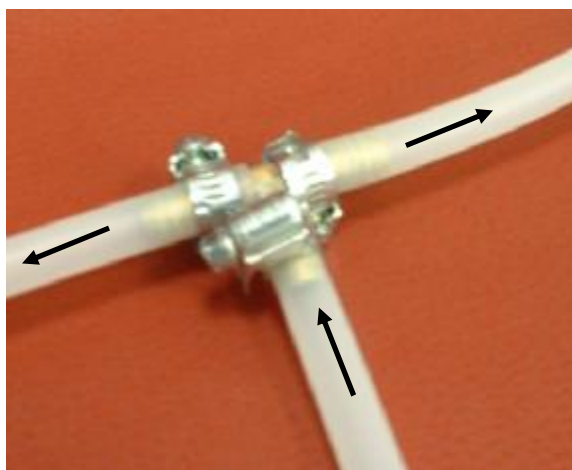


Figure 2.12 T-junction.

2.5 The Polymer System and Fabric Used in the Experiments

Plain weave and random type of e-glass fabrics [40] were used in this study. The plain weave has 18 wefts and 24 warps on a sample of 100 mm x 100mm. Its superficial (areal) density is given as 500 gr/m² and it is approximately 0.5 mm thick under typical RTM compaction conditions. The random type has an areal density of 450 gr/m².

The thermosetting polymer used is general purpose polyester [41] which has a density of 1.19 grams/cm³ and a viscosity of 0.77 Pa.s at room temperature. Some chemical agents are added to the polymer system to start cure. These are a Cobalt compound and Methyl Ethyl Ketone Peroxide [42] which are used as an accelerator and as a curing agent, respectively. 3 grams of accelerator and 3 grams of curing agent are added into 2000 grams of polyester. The mixing ratio can be altered for different room temperatures or according to the desired curing time. More information about polymer and fabric system can be found in Appendix A. Toward the end of this study, another general purpose polyester was also used [43].

Chapter 3

PROBLEMS OF RTM PROCESS AND NEED FOR A CONTROL SYSTEM

3.1 Problems of RTM Process

Resin Transfer Molding (RTM) process has many advantages over other composite manufacturing techniques. However, there are some potential problems involved in the RTM process as briefly discussed in Chapter 1. In this chapter, we will examine these issues in detail.

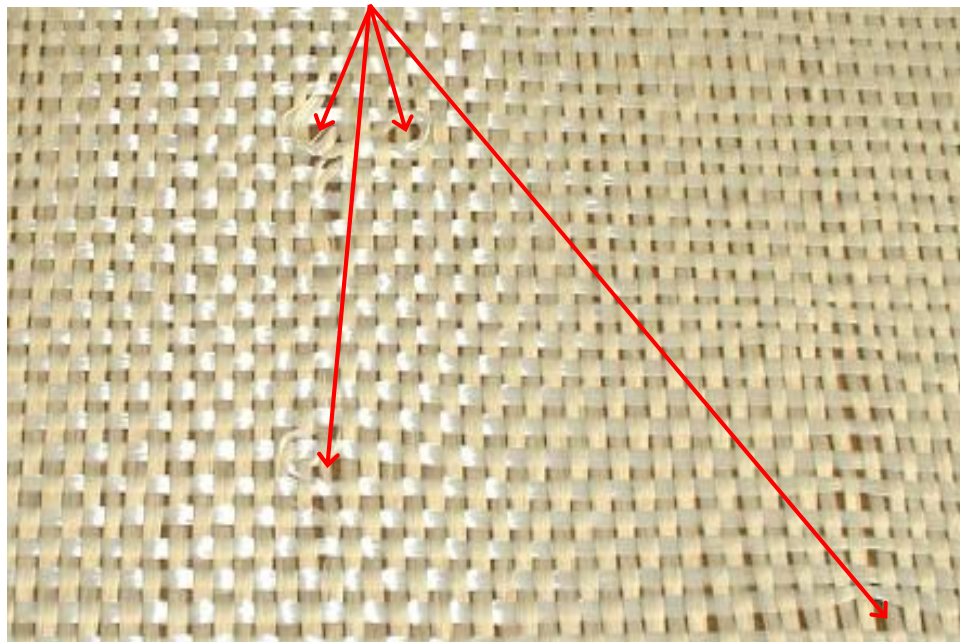


Figure 3.1 Non-uniformity of fabric.

Fabric structure may be non-uniform even in its original factory setting (Figure 3.1) and this may cause uncertainties in the process such as uncertainty in permeability. Usually, preform preparation (cutting and placing inside the mold) is done manually (Figure 3.2) and thus, it is non-repeatable.



Figure 3.2 Manual preform preparation.

RTM mold used in this study is closed by clamping bolts around the mold. Thus, a uniform compaction of fabric cannot be ensured. A hydraulic press could have been used. However, if the mold is complex shaped, even a press cannot guarantee the uniformity of compaction.

During RTM process, some parts of the fabric layers may move and change their initial arrangement. This is called *wash* of fabric (see Figure 3.3 and 3.4). This may occur due to high pressure at the injection port, inappropriate number of fabric layers placed inside the mold and hence due to insufficient compaction of the fabric preform. Wash of fabric in Figure 3.4 actually started along the edges of the mold and eventually caused wash in the mid-section.

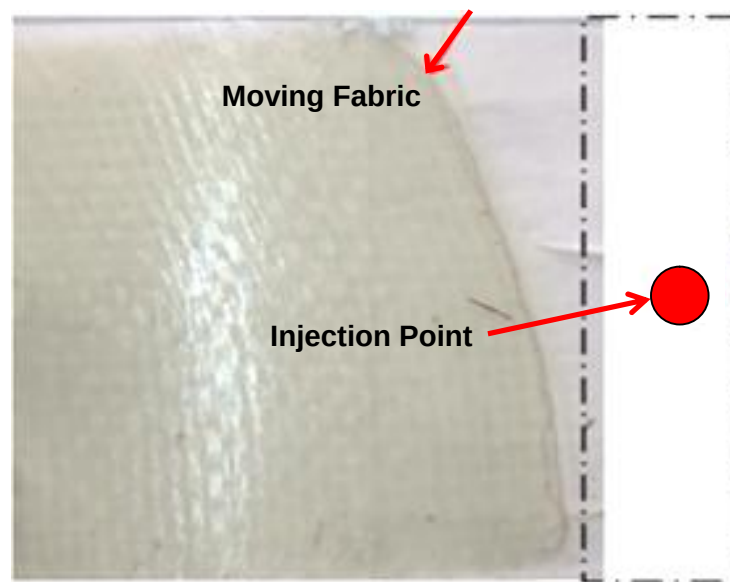


Figure 3.3 A close view of wash of fabric near the injection port.

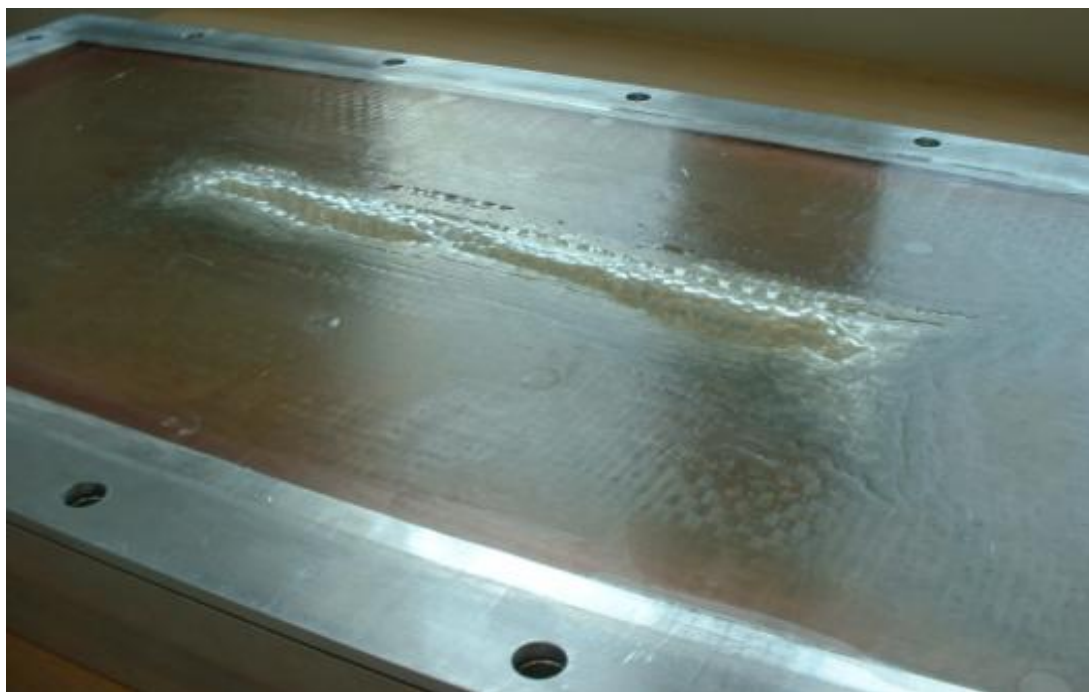


Figure 3.4 Wash of fabric in the mid-section of the mold.

One of the major problems in RTM process is the occurrence of race-tracking channels (see Figure 3.5) which are also called as ‘edge flow’ or ‘edge effect’. No matter how carefully the fabric preforms are cut, they cannot perfectly fit the mold cavity and usually there are gaps between fabric mats and mold edges. Although they are only a few millimeters wide along the mold edges and corners, presence of these small channels might cause a significant change in the local permeability and thus, a significant change in the flow pattern. For example, although a line injection was used in Figure 3.6, the flow front didn’t progress as a line. Resin raced along the two race-tracking channels, and the flow front was like a U-shape.

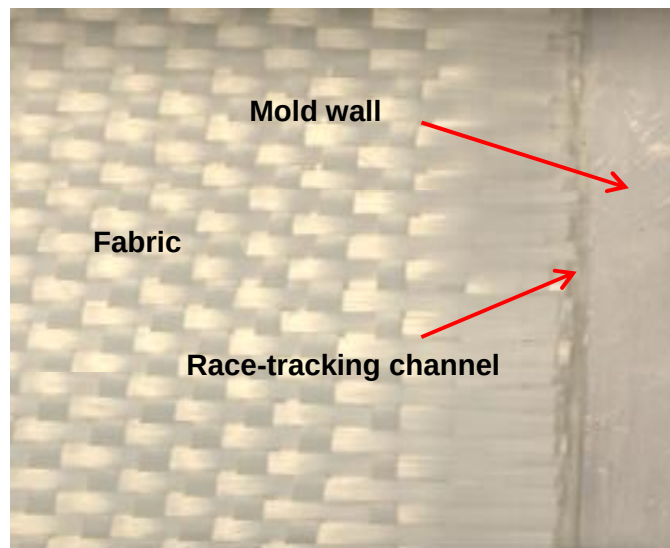


Figure 3.5 A race-tracking channel between the fabric edge and mold wall.

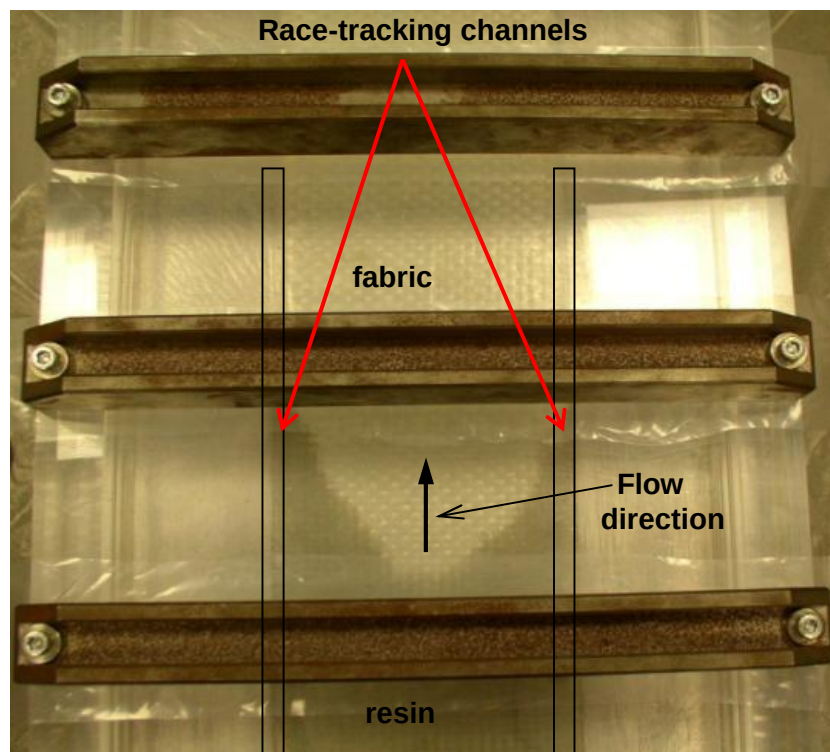


Figure 3.6 Effect of race-tracking channels on flow front.



Figure 3.7 A composite part with a macro size dry spot (void) near the ventilation gate.

Dry spot (void) formation (Figure 3.7) is a significant problem to pay attention during the mold filling stage. Dry spot size may be in macro and/or micro scale. If there is some amount of air entrapped at a certain region inside the mold cavity, this prevents wetting of the fabric

at that region, and a macro size dry spot occurs. In the case of high injection flow rates, as the flow front of resin passes through fabric, it might not be saturated completely and micro size dry spots occur. That's why RTM injections in this study are made with very low injection flow rates (100-200 cc/min). Dry spots may also occur due to the effects of race-tracking channels and/or wash of fabric. Parts with dry spots fail to satisfy the desired part requirements (such as mechanical properties and protection against ambient). One of the main goals of the RTM process is to produce parts free of dry spots.

The issues cited above can be summarized as follows:

- Non-uniformity of fabric, thus uncertainty in permeability,
- Non-repeatable preform preparation and mold compaction,
- Wash of fabric,
- Race-tracking channels, and
- Micro and/or macro size dry spot (void) formation.

3.2 Need For a Control System

Due to the issues mentioned, a control system is needed to fully automate the process, to manufacture void free parts, and to decrease cycle cost and time. Attempts and studies to launch such control systems have already been mentioned in Chapter 1. The basis of the control system that is used in this study will be discussed here.

Considering the current experimental set-up and the tools in hand, an integration of the following elements are made for developing an efficient control system:

- E-glass fabric and resin,
- RTM Mold,
- Injection machines with flow rate control (there are two of them for synchronized injection),
- Mold filling simulations using LIMS [53],
- *Sensors* capable of monitoring mold filling and if possible resin cure as well, and
- Data acquisition system using LABVIEW [54].

Necessary process parameters and control actions to be designed are as follows:

- Injection parameters (inlet flow rate and pressure),
- Location and number of gates and vents,
- Location of vacuum tubes (if a vacuum is to be drawn),
- Location and number of *sensors*,
- Opening or closing action of the gates, vents, T-junctions, and
- Switching time between these ports (if any sequential injection or ventilation is to be performed).

The key elements in the control system are flow monitoring sensors. The following two chapters will focus on the sensor systems used for flow and cure monitoring. Application and data acquisition of these systems will be described. Necessary control actions based on the sensor information will also be discussed.

Chapter 4

THERMOCOUPLES AS FLOW MONITORING SENSORS

4.1 Thermocouple Sensors

Thermocouple sensors are widely used for temperature measurement in various types of industrial applications. A very brief introduction to thermocouples was also given in Chapter 1. Thermocouples are low cost sensor systems, and they can measure temperatures in wide ranges. In particular, they have the distinct capability of measuring very high temperatures at which many other sensor systems cannot operate [44].

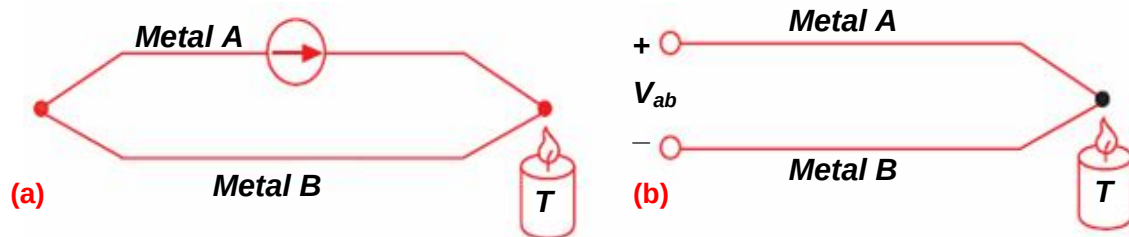


Figure 4.1 (a) The Seebeck effect, (b) Seebeck voltage [45].

As shown in Figure 4.1, if two wires made of different metal alloys (Metals A and B) are electrically shorted at both ends, and if any of the joints is heated or a temperature difference is generated between the two joints, then there is a continuous current in the circuit. This is called the thermoelectric effect, which is also known as the Seebeck effect in physics [46]. Seebeck effect constitutes the basic principle for thermocouples. Moreover, the open circuit

voltage V_{ab} as shown in Figure 4.1(b) is called the *Seebeck Voltage* and it is a function of the junction temperature T .

The junction where the two metals are joined (Figure 4.1(b)) is called the *hot junction* and the other open end is called the *cold* or *reference junction* [44]. Hot junction is attached to the media of which the temperature will be measured, and the reference junction is attached to a measurement device. The Seebeck voltage is a linear function of the temperature difference between hot and reference junctions [45]. By keeping T_{ref} constant, it can be deduced that the Seebeck voltage V_{ab} is linearly proportional to T_{hot} :

$$V_{ab} = a (T_{hot} - T_{ref}) \quad \text{where } a = \text{Seebeck coefficient} . \quad (4.1)$$

The industrial standard for T_{ref} is 0°C [47].

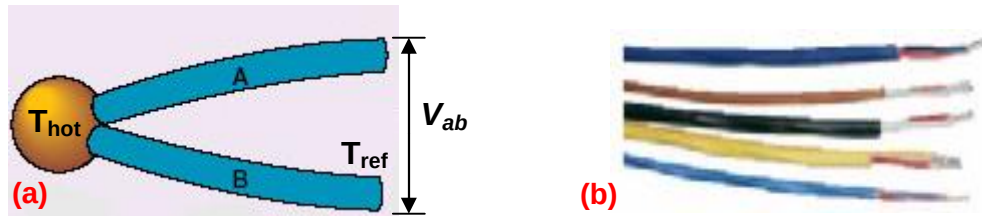


Figure 4.2 (a) Seebeck voltage, V_{ab} [47], (b) Thermocouple wires [48].

Thermocouples are available in the form of wires (see Figure 4.2(b)). As in Figure 4.3, they have ceramic or metallic insulations and sheathed with different type of materials such as stainless steels and Inconel (nickel and chromium content alloy) [49]. They also have PVC or Teflon coatings over the sheath layers for trouble-free use in different environments [50].

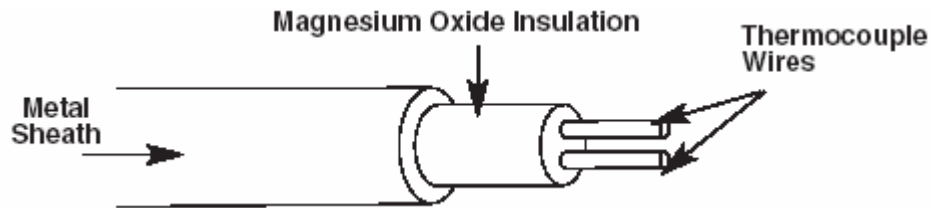


Figure 4.3 Insulation and sheath layers for thermocouple wires [48].

Different combinations of metals, which thermocouple wires are made of, specify the type or the so-called calibration of thermocouples. There are various calibrations (E, J, K, R, S and T) for use in different temperature ranges. The maximum temperature limit of a specific calibration is determined by the wire diameter of the thermocouple. Major calibrations and their temperature ranges versus wire diameters are given in Tables 4.1 [51] and 4.2 [48].

Table 4.1 Major calibrations for thermocouple wires [51].

TYPE E	Nickel, Chromium (+)	versus	Constantan (-)
TYPE J	Iron (+)	versus	Constantan (-)
TYPE K	Nickel, Chromium (+)	versus	Nickel, Aluminum Silicon (-)
TYPE R/S	Platinum, Rhodium (+)	versus	Platinum (-)
TYPE T	Copper (+)	versus	Constantan (-)

Table 4.2 Maximum temperature limits for thermocouples vs. wire diameters [48].

Type	Wire Size (inches) / Max. Temperature (°C)					
	0.128 in.	0.064 in.	0.032 in.	0.020 in.	0.013 in.	0.010 in.
E	870	650	540	430	430	370
J	760	590	480	370	370	320
K	1260	1090	980	870	870	760
R/S	200	200	200	200	200	150
T	370	370	260	200	200	150

4.2 Thermocouples as Flow Monitoring Sensors

With the idea of making use of a low cost and practical detection system, thermocouple sensors were tried to be adopted to the current system for flow and cure monitoring purposes. J type thermocouples, one of the most commonly used calibration for moderate temperatures, were selected and used. More information on the thermocouples used in this study is available in Appendix B.

The curing reaction that takes place in the current thermoset resin system is exothermic [52] and thus, the temperature rise due to the heat release during curing is likely to be detected by the thermocouple sensors. If thermoset polymer is heated prior to injection, it is also possible to detect flow front propagation as well as resin cure.

For this purpose, thermocouple wires are placed inside multi-functional hollow bolts. Copper tips are manufactured and attached to the hot junction side of the thermocouple sensors. Copper tips serve to seal the bolts and to prevent leakage of high pressurized resin during RTM injections. Tips are made of copper for high thermal conductivity and the thickness of the tip heads are manufactured such that they are as thin as possible. After thermocouple wires with copper tips are placed inside bolts, silicon material is injected from the other open end of the bolt to fill the rest of the bolt cavity for ensured sealing.

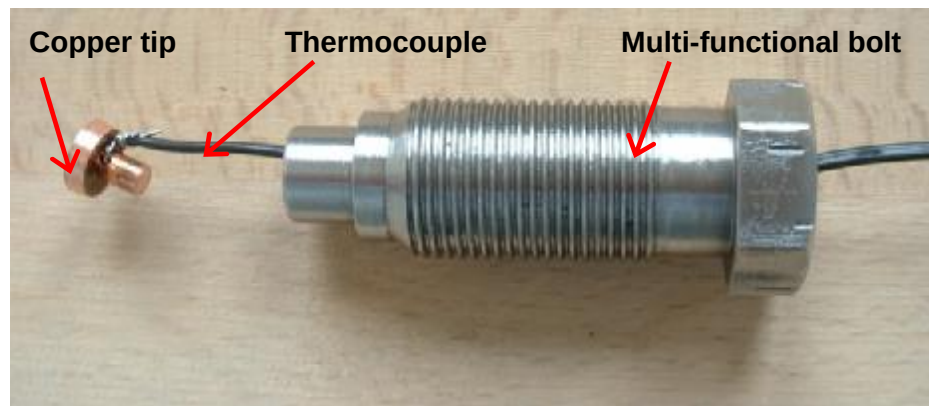


Figure 4.4 Thermocouple sensor with a copper tip inserted inside a bolt.

Thermocouple sensors are placed at discrete positions on the mold surface. An example configuration is given in Figure 4.5. Prior to injection, resin is heated up to certain temperatures above room temperature using the injection machine's built-in heating system although no heating was required for the current polymer system. In fact, heating the resin accelerates the curing action, and increases the required injection pressure as the resin gets more viscous toward the end of injection. Therefore, the temperature to which the resin is heated should be decided carefully such that there is sufficient time to fill the mold completely before significant curing takes place.

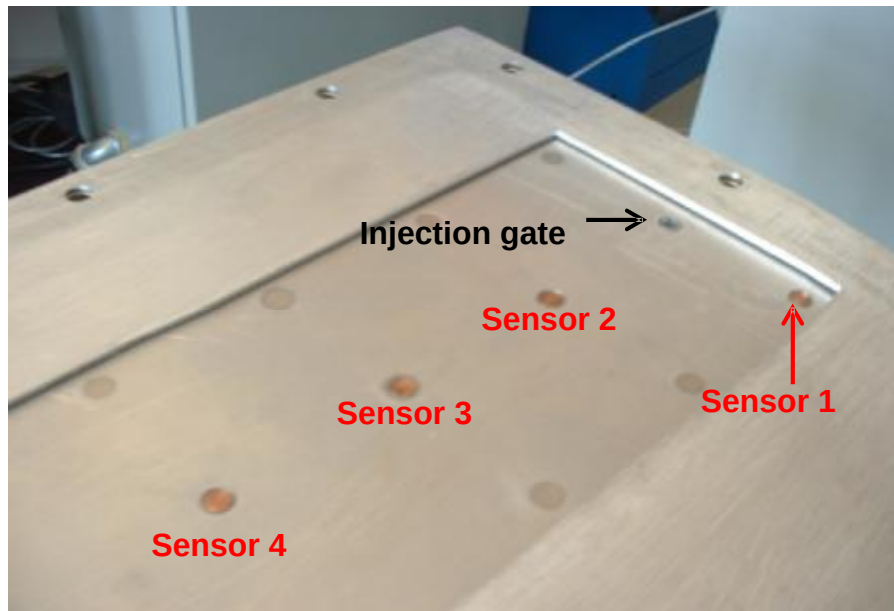


Figure 4.5 An example for thermocouple configuration on the mold surface.

4.2.1 Data Acquisition (DAQ) Program

Using LabVIEW [54], a program was developed for the data acquisition and analysis of the thermocouple sensor readings. Thermoset resin is heated prior to being injected such that its temperature is above room temperature by about 10-20°C. During an RTM injection, the

program records the elapsed time versus temperature data according to the sampling frequency specified. *Threshold temperature* and *ambient temperature* are also specified by the user as inputs to the program.

Ambient temperature is measured using a separate thermocouple just before starting an RTM injection. During the injection, when a thermocouple reading exceeds the value of the ambient temperature plus the threshold temperature, the program designates an “arrival signal”, meaning that resin has reached that specific thermocouple location:

$$\text{If } T \geq T_{\text{ambient}} + T_{\text{threshold}} \Rightarrow \text{RESIN ARRIVAL !} \quad (4.2)$$

Specifying a proper threshold temperature is very important. Value set for the threshold temperature affects the system’s response time to designate resin arrival for a thermocouple sensor. Thermocouple readings, though converted into Centigrade, are originally in the range of milli-volts and this means the readings are very vulnerable to the environmental noises. In addition, the length of each thermocouple wire between the hot and cold junctions (between the mold and the DAQ card) is too long (close to 2 m) and this also increases the possibility of the system being affected from any type of noises. Thus, there are some unexpected peaks in the readings due to these noises. In Figure 4.6, presence of noise in a thermocouple reading is shown for a thermocouple sensor placed in the mold for the measurement of room temperature of 20°C.

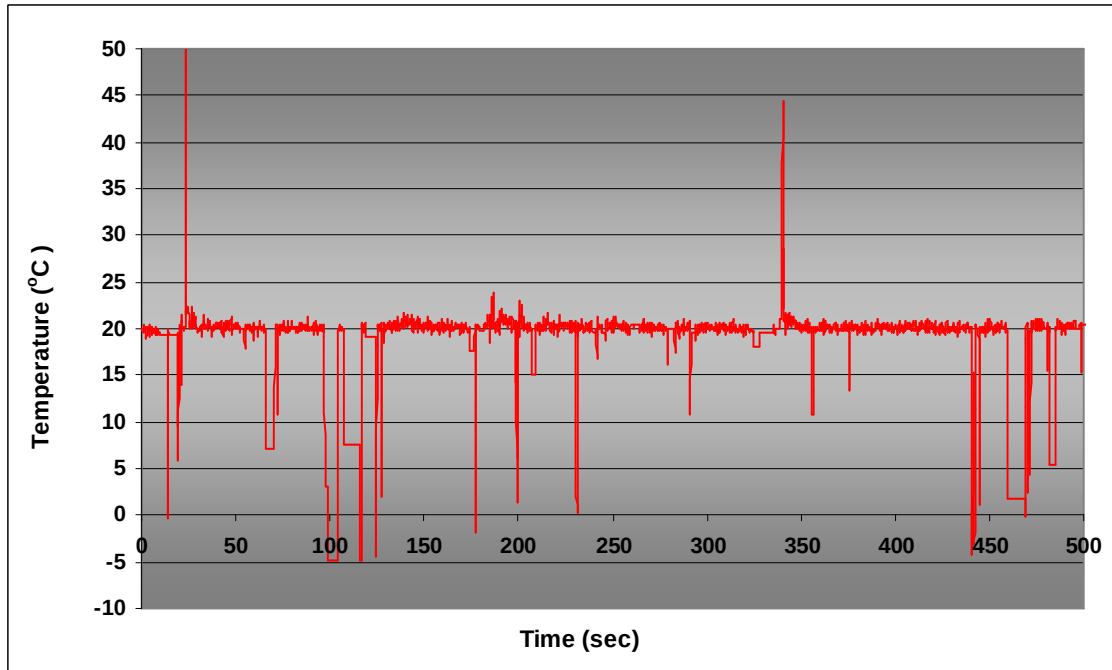


Figure 4.6 Presence of noise in thermocouple readings.

If a low value is set for the threshold temperature so that the system will respond fast, it is very likely that the program will give arrival signals not because of resin arrival but because the threshold value of the readings is exceeded by the peaks or the oscillations generated due to the noises. Thus, the threshold temperature should be chosen such that it is not very low to prevent any false arrivals; and such that it is not too high either so that the respond time of the sensor is reasonably short. Choosing a high threshold value is also inferior for the reason that resin cannot be heated up to elevated temperatures.

Choosing a right value for the threshold temperature may not always help for a faultless measurement since noises are always present in the system. A sub-algorithm is implemented into the LabVIEW program to eliminate the false arrivals substantially. The program gives an arrival signal only when all of the three consecutive readings exceed the sum of the threshold and the ambient temperatures. For moderate frequencies, this sub-algorithm works

well in eliminating the false arrivals and without lowering the system respond too much. Moreover, data readings between values -5°C and 100°C are cropped and the rest is ignored.

After detecting the resin arrival correctly, the corresponding time data is stored as the *arrival time* for that sensor. Arrival time data for all sensors are recorded and arranged such that each sensor is given an *order* according to its arrival time.

Different combinations of sensor orders make up different *scenarios* [10,11,12]. For example, if three sensors A, B and C are used, the possible scenarios will be as in Table 4.3.

Table 4.3 Possible scenarios, sensor order and arrival time for three sensors A, B and C.

Scenario #	Sensor Order	Arrival Time
1	A B C	$t_A < t_B < t_C$
2	A C B	$t_A < t_C < t_B$
3	B A C	$t_B < t_A < t_C$
4	B C A	$t_B < t_C < t_A$
5	C A B	$t_C < t_A < t_B$
6	C B A	$t_C < t_B < t_A$
7	A [C B]	$t_A < t_C \approx t_B$
8	[C B] A	$t_C \approx t_B < t_A$
9	B [C A]	$t_B < t_A \approx t_C$
10	[C A] B	$t_A \approx t_C < t_B$
11	C [B A]	$t_C < t_B \approx t_A$
12	[B A] C	$t_B \approx t_A < t_C$
13	[A B C]	$t_A \approx t_C \approx t_B$

In general, when N number of sensors are used, the program specifies a flow scenario when the resin arrives at $N-1$ number of sensors by giving the last order to the undetected sensor for a faster scenario realization. A scenario file, which is also required as an input to the program, is illustrated in Table 4.4.

Table 4.4 A scenario file for N number of sensors.

Scenario No.	Order 1	Order 2	...	Order N	Control Action
1	1	2	...	N	scenario_1_order_12..._action_1
2	1	3	...	N	scenario_2_order_13..._action_2
...	...	...	...	...	...

A parameter called *minimum time difference* is another input parameter which determines the minimum time difference between any set of arrival time data to correlate them with scenarios. For any two sensors, if the difference Δt between arrival time data is smaller than the minimum time difference parameter, then the arrival times are practically considered to be equal to each other. Table 4.5 shows four sample cases and demonstrates the use of minimum time difference parameter for thermocouple sensors A, B and C with arrival time data t_A , t_B and t_C .

Table 4.5 Scenario assignment according to the minimum time difference parameter.

Case	Arrival Time (sec)			Scenario
	t_A	t_B	t_C	
1	10	15	25	1
2	25	15	10	6
3	20	20	20	13
4	40.5	40	39	6 or 13 ?

In the first three cases of Table 4.5, arrival times for the sensors A, B, and C and their corresponding scenarios (Scenario 1, Scenario 6 and Scenario 13, see Table 4.3) are shown. For the 4th case, the order of the arrival time data is the same with Scenario 6, but the arrival time data of the sensors are pretty close to each other as in Scenario 13. Thus, 4th case can be named as either Scenario 6 or 13 depending on the specified value of the minimum time difference parameter. In this example, let's assume that a value of "2 seconds" is specified

for the minimum time difference. Then, 4th case will be named as Scenario 13, since all the Δt between the arrival times of the sensors are smaller than “2 seconds”:

$$\Delta t_{A,B} = |t_A - t_B| < 2, \quad \Delta t_{A,C} = |t_A - t_C| < 2 \quad \text{and} \quad \Delta t_{B,C} = |t_B - t_C| < 2 \quad (4.3)$$

Hence, practically speaking $t_A \approx t_C \approx t_B$. However, if the minimum time difference parameter were specified as “0.4 seconds”, then arrival would be considered as $t_C < t_B < t_A$ and 4th case will correspond to scenario 6.

Thermocouple sensors have a differential input connection to the DAQ card and they need to be somehow calibrated. For this purpose, the current DAQ program takes the average of the first 100 readings and subtracts this value from the ambient temperature. The result is named as *shift factor* and all the following readings are updated by this parameter. (See the pseudo-code given in Figure 4.7)

Having described the data acquisition algorithm, all of the input parameters can be listed as follows:

- Number of sensors,
- Sampling frequency,
- Ambient temperature,
- Threshold temperature,
- Minimum time difference for ordering resin arrivals, and
- Scenario file containing the possible flow scenarios.

The major task of this DAQ program is to monitor the resin flow and to propose necessary control actions to fill the mold completely. The program first detects the positions where resin has reached, then it generates a flow scenario based on the order of sensors being triggered and matches this scenario with one of the possible scenario files that were already defined. It finally suggests a corresponding control action if needed. The pseudo-code of the

whole DAQ program is given in Figure 4.7. A screen shot of the LabVIEW screen and information about the DAQ cards are given in Appendix B.

```

Load scenario file
Open an output file

Read average of first 100 temperature data from 1st channel
    scale_factor = ambient temp.- average temp.
Read system time
Initialize temp array, arrival_time array, flag array, order array

while (stop button is not pressed)
    Read sampling frequency
    Read data from all channels

        for i=1 to # of channels
            Read temperature
            temperature = temperature + scale_factor
            update temp array[i]

            if(temp[i]& temp[i+1]& temp[i+2] > threshold)
                if(flag[i] == false)
                    update arrival_time[i]
                    flag=true
                    update flag[i]
                end
                if(flag == true for any flag except flag[i])
                    if ( $\Delta t$  > minimum time difference)
                        order[i]=max(order)+1
                    else
                        order[i]=max(order)
                    end
                end
            else
                order[i]=1
            end
        end
    end

        for i=1 to # of scenario files
            if(scenario ordering==order)
                display scenario number, ordering and control action
            end
        end

Write time and temperature to output file
end while

```

Figure 4.7 The pseudo-code of the DAQ program.

4.2.2 Experiments with Thermocouple Sensors and Results

After making experiments with the thermocouple sensors, a reasonable threshold temperature value (about 3-5°C) was selected and the algorithm preventing the false arrivals is implemented. Using the injection machine's heating system, resin was heated up to 10-15°C degrees above room temperature. Surprisingly, in our initial RTM experiments, when the resin arrived at sensor locations, thermocouple readings did not change significantly. Thus, detection of resin arrival could not be made.

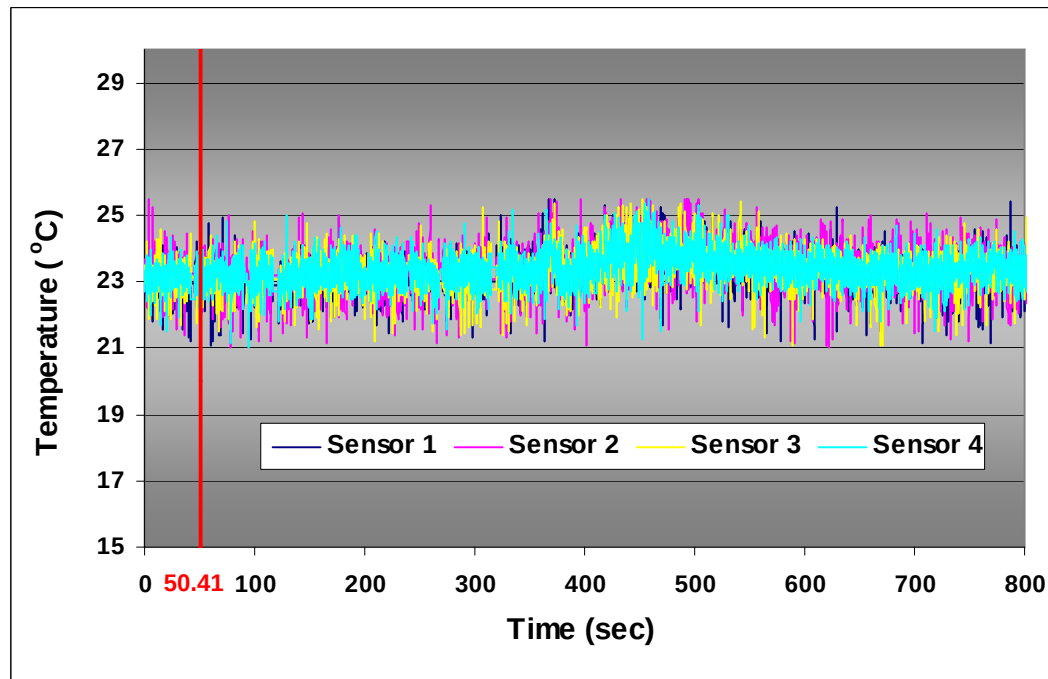


Figure 4.8 Thermocouple readings for a sample injection with heated resin.

For the sensor locations shown in Figure 4.5, and a resin injection temperature of 33.3 °C, results of a sample experiment are shown in Figure 4.8. The ambient temperature for this experiment was about 23°C, and the threshold temperature was set to 2°C. Injection start time

was 50.41 seconds as it is shown with the solid red line in Figure 4.8. In spite of the very low threshold value chosen, no detection could be made, and hence no arrival signals were received. It is risky to heat the resin more than 10-15°C degrees above the room temperature since curing starts earlier at elevated temperatures, and the resin viscosity increases. In this sample experiment, with the resin injection temperature of 33.3 °C, injection pressure rapidly increased to the 100 psi (≈ 7 bars) limit since the viscosity of resin increased significantly. Furthermore, high injection pressure bears the danger of resin leakage and blow up of connection tubes. Thus, it seems very hard to acquire detection of resin by using the thermocouple sensors due to the limitations of our process parameters.

4.3 Dummy Resin (Water) Injections

As resin cannot be heated to elevated temperatures due to the issues mentioned in Section 4.2, significant rise of temperature is hard to encounter and arrival signals cannot be received. To better analyze the problems associated with thermocouple sensors, and for ease of repeatability of the process, water was used in RTM injections. Dummy water simulates the polymer resin, and sponge was used instead of fabric preform as shown in Figure 4.9.

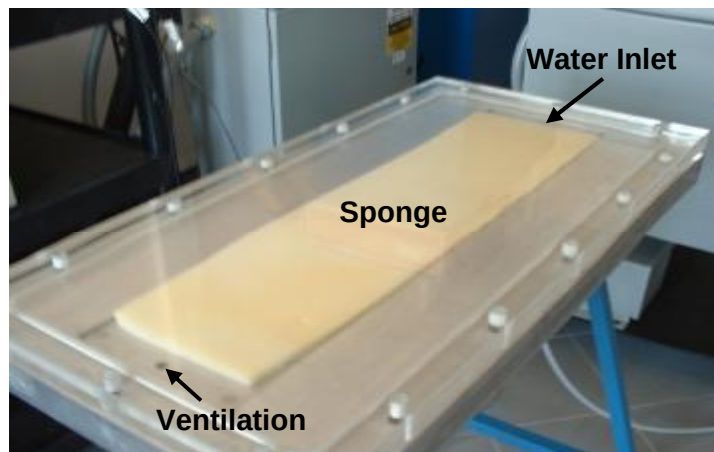


Figure 4.9 Water experiments and investigation of problems related with thermocouples.

Water can be heated up to higher temperatures than our polyester resin since water does not cure as polyester, and also water has a very low viscosity (on the order of one hundredth of thermoset resin viscosity) and, injection pressures do not considerably increase. Next sections present results of water experiments for three different sensor configurations. Injections were done in two different ways: a) using the injection machine, and b) the water tap in the laboratory.

The injection machines in use do not have the capacity to make injections with flow rates more than 500 cc/min. To see the effect of an increase on the injection flow rate, tap water in the laboratory is used. Using the tap, hot water with temperature of about 45-50°C and flow rates of about 3000 cc/min can be obtained. The flow rate of the tap water was measured using a chronometer and a scale. Water continuously enters and leaves the mold during a specified time interval.

4.3.1 Configuration 1

Thermocouple sensors are placed in the mold with the configuration shown in Figure 4.10. Sensor 7 is not shown which is just next to Sensor 6, following the linear configuration.

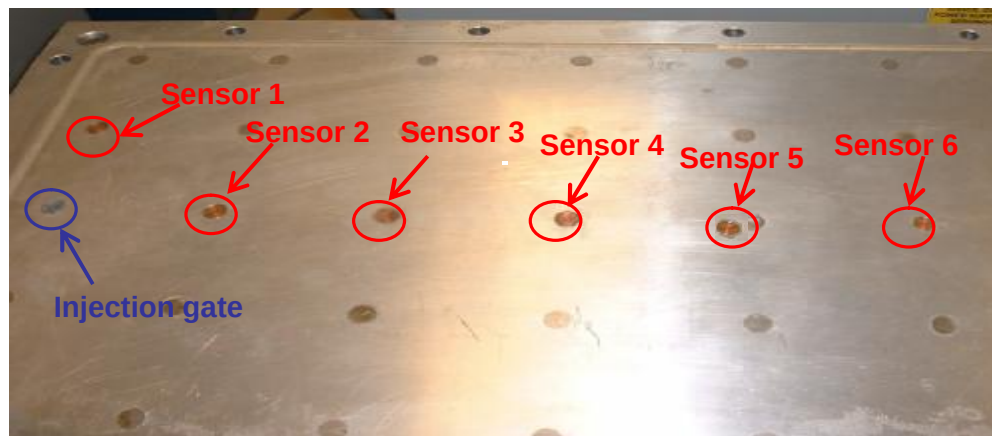


Figure 4.10 Thermocouple Configuration 1.

4.3.1.1 Sample Injection 1 (By using tap water)

For Configuration 1, results of a sample tap water injection are presented here. Injection parameters and the results are given in Table 4.6 and Figure 4.10 respectively. As before, the solid red line represents the injection start time, t_{start} . In this experiment, Sensor 1 is located in the line injection area (where there is no fabric), and almost a one-dimensional flow is generated in the longitudinal direction of Sensors 2, 3,..., 7.

Table 4.6 Injection parameters of Sample Injection 1 for Configuration 1.

Injection flow rate (Water), Q_{inj}	3300 cc/min.
Injection temperature (Water), T_{inj}	46 °C
Ambient temperature, T_{amb}	26.9 °C
Injection start time, t_{start}	18.92 sec.
Threshold temperature, ΔT	2.5 °C

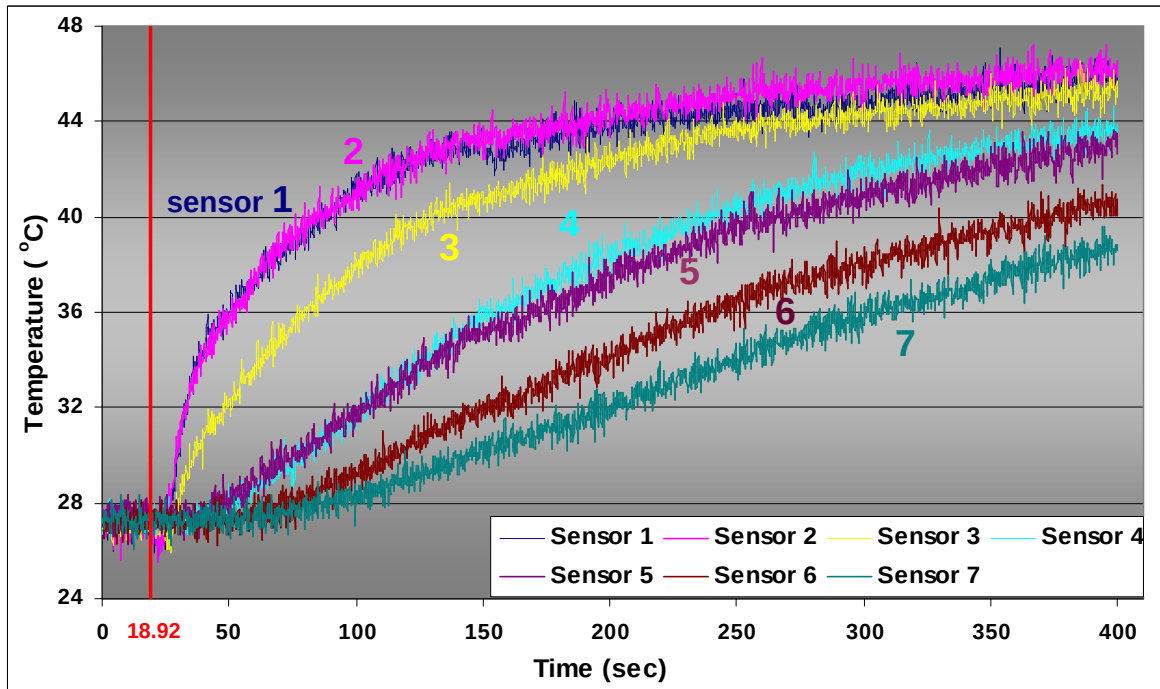


Figure 4.11 Results of Sample Injection 1 for thermocouple Configuration 1.

4.3.2 Configuration 2

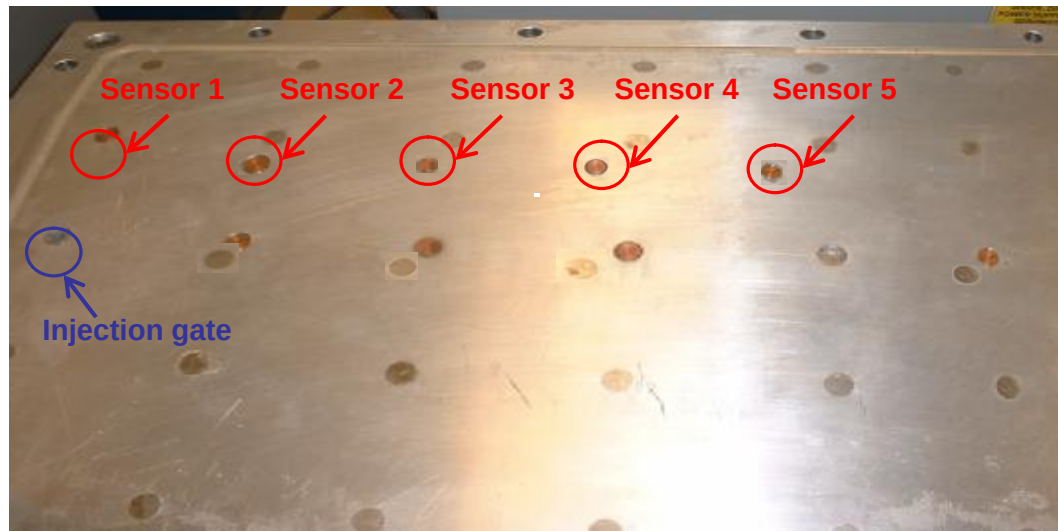


Figure 4.12 Thermocouple Configuration 2.

In this configuration, experiments are made using both the injection machine and the tap water. An exit thermocouple wire is attached to one of the ventilation tubes to monitor the water exit temperature from the mold (Figure 4.13).

4.3.2.1 Sample Injection 2 (By using tap water)

Table 4.7 Injection parameters of Sample Injection 2 for Configuration 2.

Injection flow rate (Water), Q_{inj}	3300 cc/min.
Injection temperature (Water), T_{inj}	50 °C
Ambient temperature, T_{amb}	23 °C
Injection start time, t_{start}	76.61 sec.
Threshold temperature, ΔT	5 °C

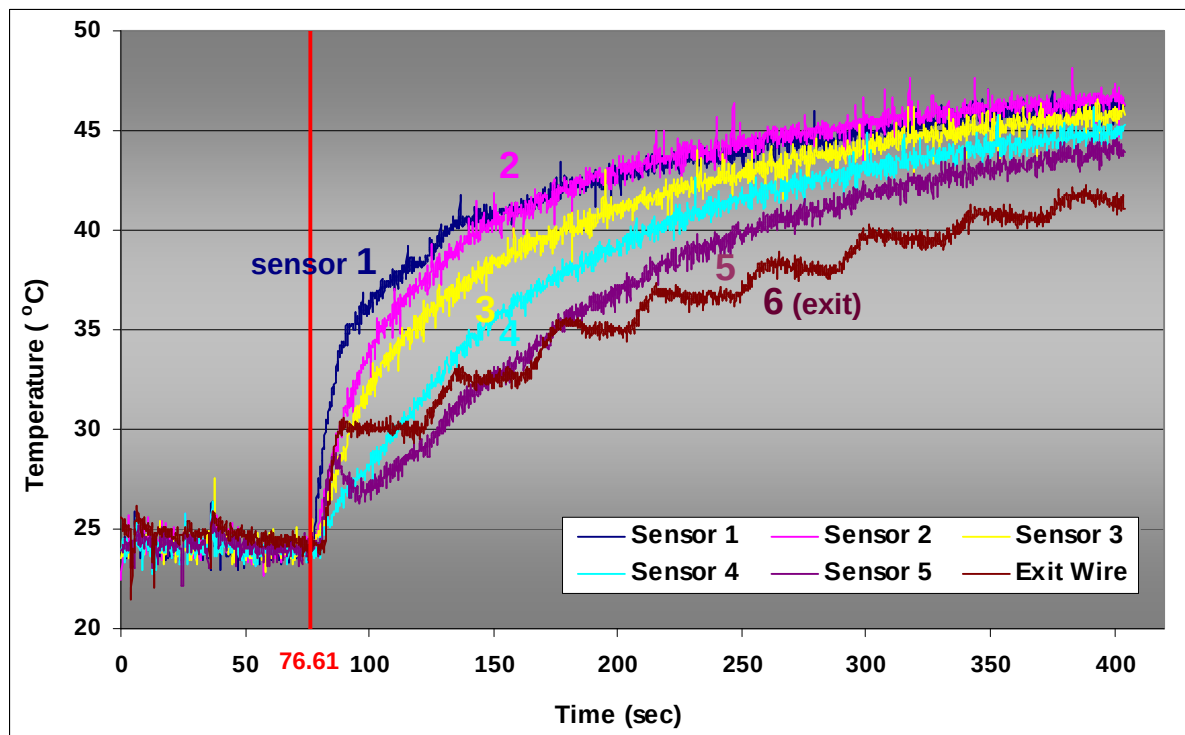


Figure 4.13 Results of Sample Injection 2 for thermocouple Configuration 2.

4.3.2.2 Sample Injection 3 (By using tap water)

With almost the same injection parameters, except that the flow rate is lowered to one thirds of the previous experiment.

Table 4.8 Injection parameters of Sample Injection 3 for Configuration 2.

Injection flow rate (Water), Q_{inj}	1100 cc/min.
Injection temperature (Water), T_{inj}	45 °C
Ambient temperature, T_{amb}	23 °C
Injection start time, t_{start}	25.59 sec.
Threshold temperature, ΔT	5 °C

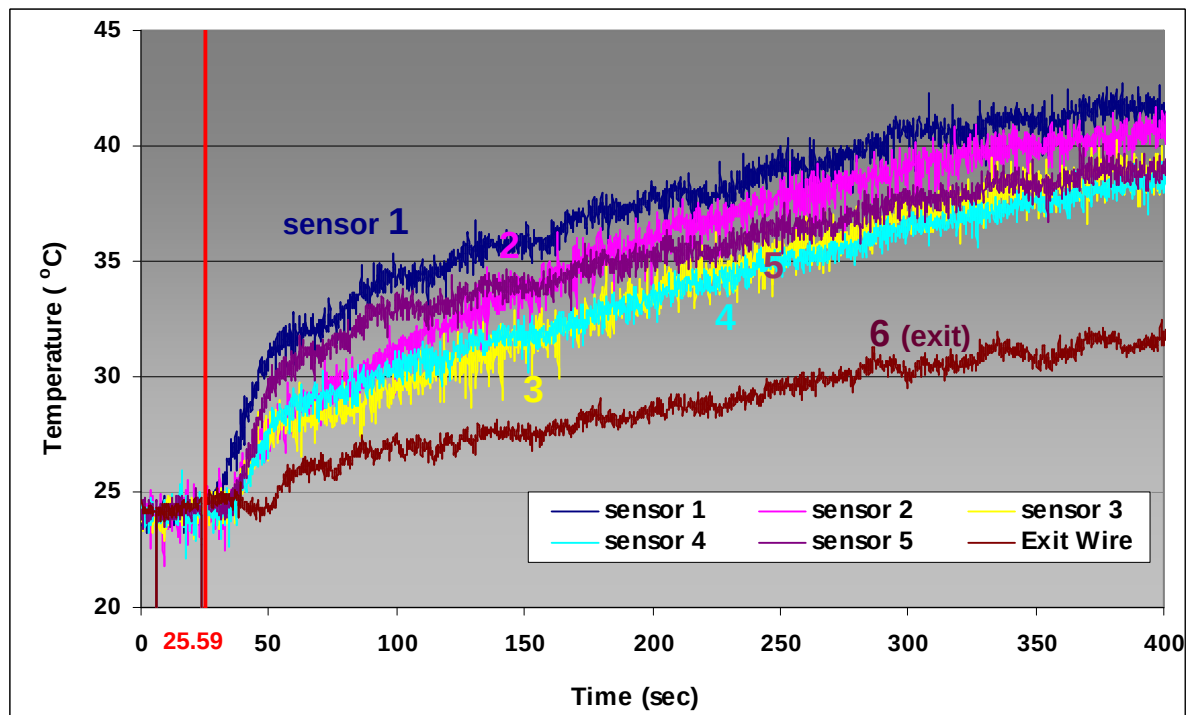


Figure 4.14 Results of Sample Injection 3 for thermocouple Configuration 2.

4.3.2.3 Sample Injection 4 (By using injection Machine)

This time, the injection is repeated using the injection machine (and hence with a lower flow rate than water experiments). The same configuration of sensors and a higher injection temperature were used.

Table 4.9 Injection parameters of Sample Injection 4 for Configuration 2.

Injection flow rate (Water), Q_{inj}	400 cc/min.
Injection temperature (Water), T_{inj}	70 °C
Ambient temperature, T_{amb}	23 °C
Injection start time, t_{start}	88.93 sec.
Threshold temperature	5 °C

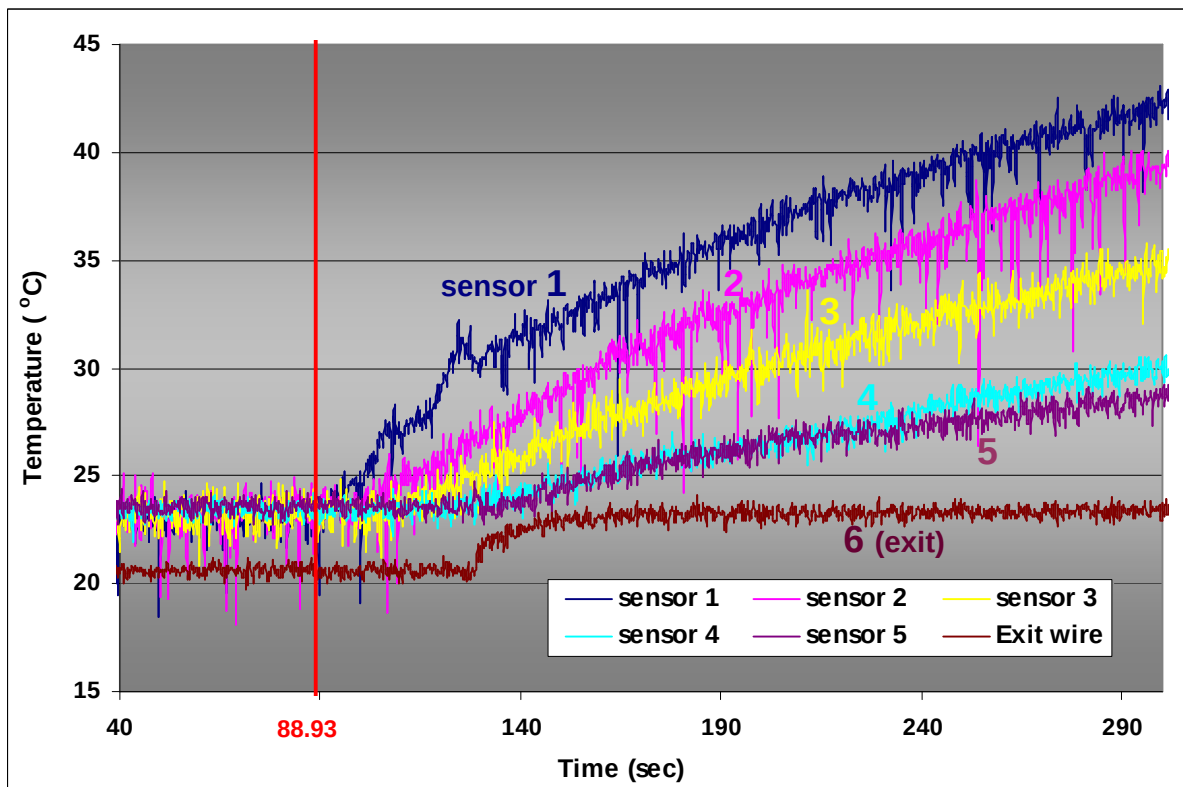


Figure 4.15 Results of Sample Injection 4 for thermocouple Configuration 2.

4.3.3 Configuration 3

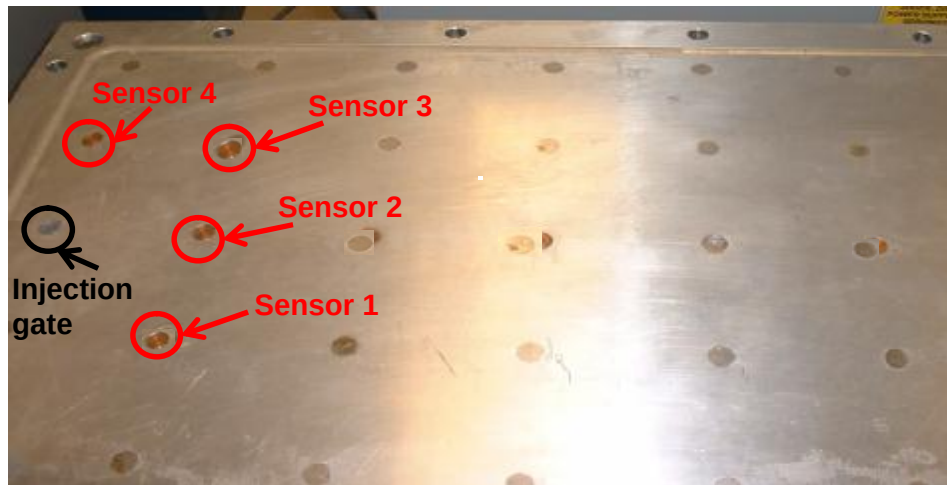


Figure 4.16 Thermocouple configuration 3.

4.3.3.1 Sample Injection 5 (By using injection Machine)

Table 4.10 Injection parameters of Sample Injection 5 for Configuration 3.

Injection flow rate (Water), Q_{inj}	250 cc/min.
Injection temperature (Water), T_{inj}	77.8 °C
Ambient temperature, T_{amb}	20 °C
Injection start time, t_{start}	63 sec.
Threshold temperature, ΔT	5 °C

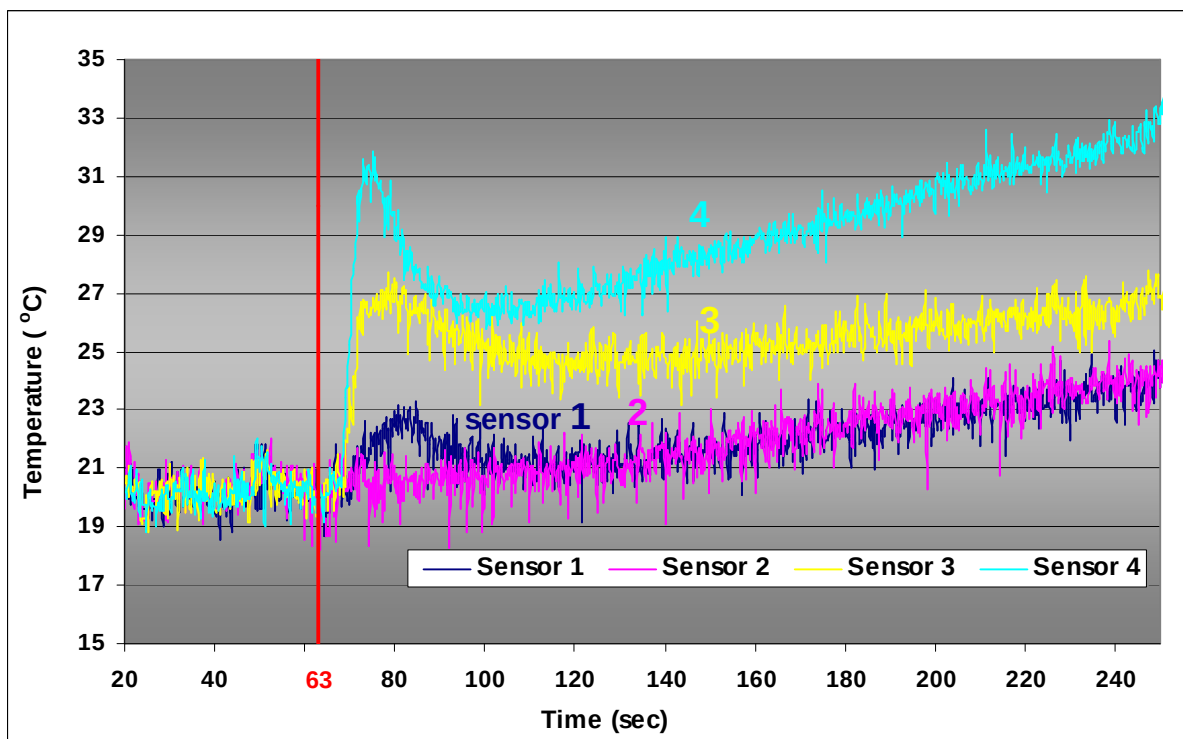


Figure 4.17 Results of Sample Injection 5 for thermocouple Configuration 3.

4.4 Problems with Thermocouple Sensors

Several water injection experiments show that the major problems related to thermocouple readings are:

- *High heat transfer (loss)* by conduction from the resin to the mold.
- *Low resin flow rate*. Typical RTM injections are generally done with flow rates lower than 500 cc/min. With this low flow rate, it takes a longer time for resin to reach a particular sensor. Thus, detection gets harder for the sensors away from the injection point.
- *Threshold temperature* should be kept *low* to detect resin arrival at all sensors regardless of their location. However, this might cause misdetection of resin arrival due to presence of noise in DAQ system.
- Resin *cannot be heated* to high temperatures above room temperature since this speeds up the cure process and increases the required injection pressure.
- Due to the transient heat transfer from the copper tip to the sensor, there is a *delay* between the time when the resin actually arrives at the sensor position and the time the program designates an arrival.

Chapter 5

LINEAL AND VOLTAGE POINT SENSORS

5.1 Lineal Sensors

As briefly discussed in Chapter 1, lineal sensors [33,34] are simple sensor systems capable of detecting resin movement by using two parallel electrically conductive wires attached to an electrical circuit.

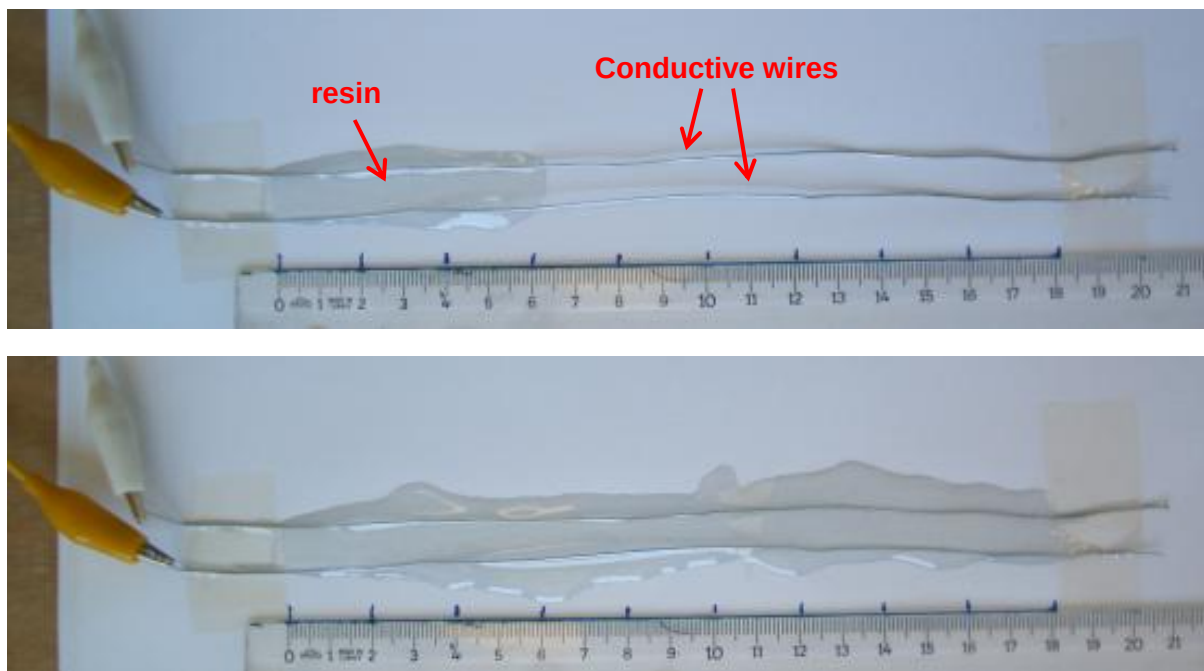


Figure 5.1 Lineal sensor system. The sensor is partially, or completely covered by resin at the top and bottom photographs, respectively.

As shown in Figure 5.1, a lineal sensor is composed of two parallel conductive wires placed at a certain distance to each other (on the order of millimeters), and resin is allowed to flow through the gap between the wires. As resin flows, an electrical conductance can be attained between these wires. Using this property, an electrical circuit [33] can be constructed to detect the presence of resin. The circuit is shown in Figure 5.2.

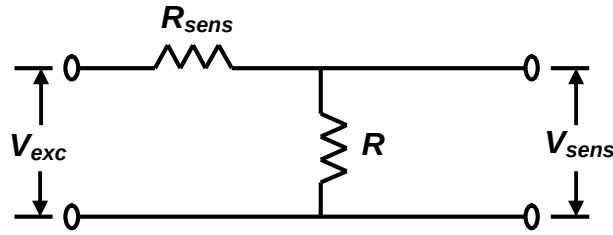


Figure 5.2 Simple electrical circuit to detect resin.

This simple circuit composes of two resistances: R_{sens} and R . An excitation voltage, V_{exc} is applied to these resistances, and the output voltage V_{sens} over the resistance R is measured. The two wires constitute the resistive element, R_{sens} of this electrical circuit. They are connected to the circuit by using two connectors (Figure 5.3). The relation between V_{exc} and V_{sens} can be given by Ohm's Law as follows:

$$V_{sens} = \frac{R}{R + R_{sens}} V_{exc} . \quad (5.1)$$

A schematic of the lineal sensor system is shown in Figure 5.3. In the absence of resin, the circuit is open and there is no current flowing through the circuit. In other words, only air exists between the wires, hence $R_{sens} = R_{air}$ (very large), and V_{sens} is practically zero. Resin behaves like a switch for the circuit. As it starts to flow between the wires, the circuit is closed with an increasing volume of resin and the resistance R_{sens} decreases. Thus, V_{sens} reading increases.

The resistance generated by the resin is extremely high (on the order of giga-ohms) and it is really hard to drive any significant current through it (when the excitation voltage is typically 10 Volts). A second high value resistance R is used as a voltage divider so that the

voltage V_{sens} over this resistance would have some portion of the excitation voltage V_{exc} . In this study, V_{exc} is chosen as 10 V DC (direct current) which is a typical value for a DAQ card or a power supply. As R_{sens} changes by resin contact, a change in the output voltage V_{sens} can be measured under the constant excitation voltage V_{exc} . To measure a considerable value for V_{sens} , R should be chosen as close to R_{sens} as possible. In this study, R is chosen as $10\text{ M}\Omega$ (a conventional high resistance value).

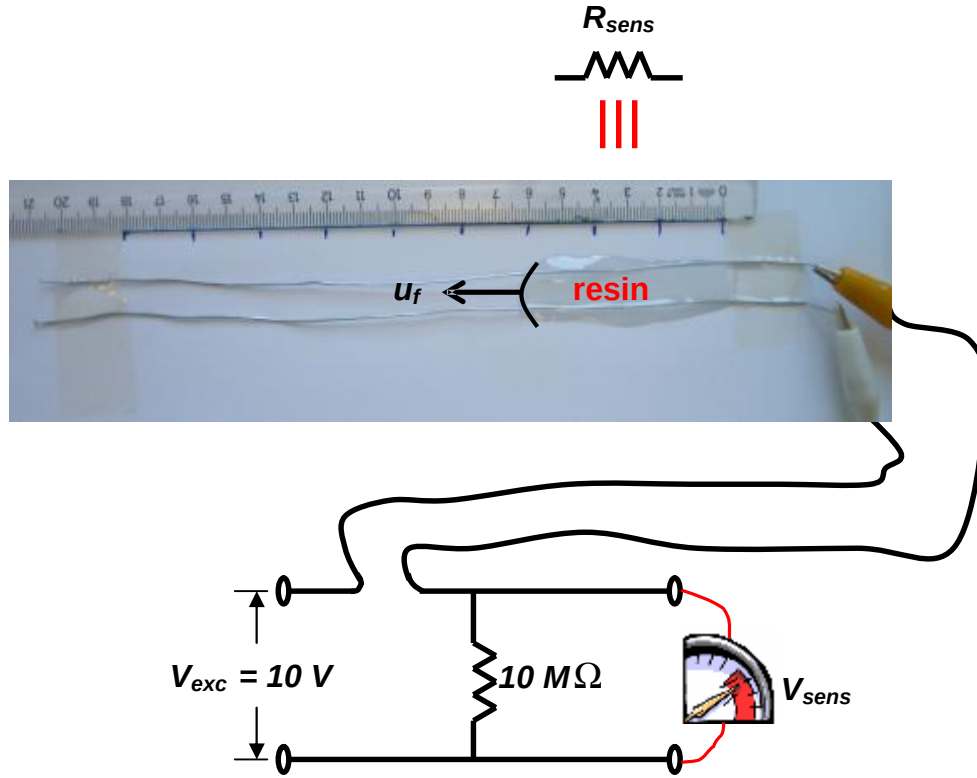


Figure 5.3 Schematic for the linear sensor system (u_f is the resin flow front velocity). Resin functions as a resistance (R_{sens}) between the two wires.

Even the chosen high resistance, R (on the order of mega-ohms) remains small compared to the resin's resistance R_{sens} . Therefore, V_{sens} is still small compared to V_{exc} . Despite the fact that V_{sens} readings are not considerably high, V_{sens} readings will be the key element in

detecting the resin arrival as it will be described in the following sections. Next section discusses linear sensor experiments and results.

5.2 Lineal Sensor Experiments and Results

Lineal sensor experiments similar to those that of Barooah and his colleagues [33] were made here as well. The reason for this was to understand that system, and develop a different sensor system that will not have the drawbacks of the former one.

As Barooah et al. noted, V_{sens} readings depend on several parameters including:

- the gap width between the wires,
- the material of the wires,
- the length and diameter of the wires,
- the type of resin used, and
- different compositions of additives used in resin for cure reaction.

In this section, results of lineal sensor experiments that were made by using copper wires will be given. Copper wires with a length of 20 cm, and with two different diameters: 0.25 mm and 0.35 mm, are used. Figures 5.4 and 5.5 show the corresponding voltage readings (V_{sens}) for different gap widths, s . Figures 5.6 and 5.7 show the change in resistance (R_{sens}) as the wetted length of the wires increases for the same set of gap widths.

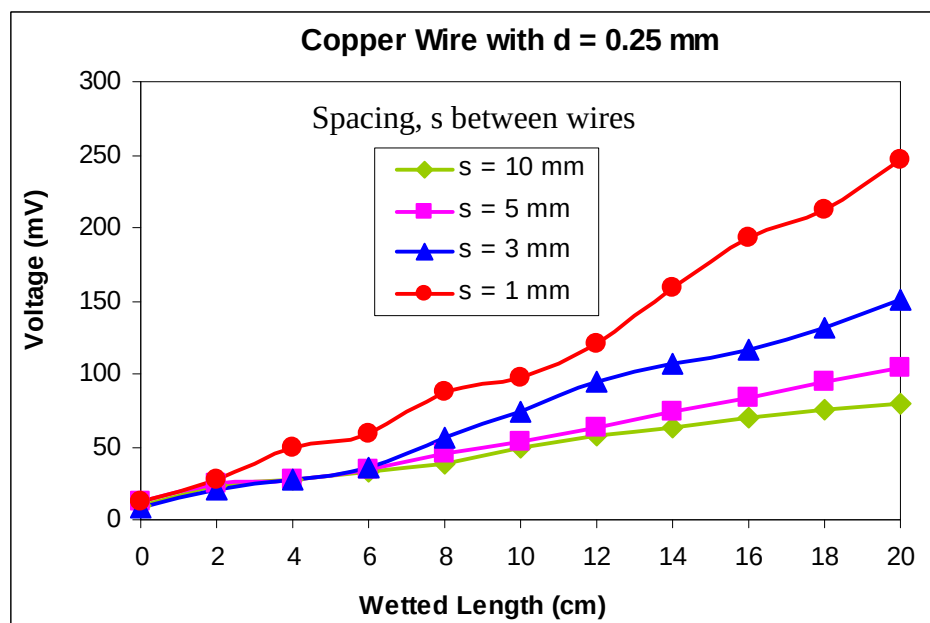


Figure 5.4 Wetted length versus voltage readings for copper wire with 0.25 mm diameter.

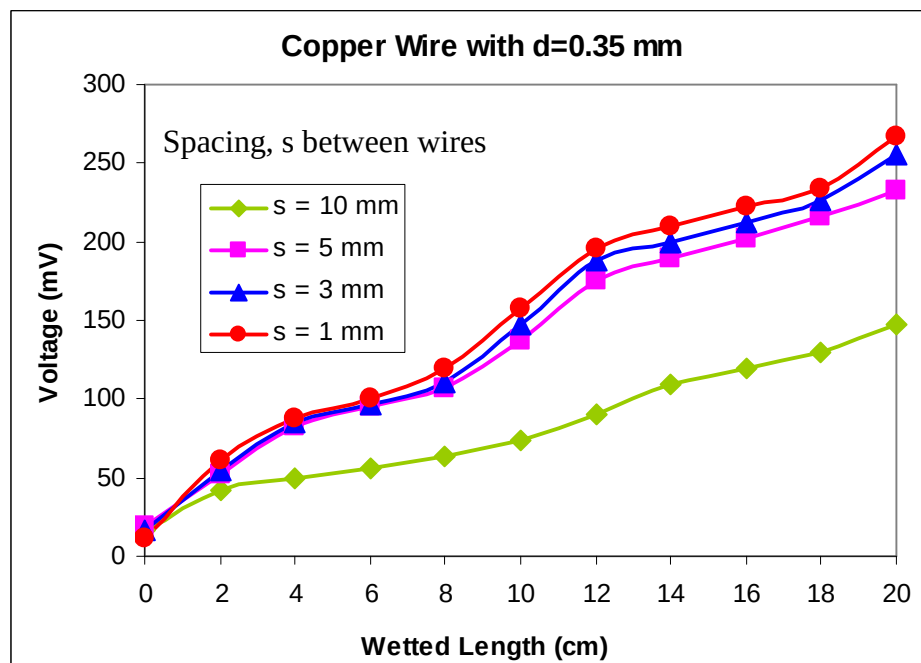


Figure 5.5 Wetted length versus voltage readings for copper wire with 0.35 mm diameter.

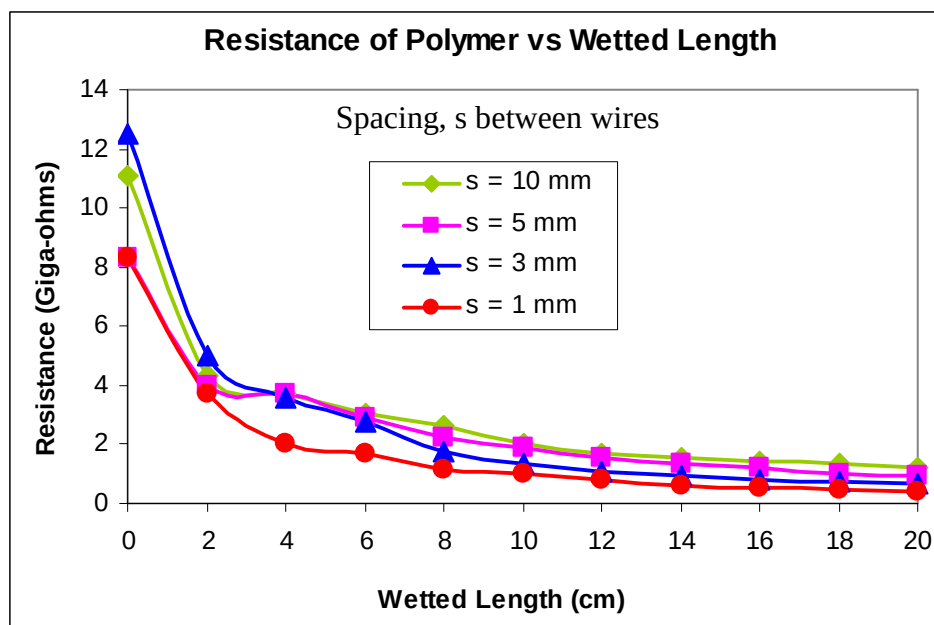


Figure 5.6 Wetted length versus resistance of polymer for copper wire with $d = 0.25$ mm.

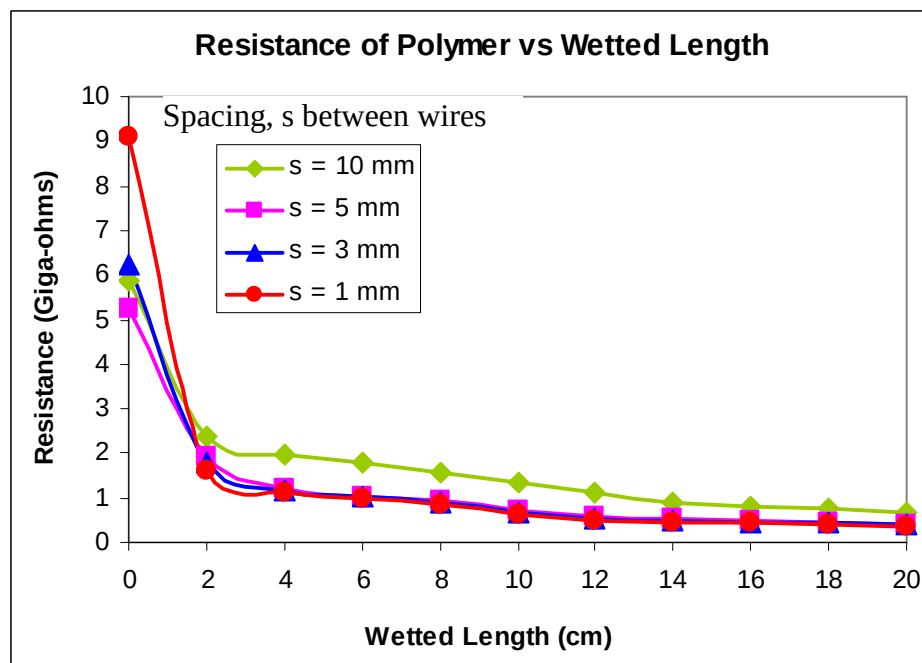


Figure 5.7 Wetted length versus resistance of polymer for copper wire with $d = 0.35$ mm.

Figures 5.4 to 5.7 show that voltage readings (V_{sens}) significantly increase with decreasing gap width(s) and increasing wetted wire length since R_{sens} decreases. The changes in resistance of polymer shown in Figures 5.6 and 5.7 are calculated by using Equation (5.1). As seen from the figures, the changes in voltage readings are only on the order of milli-volts since changes in resistance of polymer (R_{sens}) is on the order of giga-ohms.

Figures 5.8 and 5.9 show voltage readings (V_{sens}) and changes in resistance of polymer (R_{sens}) for different concentrations of additives used for cure reaction. In these experiments, copper wire with a diameter of 0.35 mm and a gap width, s 10 mm are used. Additives are added to 1000 gr of polyester.

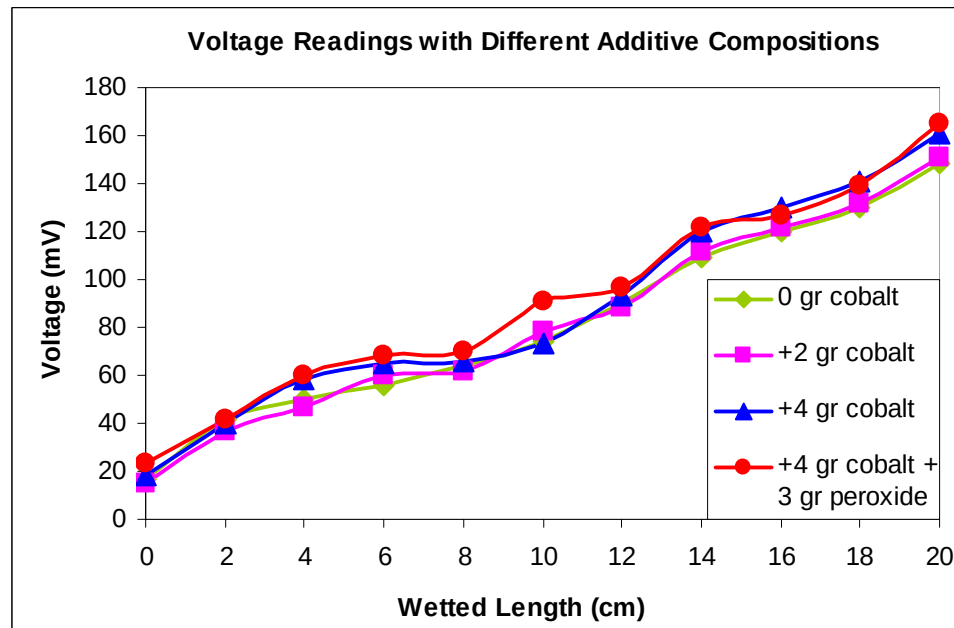


Figure 5.8 Voltage readings for different additive compositions.

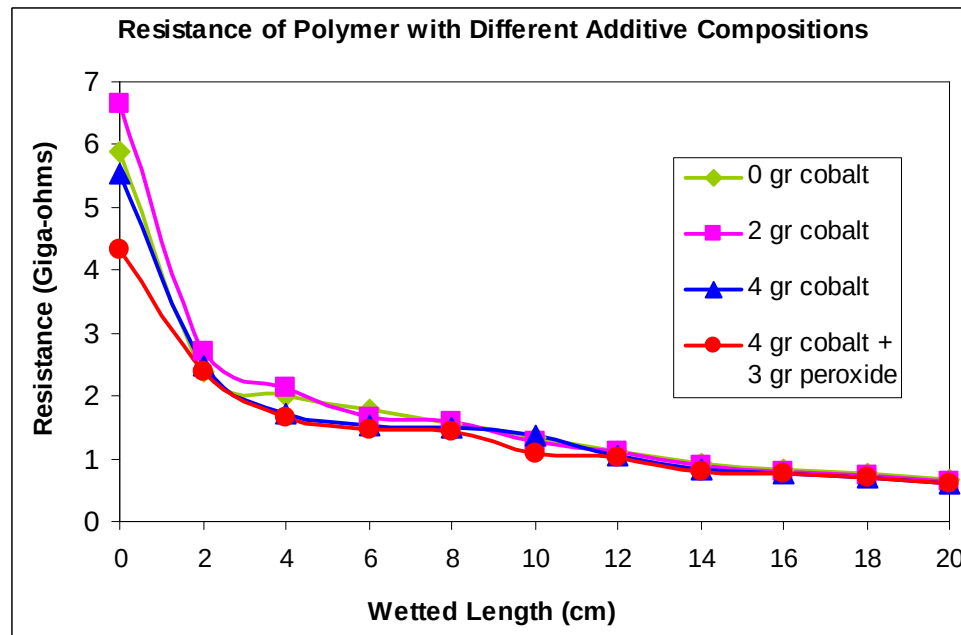


Figure 5.9 Change in resistance of polymer with different additive compositions.

Figures 5.7 and 5.8 show that as the amount of additives increases, voltage readings slightly increase, since there is a slight decrease in the resistance readings.

Due to the very small amplitude of the voltage readings and ambient noises, the readings are not zero when the wetted length is equal to zero.

As shown in Figure 5.10, another experiment was made to test the voltage readings for different wetted sections of the wires. Copper wires which have a diameter of 0.35 mm, a length of 20 cm, and a gap width of $s = 5$ mm are used. In the first experiment, multiple sections of the wires which add up to 10 cm (4 cm + 2 cm + 2 cm) are wetted by resin (see Figure 5.10(a)). Then, in the second experiment, the wires are wetted by the same amount, 10 cm, within a single section (see Figure 5.10(b)). The corresponding voltage readings are measured as 133 mV for both experiments (notice that the reading of the second experiment is in close agreement with the value 137 mV of Figure 5.5, for wetted length of 10 cm and a gap width of 5 mm). The result of this experiment shows that the voltage readings are only

dependent on the “total” wetted wire length, and they are independent of the location of resin on the sensor.

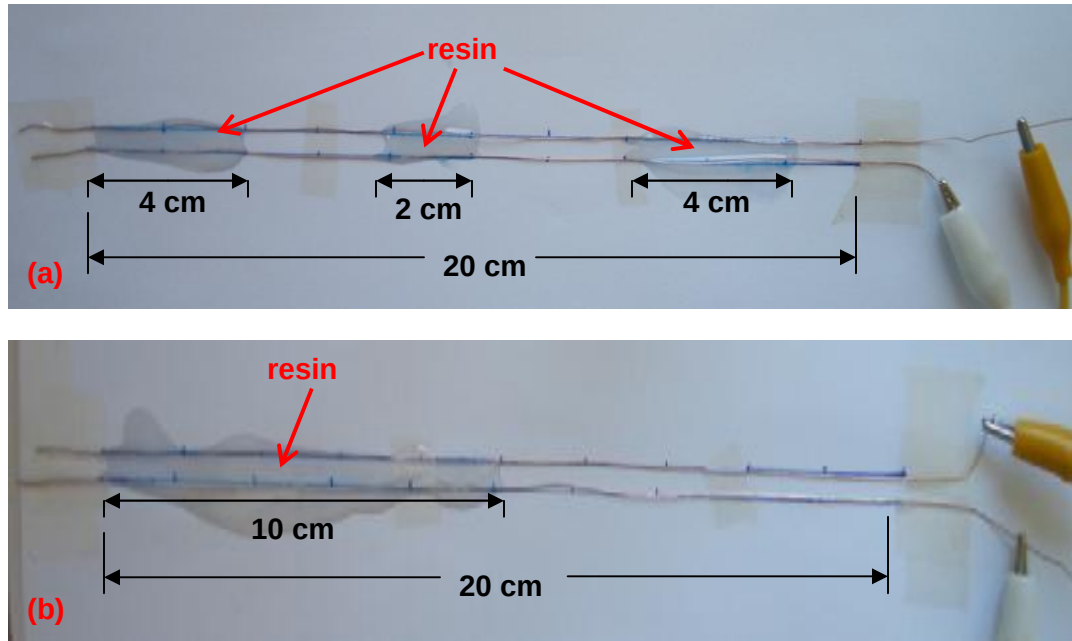


Figure 5.10 Voltage readings for different wetted sections.

Having conducted several lineal sensor experiments, it can be concluded that it is possible to get reasonably high voltage readings by laying down lineal sensor wires on the mold surface along the direction in which the polymer is expected to flow, and placing as many couple of wires as possible. By this way, a good way of resin flow monitoring can be achieved as done in the studies mentioned in Chapter 1.

Lineal sensors have the advantages of simplicity, low cost and continuously monitoring resin flow and cure. However, because the voltage readings do not depend on the location of the resin, the readings may sometimes be misleading. As demonstrated in Figure 5.10, if the resin does not continuously wet the lineal sensor wires starting from only one end of the

wires, then the voltage readings will not be useful and they will be misleading in detecting the flow front position.

Furthermore, placement of the wires might be troublesome. The same gap width must be maintained throughout the whole system for repeatable, and hence reliable measurements. Since the lineal sensor wires remain in the final part, they affect both resin flow and mechanical properties of the finished part. As a solution to this issue, a new mold design could be necessary for inserting lineal sensors into the mold instead of simply placing them to the surface. For instance, thin grooves can be machined on the mold surface. However, since lineal sensors are made of thin wires, they will either stick to the part or fracture during de-molding.

5.3 Printed Wirings

As an alternative to lineal sensors, it is possible to develop point sensors [8,10,11] which detect resin arrival based on the similar principal. When resin arrives at a discrete sensor location, a change in the voltage reading will occur, and an arrival signal will be generated. This idea was earlier implemented by Lawrence et al. in [8].

By using the knowledge gained from the previous lineal sensor measurements, different wire configurations were designed to be used in point sensors. To get considerable voltage readings, wrapping (to increase length) is used and the gap width is kept as small as possible. The figures are drawn by Matlab and some of them are shown in Figure 5.11. As the next stage, these drawings are printed on circuit boards as shown in Figure 5.12. Then, they are connected to the simple electrical circuit used in the lineal sensors (Figure 5.2). A piece of e-glass fabric was placed on these samples and resin was dropped onto the fabric to get the corresponding voltage readings. Table 5.1 shows the results for the voltage readings.



Figure 5.11 Different wire configurations.

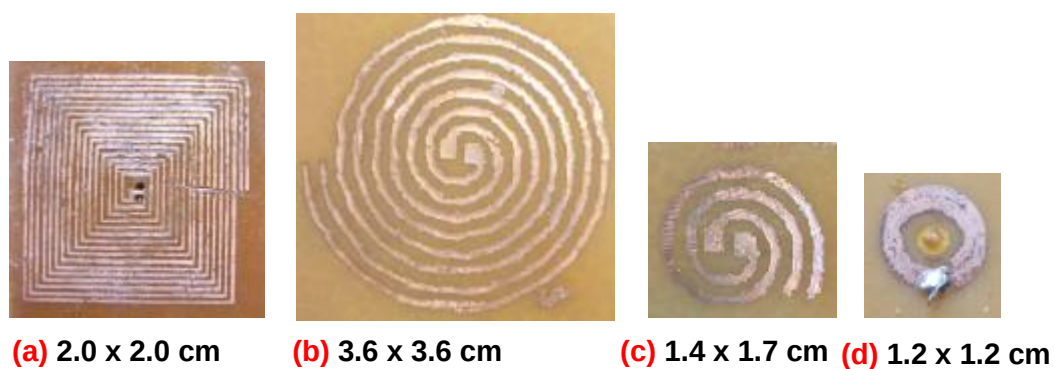


Figure 5.12 Printed wirings on circuit boards.

Table 5.1 Voltage readings for the samples shown in Figure 5.11.

Configuration	Dimensions (cm)	Voltage reading when fully wetted (mV)
(a)	2.0 x 2.0	80
(b)	3.6 x 3.6	50
(c)	1.4 x 1.7	27
(d)	1.2 x 1.2	8

Readings given in Table 5.1 show slight variations between multiple experiments, and maximum voltage readings that could be recorded are given. Readings are recorded when the total wiring areas (dimensions shown) of the samples are completely wetted. Configuration (a) in Figure 5.8 has the largest voltage reading since the total length is the biggest and also, the gap width is the smallest (smaller than 1mm). Configuration (b) and (c) have almost the same gap width, but (b) has a larger voltage reading since there are more windings and hence it has a longer wire length than (c). Configuration (d) has the lowest reading of all since wire length is the smallest and gap width is the largest.

Readings in Table 1 show that voltage point sensors can be produced capable of detecting flow of resin, and they can fit into the hollow multi-functional bolts used in the current RTM system. However, one should note that even the maximum values of the readings are quite low for DAQ purposes considering the noises in the system. The readings will need to be amplified.

5.3.1 Manufacture of the wire configurations

Basic PCB (Printed Circuit Board) principles are applied in printing of the drawings (Figure 5.12(a, b, c and d)) on circuit boards. Different wiring shapes (Figure 5.11) are first printed on PCB sheets [55] using the conventional office printers. Then, they are placed on pertinax (a phenol formaldehyde resin [56]) boards and ironed so that the traces of the drawings are transferred onto the board. Lastly, the pertinax substrate is etched with hydrogen peroxide and hydrogen chloride [57] to remove unwanted copper so that copper remains only on the drawing traces as in Figure 5.12.

The board printing process described above is done manually and should be performed carefully for all the drawings to have the same quality. Sometimes, the drawings might be blurry and this affects the wire size on the drawings. Especially, if the gap width is small, it is hard to produce the drawings of the same quality at all times. To have small gap widths,

special attention must also be paid to avoid any electrical contact (conductance) of the wires otherwise the sensor would be useless. For instance, for the printed board shown in Figure 5.12(a), it was possible to produce a proper one only after making several trials of printing.

The experiments with printed boards show that the voltage readings are generally not high enough and they are on the order of milli-volts. To increase the readings, printed wires with smaller gap widths can be used. However, the printing process of these wires is tiresome and not repeatable. Considering the placement of the printed boards into the multi-function bolts, size is another problem. The tip of the bolts has a diameter of about 1cm, thus the boards should be small enough to fit into these bolts. As the boards get smaller, the printing process gets even harder and the voltage readings greatly fall due to short wiring length as illustrated in the previous section. Furthermore, the thickness (perpendicular to board's surface) of the wires are on the order of micrometers, and this thin layer of copper can be easily scratched or removed once resin cures and the part is demolded. Hence, sensors of this type will not last long.

5.4 Voltage Point Sensors

Due to the issues mentioned above, printed wirings are replaced with a new design which provides the interaction of resin and a similar electrical circuit used for lineal sensors. The new system should have the following characteristics:

- It must be durable and resistant to resin contact, curing and part demolding.
- It must fit into the multi-function bolts.
- Its manufacturing must be easy, repeatable and has a low cost.
- Its voltage readings should be high enough for data acquisition purposes.
- Sealing of the bolts must be ensured, hence resin leakage must be prevented.

In Figures 5.13 and 5.14, the new design is shown. A copper tube and a copper rod are manufactured and fitted concentrically into a multi-function bolt. Insulating plastic tubes [58] (Figure 5.14(b)) separate the copper tubes and prevent any electrical conductance. The new design integrated into the current RTM system is named as the *voltage point sensor*.

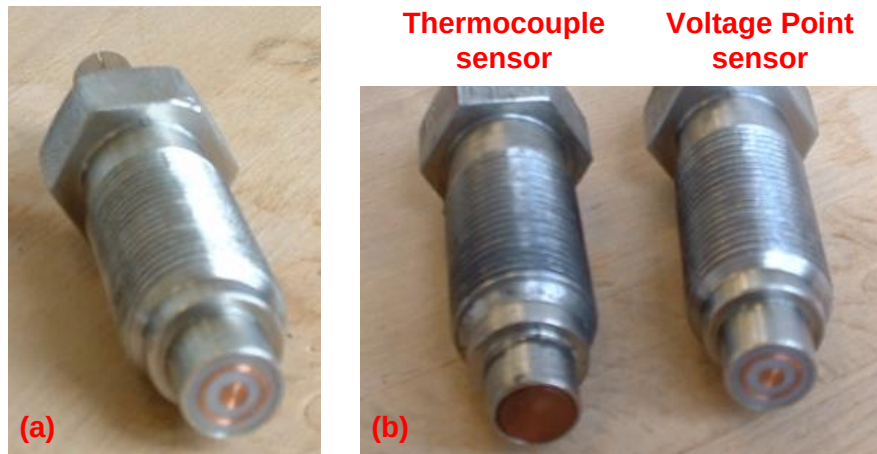


Figure 5.13 (a) A voltage point sensor, (b) same sensor next to a thermocouple sensor.

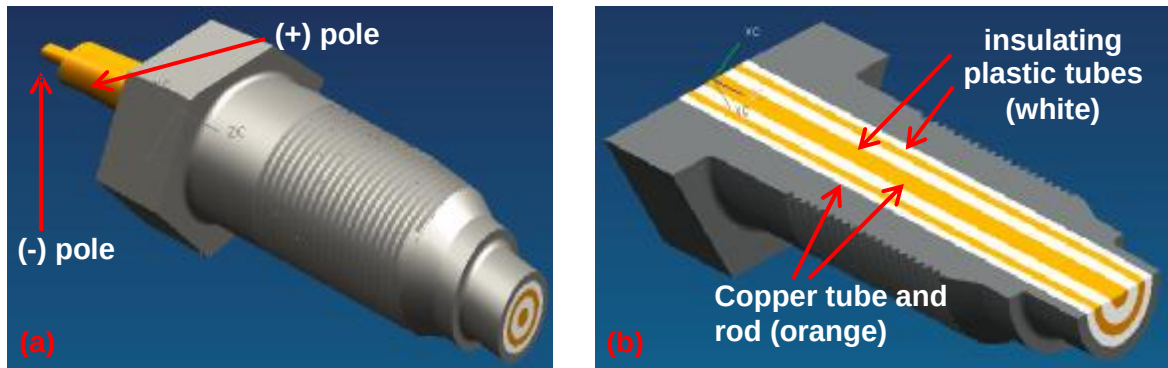


Figure 5.14 Voltage point sensor: (a) solid model, (b) cross-sectional view.

In Figure 5.13(b), two alternative sensor types are shown side by side: a thermocouple sensor and a voltage point sensor. Figure 5.14(b) shows a cross-section of the voltage point sensor for a better visualization.

The voltage point sensors described have a standardized construction. Bolts integrated with these sensors can be repeatedly manufactured with each specimen having the same exact specifications. By this way, it is expected that variances (as present in printed wirings) are eliminated.

The copper rod and tube, and hard insulating plastic tubes are tightly fitted into a bolt for a fine sealing. They are not affected from resin contact, cure or part demolding.

Since the resin, which is usually accepted as a non-conducting material due to its extremely high resistance, is going to be used as a circuit element, the insulating plastic between the copper tubes should be chosen carefully. It should have a much higher resistance than the resin, otherwise the circuit would already be closed in its initial unwetted usage. The insulating plastic used in this study [58] meets this requirement.

5.4.1 The Integrated System for Voltage Point Sensors

Several tests with voltage point sensors proved that the voltage reading of a single sensor is about 20 milli-volts, and this reading has to be amplified for data acquisition purposes, since it can be considered at the signal noise levels. The amplifying process can be performed by a simple op-amp circuit. However, the input impedance generated by the 10 M Ω resistance and the resistance of resin (R_{sens}) is too high and the voltage reading V_{sens} cannot be directly amplified. For this purpose, a high input impedance op-amp is necessary to serve as an ADC (analog to digital converter) buffer. After the buffering process, the DC voltage can be amplified using a conventional op-amp.

The sensor circuits with non-amplified and amplified voltage readings are shown in Figure 5.15. Figure 5.15(b) shows the two op-amps used as buffer and amplifier.

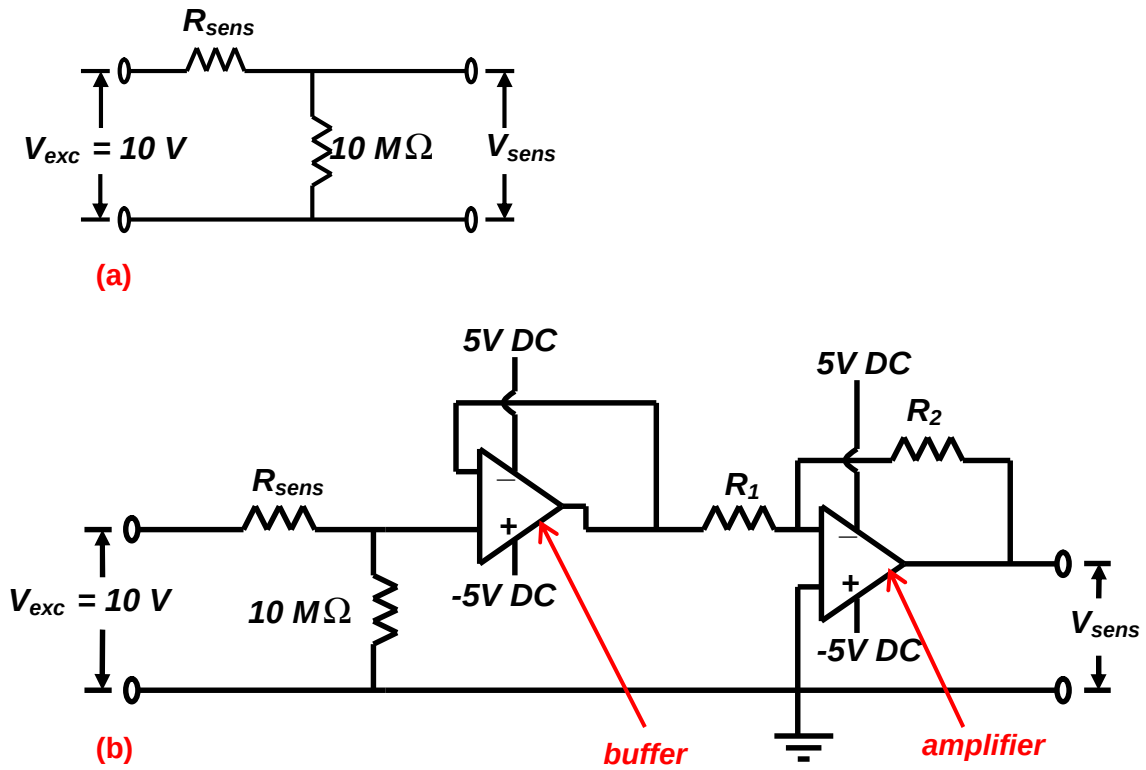


Figure 5.15 The sensor circuit with voltage readings; (a) non-amplified: V_{sens} , (b) amplified: V_{sens} .

To overcome some of the drawbacks of circuit shown in Figure 5.15(b), further improvements were made as explained below. The modified circuit is shown in Figure 5.16. The circuit is manufactured on PCB (Printed Circuit Board) as shown in Figures 5.16, 5.17 and 5.18. The elements of this circuit can be described as follows:

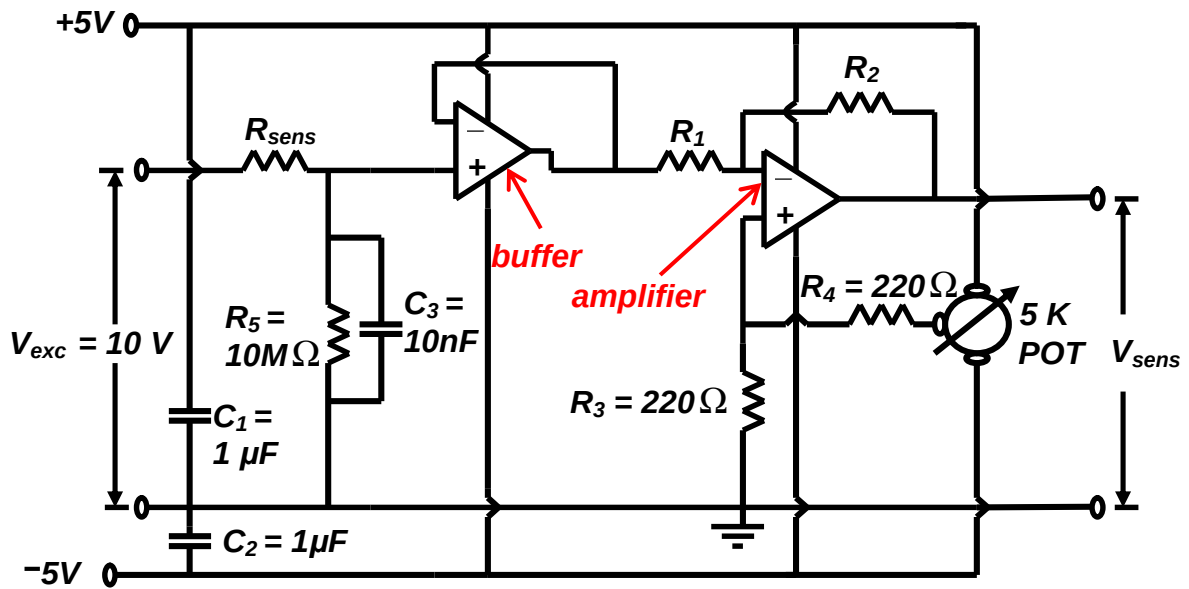


Figure 5.16 The improved amplifying circuit for an integrated sensor system.

Op-Amp (buffer): This is used as an ADC buffering op-amp with high input impedance. It isolates the high impedance system and makes DC voltage amplifiable by a conventional op-amp. An op-amp, OPA655P [59] is used with an input impedance of $10^{12} \Omega$. This op-amp operates with $\pm 5V$ DC.

Op-Amp (amplifier): This op-amp is used as the conventional inverting op-amp for amplification. An LM358P [60] is used for this purpose, since both op-amps (LM358P and OPA655P) can be driven by the same $\pm 5V$ DC voltage. The gain (voltage amplifying ratio) of this op-amp is adjusted by the resistances R_1 and R_2 . The amplifying ratio is R_2 / R_1 . In this study, amplifying ratio, $R_2 / R_1 = 100$ was taken.

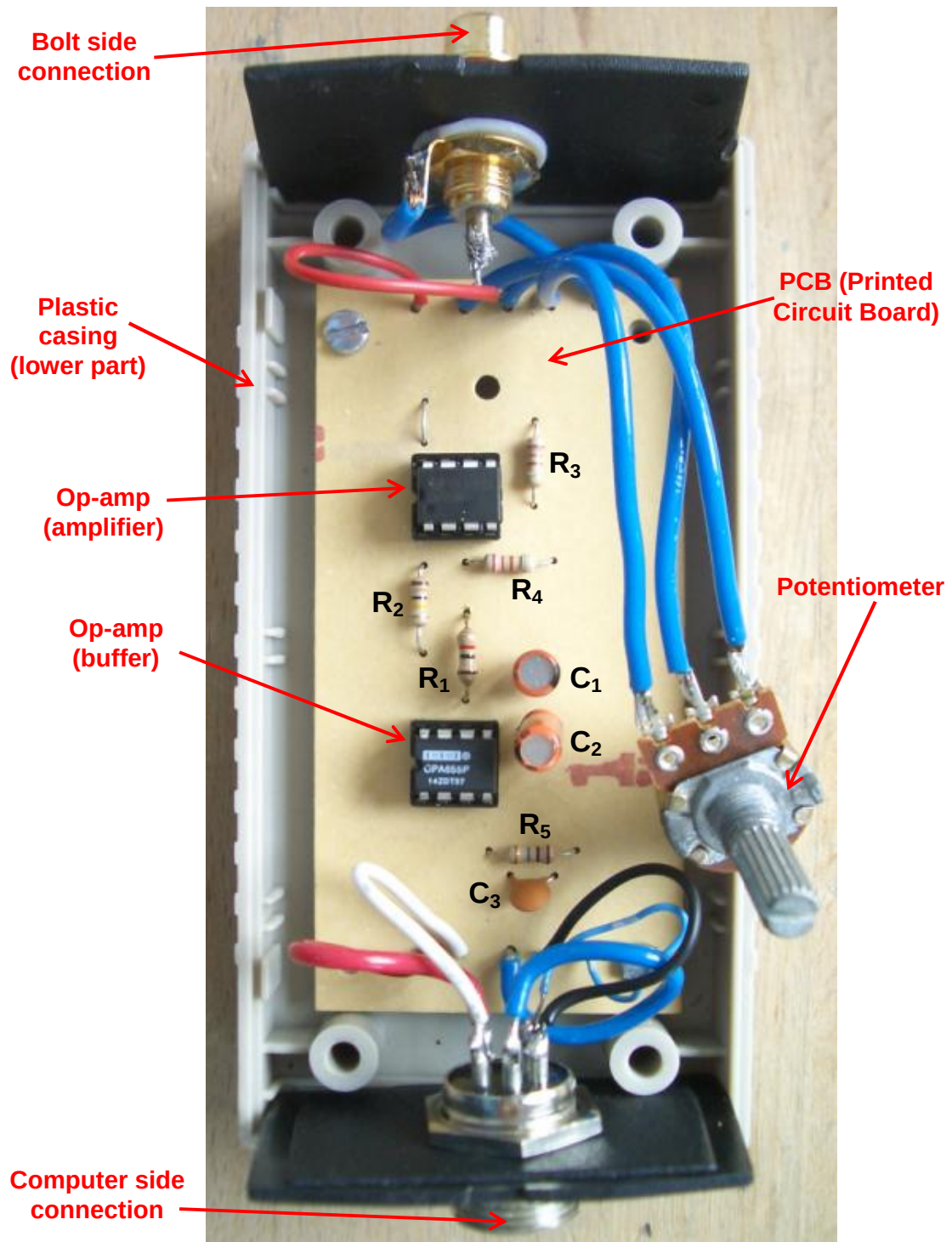


Figure 5.17 The PCB circuit elements and its casing (box) to be used in the voltage point sensor system.

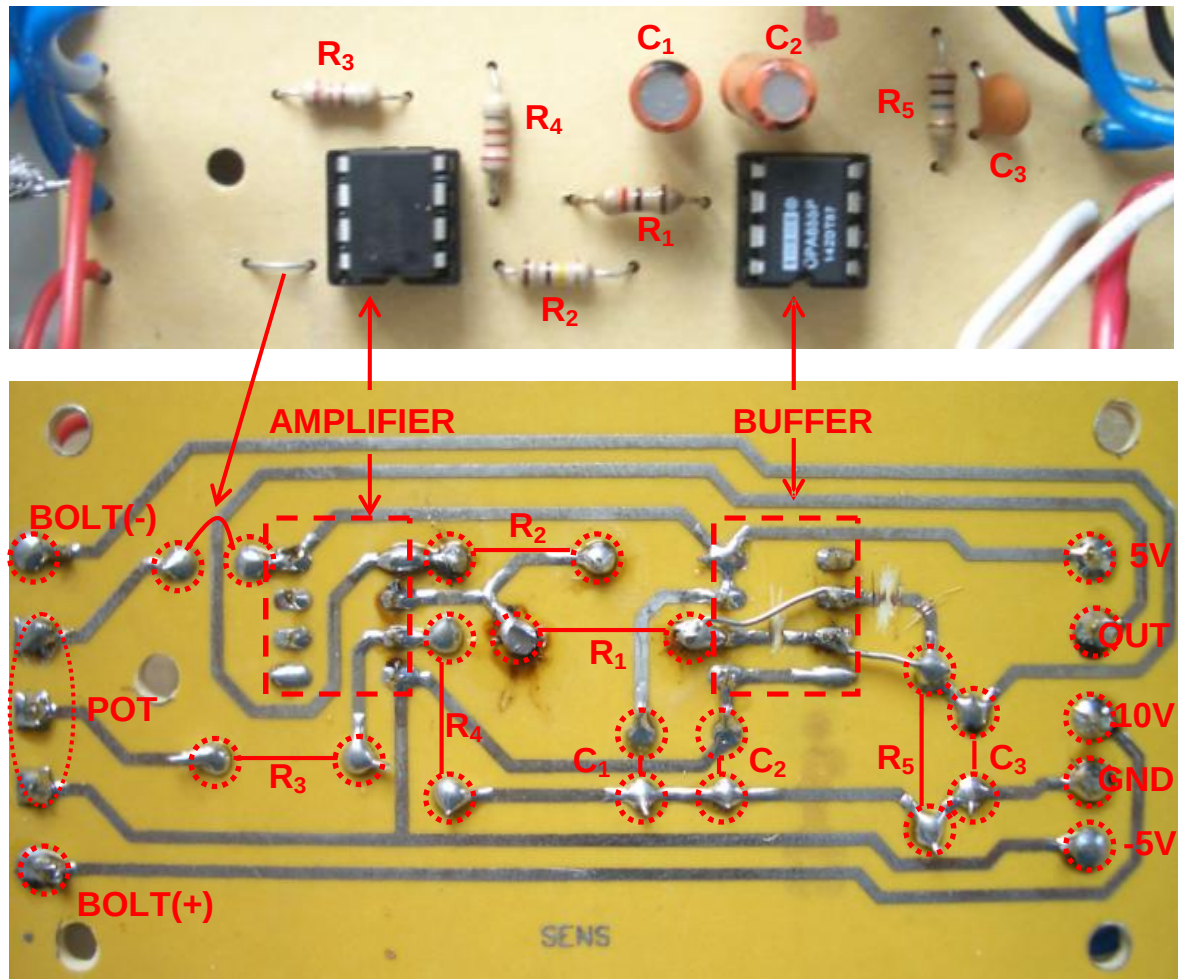


Figure 5.18 Closer view for the electrical connections.

Capacitors: Capacitors C_1 and C_2 of $1\mu F$ each, are connected between $\pm 5V$ DC sources and ground in order to compensate for any fluctuations in the power source. These work as fuses in the system to prevent any possible damage to the op-amps. Capacitor C_3 of $10nF$ is used in order to filter the output signal on $R_5 = 10M\Omega$ resistance. This way, after the noise on the output signal is reduced, it is sent to the computer.

Potentiometer (POT): Since the buffering op-amp deals with very high impedances, some amount of noise is present at the output of this op-amp. Thus, when the circuit is not closed, (i.e. before resin arrives at sensor location) noise levels of 0.5 Volts are seen on the output signal. In order to detect the resin arrival by multiple sensors clearly, this amplified noise value is offset by a potentiometer and made zero by adjusting the potentiometer to an appropriate value. The potentiometer is connected to the circuit by two resistances, R_3 and R_4 of the same value ($220\ \Omega$).

Each PCB circuit is placed in a commercially available and low cost plastic casing (box) and the suitable connections are made for the integration of the voltage point sensors with the mold and the DAQ system (Figures 5.19, 5.20, 5.21, 5.22 and 5.23). The casings are placed adjacent to the lower part of the mold (attached to bolts) so that surrounding noises will be reduced. Shielded cables carry power sources and DAQ signals to these casings.



Figure 5.19 Bolts and the circuit casings.

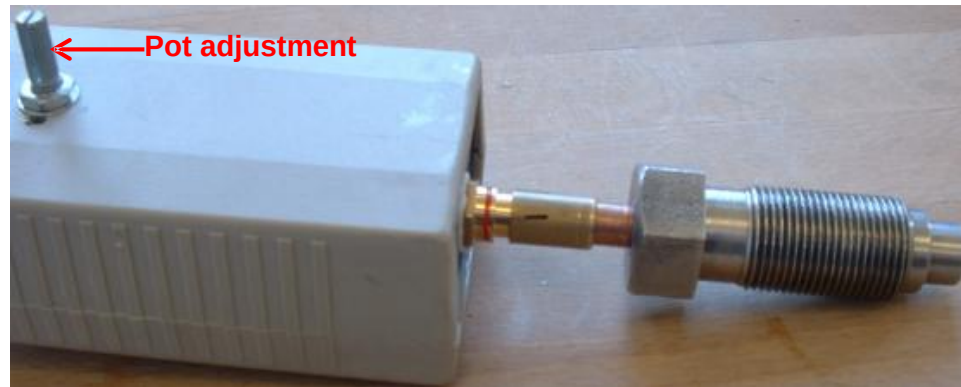


Figure 5.20 Connection between casing and bolt. Pot adjustment button is also shown.



Figure 5.21 Connections for the circuit boxes: (a) bolt side, and (b) DAQ-computer side.

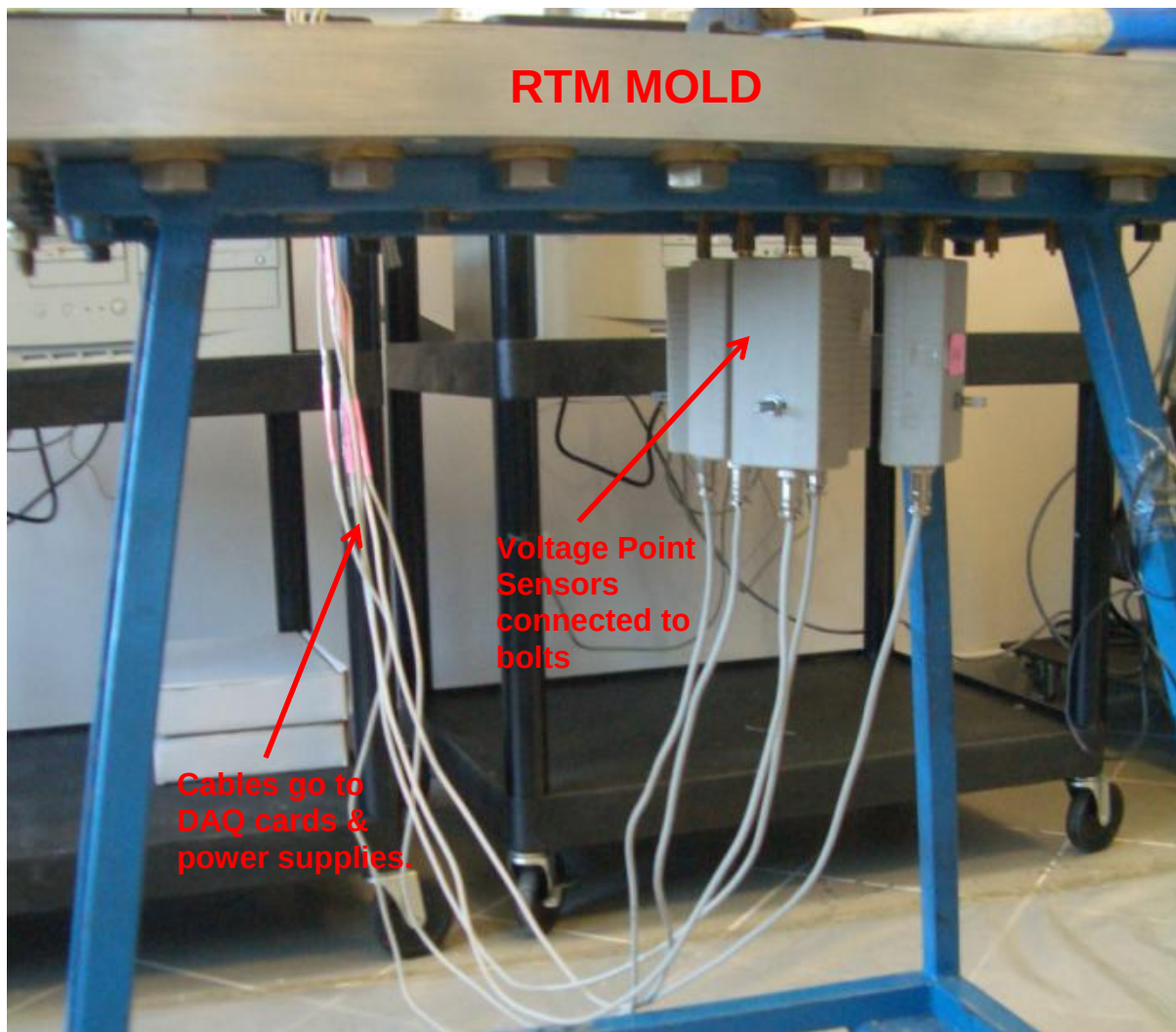


Figure 5.22 Electrical circuits of voltage point sensors are connected to the bottom of the mold to keep the noise level low.



Figure 5.23 Another picture of point voltage sensors mounted on the mold, and the cables of the sensors are connected to the DAQ and power supply.

5.4.2 DAQ System and Experiments with Voltage Point Sensors

DAQ system was adopted from the thermocouple sensors systems studied in earlier part of this study. The LabVIEW program used for the thermocouple configuration was modified for the voltage point sensors. The differences from the previous LabVIEW code are:

- There is no threshold temperature for detection of the sensors, but a voltage threshold input is needed. User defines a threshold voltage, and when the voltage readings are above that value, arrival of the resin is detected at that location. By using the polymer system mentioned earlier, and our developed sensors, a typical $V_{threshold} = 1 \text{ V}$ is proper. It is high enough so that it eliminates the possibility of misdetection of resin arrival due to noise. And it is also low enough so that it can guarantee to detect actual resin arrival, since typical voltage shift is $\sim 3\text{-}4.5 \text{ V}$ when the resin arrives at sensor location.
- In order to further reduce the effect of noise, a simple filtering scheme was applied while measuring V_{sens} . DAQ system considers V_{sens} as the average of the last ten voltage readings (i.e., the latest one measured at that instant plus the previous nine values, and then divided by ten). For verification of our filtering scheme, during each injection, both raw and filtered voltage data are stored, and then examined after the injection. Filtering scheme (= averaging the latest ten values) seems to work eliminating the misdetection and still not sacrificing too much in terms of a delay of detection. Because, this averaging scheme delays the sudden voltage rises, when resin arrives at sensor location. However, since our typical sampling frequency is about 10 Hz, the detection will not be delayed longer than a fraction of a second.

For further information about the DAQ, the reader can refer to Appendix B.

With the voltage point sensors, experiments were performed to detect the flow front position of the resin. An experiment was performed with 6 layers of random fabric, and spacer frame of thickness 3 mm. In this experiment, 4 voltage point sensors were used with 1 V threshold voltage. Sampling frequency of the data acquisition system was set to 5 Hz with a buffer size of 10 elements (i.e., averaging of the last 10 voltage readings for filtering purpose). The sensor configuration is given in Figure 5.24.

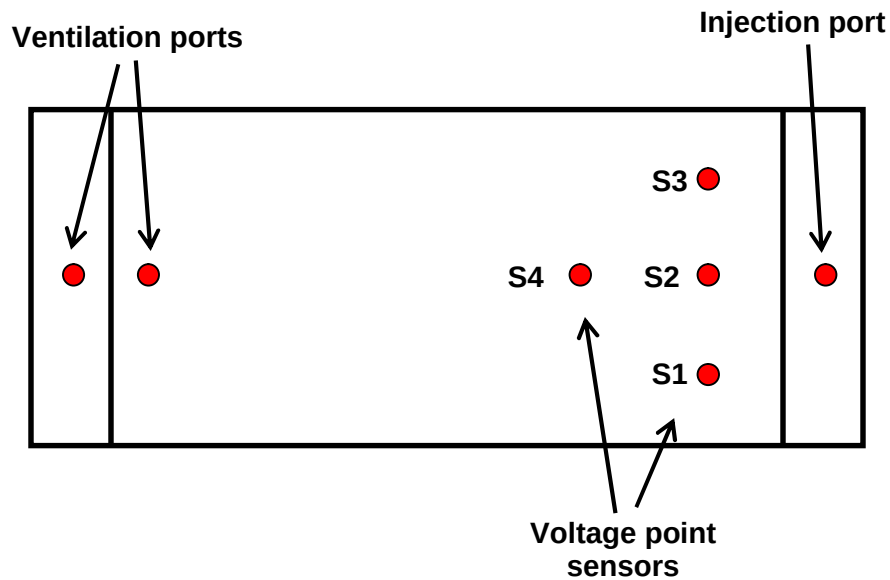


Figure 5.24 Sensor configuration for experiments with voltage point sensors.

Figure 5.25 shows the voltage readings for the sensors during the whole process (from the beginning of injection to demolding). As expected, all the sensor reading values make a peak at the resin arrival time, and then gradually converge to zero, since the resin cures and becomes an electrically insulator composite material. By this method, curing of the resin can also be monitored through the data acquisition system.

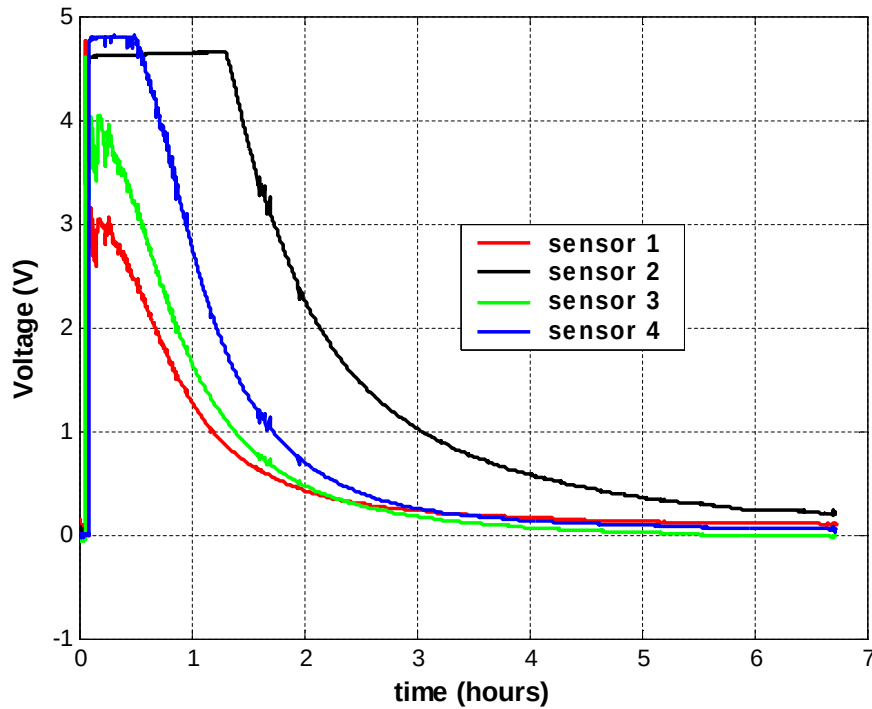


Figure 5.25 Experimental voltage data for the whole process (injection and curing stages).

In the Figure 5.26, the detection of resin arrival at the sensor locations can be clearly seen with sharp jumps in voltage readings. According to these results, the resin arrived to the first and the third sensors initially, which means there are race-tracking channels on each side of the mold. The resin then arrives to the second sensor, which illustrates a U-shaped flow front. Fourth sensor was triggered lastly as expected.

The difference of the voltage values are because of the potentiometer adjustments. The first and third sensors have different offset values adjusted by the potentiometer, this makes them having different responses (voltage values) to the resin arrival. In the electrical circuits of Sensors 2 and 4, an amplifying ratio of $R_2 / R_1 = 100$ was selected. Sensors 1 and 3 had a lower ratio of $R_2 / R_1 = 20$. The effects of these two different amplifying ratios are clearly seen in Figures 5.25 and 5.26. “Consistent” peak values of Sensors 2 and 4 are very close to

5V, which is the voltage value that the op-amps are driven with in the circuit, since no op-amp can give a higher voltage output than it is driven with.

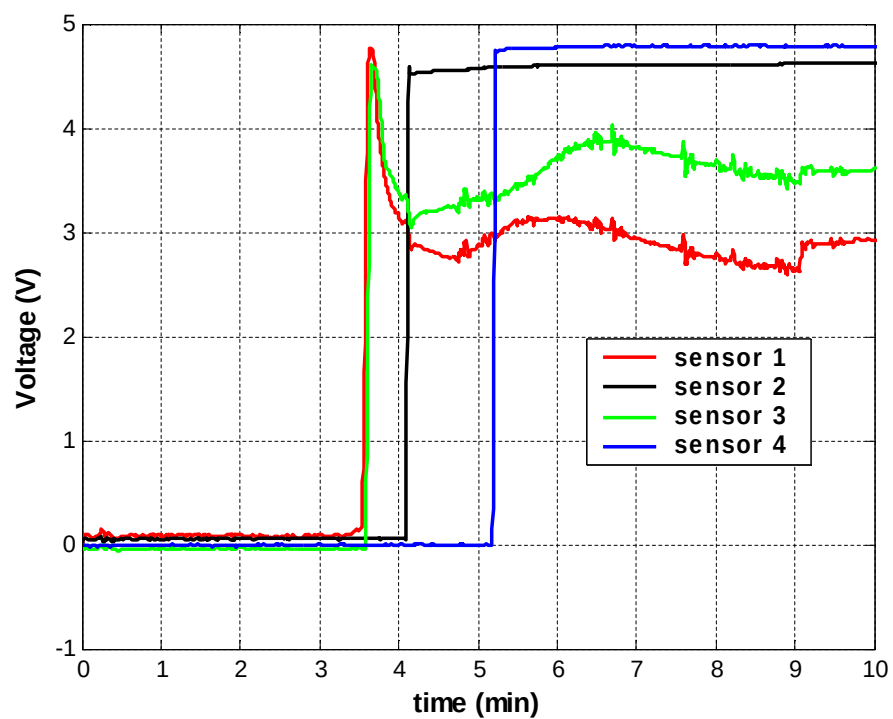


Figure 5.26 Experimental voltage data for the detection of resin arrival only during injection stage.

Chapter 6

CALCULATION OF THE EQUIVALENT PERMEABILITY OF RACE-TRACKING CHANNELS (USING STOKES FLOW MODEL AND FINITE DIFFERENCE METHOD)

6.1 Darcy's Law and Permeability Tensor

Fluid flow through a porous and permeable medium is given by an empirical law called Darcy's Law [61]. In RTM applications where the Reynolds number is small (i.e. inertial forces are negligible compared to viscous forces, and hence quasi steady flow assumption is made), flow of resin through a fabric preform can be modeled by this law. It gives a relation between its average velocity and resin pressure gradient:

$$\bar{u} = -\frac{K}{m} \nabla P \quad (6.1)$$

where

$\bar{u}$: volume averaged velocity

m : viscosity of the fluid

∇P : pressure gradient vector

K : permeability tensor of the preform which can be written as:

$$K = \begin{pmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{pmatrix}. \quad (6.2)$$

In open form, Darcy's Law can be rewritten as:

$$\begin{pmatrix} \bar{u}_x \\ \bar{u}_y \\ \bar{u}_z \end{pmatrix} = -\frac{1}{m} \begin{pmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{pmatrix} \begin{pmatrix} \partial P / \partial x \\ \partial P / \partial y \\ \partial P / \partial z \end{pmatrix}. \quad (6.3)$$

In most of the LCM (Liquid Composite Molding) processes, the thickness of the part is much smaller than its in-plane directions [62]. Thus, the resin flow in RTM process can be considered as two-dimensional flow. For the permeability calculations of race-tracking channels (as it will be discussed in this section), resin flow will be considered as one dimensional flow. Then, Darcy's Law for two and one dimensional flows will respectively become:

$$\begin{pmatrix} \bar{u}_x \\ \bar{u}_y \end{pmatrix} = -\frac{1}{m} \begin{pmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{pmatrix} \begin{pmatrix} \partial P / \partial x \\ \partial P / \partial y \end{pmatrix} \quad \text{and} \quad \bar{u} = -\frac{K}{m} \frac{dP}{dx} \quad (6.4)$$

6.2 Race-tracking Channels

As already discussed in previous chapters, race-tracking channels are one of the major problems of the RTM process. They are low permeability air channels through which resin can flow with less resistance than through bulk fabric preform. Modeling of race-tracking channels is necessary since they may significantly alter the flow of resin. If they are not correctly predicted during the design of mold and process parameters, flow front patterns are affected so that the part might not be filled completely. Incomplete filling results in manufacturing of defective parts lacking the desired mechanical properties.

Permeability calculations for a race-tracking channel help to model the flow inside the mold and help to take precautions against race-tracking. Provided that the equivalent

permeability of a race-tracking channel is known in advance, it can help to drive the RTM process to a successful completion.

In this chapter, equivalent permeability values for race-tracking channels in the form of different geometrical shapes are calculated by using Stokes Flow model, and finite difference method (FDM) as the solution technique.

This approach will be tested for rectangular and circular cross-sections for which analytical solutions are available. Then, it will be applied for other cross-sections (elliptical, triangular and a very irregular section) that are likely to occur along the edges of a compacted preform.

To start with a simple case, a race-tracking channel with rectangular cross section is illustrated schematically in Figure 6.1. A schematic demonstration of the effect of race-tracking channel on resin flow front is shown in Figure 6.2.

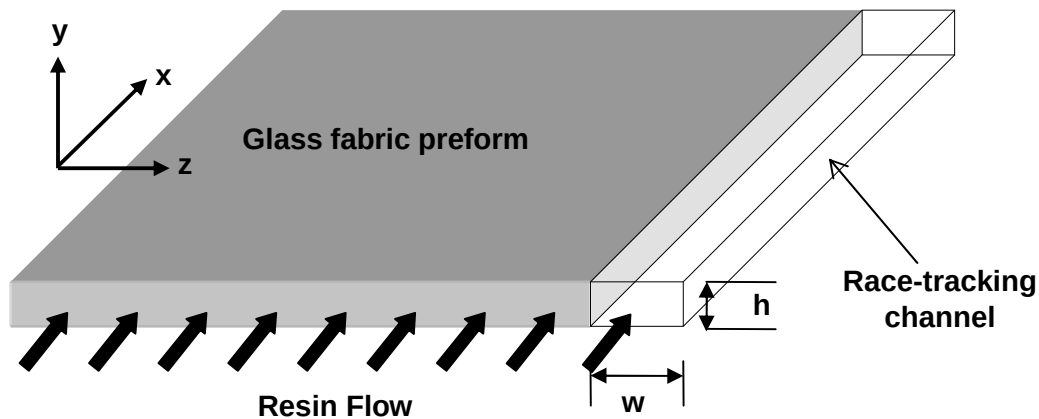


Figure 6.1 Schematic of a race-tracking channel.

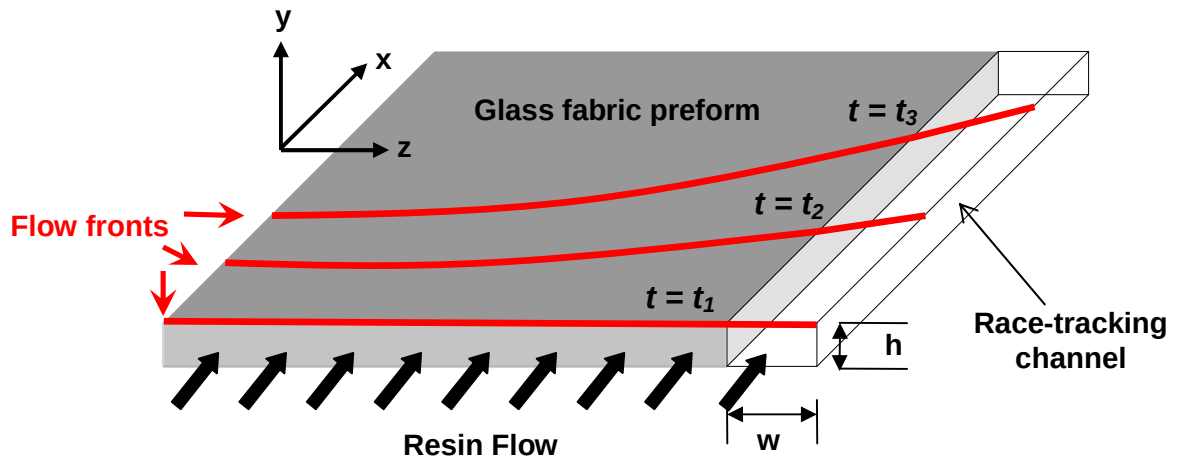


Figure 6.2 Effect of a race-tracking channel on the flow front propagation.

6.3 Governing Equations for Flow Through a Race-Tracking Channel

The governing equations to calculate the permeability of a race-tracking channel are the continuity (conservation of mass) and Navier Stokes equation in x direction (conservation of momentum with the assumption of Newtonian fluid, i.e., a linear relation between shear stress and strain rate tensors). Here are the assumptions made while solving these equations:

Assumptions:

- Low Reynolds number flow $\implies$ Quasi-steady flow, $\partial(\)/\partial t = 0$.
- Laminar flow.
- $w = 0$, no flow in z direction.
- Fully developed flow, $\partial u/\partial x = 0$ and $\partial v/\partial x = 0$.
- Flow of incompressible and Newtonian fluid.
- Negligible body forces ($F_B = 0$).

Continuity equation:

$$\cancel{\frac{\partial u}{\partial x}} + \frac{\partial v}{\partial y} + \cancel{\frac{\partial w}{\partial z}} = 0 \quad \Rightarrow \quad \frac{\partial v}{\partial y} = 0 \quad \Rightarrow \quad v = v(x).$$

But the flow is fully developed, thus $v = 0$.

Navier Stokes equation in x direction: (in y and z directions, all terms are zero.)

$$\begin{aligned} r \left[\cancel{\frac{\partial u}{\partial t}} + u \cancel{\frac{\partial u}{\partial x}} + v \cancel{\frac{\partial v}{\partial y}} + w \cancel{\frac{\partial w}{\partial z}} \right] &= -\frac{\partial P}{\partial x} + m \left[\cancel{\frac{\partial^2 u}{\partial x^2}} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right] + \cancel{F_B} \\ \Rightarrow \frac{\partial P}{\partial x} &= m \left[\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right] = \text{constant} \end{aligned} \quad (6.5)$$

Since the flow is fully-developed, u is not a function of x , that means $u = u(y, z)$. Hence, right hand side of Equation(6.5) is not a function of x , and Equation(6.5) can be satisfied only if $\partial P / \partial x = \text{constant}$. Thus, in the following equations, partial derivative $\partial P / \partial x$ will be replaced by dP / dx as P is not a function of y or z .

A non-dimensional analysis is performed, and Equation (6.5) is written in the non-dimensional form as follows:

$$\frac{dP}{dx} = m \left[\frac{u_{ref}}{y_{ref}^2} \frac{\partial^2 u^*}{\partial y^{*2}} + \frac{u_{ref}}{z_{ref}^2} \frac{\partial^2 u^*}{\partial z^{*2}} \right] \quad (6.6)$$

where

$$y = y^* y_{ref}, \quad y_{ref} = h \quad (6.7)$$

$$z = z^* z_{ref}, \quad z_{ref} = w \quad (6.8)$$

$$K = K^* K_{ref}, \quad K_{ref} = \frac{h^2}{12} \quad (6.9)$$

$$u = u^* u_{ref}, \quad u_{ref} = -\frac{K_{ref}}{m} \frac{dP}{dx} = -\frac{h^2}{12m} \frac{dP}{dx}. \quad (6.10)$$

Using Equations (6.7)-(6.10), Equation (6.6) can be rewritten as:

$$\frac{dP}{dx} = \frac{u_{ref} m}{h^2} \left[\frac{\partial^2 u^*}{\partial y^{*2}} + \left(\frac{h}{w} \right)^2 \frac{\partial^2 u^*}{\partial z^{*2}} \right] \implies \frac{\partial^2 u^*}{\partial y^{*2}} + \left(\frac{h}{w} \right)^2 \frac{\partial^2 u^*}{\partial z^{*2}} = -12. \quad (6.11)$$

No-slip boundary condition will be assumed. For rectangular channel:

$$u = 0 \quad \text{along four edges: } z^* = 0, \quad z^* = 1, \quad y^* = 0, \quad y^* = 1. \quad (6.12)$$

6.4 A Non-Dimensional Finite Difference Method for Rectangular Channels

Equation (6.11) is the non-dimensional differential equation for Stokes flow. A finite difference method will be used to solve Equation (6.11) with no-slip boundary conditions assumed along the edges of the channel. Second order derivatives in Equation (6.11) will be approximated with second order central finite difference formulations. In Figure 6.3, a grid is generated for a race-tracking channel with rectangular cross-section. Then, in Figure 6.4, this grid is translated into a non-dimensional grid to be used in the finite difference method. The width and height of the channel are non-dimensionalized in y and z directions. Thus, both are equal to “1” in non-dimensional form.

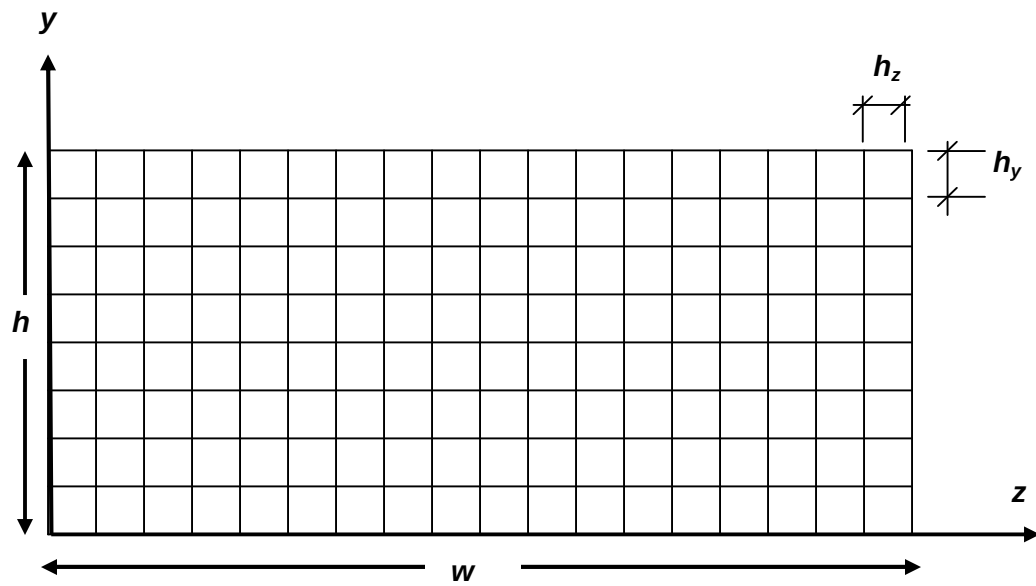


Figure 6.3 A grid for a race-tracking channel with rectangular cross-section.

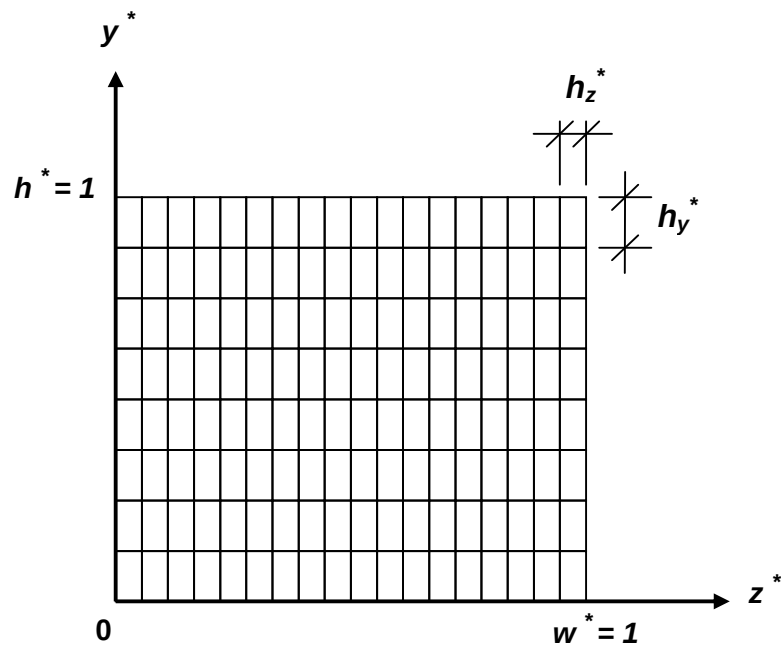


Figure 6.4 Non-dimensionalized grid to be used in the Finite Difference Method.

Second order central finite difference formulations [63] are used to approximate derivatives in Equation (6.11):

$$\frac{\partial^2 u^*}{\partial y^{*2}} = \frac{u^*(i, j+1) - 2u^*(i, j) + u^*(i, j-1)}{h_y^{*2}} + O(h_y^{*2}) \quad (6.13)$$

$$\frac{\partial^2 u^*}{\partial z^{*2}} = \frac{u^*(i+1, j) - 2u^*(i, j) + u^*(i-1, j)}{h_z^{*2}} + O(h_z^{*2}) \quad (6.14)$$

In Equations (6.13) and (6.14), h_z^* and h_y^* are the non-dimensional lengths of elements as shown in Figure 6.4. Second and higher order terms are neglected. As the node numbering in Figure 6.5 implies, Equations (6.13) and (6.14) can be used only for interior nodes since these are “central differences”. For exterior (boundary) nodes, velocity at four edges of the channel is zero due to the assumption of no-slip boundary condition. Thus, there is no need for the calculation of velocity at exterior nodes.

In the non-dimensional grid formed, there are N_z elements in z direction and N_y elements in y direction; meaning that this is a grid containing $(N_z+1) \times (N_y+1)$ number of nodes and the lengths of the non-dimensional elements (h_z^* and h_y^*) will be $1/N_z$ and $1/N_y$ respectively (see Figure 6.4). In this study, $N_y = N_z$ is used.

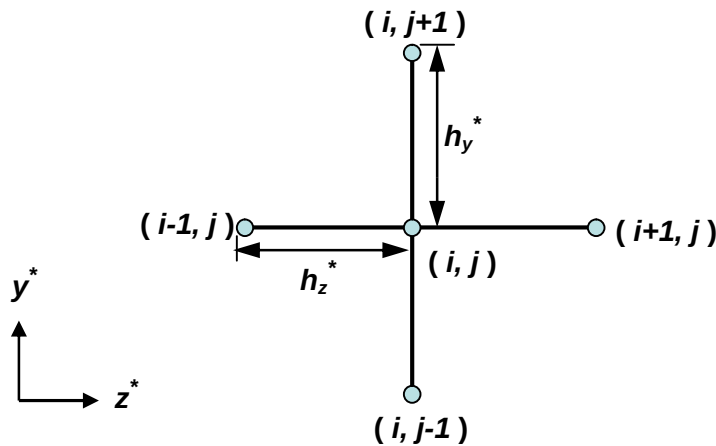


Figure 6.5 $(i, j)^{\text{th}}$ center node in the grid and its neighbour nodes.

If Equations (6.13) and (6.14) are substituted into Equation (6.11) for the solution of $u^*(i, j)$, the following equation can be obtained:

$$u^*(i, j) = \frac{c_1}{c_3} \left[u^*(i+1, j) + u^*(i-1, j) \right] + \frac{c_2}{c_3} \left[u^*(i, j+1) + u^*(i, j-1) \right] + \frac{12}{c_3} \quad (6.15)$$

where

$$c_1 = \left(\frac{h}{w} \right)^2 \frac{1}{h_z^{*2}}, \quad c_2 = \frac{1}{h_y^{*2}} \quad \text{and} \quad c_3 = 2(c_1 + c_2).$$

At each node of the grid shown in Figure 6.4, Equation (6.15) is used to solve for $u^*(i, j)$ using the Gauss Seidel iteration method. In the Gauss Seidel method [66], u^* at all nodes are assigned with an initial estimate, say, zero velocity. Then, at each node, velocity term appearing on the left hand side of Equation (6.15) is calculated by substituting the currently updated estimate values of velocities to the right hand side of Equation (6.15). This iteration is continued until the error term (see below) between two velocity iterations is small enough (stop the iteration if error < tolerance). Details of the solution can be found in the MATLAB [68] code “*K_Rectangular_Racetracking_channel_nondim.m*” in Appendix C.

error = norm of two consecutive velocities

$$= \sqrt{\sum_{i=1}^{N_y+1} \sum_{j=1}^{N_z+1} \left[u^{updated}(i, j) - u^{current}(i, j) \right]^2}$$

Next, to find the equivalent permeability, the calculated velocity distribution is used to determine the total flow rate. At each node,

$$\Delta Q^*(i, j) = u^*(i, j) \Delta A \quad (6.16)$$

where $\Delta A = h_z^* h_y^*$ is the area of a non-dimensional control area for internal nodes. The control areas for the boundary nodes are either $h_z^* h_y^* / 2$ or $h_z^* h_y^* / 4$ (see Figure 6.6).

However, as already mentioned, $u = 0$ at these nodes, and they have no contribution to flow rate calculation.

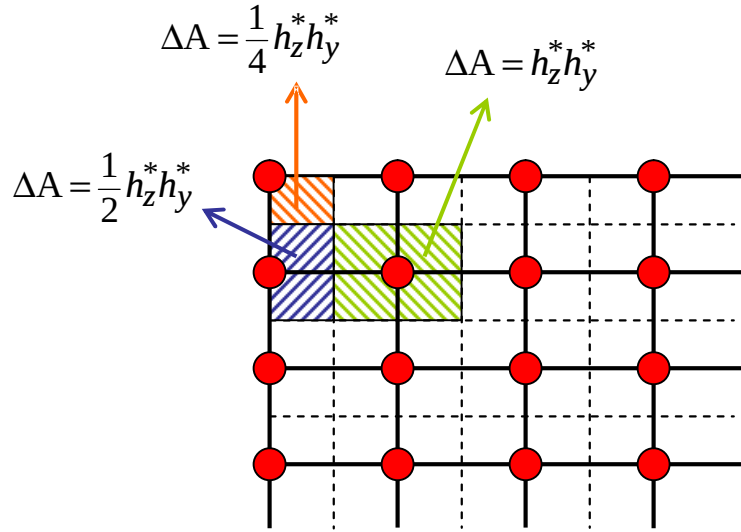


Figure 6.6 Control areas for the boundary and central nodes.

Then, the total non-dimensional flow rate can be calculated as follows:

$$Q^* = \sum_{i=1}^{(N_z+1)} \sum_{j=1}^{(N_y+1)} \Delta Q^*(i, j) \quad (6.17)$$

where N_z and N_y are the number of elements in z and y directions and $(N_z+1) (N_y+1)$ is the total number of nodes in the grid. Total dimensional flow rate can be written as:

$$Q = Q^* Q_{ref} \quad , \quad Q_{ref} = u_{ref} A_{ref} \quad , \quad u_{ref} = -\frac{h^2}{12m} \frac{dP}{dx} \quad , \quad A_{ref} = wh$$

$$\Rightarrow \quad Q = Q^* \left(-\frac{h^2}{12m} \frac{dP}{dx} \right) (wh) \quad (6.18)$$

Equivalent permeability of the race-tracking channel can be found by using one-dimensional Darcy's Law. The total flow rate (dimensional) can also be written as follows:

$$Q = \int_A u \, dA = \bar{u}A \quad \text{and} \quad \bar{u} = -\frac{K}{m} \frac{dP}{dx} \quad \text{using the Darcy's Law.} \implies Q = -\frac{K}{m} \frac{dP}{dx} wh \quad (6.19)$$

where $\bar{u}$ is the volume averaged velocity, and $A = wh$ is the area of the channel. Equating Equations (6.18) and (6.19) gives:

$$-\frac{K}{m} \frac{dP}{dx} wh = Q^* \left(-\frac{h^2}{12m} \frac{dP}{dx} \right) (wh) \implies K = \frac{h^2}{12} Q^* . \quad (6.20)$$

From Equation (6.9), it is known that : $K = K_{ref} K^*$ and $K_{ref} = \frac{h^2}{12}$. Then, from Equation (6.20) it is found that :

$$K^* = Q^* . \quad (6.21)$$

This means that the equivalent non-dimensional permeability is equal to the total non-dimensional flow rate (given by Equation (6.17)). The prepared MATLAB [68] code solves for velocity component $u^*(i, j)$ at each node for different h/w ratios. Then, the program calculates the non-dimensional equivalent permeability values. In the next section, for verification purpose, permeabilities of several special channel geometries will be compared with analytical solutions. Then, we will apply this solution technique for channel geometries which do not have analytical solutions available.

6.4.1 Analytical Formulations

If the condition of $w \gg h$ is satisfied in the race-tracking channel, then $u \neq u(z, y)$ and equations for Poiseuille Flow between two parallel plates [64] can be applied, since this is a pressure driven flow. Then, the following expressions can be written:

$$u_{Poiseuille}(y) = \frac{dP}{dx} \frac{1}{m} \frac{(y^2 - hy)}{2} \implies Q_{Poiseuille} = \int_0^h \frac{dP}{dx} \frac{1}{m} \frac{(y^2 - hy)}{2} w dy$$

$$\Rightarrow Q_{Poiseuille} = -\frac{dP}{dx} \frac{wh^3}{12m} \quad (6.22)$$

Equation (6.22) can be equated to Equation (6.19):

$$\begin{aligned} Q_{Darcy} = Q_{Poiseuille} &\Rightarrow -\frac{K}{m} \frac{dP}{dx} wh = -\frac{dP}{dx} \frac{wh^3}{12m} \\ \Rightarrow K &= \frac{h^2}{12} \quad \text{for } w \gg h \end{aligned} \quad (6.23)$$

This is the analytical expression of equivalent dimensional permeability for a rectangular race-tracking channel for $w \gg h$. This expression was chosen as the reference permeability (K_{ref} in Equation(6.5)) in the non-dimensional analysis presented above. Looking at Equation (6.19), as w gets very large with respect to h , in other words as h/w goes to zero, the equivalent non-dimensional permeability should approach to 1. That is:

$$K = K_{ref} \text{ or } K^* = 1 \quad \text{for } w \gg h \quad (6.24)$$

In [65], a derivation was made by solving the exact Stokes flow with the no-slip boundary conditions applied on all four edges of the rectangular channel, and taking $u = u(y, z)$. The resulting expression for equivalent dimensional permeability of a race-tracking channel is:

$$K_{exact} = \frac{h^2}{12} \left[1 - \frac{192h}{p^5 w} \sum_{i=1,3,5,\dots}^{\infty} \frac{\tanh[(ipw)/(2h)]}{i^5} \right]. \quad (6.25)$$

If this equation is non-dimensionalized and with K_{ref} (which is equal to $h^2/12$), it becomes:

$$K_{exact}^* = 1 - \frac{192h}{p^5 w} \sum_{i=1,3,5,\dots}^{\infty} \frac{\tanh[(ipw)/(2h)]}{i^5}. \quad (6.26)$$

Non-dimensional permeability values for a rectangular race-tracking channel will be calculated in two different ways: (i) by using the finite difference method as explained in Section 6.4, and (ii) by using the exact analytical expression given in Equation (6.26). Results of the two methods will be compared. In addition, as w gets very large with respect to h , the numerical solution will be compared with the analytical solution given in Equation (6.24).

In Table 6.1, convergence of non-dimensional K^* values is shown by increasing the number of elements used in the finite difference method. This is performed for a sample case where $h/w = 10$. Looking at Table 1 for $N_z=N_y=100$, K^* can be taken as 0.00936. The reason for keeping the same number of significant digits in K^* is that, the result does not change even if the number of elements is increased to $N_z=N_y=125$. For computational time considerations, number of elements are chosen as $N_z=N_y=100$ for the rest of the calculations.

Table 6.1 Convergence of non-dimensional permeability values as the number of elements increases for $h/w = 10$.

$N_z = N_y$	K^*
25	0.0092373
50	0.0093344
75	0.0093537
100	0.0093606
125	0.0093638

In the calculations made to generate Table 6.1, the tolerance for error value (norm of the difference of two consecutive velocity iterations) in the Gauss Seidel iteration method was taken as 1×10^{-8} . In Table 6.2, error tolerance values versus K^* values are shown for $h/w = 10$ by using $N_z=N_y=100$. Table 6.2 shows that it is appropriate to choose the error tolerance

value as 1×10^{-8} , the permeability value with three significant digits ($K^* = 0.00936$) is not changing for all other error tolerance values smaller than this value.

Table 6.2 Error tolerance values used in Gauss Seidel iteration method versus K^* values.

error	1×10^{-6}	1×10^{-7}	1×10^{-8}	1×10^{-9}	1×10^{-10}
K^*	0.0093521	0.0093599	0.0093606	0.0093607	0.0093607

Using a grid of 100×100 elements, and taking an error tolerance value of 1×10^{-8} , non-dimensional permeability values are calculated by using the finite difference method, and then separately by the analytical expression in Equation (6.22). In Figure 6.6, results of the two methods are plotted for different h/w values starting from $h/w = 0.1$ to $h/w = 10$ by an increment of 0.1.

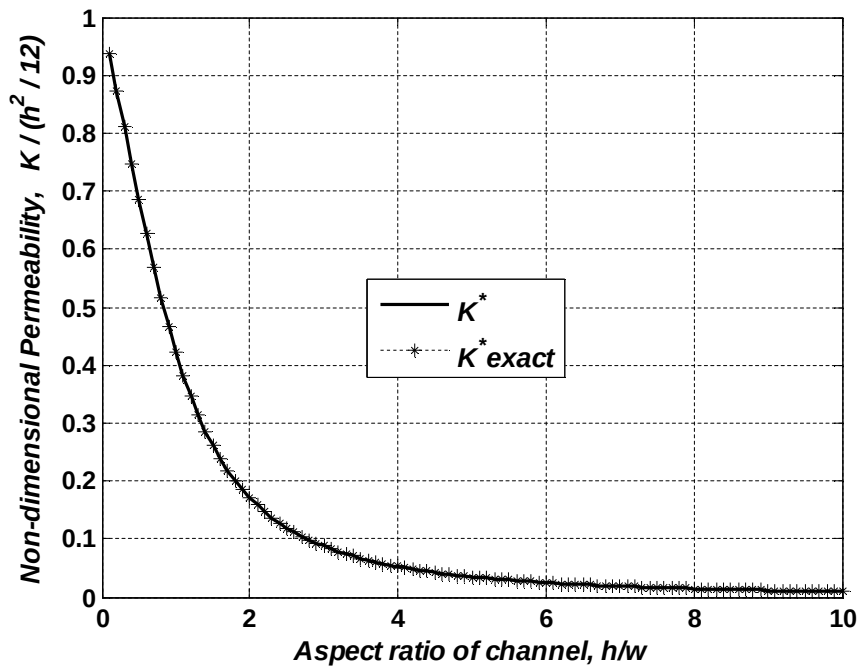


Figure 6.7 Non-dimensional permeability values obtained from the finite difference method and from the exact analytical solution.

From Figure 6.7, it can be concluded that results from the finite difference method and from the exact permeability expression are in very good agreement. In all cases, the difference between permeability values is smaller than 0.1% with respect to the exact solution results. Figures 6.8 and 6.9 show some closer sections of Figure 6.7. In Table 6.3, all of these results are tabulated for a more precise and systematic analysis of the results.

Figure 6.7 also reveals that $K^* \rightarrow 1$ as $h/w \rightarrow 0$, as expected from Equation (6.24). Running the finite difference method for a sample case of $h/w = 0.001$ gives $K^* = 0.989$ which is pretty close to 1.

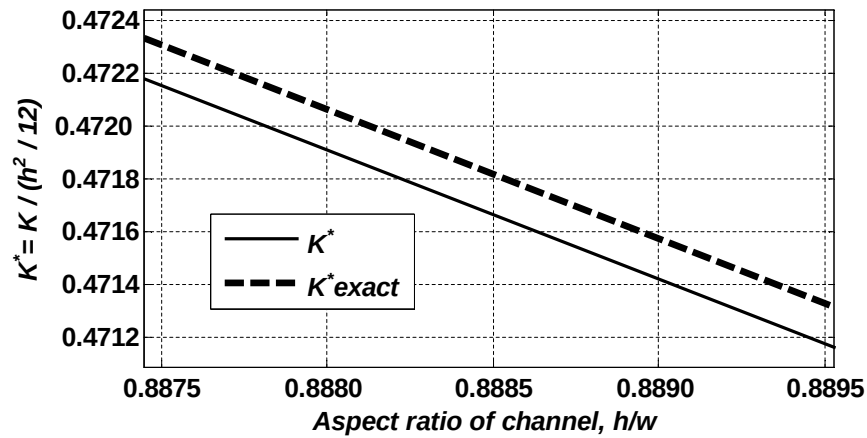


Figure 6.8 A closer section from Figure 6.7.

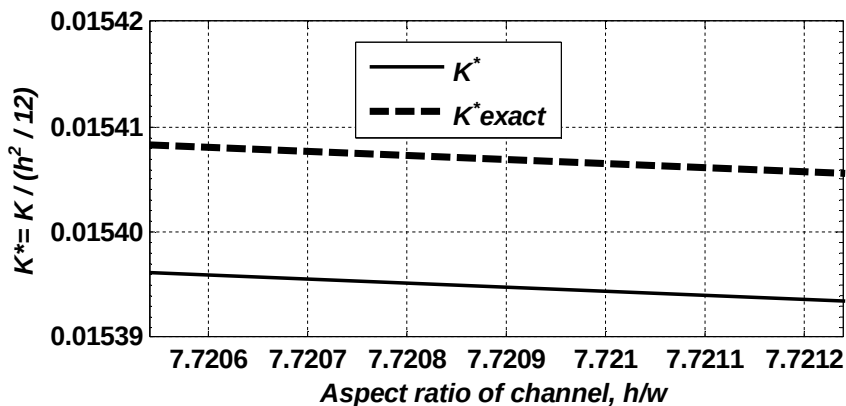


Figure 6.9 Another closer section from Figure 6.7.

Table 6.3 Non-dimensional permeability values versus aspect ratio h/w for a rectangular race-tracking channel. (Results are given with 3 significant digits.)

h/w	K^*	K^{*exact}	h/w	K^*	K^{*exact}	h/w	K^*	K^{*exact}
0.1	0.936	0.937	3.4	0.0704	0.0705	6.7	0.0202	0.0202
0.2	0.873	0.874	3.5	0.0669	0.0669	6.8	0.0196	0.0196
0.3	0.811	0.811	3.6	0.0636	0.0637	6.9	0.0191	0.0191
0.4	0.748	0.748	3.7	0.0606	0.0606	7.0	0.0186	0.0186
0.5	0.686	0.686	3.8	0.0577	0.0578	7.1	0.0181	0.0181
0.6	0.626	0.626	3.9	0.0551	0.0551	7.2	0.0176	0.0176
0.7	0.568	0.569	4.0	0.0526	0.0527	7.3	0.0171	0.0171
0.8	0.515	0.515	4.1	0.0503	0.0503	7.4	0.0167	0.0167
0.9	0.466	0.466	4.2	0.0482	0.0482	7.5	0.0163	0.0163
1.0	0.422	0.422	4.3	0.0461	0.0462	7.6	0.0159	0.0159
1.1	0.382	0.382	4.4	0.0442	0.0443	7.7	0.0155	0.0155
1.2	0.346	0.346	4.5	0.0424	0.0425	7.8	0.0151	0.0151
1.3	0.314	0.314	4.6	0.0408	0.0408	7.9	0.0147	0.0147
1.4	0.286	0.286	4.7	0.0392	0.0392	8.0	0.0144	0.0144
1.5	0.261	0.261	4.8	0.0377	0.0377	8.1	0.0140	0.0141
1.6	0.239	0.239	4.9	0.0363	0.0363	8.2	0.0137	0.0137
1.7	0.219	0.219	5.0	0.0349	0.0350	8.3	0.0134	0.0134
1.8	0.201	0.201	5.1	0.0337	0.0337	8.4	0.0131	0.0131
1.9	0.186	0.186	5.2	0.0325	0.0325	8.5	0.0128	0.0128
2.0	0.171	0.172	5.3	0.0313	0.0314	8.6	0.0125	0.0125
2.1	0.159	0.159	5.4	0.0303	0.0303	8.7	0.0122	0.0123
2.2	0.147	0.148	5.5	0.0293	0.0293	8.8	0.0120	0.0120
2.3	0.137	0.137	5.6	0.0283	0.0283	8.9	0.0117	0.0117
2.4	0.128	0.128	5.7	0.0274	0.0274	9.0	0.0115	0.0115
2.5	0.120	0.120	5.8	0.0265	0.0265	9.1	0.0112	0.0112
2.6	0.112	0.112	5.9	0.0256	0.0257	9.2	0.0110	0.0110
2.7	0.105	0.105	6.0	0.0248	0.0249	9.3	0.0108	0.0108
2.8	0.0988	0.0988	6.1	0.0241	0.0241	9.4	0.0105	0.0106
2.9	0.0930	0.0931	6.2	0.0234	0.0234	9.5	0.0103	0.0103
3.0	0.0877	0.0878	6.3	0.0227	0.0227	9.6	0.0101	0.0101
3.1	0.0829	0.0829	6.4	0.0220	0.0220	9.7	0.00993	0.00994
3.2	0.0784	0.0784	6.5	0.0214	0.0214	9.8	0.00973	0.00974
3.3	0.0743	0.0743	6.6	0.0208	0.0208	9.9	0.00954	0.00955
						10.0	0.00936	0.00937

If non-dimensional velocity is plotted using Equation (6.15), velocity profile is obtained across the race-tracking channel's cross-sectional area. In Figures 6.10, 11 and 12, velocity profiles are shown for sample cases where $h/w = 0.1$, 1, and 10 respectively. $N_z=N_y=100$ are used in all these cases. The corresponding MATLAB code, named “3D_vel_profile_Rectangular.m” is given in Appendix C.

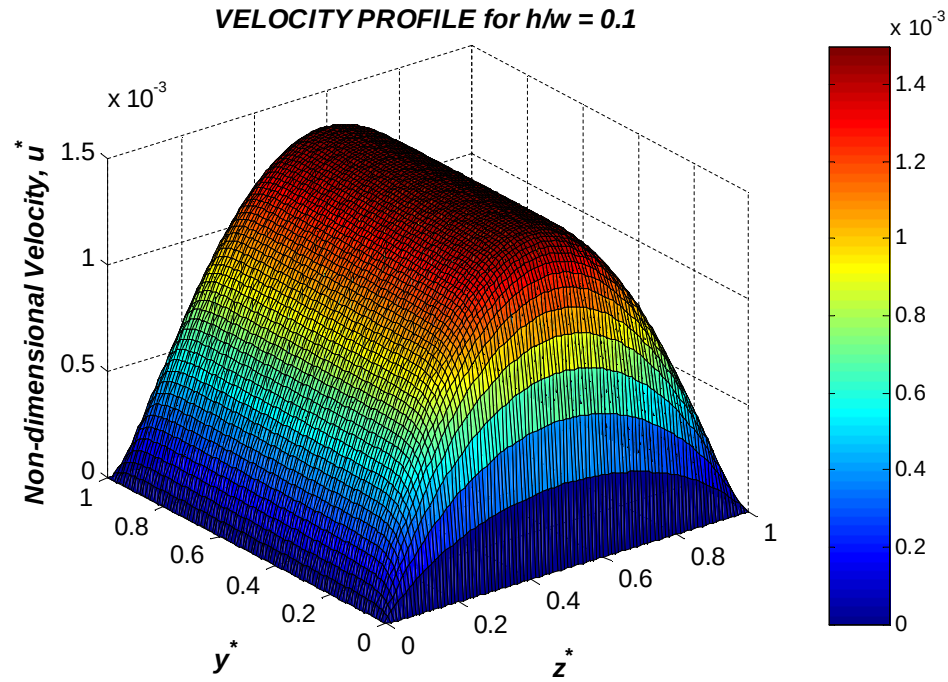
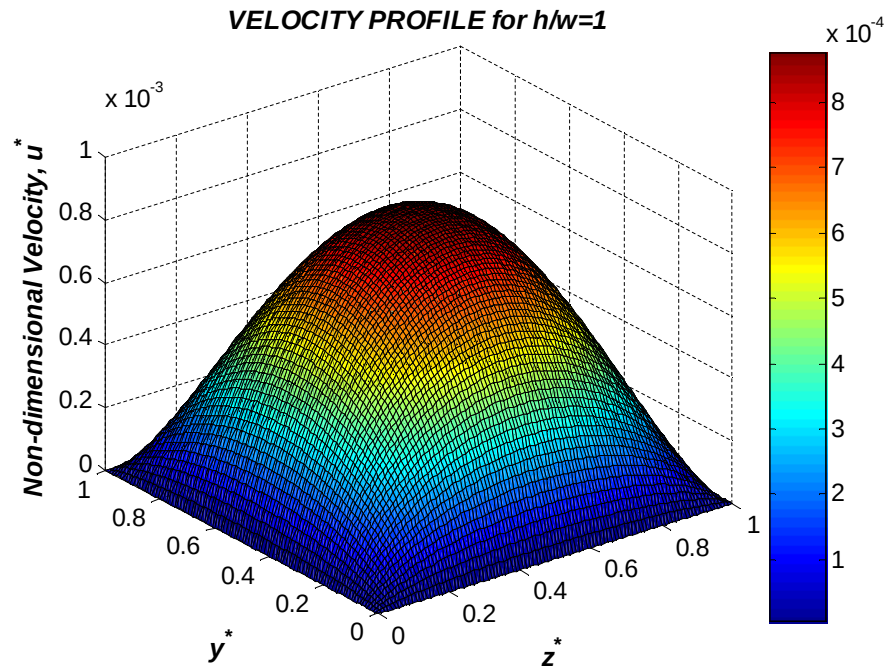
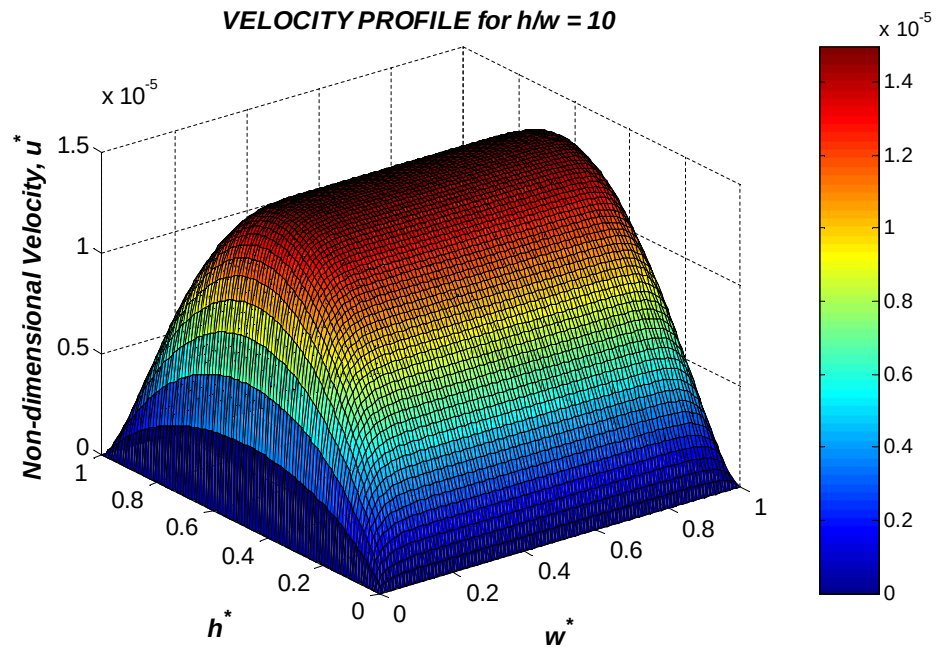


Figure 6.10 Velocity profile for a rectangular race-tracking channel with $h/w = 0.1$.

Figure 6.11 Velocity profile for a rectangular race-tracking channel with $h/w=1$.Figure 6.12 Velocity profile for a rectangular race-tracking channel with $h/w=10$.

6.5 Elliptical Race-Tracking Channels

The finite difference method solution can also be applied for race-tracking channels with other geometries such as elliptical, circular, triangular or any irregular shape. Using rectangular elements to approximate the elliptical domains, one can calculate the equivalent non-dimensional permeability as discussed in the previous sections. Figures 6.13 and 6.14 show the approximation of an elliptical domain by rectangular elements.

As in the rectangular channel case, a non-dimensional approach will be followed here. In Figure 6.14, a non-dimensional grid is shown for the calculation of the permeability of an elliptical race-tracking channel. It should be noted that, the elliptical cross-section becomes a circular one in the non-dimensional analysis. In Figure 6.14, this is designated with the circular region that is symmetric with respect to cc and dd axes. The dark colored elements approximate the hollow and circular channel and they are used in the finite difference method.

The equation of an ellipse with semi-major and semi-minor axes “ a ” and “ b ”, respectively, and centered at any point (z_0, y_0) is:

$$\frac{(z - z_0)^2}{a^2} + \frac{(y - y_0)^2}{b^2} = 1. \quad (6.27)$$

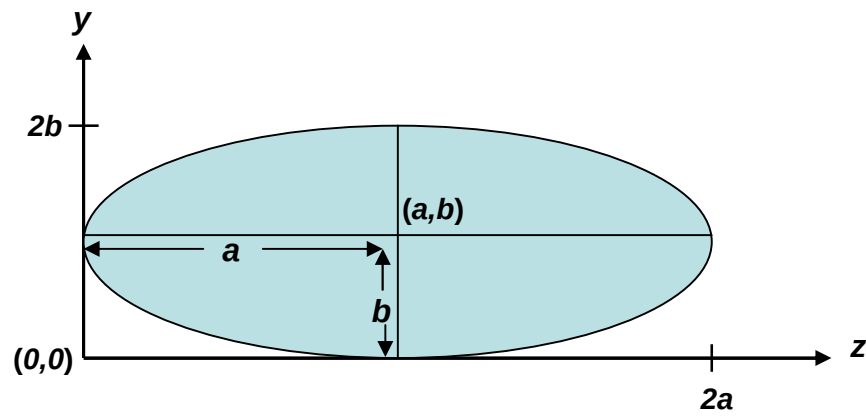


Figure 6.13 An ellipse with dimensions $2a$ and $2b$, centered at (a, b) .

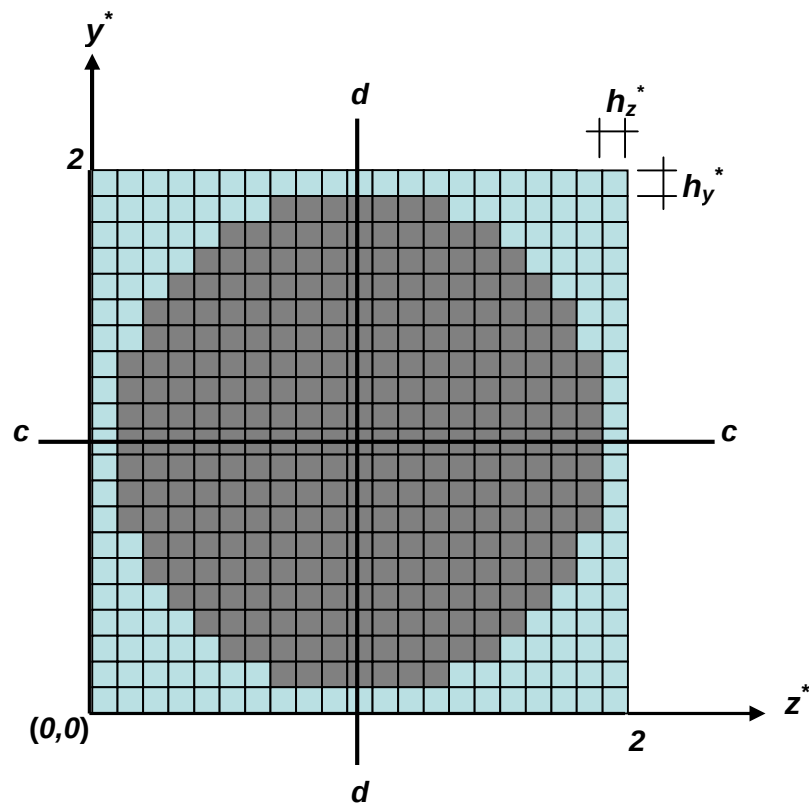


Figure 6.14 Non-dimensional grid for the calculation of the permeability of an elliptical race-tracking channel.

Equation (6.6) which was derived from Navier Stokes equations can be used here again:

$$\frac{dP}{dx} = m \left[\frac{u_{ref}}{y_{ref}^2} \frac{\partial^2 u^*}{\partial y^{*2}} + \frac{u_{ref}}{z_{ref}^2} \frac{\partial^2 u^*}{\partial z^{*2}} \right] \quad (6.28)$$

where

$$y = y^* y_{ref}, \quad y_{ref} = b \quad (6.29)$$

$$z = z^* z_{ref}, \quad z_{ref} = a \quad (6.30)$$

$$K = K^* K_{ref}, \quad K_{ref} = ab/8 \quad (6.31)$$

$$u = u^* u_{ref}, \quad u_{ref} = -\frac{K_{ref}}{m} \frac{dP}{dx} = -\frac{ab}{8m} \frac{dP}{dx}. \quad (6.32)$$

In Equation (6.31), the reason why $K_{ref} = ab/8$ is chosen as the reference permeability, comes from an analytical derivation that will be discussed in the next section.

Using Equations (6.29)-(6.32), Equation (6.28) can be rewritten as:

$$\frac{dP}{dx} = \frac{u_{ref} m}{b^2} \left[\frac{\partial^2 u^*}{\partial y^{*2}} + \left(\frac{b}{a} \right)^2 \frac{\partial^2 u^*}{\partial z^{*2}} \right] \implies \frac{\partial^2 u^*}{\partial y^{*2}} + \left(\frac{b}{a} \right)^2 \frac{\partial^2 u^*}{\partial z^{*2}} = -8 \left(\frac{b}{a} \right). \quad (6.33)$$

Using Equations (6.13) and (6.14) to approximate the second order derivatives, and rearranging, the final equation for the non-dimensional velocity becomes:

$$u^*(i, j) = \frac{c_1}{c_3} (u^*(i+1, j) + u^*(i-1, j)) + \frac{c_2}{c_3} (u^*(i, j+1) + u^*(i, j-1)) + \frac{8}{c_3 R} \quad (6.34)$$

where

$$R = \frac{a}{b}, \quad c_1 = \frac{1}{h_z^{*2}}, \quad c_2 = \frac{1}{h_y^{*2} R^2} \quad \text{and} \quad c_3 = 2(c_1 + c_2).$$

At boundary nodes, velocity is zero due to the no-slip boundary condition, and Equation (6.34) can be applied for interior nodes only. Finite difference method is applied to calculate non-dimensional velocity values at each of the interior nodes. The square grid used in the

analysis has dimensions of 2×2 , since the non-dimensional circle has a radius of 1 and centered at (1,1) (see Figure 6.14). Inputs to the program are the sizes of the non-dimensional increments, h_y^* and h_z^* . The program calculates the non-dimensional flow rate and then relates this to the non-dimensional permeability as shown below. Further details of the finite difference method coding for elliptical channels can be found in “*K_Elliptical_Racetracking_channel_nondim.m*”, in Appendix C.

From Section 6.4, it is known that:

$$Q = -\frac{K}{m} \frac{dP}{dx} A \quad \text{and} \quad Q = Q^* (u_{ref} A_{ref}).$$

Here, $A = pab$ and $A_{ref} = ab$. Equating the two flow rate equations as in the rectangular channel case:

$$-\frac{K}{m} \frac{\partial P}{\partial x} pab = Q^* \left(-\frac{K_{ref}}{m} \frac{\partial P}{\partial x} ab \right) \implies K^* = \frac{K}{K_{ref}} = \frac{Q^*}{p}. \quad (6.35)$$

Table 6.4 shows non-dimensional permeability values, K^* by using decreasing element sizes h_y^* and h_z^* , for a sample case of $a/b = 2$. Considering the computation time and for convenience of use of the code, an appropriate choice of element size can be made as $h_y^* = 0.010$ and $h_z^* = 0.010$. At this element size, non-dimensional permeability can be taken as $K^* = 0.802$ and the number of significant digits selected here (= 3) will be kept in further computations for other a/b ratios. The error tolerance value in the finite difference method is set as 1×10^{-8} by a similar procedure as followed in the rectangular channel case.

Table 6.4 Non-dimensional permeability as element size decreases for an elliptical channel.

Size of grid generated (Number of nodes)	21x21	41x41	81x81	101x101	201x201	251x251
$h_y^* = h_z^*$	0.100	0.050	0.025	0.020	0.010	0.008
K^*	0.81533	0.81168	0.80452	0.80760	0.80237	0.80258

In Figure 6.15, non-dimensional equivalent permeability, K^* is plotted versus elliptical race-tracking channels' aspect ratio. It is observed that, the rate of change of permeability in the region $1 \leq a/b \leq 10$ is small compared to region $0.1 \leq a/b \leq 1$. Therefore, a/b ratios starting from 0.1 to 1 have an increment of 0.1, and 1 to 10 have an increment of 0.2. As chosen, both non-dimensional increments, h_y^* and h_z^* are taken as 0.01, and thus a grid with 201 x 201 nodes is used in the finite difference method. All of the results are tabulated in Table 6.5.

From Figure 6.15, it can be concluded that when $a/b = 1$, non-dimensional permeability $K^* = K/K_{ref}$ approaches to 1. Looking at Table 6.5, the calculated value for K^* is 1.001 at $a/b = 1$. In the next section, this result will be checked by using an analytical solution.

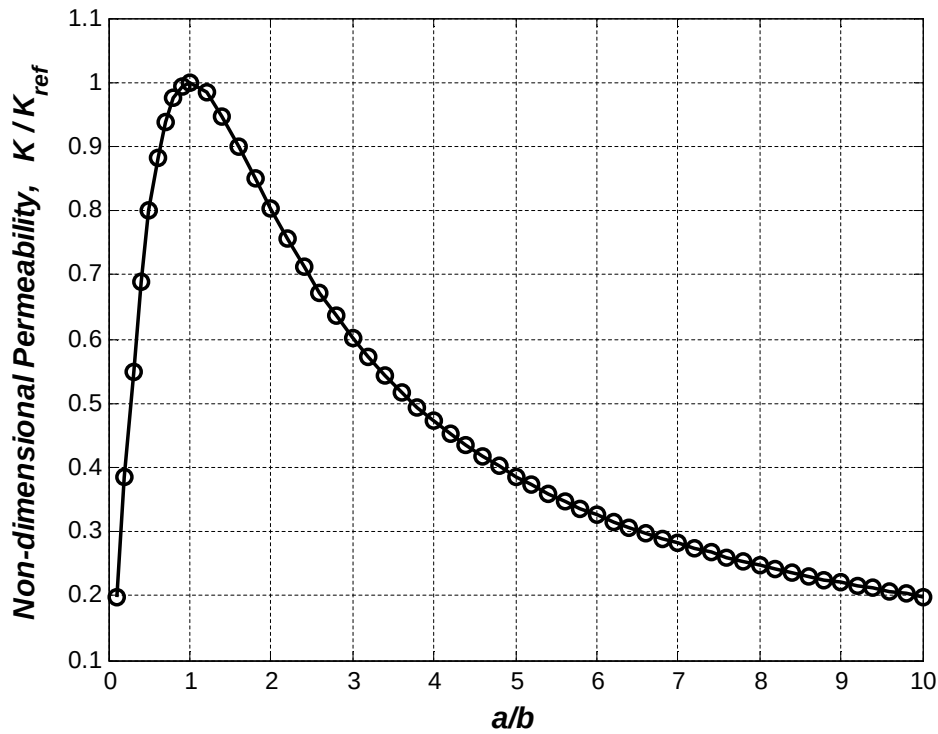


Figure 6.15 Non-dimensional permeability versus a/b ratio of an elliptical race-tracking channel.

Table 6.5 Non-dimensional permeability values for different a/b ratios for elliptical race-tracking channels.

a/b	K^*	a/b	K^*	a/b	K^*
0.1	0.198	2.8	0.636	6.4	0.307
0.2	0.384	3.0	0.602	6.6	0.298
0.3	0.550	3.2	0.572	6.8	0.289
0.4	0.689	3.4	0.544	7.0	0.282
0.5	0.799	3.6	0.518	7.2	0.274
0.6	0.882	3.8	0.494	7.4	0.267
0.7	0.939	4.0	0.473	7.6	0.260
0.8	0.975	4.2	0.453	7.8	0.254
0.9	0.995	4.4	0.434	8.0	0.247
1.0	1.001	4.6	0.417	8.2	0.242
1.2	0.985	4.8	0.401	8.4	0.236
1.4	0.948	5.0	0.387	8.6	0.231
1.6	0.901	5.2	0.373	8.8	0.226
1.8	0.851	5.4	0.360	9.0	0.221
2.0	0.802	5.6	0.348	9.2	0.216
2.2	0.756	5.8	0.337	9.4	0.212
2.4	0.713	6.0	0.326	9.6	0.207
2.6	0.673	6.2	0.316	9.8	0.203
				10.0	0.199

The calculation time was quite long: it took approximately 5 days to run the corresponding MATLAB code (on a 1.0 GB Ram PC) for the results of Table 6.5 and Figure 6.14. Figure 6.14 reveals that non-dimensional permeability values are very close to each other for a/b ratios of 0.5 and 2, and for a/b ratios 0.25 and 4, and so on. This is an expected result since the two ellipses are physically the same, one is horizontal and the other is vertical, and hence, the permeability does not change.

Figures 6.16, 6.17 and 6.18 show the velocity profiles for elliptical race-tracking channels with $a/b = 0.1$, 1 (corresponds to a circle) and 10 respectively. A closer look at Figure 6.16 and 6.18 reveals that these are actually the same velocity profiles, since they correspond to the same ellipse: one ellipse is horizontal the other is vertical. The MATLAB code named “3D_vel_profile_Elliptical.m” is given in Appendix C.

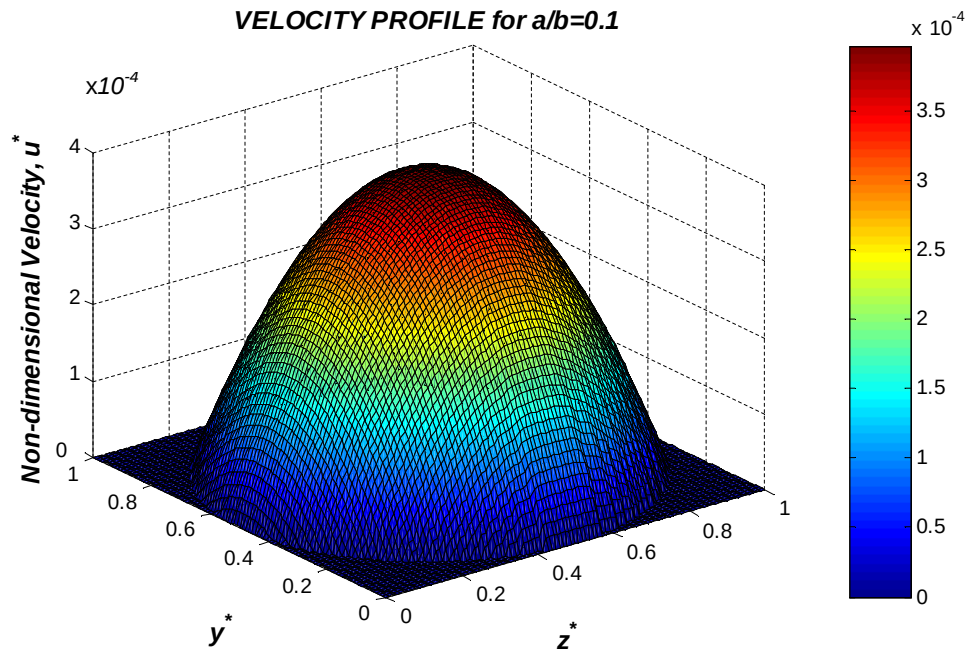


Figure 6.16 Velocity profile for an elliptical race-tracking channel with $a/b = 0.1$.

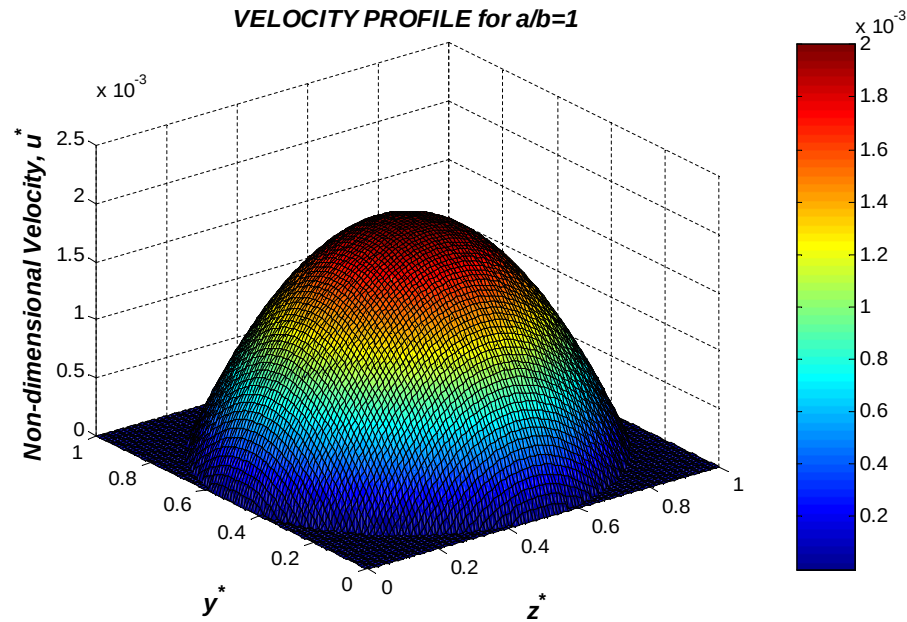


Figure 6.17 Velocity profile for an elliptical race-tracking channel with $a/b = 1$ (which corresponds to a circle)

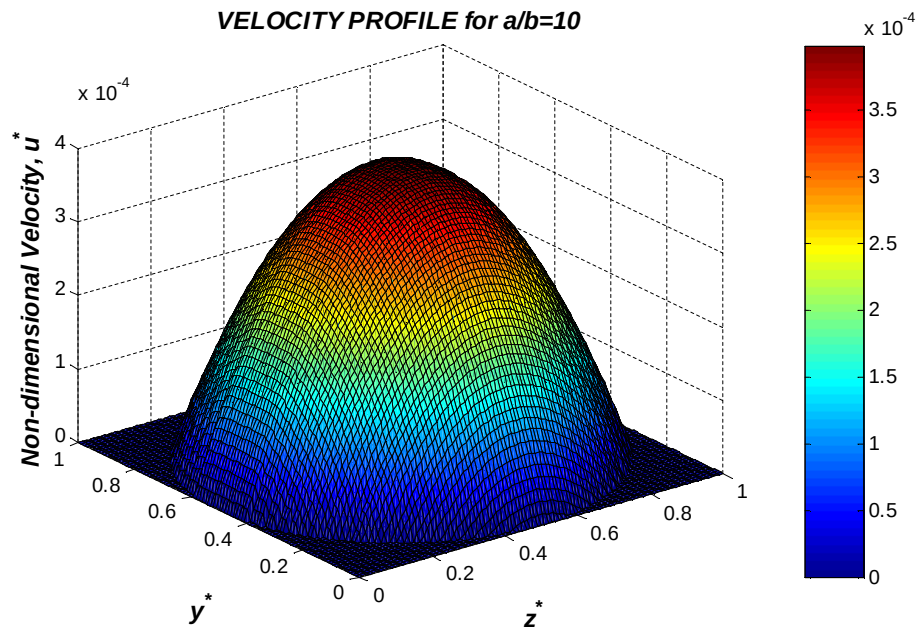


Figure 6.18 Velocity profile for an elliptical race-tracking channel with $a/b = 10$.

6.5.1 Fully Developed Circular Pipe Flow Analyzed For Verification Of Finite Difference Method

As described in the previous section, the equivalent non-dimensional permeability for an elliptical channel is calculated by using the finite difference method. By deriving an analytical equivalent permeability expression for a circular pipe, the validity of this method can be further tested. Recall that verification of the results were already done for the rectangular channel case. A race-tracking channel with an elliptical cross section will take the shape of a circular pipe for the ratio of $a/b = 1$. Then, one can compare the results of the finite difference method and the analytical expression.

One of the classical flow problems is considered here: Poiseuille flow where fluid flows through a circular channel due to a longitudinal pressure gradient as shown in Figure 6.19.

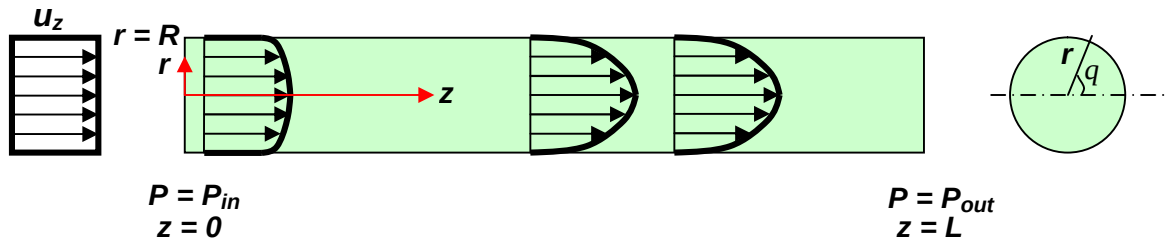


Figure 6.19 Poiseuille flow: pressure driven circular pipe flow.

Assumptions:

- Incompressible: $r = \text{constant}$
- Fully-developed flow: $\frac{\partial u}{\partial z} = 0$
- No body forces ($F_B = 0$).
- Quasi-steady flow: $\frac{\partial u}{\partial t} = 0$
- Axisymmetric: $\frac{\partial u}{\partial q} = 0$, $u_q = 0$

Boundary Conditions:

$$u_r(r=R)=0, \quad u_z(r=R)=0, \quad P(z=0)=P_{in}, \quad P(z=L)=P_{out}.$$

Continuity Equation:

$$\frac{1}{r} \frac{\partial(ru_r)}{\partial r} + \frac{1}{r} \frac{\partial u_q}{\partial q} + \frac{\partial u_z}{\partial z} = 0$$

$$\frac{1}{r} \frac{\partial(ru_r)}{\partial r} = 0 \implies ru_r \neq f(r) \implies ru_r = c_1 \implies u_r = \frac{c_1}{r}$$

$$\implies u_r(R)=0 = \frac{c_1}{R} \implies c_1 = 0 \quad \text{and} \quad u_r = 0 \quad \text{for all } r \text{ values.} \quad (6.36)$$

Momentum Equation in r direction:

$$r \left[\frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + \frac{u_q}{r} \frac{\partial u_r}{\partial q} - \frac{u_q^2}{r} + u_z \frac{\partial u_r}{\partial z} \right] =$$

$$-\frac{\partial P}{\partial r} + m \left[\frac{\partial}{\partial r} \left[\frac{1}{r} \frac{\partial(ru_r)}{\partial r} \right] + \frac{1}{r^2} \frac{\partial^2 u_r}{\partial q^2} + \frac{\partial^2 u_r}{\partial z^2} - \frac{2}{r^2} \frac{\partial u_q}{\partial q} \right] + F_{Br}$$

$$\implies -\frac{\partial P}{\partial r} = 0 \implies P \neq P(r) \implies P = P(z). \quad (6.37)$$

Momentum Equation in z direction:

$$r \left[\frac{\partial u_z}{\partial t} + u_r \frac{\partial u_z}{\partial r} + \frac{u_q}{r} \frac{\partial u_z}{\partial q} + u_z \frac{\partial u_z}{\partial z} \right] = -\frac{\partial P}{\partial z} + m \left[\frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial u_z}{\partial r} \right] + \frac{1}{r^2} \frac{\partial^2 u_z}{\partial q^2} + \frac{\partial^2 u_z}{\partial z^2} \right] + F_{Bz}$$

$$\implies \frac{\partial P}{\partial z} = m \frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial u_z}{\partial r} \right].$$

Left side is a function of z , and right side is function of r . For this equality to hold:

$$\frac{\partial P}{\partial z} = m \frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial u_z}{\partial r} \right] = \text{constant, which implies: } \frac{\partial P}{\partial z} = \frac{dP}{dz} = \frac{P_{out} - P_{in}}{L}$$

$$\Rightarrow \quad m \frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial u_z}{\partial r} \right] = \frac{P_{out} - P_{in}}{L} \quad (6.38)$$

Using the boundary condition, $u_r(r=R)=0$, and solving for $u_z(r)$:

$$u_z(r) = \frac{P_{out} - P_{in}}{4mL} (r^2 - R^2) \quad \text{and} \quad u_{z,max} = u_z(r=0) = -\frac{P_{out} - P_{in}}{4mL} R^2. \quad (6.39)$$

Volumetric flow rate:

$$\begin{aligned} \dot{Q} &= \int_A u_z dA = \int_0^R u_z 2\pi r dr = \int_0^R \frac{P_{out} - P_{in}}{4mL} (r^2 - R^2) 2\pi r dr \\ &\Rightarrow \quad \dot{Q} = -\frac{p (P_{out} - P_{in})}{8mL} R^4. \end{aligned} \quad (6.40)$$

Mean (Average) Velocity:

$$u_{z,mean} = \frac{\dot{Q}}{A} = \frac{-\frac{p (P_{out} - P_{in})}{8mL} R^4}{\pi R^2} = -\frac{(P_{out} - P_{in})}{8mL} R^2 = \frac{dP}{dx} \frac{R^2}{8m}. \quad (6.41)$$

Using Darcy's Law:

$$u = -\frac{K}{m} \frac{dP}{dx}, \quad \frac{dP}{dx} \frac{R^2}{8m} = -\frac{K}{m} \frac{dP}{dx} \Rightarrow K = \frac{R^2}{8} \quad \text{for a pipe with circular cross-section.} \quad (6.42)$$

In the previous section, reference permeability was taken as $K_{ref} = R^2/8$. As found in Equation (6.42), $K = R^2/8$ for a pipe with circular cross-section. This means that non-dimensional permeability should be equal to 1 ($K^* = K/K_{ref} = 1$, since $K = K_{ref}$). In fact, this is in quite good agreement with the previous section's finite difference method solution. Results have shown that non-dimensional permeability has the value of 1.001 for a circular

race-tracking channel. As a conclusion, the finite difference method can be considered to work fine for elliptical cross-sections besides rectangular cross-sections.

Notice that, the axis convention used here is not the same as the one used in the permeability calculations in the previous sections. Cylindrical coordinates r , q and z are used here. Label “ z ” used here corresponds to “ x ” axis that is used in the previous chapter.

6.6 Triangular Race-Tracking Channels

This section deals with the calculation of equivalent permeability of a race-tracking channel with triangular cross-section. A non-dimensional analysis together with the finite difference method will be applied just like the analysis done for other geometries in the previous sections.

Figure 6.20 shows a channel with triangular cross-section defined with dimensions a , c , h and angle a . Any three of these four parameters will be enough to define a triangular section. Equations for the two inclined edges of the triangle on the z - y plane are shown in the same figure.

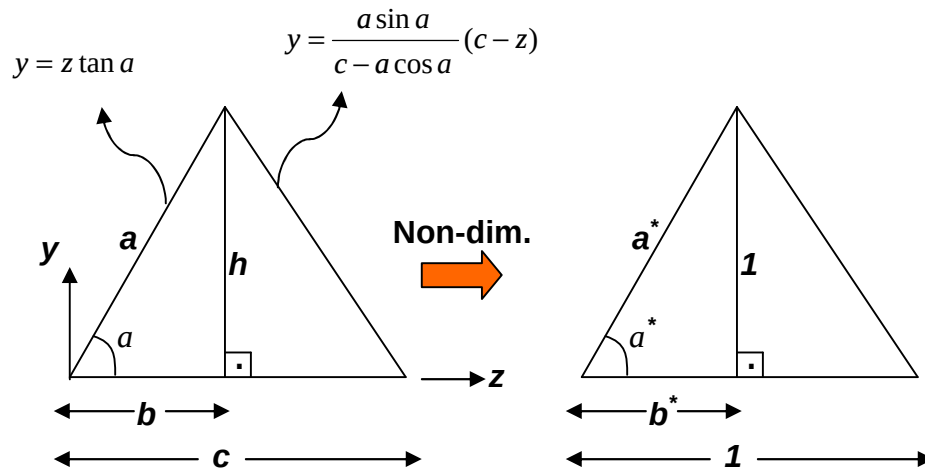


Figure 6.20 Non-dimensionalization of the triangular cross-section.

In Figure 6.20, the parameters of the triangle are non-dimensionalized by base c and height h . Notice that: $a = h / \sin a$ and $b = a \cos a$. From the non-dimensional triangle:

$$b^* = \frac{b}{c} = \frac{a \cos a}{c} \quad (b \text{ is non-dimensionalized by 'c'})$$

Also,

$\tan a^* = \frac{1}{b^*} = \frac{c}{a \cos a}$, substituting 'a' from the dimensional triangle equations:

$$\tan a^* = \frac{c}{h} \tan a \quad \Rightarrow \quad a^* = \tan^{-1} \left(\frac{c}{h} \tan a \right). \quad (6.43)$$

In Figure 6.21, a non-dimensional grid for the finite difference method is shown. The coding for this geometry is quite similar to the previous coding. Inputs to the program are angle a , c/h ratio, and increment sizes h_y^* and h_z^* . Details can be found in “*K_Triangular_Racetracking_channel_nondim.m*” in Appendix C.

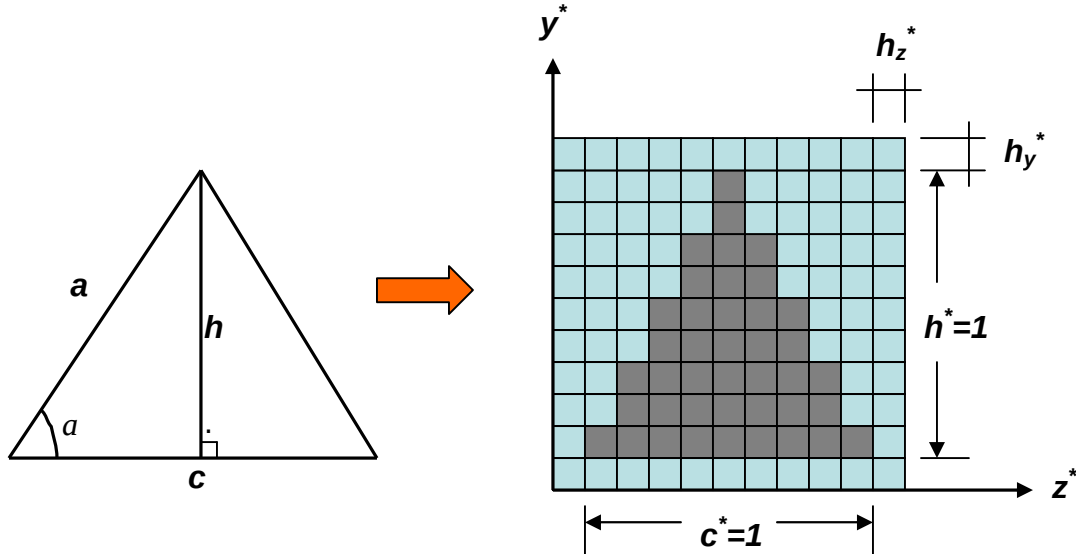


Figure 6.21 Non-dimensional grid for the triangular race-tracking channel.

The finite difference method starts with the same original equation:

$$\frac{dP}{dx} = m \left[\frac{u_{ref}}{y_{ref}^2} \frac{\partial^2 u^*}{\partial y^{*2}} + \frac{u_{ref}}{z_{ref}^2} \frac{\partial^2 u^*}{\partial z^{*2}} \right] \quad (6.44)$$

where

$$y = y^* y_{ref}, \quad y_{ref} = h \quad (6.45)$$

$$z = z^* z_{ref}, \quad z_{ref} = c \quad (6.46)$$

$$K = K^* K_{ref}, \quad K_{ref} = hc \quad (6.47)$$

$$u = u^* u_{ref}, \quad u_{ref} = -\frac{K_{ref}}{m} \frac{dP}{dx} = -\frac{hc}{m} \frac{dP}{dx}. \quad (6.48)$$

Rearranging (6.44):

$$\frac{dP}{dx} = \frac{u_{ref} m}{h^2} \left[\frac{\partial^2 u^*}{\partial y^{*2}} + \left(\frac{h}{c} \right)^2 \frac{\partial^2 u^*}{\partial z^{*2}} \right]$$

$$\text{and substituting } u_{ref} \implies \frac{\partial^2 u^*}{\partial y^{*2}} + \left(\frac{h}{c} \right)^2 \frac{\partial^2 u^*}{\partial z^{*2}} = -\frac{h}{c}. \quad (6.49)$$

Using Equations (6.13) and (6.14) to approximate the second order derivatives, and rearranging for non-dimensional velocity:

$$u^*(i, j) = \frac{c_2}{c_3} \left[u^*(i+1, j) + u^*(i-1, j) \right] + \frac{c_1}{c_3} \left[u^*(i, j+1) + u^*(i, j-1) \right] + \frac{1}{c_3 R} \quad (6.50)$$

where

$$R = \frac{c}{h}, \quad c_1 = \frac{1}{h_y^{*2}}, \quad c_2 = \frac{1}{h_z^{*2} R^2} \quad \text{and} \quad c_3 = 2(c_1 + c_2).$$

Finite difference method uses Equation (6.50) to solve for the equivalent non-dimensional permeability. The method calculates velocity and then flow rate which can be related to non-dimensional permeability. For triangular cross-sections:

$$\frac{A}{A_{ref}} = \frac{ch/2}{ch} \implies K^* = 2Q^*. \quad (6.51)$$

The algorithm handles a triangle by dividing it into two right triangles one with base b^* , and the other with base $1 - b^*$ (see Figure 6.20). Therefore, in cases of $b^* > 1$, that is when the whole cross-section is not an acute but an obtuse triangle, the algorithm fails. Needless to

say, it can be modified to handle obtuse triangular cross-sections as well. However, in this study, only acute triangular cross-sections are considered. Thus, $b^* < 1$ must be satisfied.

$$b^* < 1 \implies a^* \cos a^* < 1, \quad a^* = 1/\sin a^* \implies \cot a^* < 1 \implies a^* > 45^\circ.$$

Also, $a^* < 90^\circ$ must be satisfied to form an acute triangle. As a result,

$$45^\circ < a^* < 90^\circ. \quad (6.52)$$

To specify the element size, a simple convergence check is made as done before and $h_y^* = h_z^* = 0.01$ is chosen. Results are plotted in Figure 6.22 with an increment of 0.1 for c/h ratio. Table 6.6 summarizes non-dimensional permeability results for different a^* angles and c/h ratios.

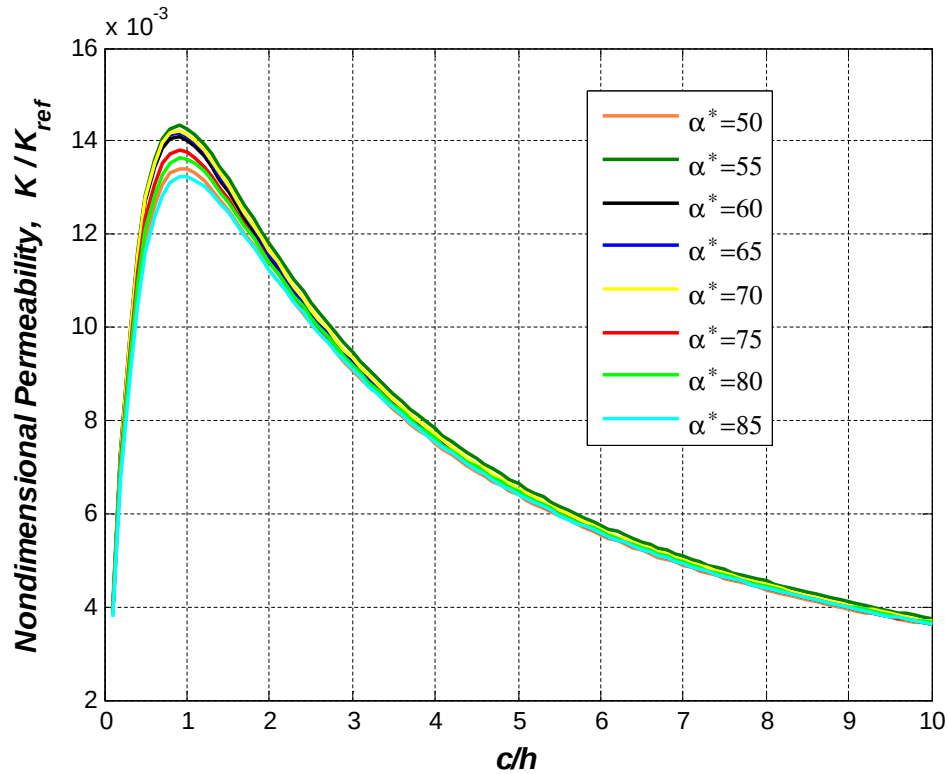


Figure 6.22 Non-dimensional permeability values for a race-tracking channel with a triangular cross-section.

The results tabulated have 2 significant digits when the elements used in FDM has a value of $h_y^* = h_z^* \approx 0.01$.

Table 6.6 Non-dimensional permeability results for triangular channels.

$\begin{matrix} \backslash & a^* \\ c/h \end{matrix}$	50°	55°	60°	65°	70°	75°	80°	85°
0.5	0.012	0.013	0.013	0.013	0.013	0.012	0.012	0.012
1.0	0.013	0.014	0.014	0.014	0.014	0.014	0.014	0.013
1.5	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.012
2.0	0.011	0.012	0.012	0.012	0.012	0.011	0.011	0.011
2.5	0.010	0.011	0.010	0.010	0.010	0.010	0.010	0.010
3.0	0.0091	0.0095	0.0092	0.0093	0.0093	0.0092	0.0092	0.0091
3.5	0.0082	0.0086	0.0083	0.0084	0.0084	0.0083	0.0083	0.0083
4.0	0.0075	0.0078	0.0076	0.0076	0.0077	0.0076	0.0076	0.0076
4.5	0.0069	0.0072	0.0070	0.0070	0.0071	0.0070	0.0070	0.0069
5.0	0.0064	0.0066	0.0065	0.0065	0.0065	0.0064	0.0065	0.0064
5.5	0.0059	0.0062	0.0060	0.0060	0.0061	0.0060	0.0060	0.0060
6.0	0.0055	0.0058	0.0056	0.0056	0.0057	0.0056	0.0056	0.0056
6.5	0.0052	0.0054	0.0052	0.0053	0.0053	0.0052	0.0053	0.0052
7.0	0.0049	0.0051	0.0049	0.0050	0.0050	0.0049	0.0050	0.0049
7.5	0.0046	0.0048	0.0047	0.0047	0.0047	0.0046	0.0047	0.0046
8.0	0.0044	0.0045	0.0044	0.0044	0.0045	0.0044	0.0044	0.0044
8.5	0.0042	0.0043	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042
9.0	0.0040	0.0041	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040
9.5	0.0038	0.0039	0.0038	0.0038	0.0039	0.0038	0.0038	0.0038
10.0	0.0036	0.0037	0.0036	0.0037	0.0037	0.0036	0.0037	0.0036

An analytical solution for the verification of this triangular method is not available. However, considering the previous verified results, this method is expected to give correct results. The method is consistent in itself, where it calculates exactly the same permeability value for the two different triangles as shown in Figure 6.23.

A remark on the use of Gauss Seidel iteration method is be made in Appendix C. A comparison for the Gauss Seidel iteration method and Gauss elimination method is made for their usages in FDM.

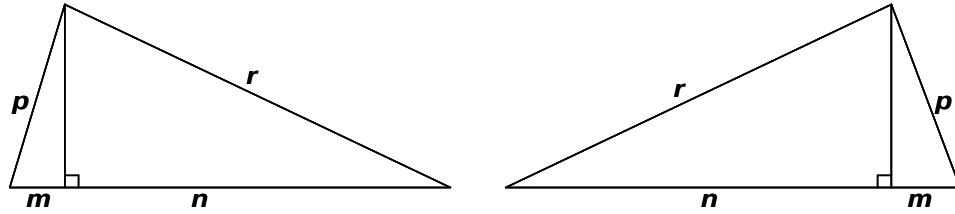


Figure 6.23 A simple check for the consistency of the method for triangular sections.

Velocity profiles (Equation (6.50)) for two sample cases are shown in Figures 6.24 and 6.25. MATLAB code named “3D_vel_profile_Triangular.m” is given in Appendix C.

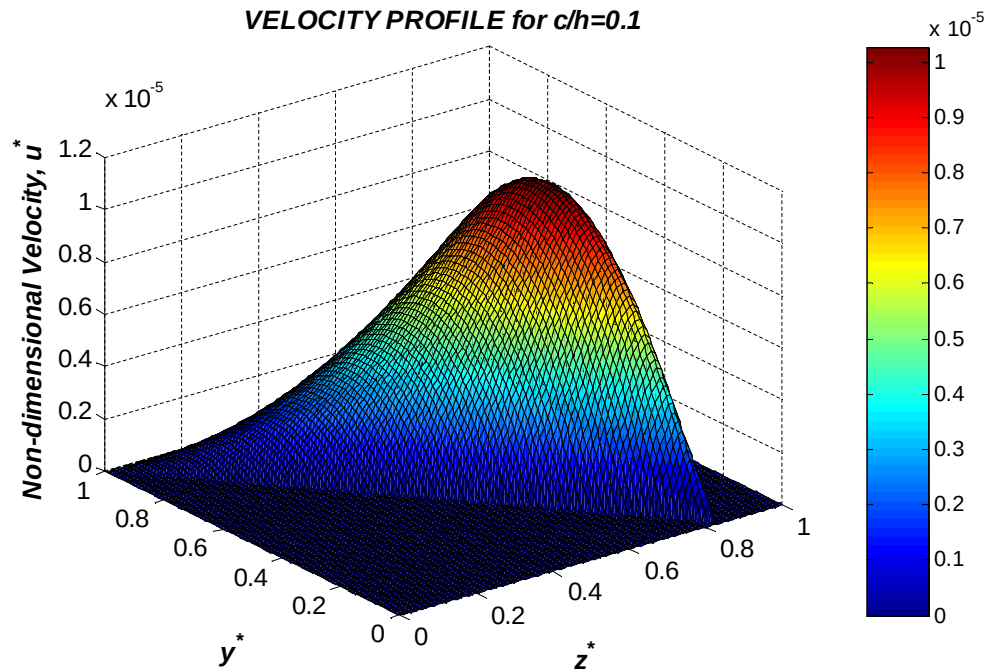


Figure 6.24 Velocity profile for a triangular channel with $a^* = 50$ and $c/h = 0.1$.

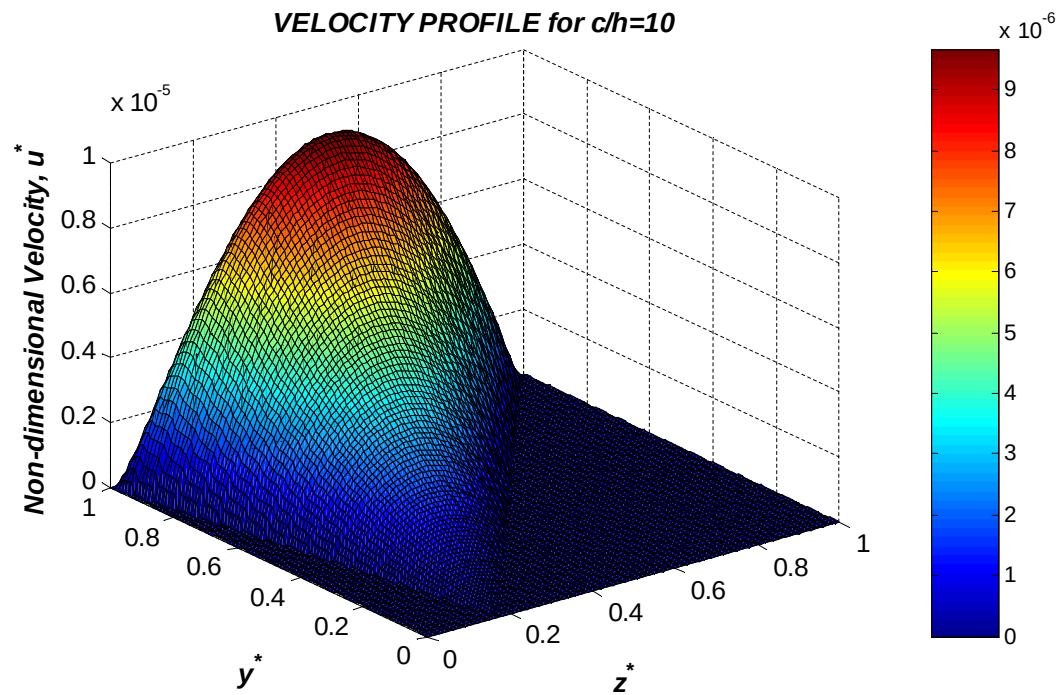


Figure 6.25 Velocity profile for a triangular channel with $a^* = 80$ and $c/h = 10$.

6.7 Race-Tracking Channels with an Irregular Shape

FDM method can also be applied to race-tracking channels which do not have a simple shape like the ones presented in the previous sections. Once a prototype composite part is inspected to get a distribution of race-tracking channel's width, w_{race} along the edges, our model can be easily applied to calculate equivalent permeabilities of corresponding channels. A schematic of such a hypothetical race-tracking channel is shown in Figure 6.26. A grid is fit to the channel, and then FDM solution method is applied as illustrated in previous sections.

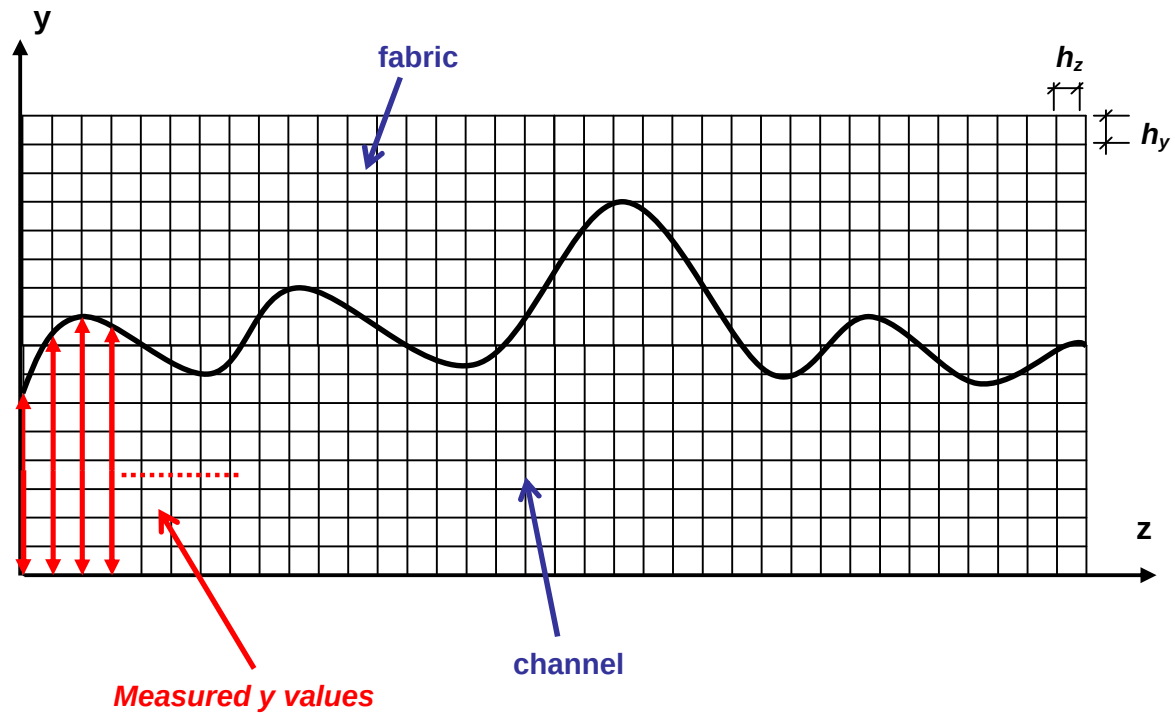


Figure 6.26 An irregular sectioned race-tracking channel.

Chapter 7

MOLD FILLING SIMULATIONS AND ONE-DIMENSIONAL PERMEABILITY MEASUREMENTS

In this chapter, we are going to use a mold filling simulation program, LIMS (Liquid Injection Molding Simulation) [53] for the following two main reasons:

- In the previous chapter, we had studied how to calculate the equivalent permeabilities of different race-tracking channels that might exist along the edges and/or corners of a preform placed in a mold. We will input this preform material data to the mold filling simulations to see if the selected locations of gates and vents, and the injection conditions can result in a complete mold filling or not.
- In addition to the equivalent permeability of race-tracking channels, we also need the permeability tensor of a bulk fabric preform to be input to the simulation program, LIMS. For that purpose, one can use a preform permeability predictor model, such as PERM [66] by carefully constructing a repetitive unit cell, and applying a pressure gradient along the direction where the component of permeability tensor is to be calculated. Velocity distribution is solved by assuming Stokes flow in between the fiber tows, and one-dimensional Darcy flow between the fabric layers in the transverse direction. Another alternative for permeability of a preform, is to preform one-dimensional injections, and by using Darcy's Law and experimental injection pressure data, calculate the permeability component along the flow direction. However, it is a very difficult task to obtain precisely one-dimensional flow due to nonuniformity of preform and race-tracking effects. Thus, we will use mold filling

simulations to come up with a correction factor for permeability calculations after matching the experimental and simulation results.

Since LIMS is going to be used as a design tool, one needs to understand how the mold filling is modeled. In the next section, we will go over that model.

7.1 Modeling of Mold Filling

In typical RTM applications, the thickness of the mold cavity is much smaller than in-plane dimensions. Hence, the flow in thickness direction can be usually neglected.

7.1.1 Governing Equations

As studied earlier, for low Reynolds number flows through a porous fabric, Darcy's Law replaces the conservation of momentum equation:

$$\begin{pmatrix} \bar{u}_x \\ \bar{u}_y \end{pmatrix} = -\frac{1}{m} \begin{pmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{pmatrix} \begin{pmatrix} \partial P / \partial x \\ \partial P / \partial y \end{pmatrix} \quad (7.1)$$

where $\bar{u}_x$ and $\bar{u}_y$ are the averaged velocity components through the thickness direction z , m is the resin viscosity, K_{ij} is the ij^{th} component of permeability tensor, and $\partial P / \partial x$ and $\partial P / \partial y$ are the pressure gradients in x and y directions, respectively.

Conservation of mass for 2D and quasi-steady flows is given as follows:

$$\frac{\partial}{\partial x}(\bar{u}_x) + \frac{\partial}{\partial y}(\bar{u}_y) = 0 . \quad (7.2)$$

By substituting Equation (7.1) into Equation (7.2), one can obtain the governing differential equation for isothermal resin flow [67]:

$$\frac{\partial}{\partial x} \left(\frac{K_{xx}}{m} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial x} \left(\frac{K_{xy}}{m} \frac{\partial P}{\partial y} \right) + \frac{\partial}{\partial y} \left(\frac{K_{yx}}{m} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{K_{yy}}{m} \frac{\partial P}{\partial y} \right) = 0. \quad (7.3)$$

This differential equation has resin pressure, P as the only unknown.

In order to simulate the propagation of flow front, Equation (7.3) is solved by using Finite Element Method (FEM) within the filled region only. In order to get a unique solution the following boundary conditions are used. After the solution of P , the flow front is advanced by using a control volume approach as explained in the next section.

7.1.2 Boundary conditions:

At the injections gate(s), either one of the following boundary conditions is used:

a1) Constant injection pressure:

$$P = P_{inj}. \quad (7.4)$$

or,

a2) Constant injection flow rate: (as applied in the experiments of this study)

$$A \left(-\frac{K}{m} \cdot \nabla P \right) \cdot n = -Q_{inj}. \quad (7.5)$$

b) At the mold wall, there is no leakage of resin, and hence the normal component of velocity is zero:

$$\bar{u}_n = -\frac{1}{m} \left(K_{nn} \frac{\partial P}{\partial n} + K_{nt} \frac{\partial P}{\partial t} \right) = 0 \quad (7.6)$$

where n and t are the normal and tangential direction on the mold wall.

c) At the flow front connected to a ventilation:

$$P_{ff} = P_{vent}. \quad (7.7)$$

d) At the flow front disconnected from a ventilation:

$$\frac{P_{void} V_{void}}{T_{void}} = \text{constant}. \quad (7.8)$$

The governing differential equation (Equation (7.3)) and the boundary conditions are illustrated in Figure 7.1.

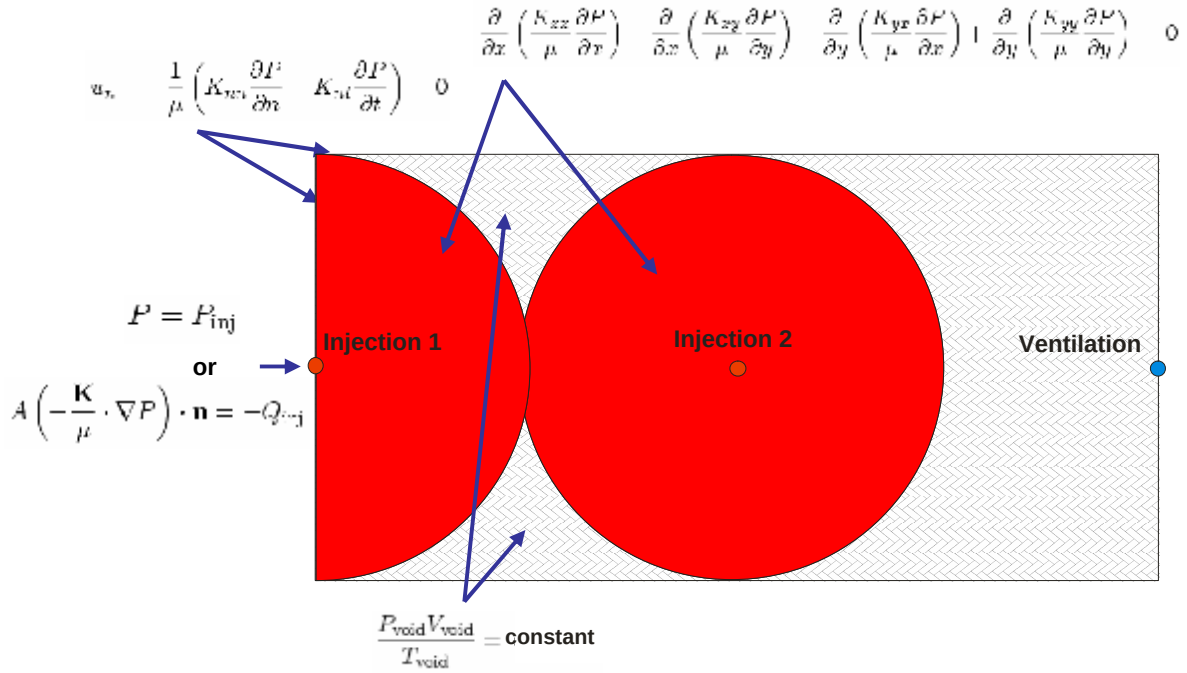


Figure 7.1 Governing differential equation and boundary conditions for modeling the resin flow.

7.2 Numerical Mold Filling Simulations (by using LIMS)

In this study, LIMS [53] is used for simulating the filling stage of RTM process. As stated in previous chapters, LIMS is an element of the integrated control system, and enables mold filling simulations for different injection conditions. It is used as a design tool for determination of the location of the injection and ventilation ports, and sensors. In this chapter, contribution of LIMS to 1D permeability measurements will be demonstrated.

LIMS uses FEM/CV (Finite Elements/Control Volume) method for the solution of the pressure distribution inside a mold, and then for flow front progression with time. A post-

processor program such as MATLAB [68] is used after LIMS for drawing contour plots of flow front at different times, and for animating the filling process. A brief description of the FEM/CV method is given below.

First, the continuous domain of mold cavity is represented with a discrete mesh. Pressure distribution is expressed by using the nodal pressure values, P_i and “interpolation functions”, $N_i(x, y)$ within elements of the mesh as follows:

$$P^e = \sum_{i=1}^n N_i P_i. \quad (7.9)$$

Galerkin FEM is applied that yields the following set of equations:

$$[[S^e]] [P] = [f] \quad (7.10)$$

where

$$S_{ij}^e = \int_{\Omega} \left(\frac{K_{xx}}{m} \frac{\partial N_j}{\partial x} \frac{\partial N_i}{\partial x} + \frac{K_{yy}}{m} \frac{\partial N_j}{\partial y} \frac{\partial N_i}{\partial y} + \frac{K_{xy}}{m} \frac{\partial N_j}{\partial x} \frac{\partial N_i}{\partial y} + \frac{K_{xy}}{m} \frac{\partial N_j}{\partial y} \frac{\partial N_i}{\partial x} \right) d\Omega. \quad (7.11)$$

While the unknown P_i 's are being solved as explained above, only the nodes of resin-filled section (shown with darker region in Figure 7.2) is used, since the pressure in the rest of the mold is equal to P_{vent} (which is usually equal to zero).

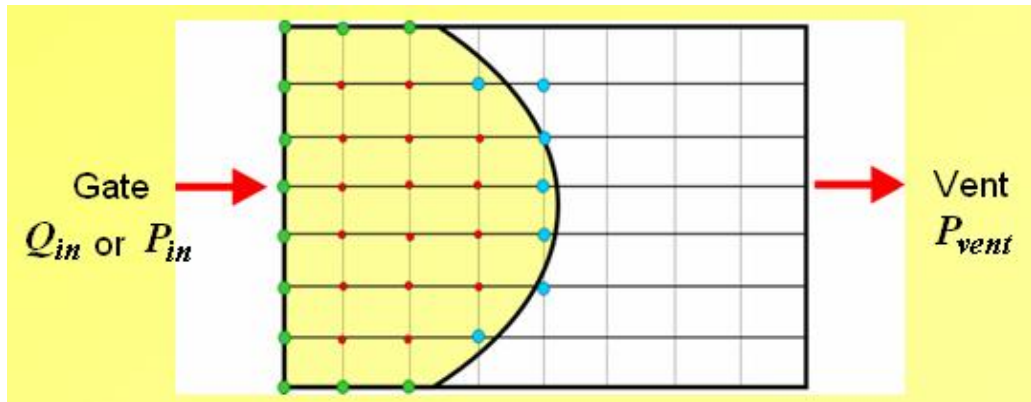


Figure 7.2 Resin-filled region to be used for the calculation of pressure.

After the pressure is solved by using FEM, then the flow front is advanced as follows. Flux from the j^{th} control area to i^{th} control area (Figure 7.3) is calculated:

$$q_{ij} = - \int_{s_{ij}} \left(\frac{h}{m} \mathbf{n} \cdot \mathbf{K} \cdot \nabla P \right) ds \quad (7.12)$$

and then, the total flux from all the neighbor control areas to the i^{th} control area is calculated by summing the individual fluxes:

$$Q_i = \sum_{j=1}^n q_{ij} \Delta t. \quad (7.13)$$

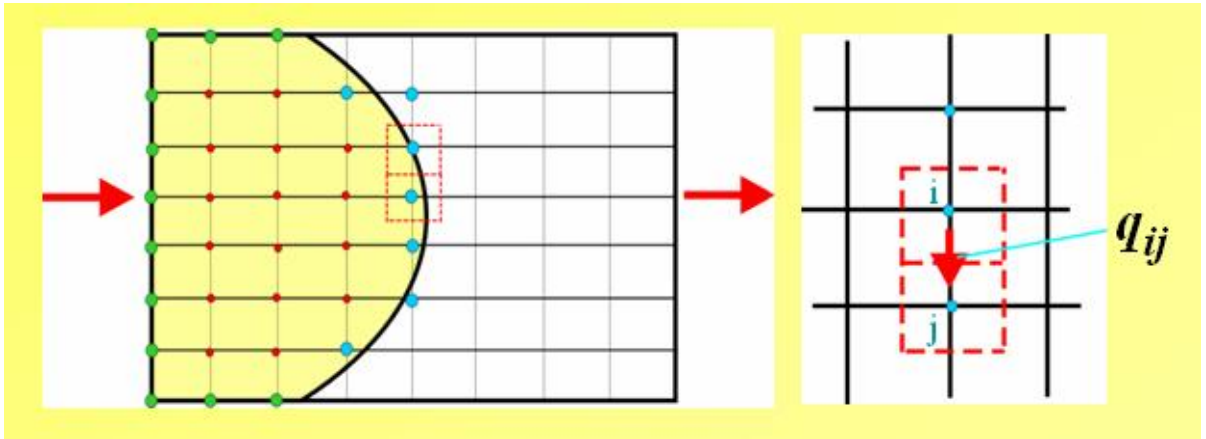


Figure 7.3 Resin flux from one control area to the adjacent one.

This solution scheme (i.e., “FEM for P and CV for flow front advancement”) is repeated until the entire mold is filled.

7.3 Preparation of FEM Mesh for LIMS input file

7.3.1 LIMS Input File

```
* MESH
NODES
* node, x, y, z
1 0.000 0.000 0.000
2 0.008 0.000 0.000
3 .....

ELEMENTS
* element, mat, gap, nodes
1 1 0.005 1 2 91 90
2 1 0.005 .....
.....

1761 2 0.005 1781 1782 1871 1870
1762 2 0.005 .....
.....

* viscosity input block
Viscosity
*MODEL, ETA
1, 0.5
ENd
* end of viscosity block

* material block
Material
*K11, K22, K12, IAX, VF
5.00e-09, 5.00e-09, 0.0, 1, .471
5.00e-08, 5.00e-08, 0.0, 1, .471
.....
END
* end of material block

CHarge
* node #, fill factor
982, 1
893, 1
END
* end of charge block

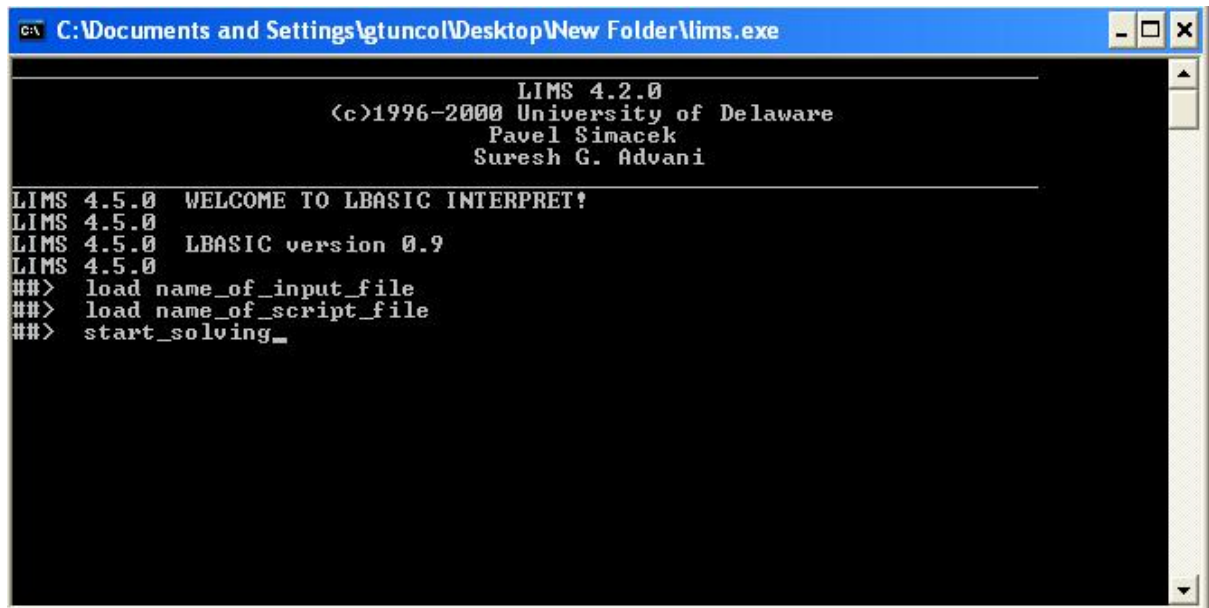
Gate
* node #, type, value
982 2 0.83335e-6
893 2 0.83335e-6
END
```

Figure 7.4 Different sections of LIMS input file.

Figure 7.4 shows different blocks (sections) of a LIMS input file. Each block specifies a different information for LIMS. Nodes block contains node number and their x, y, z coordinates. Elements block contains element number, material-type number (mat), mold thickness (gap), and the connectivity of the nodes for each element. Separate material numbers can be assigned for sections having different material property (such as permeability, thickness, or fiber volume fraction). Viscosity block contains the viscosity value for the resin. Material block contains permeability tensor information and the fiber volume fraction ($V_f = 1-f$) where f is the porosity ratio of the preform.

Each line in the material block corresponds to different material types. The first line corresponds to material type 1, the second line corresponds to material type 2, and so on. Charge block specifies information on the filling percentage (fill factor = 100 % corresponds to a complete saturation of the fabric at that location) of the injection nodes. Gate block specifies the injection nodes and the type of injection (the most commonly used two alternatives are; 1: constant pressure, and 2: constant flow rate). Injection pressure or flow rate is specified on the same line if the gate type is 1 or 2, respectively.

Apart from the input file (text file with a .in extension), LIMS needs a script file (text file with a .lb extension) where commands are written for LIMS solution and for generation of output files for post-processing. A sample script file is given in Appendix D. Figure 7.5 shows LIMS screen and the input commands for LIMS to start solution. With “load” command, the input and script files are loaded. After typing and entering the procedure name (e.g. start_ solving) that is used in this script file, input file is read and the necessary control schemes are activated.



```
C:\Documents and Settings\gtunco\Desktop\New Folder\lms.exe

LIMS 4.2.0
<c>1996-2000 University of Delaware
Pavel Simacek
Suresh G. Advani

LIMS 4.5.0 WELCOME TO LBASIC INTERPRET!
LIMS 4.5.0
LIMS 4.5.0 LBASIC version 0.9
LIMS 4.5.0
##> load name_of_input_file
##> load name_of_script_file
##> start_solving_
```

Figure 7.5 LIMS screen.

It is possible to print various information about mold filling on the LIMS screen. As shown in Figure 7.6, information such as time, number of empty and filled nodes can be viewed as LIMS progresses. However, for a detailed analysis of results, a post-processor such as MATLAB is used.

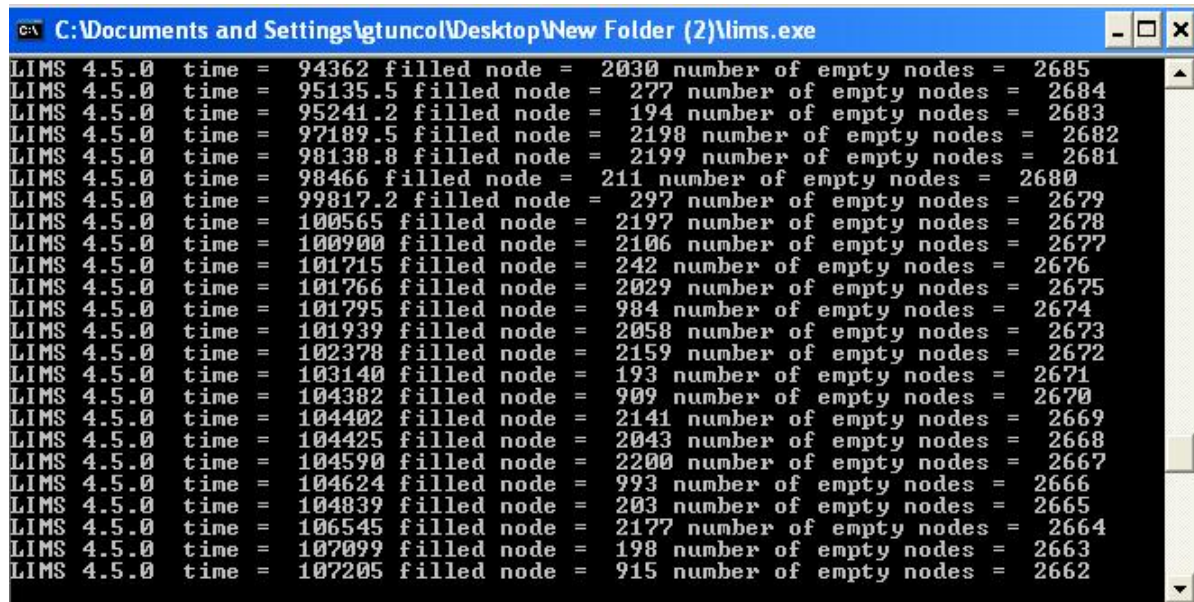


Figure 7.6 Information on mold filling as LIMS progresses.

7.3.2 FEM Mesh Created by Unigraphics

To generate the input file for LIMS, a FEM mesh generator is necessary. In this study, Unigraphics [69] was used to generate the FEM meshes and obtain the corresponding mesh data. Shell elements were used in this study. Figure 7.7 shows two examples of the meshes created by Unigraphics. In order to adjust the format of Unigraphics' output file according to LIMS's required format, a transformation file was developed in MATLAB. A sample input file preparation is documented in Appendix D.

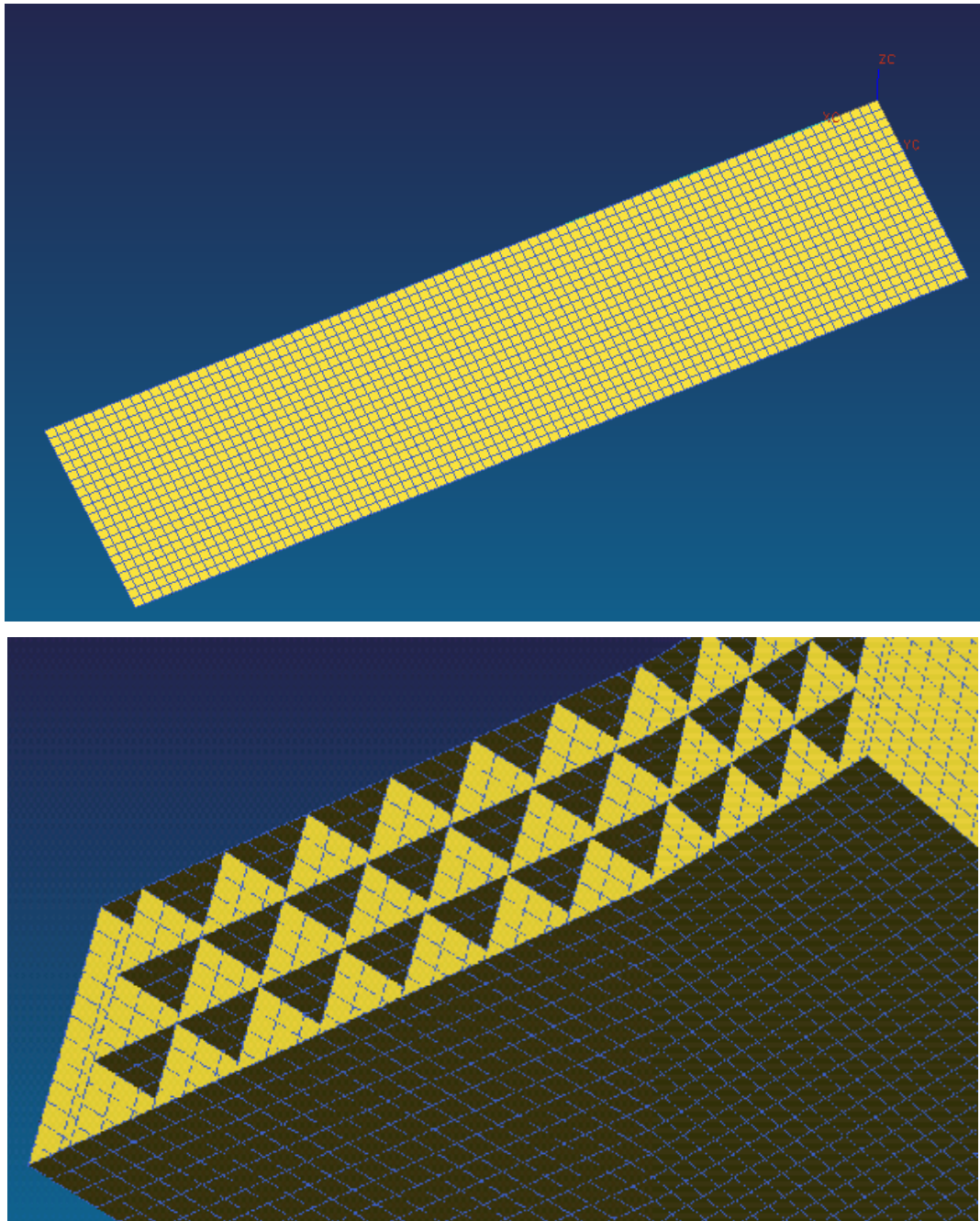


Figure 7.7 Two sample meshes created by Unigraphics using shell elements.

7.4 One-dimensional (1D) Permeability Measurements

7.4.1 Introduction

For accurate LIMS simulations, the input permeability value has to be assigned accurately. For this purpose, permeability of the preform must be available. In the literature, mathematical models were proposed, and databases were created for preform permeability [13,14,15,34]. Alternatively, one can do 1D injection experiments to measure the permeability. However, it is difficult to create a perfectly 1D injection due to the variations involved and the non-uniform structure of fiber preforms. Thus, results may vary from one experiment to the other.

With 1D experiments, preform permeability in the flow direction can be measured. To measure the permeability in the other principal direction, preform should be rotated and the experiment should be repeated .

In order to derive a relation between the permeability and experimental injection data, we will follow Simon Bickerton's study [70] as outlined in the following section.

7.4.2 Relation between Permeability and Experimental Injection Data

As discussed in Chapter 6, Darcy's Law takes the following form for 1D case:

$$\bar{u} = -\frac{K}{m} \frac{dP}{dx} \quad \text{and} \quad \bar{u} = f u_f \quad \Rightarrow \quad u_f = -\frac{K}{fm} \frac{dP}{dx}. \quad (7.14)$$

where

u_f : velocity of flow front, [m/s]

K : permeability of the preform in the direction of flow, [m²]

f : porosity of fabric preform, [varies between 0 and 1; dimensionless]

m : viscosity of polymer, [Pa.s]

P : resin pressure, [Pa]

x : axis in flow direction, [m]

$\bar{u}$: volume averaged resin velocity, [m/s]

Experiments are made under a constant flow rate, thus:

$$Q = \text{constant} = \bar{u}A = (f u_f)(wh) \quad \Rightarrow \quad u_f = \frac{Q}{f wh} = \text{constant} \quad (7.15)$$

where $A = wh$ is the cross-sectional area, and w and h are the width and thickness of the mold cavity, respectively.

Equating Equations (7.14) and (7.15), one can get:

$$-\frac{K}{fm} \frac{dP}{dx} = \frac{Q}{f wh} \quad \Rightarrow \quad \frac{dP}{dx} = -\frac{Qm}{K wh} = \text{constant} \quad (\text{since } Q = \text{constant}) \quad (7.16)$$

According to Equation (7.16), pressure decreases linearly in the flow direction. The boundary conditions are: $P(x = x_f) = 0$ and $P(x = 0) = P_{in}$, where P_{in} is the injection pressure. Then, dP/dx can be rewritten as:

$$\frac{dP}{dx} = \frac{P(x_f) - P(0)}{x_f - 0} = \frac{0 - P_{in}(t)}{u_f t} \quad (7.17)$$

where x_f is the location of flow front, and $x_f = u_f t$. If we insert Equation (7.15) in Equation (7.17):

$$\frac{dP}{dx} = -\frac{P_{in}(t) f wh}{Q t} \quad (7.18)$$

Equating Equations (7.16) and (7.18):

$$-\frac{Qm}{K wh} = -\frac{P_{in}(t) f wh}{Q t} \quad \Rightarrow \quad P_{in}(t) = \left(\frac{Q}{wh} \right)^2 \frac{m}{f K} t \quad (7.19)$$

Solving for K in Equation (7.14) gives:

$$K = \left(\frac{Q}{wh} \right)^2 \frac{m}{f} \frac{1}{\frac{dP}{dt}} \quad (7.20)$$

where dP/dt is the slope of injection pressure.

Hence, once we know the parameters Q , w , h , μ and f , and record the experimental injection pressure, we can calculate the permeability, K by using Equation (7.20). But, first, a first order polynomial (= straight line) should be fitted to experimental $P(t)$ by using a method such as “least square method” to find dP/dt .

In Figure 7.8, our RTM set-up which was also used in 1D experiments, is shown. A constant flow rate injection with a pressure set point was made for the 1D experiments. Pressure set point is needed just for safety reasons. When P_{in} reaches this critical value, injection boundary condition is switched from constant Q to constant P_{in} . Otherwise, our tubing and/or mold might not guarantee sealing of resin properly. Using the Floware software, constant flow rate Q is specified, and the time versus experimental injection pressure, P_{in} data are recorded.

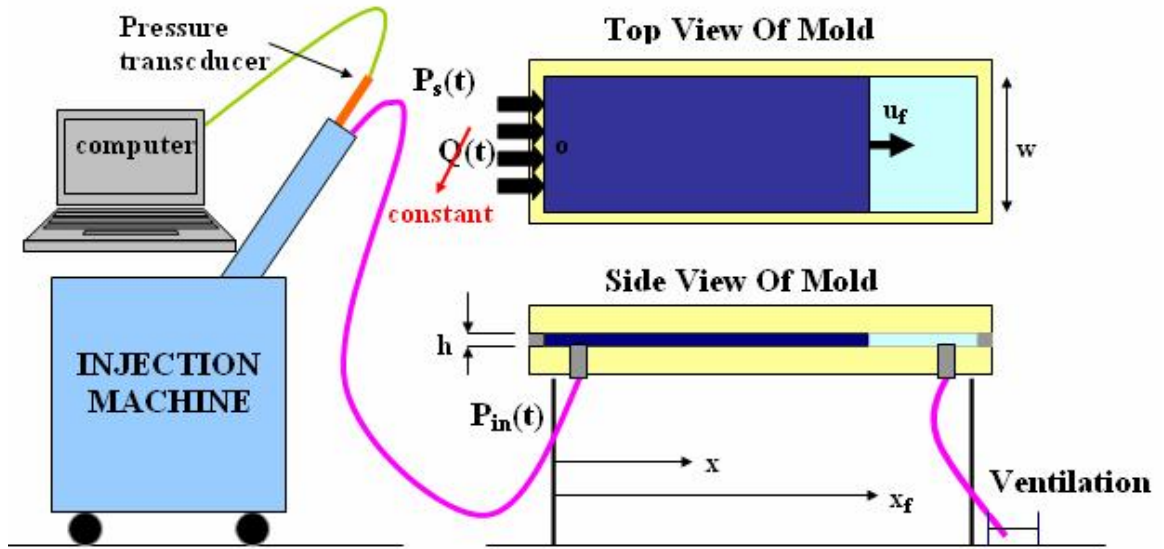


Figure 7.8 Experimental set-up for 1D experiments.

As shown in Figure 7.8, the flow front must be linear in the case of a 1D injection. For this condition to be satisfied, the preform must be uniform and it should perfectly fit the mold cavity. When this perfectly 1D injection was obtained, then one can use

$$K_{1D} = \left(\frac{Q}{wh} \right)^2 \frac{m}{f} \frac{1}{\left(\frac{dP}{dt} \right)_{1D}} . \quad (7.21)$$

This is exactly the same as Equation (7.20), however, emphasizing that the flow is really 1D. However, as discussed in the previous chapters, this is not usually possible due to the non-uniform structure of the preform and due to the disturbances such as race-tracking channels.

As shown in Figure 7.9, presence of race-tracking channels disturb the 1D flow conditions, and the flow will become two-dimensional. Hence, the method proposed for the 1D permeability calculation given by Equation (7.21) seems to be not valid for this case of

2D flow. In the next section, use of 1D permeability measurements in the presence of race-tracking channels will be discussed by correcting the experimental data.

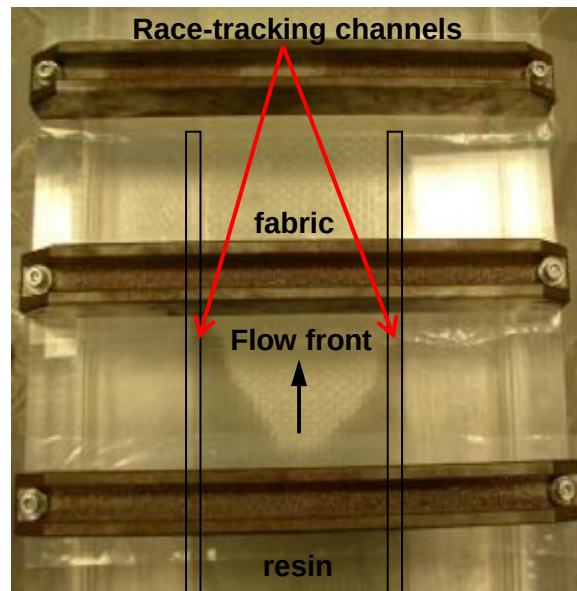


Figure 7.9 Race-tracking channels disturb the linear flow front assumption even though a lineal injection gate (at the bottom of the photograph) was used to create a 1D flow.

7.4.3 Permeability Measurements

In this section, results of LIMS simulations made for 1D permeability measurements will be given and discussed. Dimensions of the mold cavity that is used in this study, and a sample mesh are shown in Figures 7.10 and 7.11. As noted before, sections with different permeabilities have to be specified for LIMS simulations. These sections are designated with numbers as shown in Figure 7.10. These are: empty channels (i.e., no fiber exists) to create lineal injection and ventilation (1); race-tracking channels (2); and the bulk preform (3). In the sample mesh shown in Figure 7.11, these sections are shown with different colors.

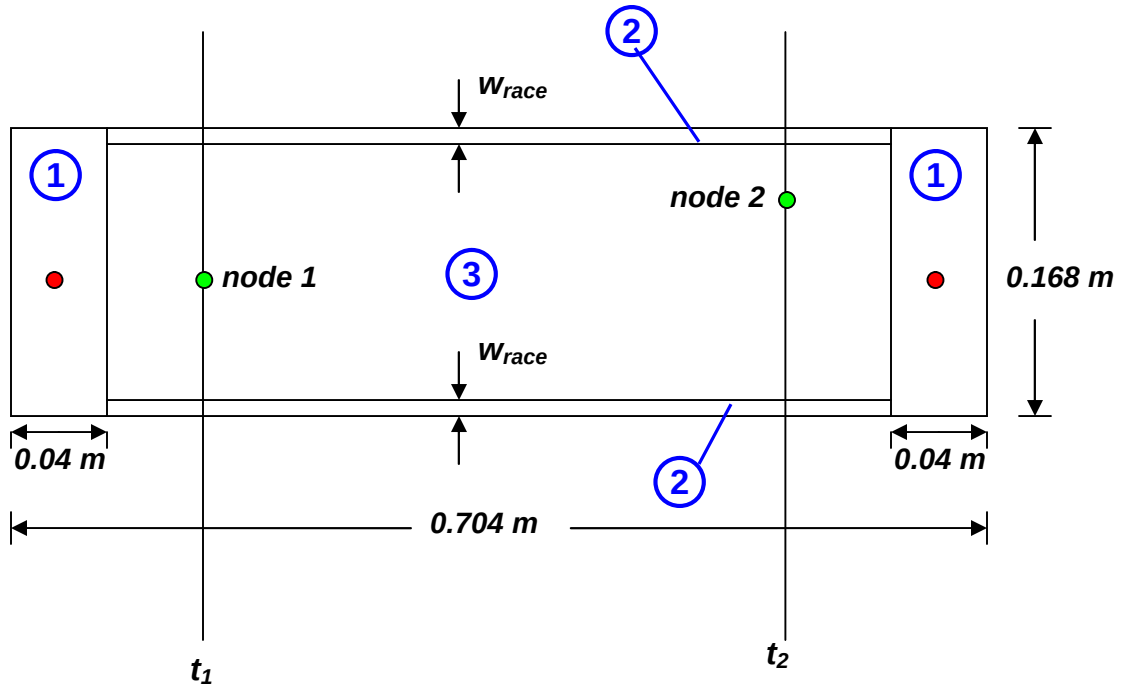
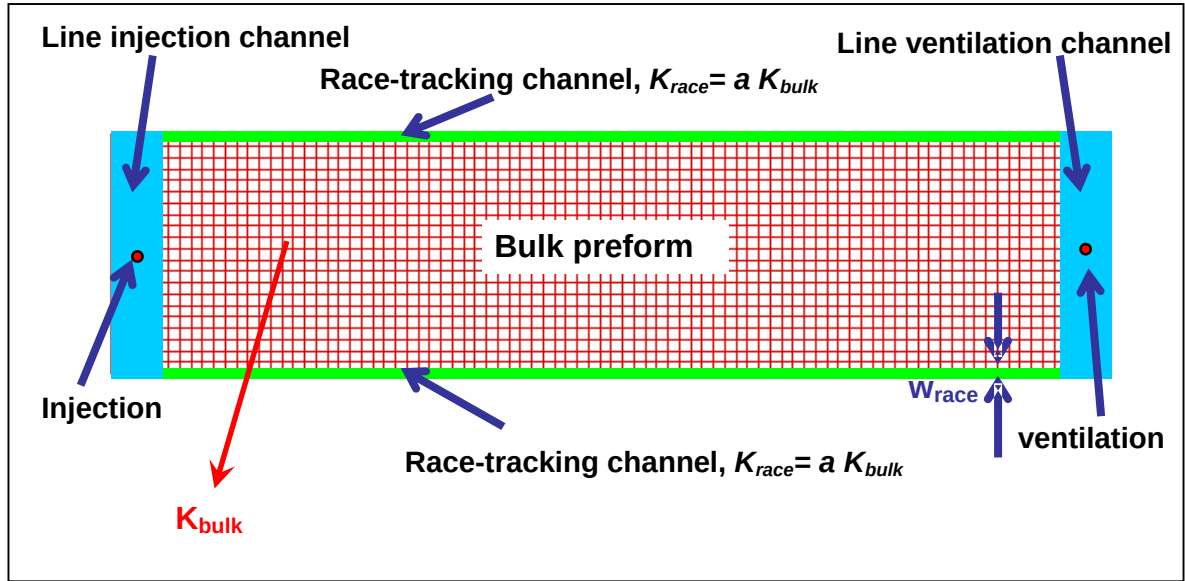


Figure 7.10 Dimensions of the mold cavity, and sections 1, 2, and 3 with different material property for the fabric preform.

Within the LIMS' script file, the elements included in these sections are assigned with their corresponding fiber volume fraction, V_f and permeability tensor components, K_{11} , K_{22} , and K_{12} . For this job, LIMS' SCALEPERM command is used as follows: SCALEPERM(i , scale_factor) where i is the element number, and scale_factor is used to scale the permeability tensor that was originally entered through the input file.



7.11 Sample mesh for the mold cavity.

In this study, the following parameters were used:

- Part dimensions: $L = 0.704 \text{ m} \times W = 0.168 \text{ m} \times h = 0.005 \text{ m}$
- Element size: $8 \times 8 \text{ mm}$ (uniform quadrilateral)
- Mesh: 1958 nodes and 1848 elements
- Scale factor for equivalent permeability of race-tracking channels,

$$a = \frac{K_{\text{race}}}{K_{\text{bulk}}} = 1, 10, 50, 100, 500, \text{ and } 1000.$$

- Bulk preform permeability, $K_{\text{bulk}} = 5 \times 10^{-9} \text{ m}^2$
- Resin viscosity, $\mu = 0.5 \text{ Pa.s}$
- Injection flow rate, $Q = 100 \text{ cc/min} = 1.667 \times 10^{-6} \text{ m}^3 / \text{s}$
- Fiber volume fraction, $V_f = 1 - f = 0.471$.

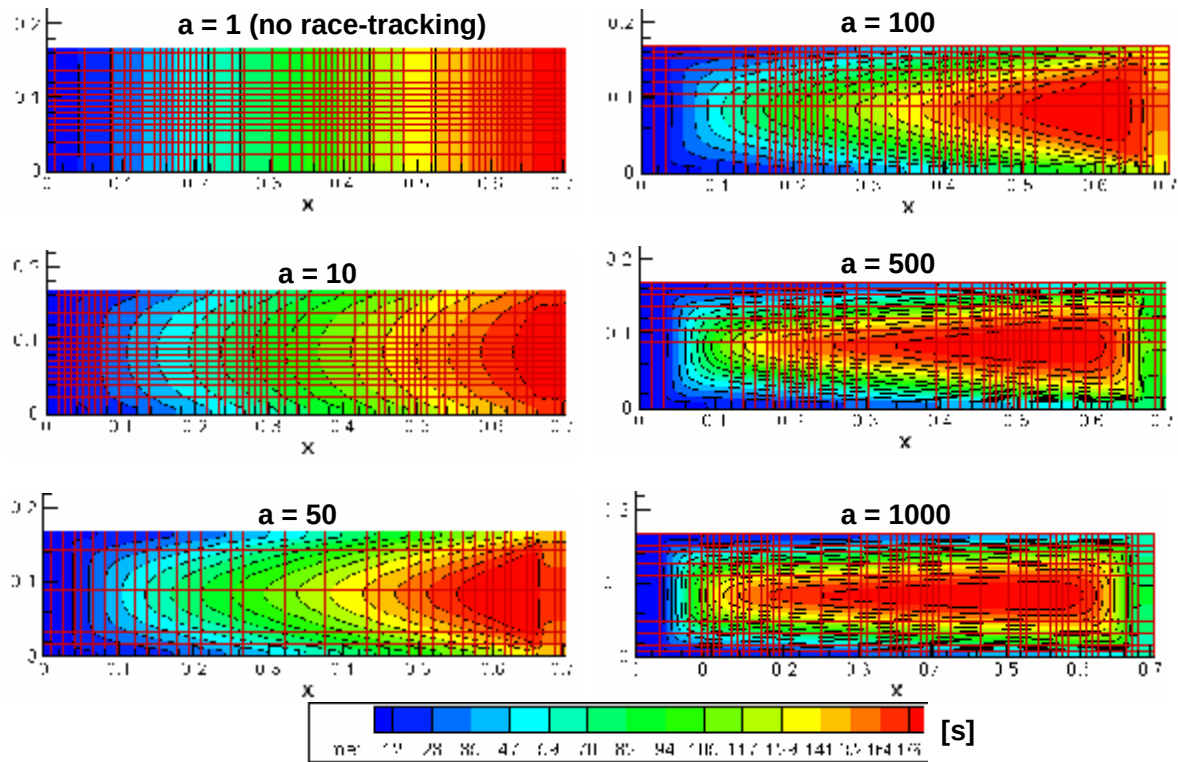


Figure 7.12 Flow front propagation for different equivalent permeabilities of race-tracking channels along both sides of the mold. Here, $a = K_{race}/K_{bulk}$.

For six different values of a (1 through 1000), mold filling simulations were carried out by using LIMS. It was assumed that the same and uniform race-tracking channels exist along both sides of the mold. Locations of flow front at different times are shown with different colors. One can notice the following results:

- In all of these cases, it was simulated to have vacuum drawn. Hence there was no ventilation used in input files. Since the injection type was a “constant flow rate” type, all of the fillings took 187.5 seconds. This was expected since the total porous volume is given as follows:

$$\begin{aligned} V_{porous} &= (0.040) (0.168) (0.005) (1) \\ &+ (0.040) (0.168) (0.005) (1) \\ &+ (0.704-0.080) (0.168) (0.005) (0.471) \\ &= 3.14 \times 10^{-4} \text{ m}^3 \end{aligned}$$

Since the injection is done at constant flow rate, it took

$$\text{Time to fill} = t_{fill} = \frac{V_{porous}}{Q} = \frac{3.14 \times 10^{-4}}{1.667 \times 10^{-6}} = 188.4 \text{ seconds.}$$

which closely agrees with LIMS' solution.

- By looking at Figure 7.12 and 7.13, it is clear that none of the cases, except the one corresponding to $a = 1$, is 1D. However, especially for the two cases where $a = 10$ and 50, the flow front profile did not significantly change between some time values. In Figure 7.13, the corresponding simulated injection pressure was plotted only in $t_1 \leq t \leq t_2$ time domain. The flow front arrives at the virtual sensors at locations Nodes 1 and 2 at $t = t_1$ and $t = t_2$, respectively as shown in Figure 7.10.

Injection pressure, $P_{in}(t)$ rises almost linearly in this time domain for relatively low values of a . However, although dP/dt is almost constant in $t_1 \leq t \leq t_2$, their values are different for different a values as tabulated in Table 7.1.

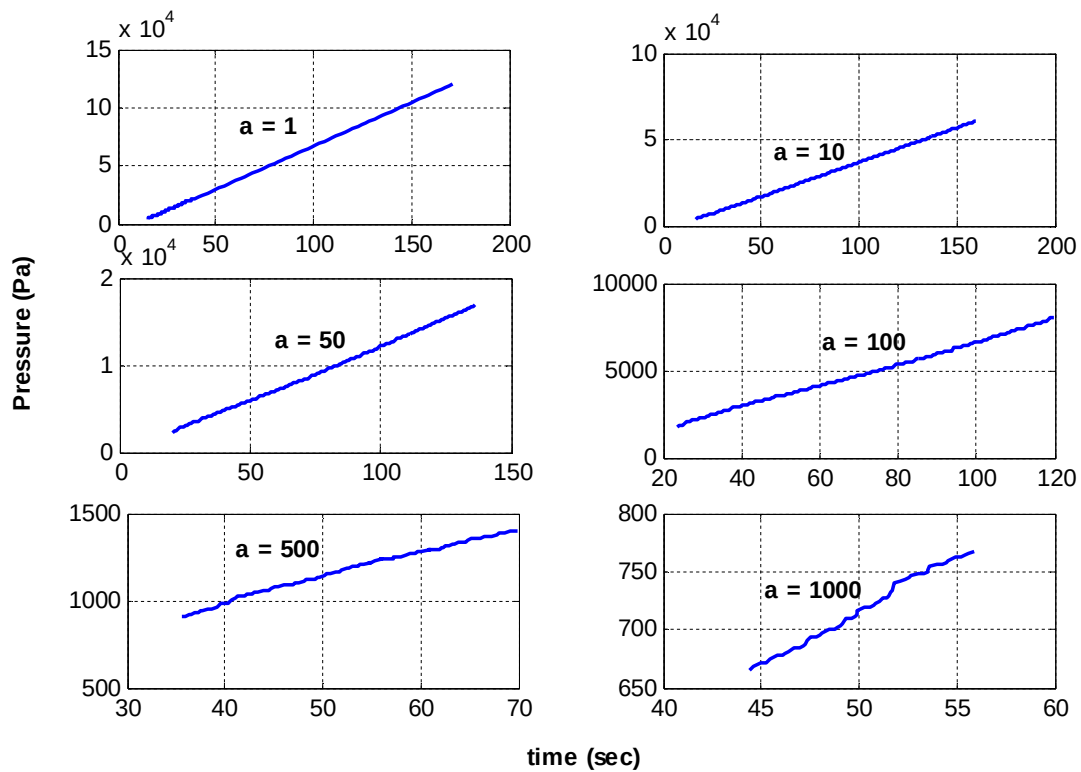


Figure 7.13 Simulated injection pressure, $P_{in}(t)$ corresponding to the six different cases in Figure 7.12.

Table 7.1 Time rate change of simulated injection pressure.

a	dP/dt [Pa/s] in $t_1 \leq t \leq t_2$ (by using a curve fit to $P(t)$ by using a least square method)
1	741.6
10	399.1
50	124.2
100	62.23
500	14.39
1000	9.452

If one mistakenly substitutes dP/dt values into Equation (7.21), then the following wrong values will be obtained (except for $a = 1$ case):

Table 7.2 Permeability calculations by using Equation (7.21)

a	K [m²] from Equation 7.21
1	$5.00 \times 10^{-9} \text{ m}^2$ (correct !)
10	$9.33 \times 10^{-9} \text{ m}^2$
50	$2.99 \times 10^{-8} \text{ m}^2$
100	$5.98 \times 10^{-8} \text{ m}^2$
500	$2.59 \times 10^{-7} \text{ m}^2$
1000	$3.94 \times 10^{-7} \text{ m}^2$

One can obtain a correction factor, $c = (dP/dt)_{ID} / (dP/dt)_{exp}$ by using the values in Table 7.2. The correction factor, c is plotted for $1 \leq a \leq 1000$ in Figure 7.14.

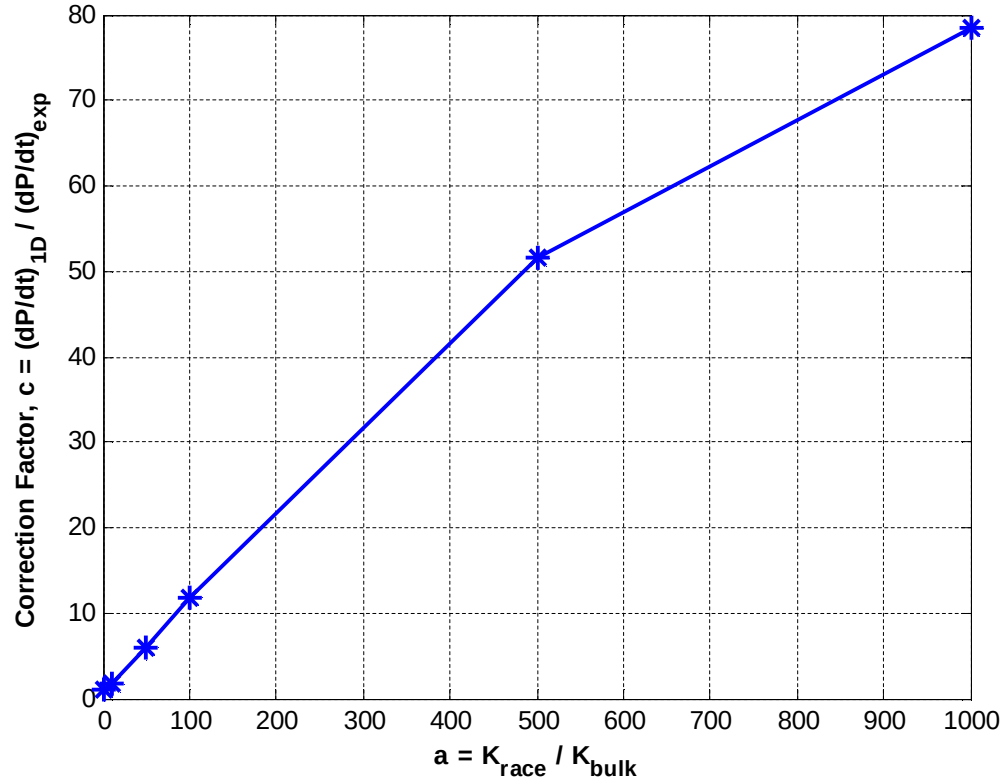


Figure 7.14 Correction factor c as a function of a , for $a = 1, 10, 50, 100, 500, 1000$. (Race-tracking channel width is defined by one element: $w_{\text{race}} = 8\text{mm}$.)

In order to study the effect of mesh size on the results, a finer mesh was prepared by using an element size of $2\text{mm} \times 2\text{mm}$, and also a denser range of permeability scale factor, a ($= 1, 2, 3, \dots, 9, 10, 20, 30, \dots, 90, 100, 200, 300, \dots, 1000$) was considered. The results of coarse and fine meshes are plotted together in Figure 7.15.

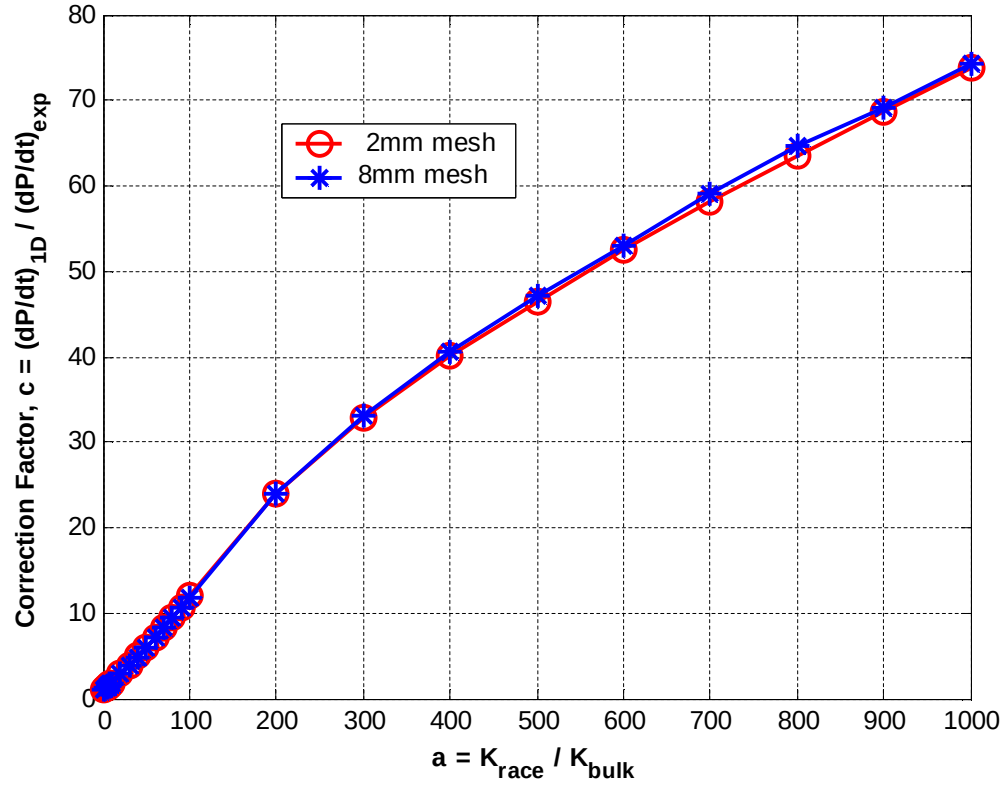


Figure 7.15 Comparison of 2 x 2 mm mesh and 8 x 8mm mesh with $w_{\text{race}} = 8$ mm race-tracking channel width for a values: 1, 2,3, ...9, 10, 20,...,90,100, 200, ...,900,1000.

Correction factor, c , was calculated by running a series of mold filling simulations for different widths of race-tracking channels, and plotted in Figure 7.16.

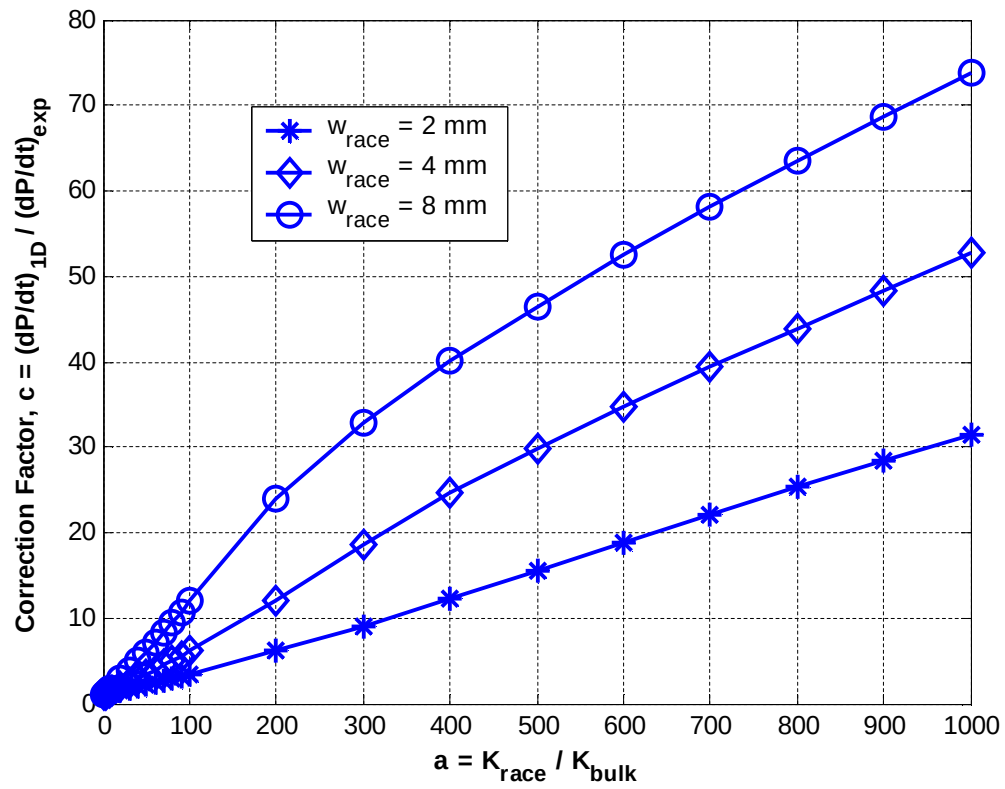


Figure 7.16 Correction factors for a race-tracking channel width of $w_{race} = 2, 4, 8 \text{ mm}$.

Element size of 2mm x 2mm is used.

Here is what we propose to be able to use $(dP/dt)_{\text{exp}}$ of an actual experiment to calculate preform permeability even though the flow might not be perfectly 1D:

- Do the injection, and record time versus $P_{\text{in}}(t)$.
- Observe the width of race-tracking channel, w_{race} and corresponding $a = K_{\text{race}} / K_{\text{bulk}}$ (ratio of equivalent permeability of race-tracking channel over bulk permeability) by comparing the experimental flow front profile through transparent mold lid and simulated results such as the ones shown in Figure 7.12.
- By using these two values (w_{race} and a), find the correction factor c .
- Then, one can predict K_{bulk} approximately as follows:

$$K_{\text{bulk}(1\text{D})} = c \left(\frac{Q}{wh} \right)^2 \frac{m}{f} \frac{1}{\left(\frac{dP}{dt} \right)_{\text{exp}}}$$

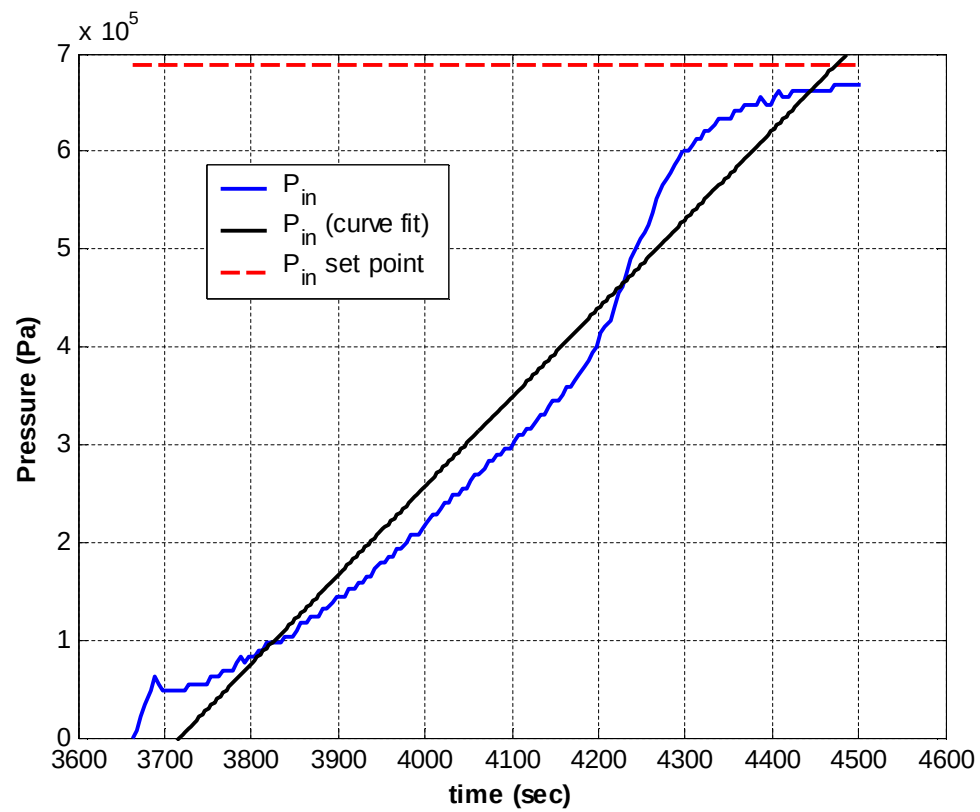


Figure 7.17 Injection pressure data from a sample experiment.

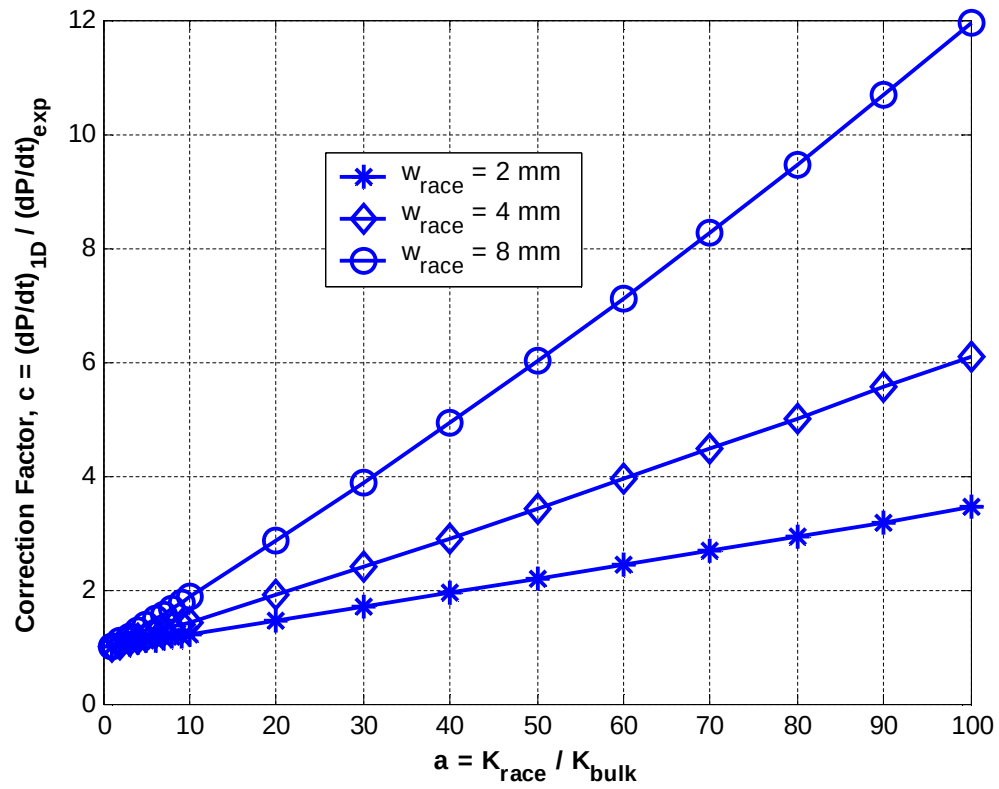


Figure 7.18 Correction factors (corresponding to $1 \leq a \leq 100$) for a race-tracking channel width of $w_{race} = 2, 4, 8 \text{ mm}$. Element size of $2 \text{ mm} \times 2 \text{ mm}$ is used.

In order to illustrate our approach, we consider a sample case below.

We did an injection. Injection pressure, $P(t)$ and a linear fit to it are shown in Figure 7.17. The slope of this curve fit is $dP/dt = 910.03$ Pa/s. From the qualitative visual inspection of the flow front profile, it was concluded that $a \approx 20$ -100. Also, from the inspection of finished part, the race-tracking channel width was close to 2mm. By using Figure 7.18, the correction factor was found to be between ~ 2 and ~ 4 . Hence, the lower and upper bounds of bulk permeability can be predicted as follows:

$$K_{bulk,lower} = c_{lower} \left[\left(\frac{Q}{wh} \right)^2 \frac{m}{f} \frac{1}{\left(\frac{dP}{dt} \right)_{exp}} \right]$$

$$= 2 \left[\left(\frac{1.667 \times 10^{-6}}{0.168 \times 0.005} \right)^2 \frac{0.5}{(1-0.471)} \frac{1}{910.03} \right] = 8.18 \times 10^{-9} \text{ m}^2$$

$$K_{bulk,upper} = c_{upper} \left[\left(\frac{Q}{wh} \right)^2 \frac{m}{f} \frac{1}{\left(\frac{dP}{dt} \right)_{exp}} \right]$$

$$= 4 \left[\left(\frac{1.667 \times 10^{-6}}{0.168 \times 0.005} \right)^2 \frac{0.5}{(1-0.471)} \frac{1}{910.03} \right] = 16.4 \times 10^{-9} \text{ m}^2$$

Hence, K_{bulk} is predicted to have a value between 8.18×10^{-9} and $16.4 \times 10^{-9} \text{ m}^2$.

Chapter 8

CONCLUSION

Experiments with thermocouple sensors proved that they are not suitable for monitoring of mold filling and resin cure in the current system. The necessary temperature difference for detection cannot be maintained, hence they are not proper for room-temperature applications. Conductive heat loss from polymer to mold wall is a serious issue to be considered while using these sensors. If an adequate amount of resin flow rate and an adequate amount of temperature difference between the thermocouple wires and resin can be achieved, then it is possible to monitor the flow of resin. Due to exothermic nature of the curing reaction, and then cooling during solidification, there is a considerable amount of change in temperature and thermocouple sensors can also be used for cure monitoring.

Both voltage lineal and point sensors can be used to monitor both mold filling and resin cure. Lineal sensors can continuously monitor the resin flow along the sensor length whereas a point sensor can only inform us if polymer arrived at a particular discrete location or not.

Although a point sensor is used to monitor only a discrete point in the mold, it can exactly specify if resin arrived at that particular point or not. However, with moving polymer, lineal sensors can only give information about the “total wetted fraction” of the sensor, and they may sometimes be misleading, since it is hard to conclude what section(s) are wetted.

One other advantage of point sensors over lineal ones is that, they do not need a very precise calibration as lineal sensors need. In order to decide what fraction of lineal sensors was wetted by polymer, the user needs a very precise “wetted length versus voltage”

database available. However, as the spacing between the two parallel wires changes, or polymer's electrical resistance changes, which is very likely to occur from one batch of polymer to another, this relation (length versus voltage) will show variations. Hence, experimental voltage data might not be correctly converted into fraction of the length where the sensor is wetted. In contrast, point sensors function as an ON or OFF switch. Voltage reading over a part of the developed electrical circuit makes a very significant jump when resin arrives at the sensor location. The magnitude of this voltage jump is not very crucial as long as its order of magnitude is higher than the typical noise in the system. Our experiments with these sensors indicated quick and reliable responses. These point sensors are also durable compared to lineal ones. Their cost is also lower than many other sensor systems.

Permeability of race-tracking channels is an important factor to be accounted for, in mold filling simulations. By using Stokes flow model, and no-slip boundary condition, equivalent permeability of race-tracking channels could be calculated. The model is numerically solved by using finite difference method. After verifying the results for simple channel geometries where analytical solutions are available, we could study irregular shapes as well. This approach could be useful to analyze the effect of race-tracking channels inspected along the mold edges and corners, on mold filling results.

Since perfectly 1D injections are difficult to generate, a procedure was proposed to correct the calculation of permeability by using a correction factor after matching experimental race-tracking channel width and flow front profile with a set of previously simulated cases. By this way, permeability of bulk preform, which is a significant material data to be used in simulations and various analysis, can be calculated (even though not precisely) by using these non-perfect 1D injection experiments.

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VITA

GÖKER TUNÇOL was born in İzmir, Turkey on September 25, 1980. He received his B.S. degree in Mechanical Engineering from Middle East Technical University (METU), Ankara, in 2003. During his B.S. degree, he and his teammate constructed a line tracking robot and received 3 awards for: Best Overall Design, Best prediction and a 3rd place among 15 projects in the Mechanical Engineering Design Competition held on January 23, 2003 at Middle East Technical University in association with Queens University, Canada. Since 2003, he has enrolled to the M.S. program in Mechanical Engineering at Koc University as a teaching and research assistant. He has been studying in the “Monitoring of Resin Flow and Cure in Resin Transfer Molding (RTM) Process” project since September 2003. He is planning to pursue a Ph.D. degree in the Mechanical Engineering Department at Michigan State University, USA.

APPENDIX A

A1. Dewester 196 (DYO Dewilux 511-0196) general purpose polyester

Properties: Density = 1.19 grams / cm³, Viscosity = 0.77 Pa.s (at room temperature).



Mixing ratio: (Suggested by supplier)

	Amount
Dewester 196 (DYO Dewilux 511-0196)	1000 gram
Accelerator (549-0050)	50 ml
Cure agent (549-0040)	15-20 ml

In this study, we used 1.5 grams of Cobalt compound (accelerator) and 1.5 grams of Methyl Ethyl Ketone Peroxide (cure agent) per 1000 grams of polymer.

Viscosity:

Measured by Brookfield DV-II + Viscometer, spindle no:3, at 22°C, density of polymer (Dewester196, DYO Dewilux 511-0196) at this temperature was 1.19 gram/cm³. Viscosity, μ is taken as = 770 mPa.s = 0.77 Pa.s. according to this measurement.

Spindle of shaft [rpm]	Viscosity (mPa.s)	Torque percentage [%]
1	750-800	0.8
2	750-800	2.0
2.5	760-800	2.0
4	775-800	3.1
5	760-780	3.9
10	760-770	7.7
20	760-765	15.3
50	764-766	38.2
100	768-769	76.9

A2. RTM Injection Machines (x2):

Manufacturer:	Radius Engineering Inc., Utah, USA (RADIUS)
Model:	Radius 2100 cc Electric RTM Injection Cylinder Version 5.17.2001
Capacity of polymer:	2100 cc
Polymer types:	Thermoset (applicable to RTM)
Maximum injection pressure:	27.5 bar (= 2.7 MPa = 400 psi)
Heating system:	Electrical heater around injection cylinder and tubes
Maximum temperature:	176°C (= 350°F)
Control:	PID temperature control Flowrate control Injection pressure set points
Power:	4.8 kW (240 V, 20 amp)

APPENDIX B

B1. J TYPE THERMOCOUPLES USED

(i)

Company: National Instruments
E3TAM
Barbaros Bulvarı, No: 177/6
Esentepe/İstanbul
Model: 745685-J01 (J type thermocouple)
Price: \$20 / meter

(ii)

Company: Elimko Elektronik, İmalat ve Kontrol Ticaret Ltd. Şti.
8. cad., 68.sokak, No: 16
Emek, Ankara
Model: 05T2JTTEA (J type thermocouple)
Price: \$3 / meter

(Output voltage between, -5.97 , 5.21 mV and 0.01mV/ °C.)

B.2 National Instruments, 200 kS/s, 16-Bit, 16 Analog Input Multifunction Card (NI PCI 6035E)

The analog input card is used to record and process sensor readings (thermocouples and voltage point sensors). It provides the interaction between the sensor readings and the DAQ (LABVIEW) program. The specifications are given below.





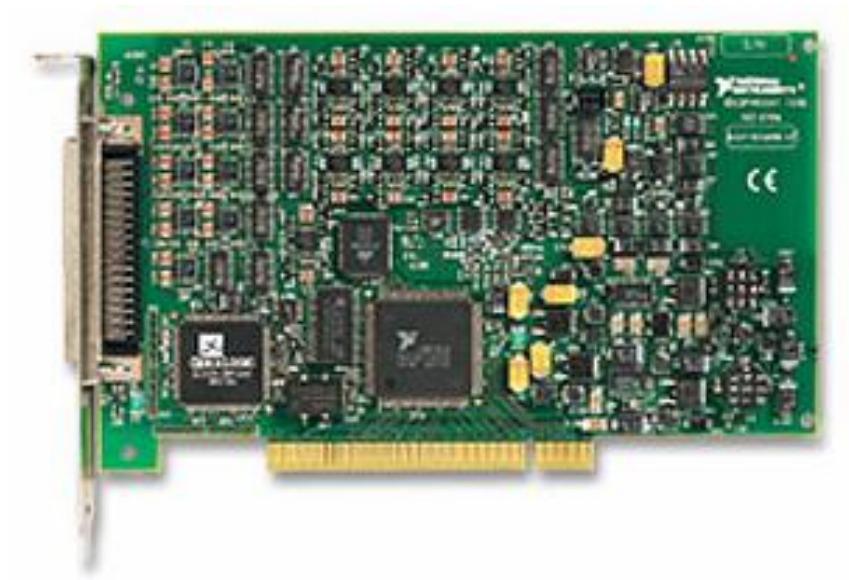
- 16 analog inputs at up to 200 kS/s, 12 or 16-bit resolution
- Up to 2 analog outputs at 10 kS/s, 12 or 16-bit resolution
- 8 digital I/O lines (TTL/CMOS); two 24-bit counter/timers
- Digital triggering
- 4 analog input signal ranges
- NI-DAQ driver simplifies configuration and measurements

Bus	Analog Inputs	Input Resolution	Max Sampling Rate	Input Range	Analog Outputs
PCI, PCMCIA	16 SE/8 DI	16 bits	200 kS/s	± 0.05 to ± 10 V	2
Output Resolution	Output Rate	Output Range	Digital I/O	Counter/Timers	Triggers
16 bits	10 kS/s ¹	± 10 V	8	2, 24-bit	Digital

Reference: <http://sine.ni.com/nips/cds/view/p/lang/en/nid/11915>

**B.3 National Instruments, 16 Bit Static Analog Output Board
(NI PCI 6704)**

The static output board is used to supply voltage and ground to the sensor systems (voltage point sensors, applicable to lineal sensors as well). Specifications are given below.



Analog Output

Number of voltage channels	16
Number of current channels on the NI 6704.....	16
Resolution	16-bit
Recommended warm-up time	15 minutes

Voltage Output

Range	± 10.1 V
Output coupling.....	DC
Output impedance	0.1 Ω max
Current drive	± 10 mA max
Load capacitance.....	10,000 pF max
Protection	Short-circuit to ground
Absolute accuracy	± 1 mV max

Current Output (NI 6704 Only)

Range.....	0.1 to 20.2 mA
Type	Source, does not require external excitation source
Output impedance.....	1 G Ω min
Output compliance.....	0 to 10 V, not clamped
Absolute accuracy.....	± 2 μ A max
Noise.....	1 μ A _{rms} , DC to 1 MHz
Protection	Short-circuit and open circuit
Power-up state	Independent, user-defined values

Digital I/O

Number of channels 8

Compatibility TTL

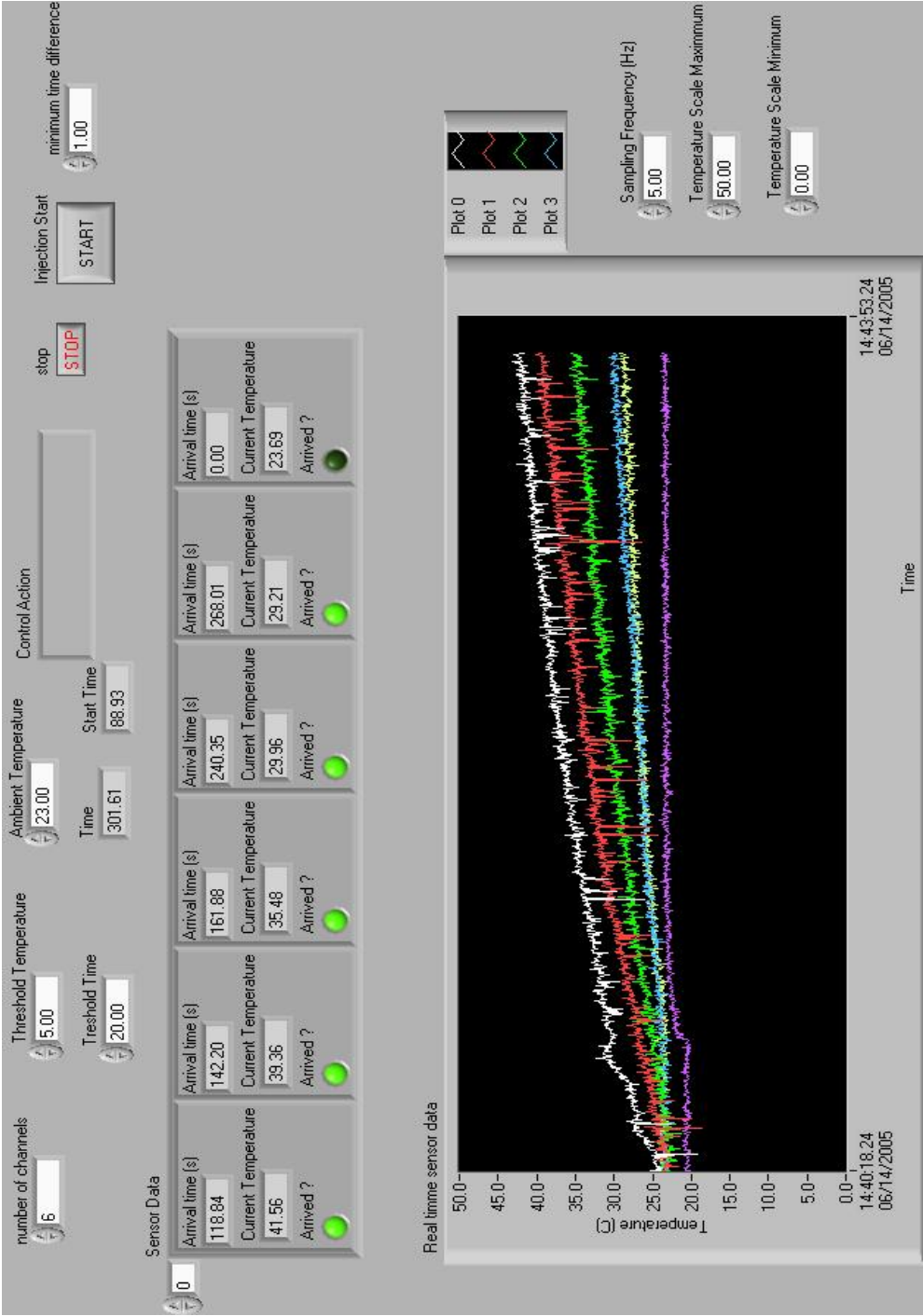
Power-on state..... Input (high impedance)

Digital logic levels

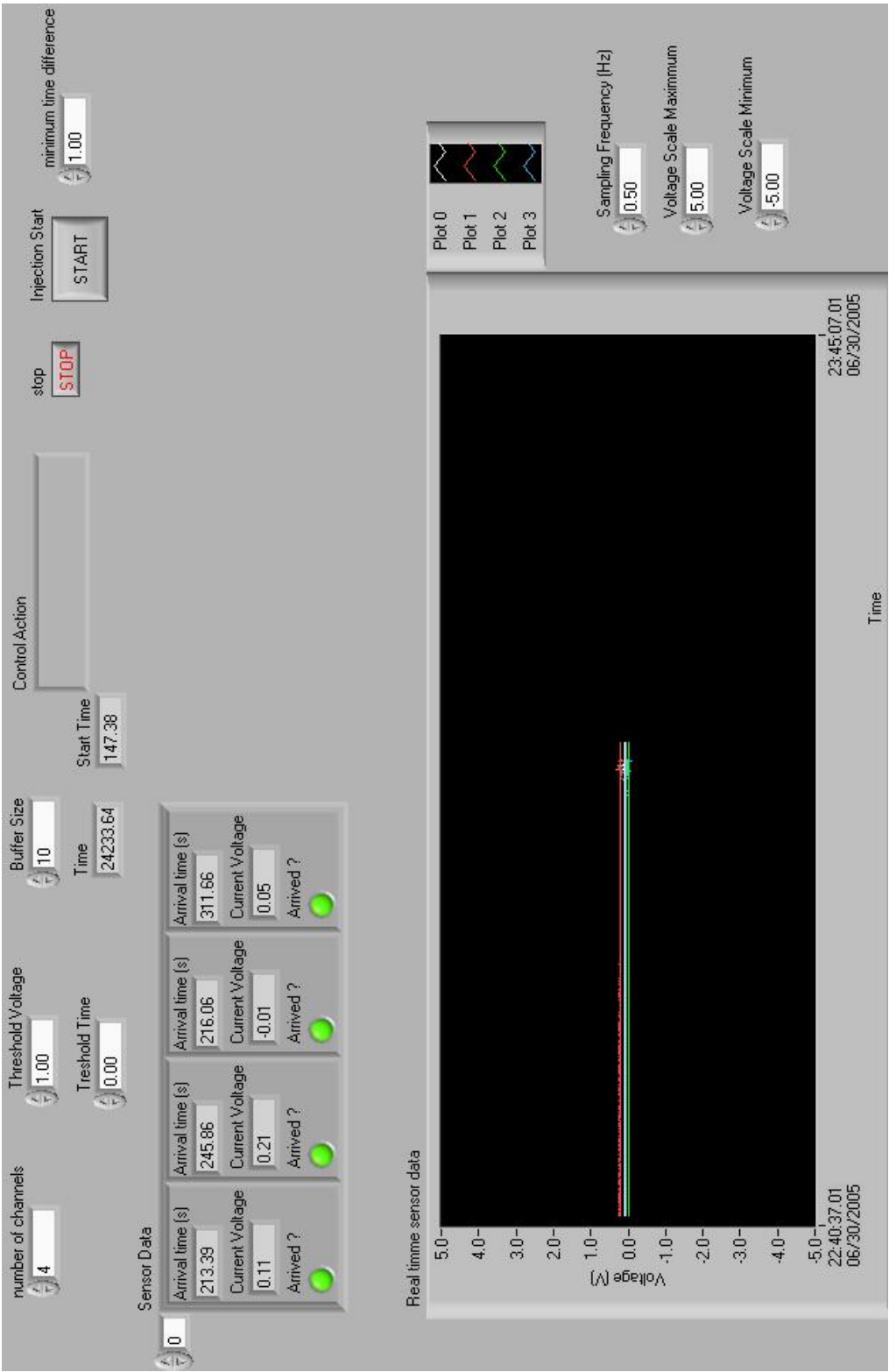
Level	Min	Max
Input low voltage	—	0.8 V
Input high voltage	2.0 V	—
Output low voltage	—	0.45 V, $I_{OL} = 16$ mA
Output high voltage	2.4 V, $I_{OH} = 16$ mA	—
Input leakage current	—	10 μ A

Reference: <http://sine.ni.com/nips/cds/view/p/lang/en/nid/10705>

**B.4 LABVIEW SCREEN FOR THE DAQ PROGRAM
(THERMOCOUPLE SENSORS)**



**B.5 LABVIEW SCREEN FOR THE DAQ PROGRAM
(VOLTAGE POINT SENSORS)**



B.6 MORE INFORMATION ON DAQ PROGRAM OF THE VOLTAGE POINT SENSORS

For the new resistive sensor system a new data acquisition and monitoring program was developed. The sensor arrival monitoring and logging algorithms are the same with those of the program created for thermocouple readings. However, some fundamental changes were made, in order to accommodate for the complexities associated with the new sensor system.

In National Instruments NI-6035E Multifunctional DAQ system, the calibration mapping for the J-type thermocouples, which actually returns a differential mili-volt output, are predefined. Furthermore, by using a Cold Junction Compensation buffer (CJC), the signal is referenced and buffered to a smooth waveform.

However the new sensor configuration obviously doesn't have a calibration curve. It also needs to have an external amplifier and buffer. The integral workings of on board amplifier and buffer are explained in the previous chapters.

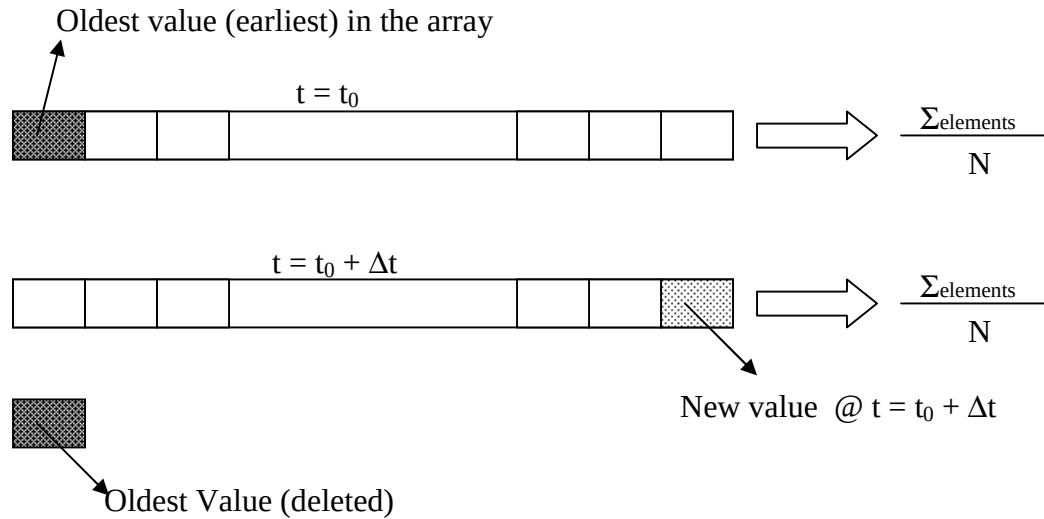
The reason for software buffering is the existing white noise within the signal. We could use the following alternatives for smoothing the signal:

- Complicated analog band-pass filters
- Digital filters based on frequency domain analysis.

The use of onboard filters is expensive in terms of space available and cost. The digital filters on the other hand, require on-the-fly Fourier transform which is computationally expensive for a program that samples, orders, displays and records data for every 200ms.

Instead, we employed some principles employed in digital voltmeters. First of all the sampling frequency is much smaller than the Nyquist frequency of the original signal, which is on the order of 10 KHz. Thus we get rid of the high frequency jitter. Later, a running average array is used to constantly average the samples with the past values. The queuing mechanism is "push and pop", the newest value is added to the last place in a dynamically

allocated array, whereas the earliest value is popped out of the array. This algorithm is illustrated below:



After we average this array, the average is recorded as the smoothed value for that sampling time-step. To make a comparison, the “raw” data, which doesn’t use software buffering, is also stored.

The necessities of the sensor application suggested that as many as 16 sensors be sampled simultaneously. However in the previous applications we had only tested up to 5 sensors. The problem was there weren’t enough “Differential” A-D conversion channels on the DAQ card. To use a “Referenced Single-ended” configuration, a reference voltage, preferably the circuit ground, is supplied to the DAQ card and all other outputs are sampled according to that reference. This also necessitated a slight altering of the data storage program, since the inverting amplifiers on the circuit returned negative voltages with respect to the circuit ground. To overcome this problem, the input waveform is “inverted”, or simply scaled by a factor of “-1”. After these modifications the DAQ board is now capable of housing up to 16

sensors simultaneously. This number can be increased by the help of an external multiplexer, though at a cost of reduced sampling frequency.

APPENDIX C

C.1 PERMEABILITY CALCULATION FOR RECTANGULAR CHANNELS

" K_Rectangular_Racetracking_channel_nondim.m "

```

close all, clear all, clc
h_over_w = [0.1:0.1:10];

for ii = 1 : size(h_over_w,2)
    Nz      = 50;          % # of elements along w      user defined
    Ny      = 50;          % # of elements along h      " "

    hy = 1 / Ny;
    hz = 1 / Nz;          %%% non-dimensional differential elements

    vel      = zeros(Ny+1,Nz+1);
    vel_new   = zeros(Ny+1,Nz+1);

    c1 = (h_over_w(ii))^2 * (1/hz^2);
    c2 = 1/hy^2;
    c3 = 2 * ( c1 + c2 );

    err = 1000;

    while (err > 1e-8) %%% ERROR TERM
        for i = 2:Ny
            for j = 2:Nz
                vel_new(i,j) = (c1/c3)*(vel_new(i-1,j) + vel_new(i+1,j)) + (c2/c3)
* (vel_new(i,j-1) + vel_new(i,j+1)) + (12/c3);
            end
        end
        err      = norm(vel - vel_new);
        vel      = vel_new;

    end
    summation(ii) = sum (sum(vel))*hy*hz;
    K_nondim(ii)  = summation(ii);

end

figure(1)
plot(h_over_w,K_nondim,'b','linewidth',2), grid
xlabel('h/w'), ylabel('Nondimensional Permeability, K / (h^2 / 12)')

%%%%% K exact calculations
for i = 1: size(h_over_w , 2)

```

```
    for j = 1:2: 1000
        G(j)= tanh(j * pi /h_over_w(i) /2) / j^5;
    end

    GH=sum(G);
    K_exact_nondim(i) = (1- (192 * h_over_w(i) / pi^5) * GH);
end

hold on
plot(h_over_w , K_exact_nondim,':','linewidth',2)
legend ('K^*', 'K^*exact')
```

C.2 VELOCITY PROFILE FOR RECTANGULAR CHANNELS

" 3D_vel_profile_Rectangular.m "

The lines below are added to the end of the previous code to plot the 3-D velocity profile.

```
w=1;
h=1;

ww=0 : hz : w;
hh=0 : hy : h;

vel_2 = vel./1e3;   %%% velocity in m/s
surf(ww,hh,vel_2)

title('VELOCITY PROFILE')
xlabel('w^*')
ylabel('h^*')
zlabel('Non-dimensional Velocity, u^* (m/s)')
```

C.3 PERMEABILITY CALCULATION FOR ELLIPTICAL CHANNELS

" K_Elliptical_Racetracking_channel_nondim.m "

```

close all; clear all; clc;

a_over_b = [0.1:0.1:10];

for ii = 1 : size(a_over_b,2)

    hy = 0.005;      % diff. increments
    hz = 0.005;

    Nz = round(2*1 / hz);

    zz = 0:hz:2*1;
    yy = 2* ( (1- (zz-1).^2) ) .^(1/2) ;    %% y dist. inside the ellipse

    Ny      = 2*round ((yy/2)/hy);  %%% SYMETRIC NODES ON BOTH UPPER AND LOWER
SIDES

    kinematic_viscosity= 1;          % [Pa.s]
    delp_x = - 10^4 / 10^3;          % DEL P / DEL X [Pa/mm]

    vel      = zeros(Nz+1,Nz+1);
    vel_new   = zeros(Nz+1,Nz+1);

    c1 = 1 / hy^2 ;
    c2 = 1 / hz^2 / a_over_b(ii)^2;
    c3 = 2*(c1+c2);

    a = Ny/2;

    err = 1000;

    while (err > 1e-8)
        j=2;

        for kk= 1 : size(Ny,2)-2 %%% -2 is for not to count for zeros in Ny
            for i = ((Nz/2)+1) - a(kk+1) +1 : ((Nz/2)+1) + a(kk+1) -1 %% interior
nodes ONLY!!
                vel_new(i,j) = (c2/c3)*(vel_new(i-1,j) + vel_new(i+1,j)) + (c1/c3)
* (vel_new(i,j-1) + vel_new(i,j+1)) + (8/a_over_b(ii)/c3);
            end
            j=j+1;
        end

        err      = norm(vel-vel_new);
        vel      = vel_new;
    end

```

```
    summation(ii) = sum (sum(vel))*hy*hz;  
    K_nondim(ii)  = summation (ii) / pi;    %%%   pi comes from A/Aref=pi  
end  
  
figure(1)  
plot(a_over_b,K_nondim,'b','linewidth',2), grid  
xlabel('a/b'), ylabel('Nondimensional Permeability,    K / K_r_e_f')
```

C.4 VELOCITY PROFILE FOR ELLIPTICAL CHANNELS

" 3D_vel_profile_Elliptical.m "

The lines below are added to the end of the previous code to plot the 3-D velocity profile.

```
a=1; b=1;

aa =0 : 1/Nz : a;
bb =0 : 1/Nz : b;

vel_2 = vel./1e3;   %%% velocity in m/s
surf(aa,bb,vel_2)

title('VELOCITY PROFILE')
xlabel('a^*')
ylabel('b^*')
zlabel('Non-dimensional Velocity, u^* (m/s)')
```

C.5 PERMEABILITY CALCULATION FOR TRIANGULAR CHANNELS

" K_Triangular_Racetracking_channel_nondim.m "

```

beta = 50*pi/180: 5*pi/180: 85*pi/180;
c_over_h = [0.1:0.1:10];

KK = zeros(size(c_over_h,2),size(beta,2));
jj = 1;

c_over_h = [0.1:0.1:10];

for beta = 50*pi/180: 5*pi/180: 85*pi/180 % in rad.  NON-DIM. ALPHA

    for ii = 1 : size(c_over_h,2)

        c      = 1 ;                               %%% non-dim.
        a      = 1/sin(beta) ;                       %%% non-dim.

        hy = 0.1;          % non-dim. diff. increments
        hz = 0.1;          %

        Nz = round (c / hz);

        zz1 = 0 : hz : a*cos(beta);
        zz2 = a*cos(beta) : hz : c;

        yy1 = tan(beta) .* zz1 ;
        yy2 = a*sin(beta) / (c-a*cos(beta)) .* ( c - zz2 ) ;

        Ny1 = round (yy1/hy);
        Ny2 = round (yy2/hy);

        kinematic_viscosity= 1;          % [Pa.s]
        delp_x = - 10^4 / 10^3;          % DEL P / DEL X [Pa/mm]

        vel      = zeros(Nz+1, Nz+1);
        vel_new   = zeros(Nz+1, Nz+1);

        RR = c_over_h(ii);
        c1 = 1/ hy^2;
        c2 = 1/ RR^2 / hz^2;
        c3 = 2*(c1+c2);

        err = 1000;
        while (err > 1e-8)
            j=2;

            for kk= 2 : size(Ny1,2)

```

```

        int_nodes1 = Ny1(kk)-1 ;    %% # of interior nodes

        for i = (Nz+1) - int_nodes1 : Nz
            vel_new(i,j) = (c2/c3)*(vel_new(i-1,j) + vel_new(i+1,j)) +
(c1/c3) * (vel_new(i,j-1) + vel_new(i,j+1)) + (1/RR/c3);
            end
            j=j+1;
        end

        for mm= 2 : size(Ny2,2)-1

            int_nodes2 = Ny2(mm)-1 ;    %% # of interior nodes

            for i = (Nz+1) - int_nodes2 : Nz
                vel_new(i,j) = (c2/c3)*(vel_new(i-1,j) + vel_new(i+1,j)) +
(c1/c3) * (vel_new(i,j-1) + vel_new(i,j+1)) + (1/RR/c3);
                end
                j=j+1;
            end

            err      = norm(vel-vel_new);
            vel      = vel_new;
        end

        summation(ii) = sum (sum(vel))*hy*hz;
        K_nondim(ii)  = 2* summation (ii);  %%%% see the derivation for this

    end

    KK(:,jj) = K_nondim';  %%%% all K* values for different angles
    jj = jj+1;

    figure(1)
    plot(c_over_h,K_nondim,'b','linewidth',2)
    xlabel('a/b'), ylabel('Nondimensional Permeability, K / K_r_e_f')

    hold on
    grid on
    legend('a^*=50','a^*=55','a^*=60','a^*=65','a^*=70','a^*=75','a^*=80',
'a^*=85')
end

```

C.6 VELOCITY PROFILE FOR TRIANGULAR CHANNELS

" 3D_vel_profile_Triangular.m "

The lines below are added to the end of the previous code to plot the 3-D velocity profile.

```
c=1; h=1;

cc =0 : 1/Nz : c;
hh =0 : 1/Nz : h;

vel_2 = vel./1e3;   %%% velocity in m/s
surf(cc,hh,vel_2)

title('VELOCITY PROFILE')
xlabel('c^*') ; ylabel('h^*')
zlabel('Non-dimensional Velocity, u^* (m/s)')
```

C.7 A REMARK ON THE FINITE DIFFERENCE METHOD

In the finite difference method, Gauss Seidel Iteration method was chosen for the solution of a linear system of equations. Another alternative could be the Gauss Elimination method. At first glance, Gauss Elimination seems to be a better approach since it is a direct method for the solution of equations, and no iterations are involved. However, when the number of equations increase substantially and large matrices are generated in the finite difference method, Gauss Elimination method becomes computationally very expensive.

In Table 1, number of elements used in the finite difference method and elapsed time using the two methods to calculate the equivalent permeability of a circular race-tracking channel are shown. With the same number of elements used in the finite difference method, the two methods calculate exactly the same permeability value, and results are not shown here. For 50x50 elements, Gauss Elimination method computes the same permeability value in a shorter time as compared to the Gauss Seidel iteration method. For 60x60 elements, it takes slightly longer time for Gauss Elimination method to compute the result. However, for 70x70 elements, elapsed time is almost tripled as compared to the Gauss Seidel method. For 80x80 elements it is even worse: MATLAB gives an error message and cannot compute the result because of insufficient memory (on a PC with 512 MB RAM). This is because Gauss Seidel method uses two nested loops with an index of 1 to 81 each to compute the permeability whereas Gauss Elimination tries to generate a matrix of size $81^2 \times 81^2 = 6561 \times 6561$ velocity vector of size 6561x1. Further details are shown in next subsection.

Table 1. Elapsed time in the finite difference method for two different methods.

# of elements used in the finite difference method	50x50	60x60	70x70	80x80
Elapsed Time in Gauss Seidel Iteration Method (sec)	15.19	30.95	55.92	76.94
Elapsed Time in Gauss Elimination Method (sec)	11.14	31.95	154.23	X

C.7.1 Solution of the velocity vector by Gauss Elimination Method

One of the examples given in Table 1 with 80x80 elements in the FD method will be considered here for the demonstration of the method.

System of linear equations in matrix form: $Au = b$

$$\begin{pmatrix} a_1 & & 0 \\ & \mathbf{0} & \\ 0 & & a_n \end{pmatrix} \begin{pmatrix} u_1 \\ \mathbf{u} \\ u_n \end{pmatrix} = \begin{pmatrix} b_1 \\ \mathbf{b} \\ b_n \end{pmatrix}$$

$$\begin{matrix} (N+1)^2 \times (N+1)^2 & (N+1)^2 \times 1 & (N+1)^2 \times 1 \\ 6561 \times 6561 & 6561 \times 1 & 6561 \times 1 \end{matrix}$$

where u = velocity vector N = total number of elements in the mesh to be used in FD method.

Solution is given by:

$$u = bA^{-1}, \text{ (or } u = A \backslash b \text{ using MATLAB's “\” operation)}$$

C.7.2 Solution Of The Velocity Vector By Gauss Seidel Method

Pseudocode:

```

 $u^{old} = \text{initial guess}$ 
while error > threshold value
  for  $i = 1 : N$ 
    for  $j = 1 : N$ 
 $u^{new}(i, j) = C_1(u^{new}(i+1, j) + u^{new}(i-1, j)) + C_2(u^{new}(i, j+1) + u^{new}(i, j-1)) + C_3$ 
    end
  end
  error = norm( $u^{old} - u^{new}$ )
   $u_{old} = u_{new}$ 
end

```

where N = total number of elements in the mesh to be used in FD method. Solution is a 81×81 velocity matrix, $u = (N+1) \times (N+1)$.

If the A matrix is sparse, Gauss Seidel method works much more efficiently than Gauss Elimination. However, Gauss Seidel method requires the A matrix to be diagonally dominant for convergence. This is just the case for our system of linear equations used to compute the permeability. Thus, Gauss Seidel method works much more efficiently than Gauss Elimination method does.

Reference: Gerald, Wheatley, “Applied Numerical Analysis”, Addison Wesley, Chapter 2, Solving Sets of Equations, Section 2.10, Iteration Methods, pp 164, 1997.

APPENDIX D

STEPS IN UNIGRAPHICS TO PERFORM MESHING

Unigraphics commands are listed below for meshing an object and then for getting the necessary mesh data:

- Ø Application > Modeling
- Ø Sketch > Rectangle (whatever needed)
- Ø Finish Sketch
- Ø Extruded Body (if a 2D or 3D object is to be created.)
- Ø Application > structures
- Ø Scenario Navigator > New Scenario
- Ø FE Model > New Mesh > 2D
- Ø Select all and define overall element size
- Ø Finite Element Model Summary > to see number of nodes and elements
(or right click on 2D mesh > Properties)

If element size too small and mesh cannot be made:

change tolerances from Preferences / Meshing.

- Ø Identify node and element > select nodes or elements > type “1 - n” to see them in order

To merge duplicate nodes on different surfaces (necessary to avoid repetition of node numbers):

- Ø Scenario Navigator > Right click on 2D mesh > Check > Duplicate Node > Merge duplicate Nodes

To edit mesh characteristics like element type and /or size:

- Ø Right click on 2d mesh > edit