

**Use of Thermocouple and Voltage Sensors
to Monitor the Resin Transfer Molding Process**

by

Murat Danışman

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Murat Danışman

and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Committee Members:

Assist. Prof. Murat Sözer (Advisor)

Assist. Prof. Havva Funda Yağcı Acar

Assist. Prof B. Erdem Alaca

Date:

ABSTRACT

Complete automation has not been achieved in manufacturing processes of composite materials due to the variations in material used and preparation of it. In this study, monitoring of the Resin Transfer Molding (RTM) process is analyzed by using two types of sensor systems: (i) thermocouple sensors and (ii) point-voltage sensors. The ultimate goal of the whole project is to control the Resin Transfer Molding (RTM) process by integrating the sensors, mold, injection machine, data acquisition system, and mold filling simulations. This particular study is mainly on the analysis of the two sensor systems.

In the thermocouple sensors section, a mathematical model based on 1D flow and 2D unsteady energy conservation was developed to investigate the heat transfer between resin and mold walls. The numerical solution of this model is in qualitative agreement with the results of our experiments by showing that there are some constraints on usage of thermocouple sensors. With the use of typical RTM materials and injection parameters, thermocouples should not be preferred over other sensor types, or they should be used with a caution due to the inadequacies investigated in this study.

In the voltage sensors section, both lineal- and point-voltage sensors are investigated. The results of our experiments show that, although the gradually varying in-situ data of a lineal sensor is more informative than a point-voltage sensor, lineal-voltage sensors might mislead the user if the resin covers the wires at multiple sections, or the resin covers the wires starting from an unexpected section. Multiple point-voltage sensors were used in this study as flow monitoring tools. The simple electrical circuit of a conventional voltage sensor was improved to amplify the output voltage. The accuracy and reliability of this new sensor system was verified by comparing the in-situ sensor data with the visually recorded resin flow.

ÖZET

Kompozit malzeme üretim yöntemlerinde malzeme ve hazırlanışındaki değişkenlikler sebebiyle, henüz tamamiyle otomasyona geçilememiştir. Bu çalışmada, reçine transfer kalıplama tekniği (RTM), iki ayrı algılayıcı sistemi (sıcaklık algılayıcıları ve voltaj algılayıcıları) ile analiz edilmiştir. Projenin tümünde genel amaç algılayıcılar, kalıp, enjeksiyon makinesi, veri toplama sistemi ve kalıp dolum simülasyonları birleştirilerek, RTM tekniğini kontrol etmektir. Bu çalışma özellikle yukarıda adı geçen iki algılayıcı sisteminin analizinden oluşmaktadır.

Sıcaklık algılayıcı kısmında, tek boyutlu akışa ve iki boyutlu kararsız enerji korunumuna dayanan bir matematiksel model geliştirilerek, reçine ve kalıp duvarları arasındaki ısı geçişi araştırılmıştır. Hem bu modelin sayısal çözümlemesi ve hem de yaptığımız deneyler sıcaklık algılayıcılarının kullanımının bazı kısıtlamaları olduğunu göstermiştir. Tipik RTM malzemelerinin ve enjeksiyon parametrelerinin kullanıldığı durumlarda, sıcaklık algılayıcılarının diğer algılayıcı türlerine kıyasla yetersiz kaldığı; veya kullanıldığı durumlarda yetersizliklerinden dolayı dikkatle kullanılmaları gerektiği bu çalışmada gözlenmiştir.

Voltaj algılayıcı kısmında, doğrusal ve noktasal voltaj algılayıcıları incelenmiştir. Deneylerimizin sonuçlarına göre, doğrusal algılayıcıların değişen verileri noktasal algılayıcılara göre daha detaylı bilgilendirici görünse de, kullanıcıyı reçinenin algılayıcının çeşitli kısımlarını mı yoksa tek bir kısmını mı kapladığı konusunda yanıltabilir. Çok noktalı voltaj algılayıcıları bu çalışmada akışı izlemek için kullanılmıştır. Ölçülen voltaj değeri geleneksel bir voltaj algılayıcısının basit elektrik devresinin geliştirilmesi ile artırılmıştır. Bu yeni algılayıcı sistemin doğruluğu ve güvenilirliği algılayıcıdan alınan verilerin ve reçine akışının görsel kayıtlarının karşılaştırılması ile doğrulanmıştır.

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NOMENCLATURE

V_f	Fiber volume fraction
ϕ	Porosity
E	Modulus of elasticity [GPa]
UTS	Ultimate tensile strength [MPa]
t_{cu}	Thickness of copper [m]
R_m	Resistance of fiber-epoxy composite [Ω]
C_m	Capacitance of fiber-epoxy composite [F]
T_{ref}	Reference temperature for thermocouple [$^{\circ}\text{C}$]
T_{hot}	Temperature of the hot junction [$^{\circ}\text{C}$]
α	Seebeck coefficient for thermocouple
h_{um}	Height of the upper mold [m]
h_{lm}	Height of the lower mold [m]
h_{mc}	Height of the mold cavity [m]
Δx	Increment in the x direction [m]
Δy	Increment in the y direction [m]
Δz_1	Increment in the upper part of the mold [m]
Δz_2	Increment in the mold cavity [m]
Δz_3	Increment in the lower part of the mold [m]
u	Velocity of resin [m/s]
u_f	Velocity of flow front [m/s]
Q	Flow rate [m^3/s]
A	Cross-sectional area [m^2]
w	Width of the mold cavity [m]
Br	Brinkman constant
μ	Viscosity [Pa.s]

τ	Viscous dissipation [W]
T_{∞}	Ambient demperature [$^{\circ}\text{C}$]
k	Conductive heat transfer coefficient [W/(m. $^{\circ}\text{C}$)]
Gz	Graetz number
Pe	Peclet number
α	Effective thermal diffusivity of the saturated fabric [m^2/s]
d_p	Fiber diameter [m]
t	Simulation time [s]
L	Characteristic flow length [m]
ρ_a	Density of air [kg/m^3]
c_{pa}	Specific heat of air [J/(kg. $^{\circ}\text{C}$)]
k_a	Thermal conductivity of air [W/(m. $^{\circ}\text{C}$)]
ρ_f	Density of fiber [kg/m^3]
c_{pf}	Specific heat of fiber [J/(kg. $^{\circ}\text{C}$)]
k_f	Thermal conductivity of fiber [W/(m. $^{\circ}\text{C}$)]
ρ_r	Density of resin [kg/m^3]
c_{pr}	Specific heat of resin [J/(kg. $^{\circ}\text{C}$)]
k_r	Thermal conductivity of resin [W/(m. $^{\circ}\text{C}$)]
$k_{x,eq}$	Thermal conductivity of material in x direction [W/(m. $^{\circ}\text{C}$)]
$k_{z,eq}$	Thermal conductivity of material in z direction [W/(m. $^{\circ}\text{C}$)]
$T_{f,initial}$	Initial temperature of the dry fabric [$^{\circ}\text{C}$]
ρ_{um}	Density of upper mold [kg/m^3]
c_{pum}	Specific heat of upper mold [J/(kg. $^{\circ}\text{C}$)]
k_{um}	Thermal conductivity of upper mold [W/(m. $^{\circ}\text{C}$)]
ρ_{lm}	Density of lower mold [kg/m^3]
c_{plm}	Specific heat of lower mold [J/(kg. $^{\circ}\text{C}$)]
k_{lm}	Thermal conductivity of lower mold [W/(m. $^{\circ}\text{C}$)]

ρ_{mc}	Density of mold cavity [kg/m ³]
c_{pmc}	Specific heat of mold cavity [J/(kg °C)]
k_{mc}	Thermal conductivity of mold cavity [W/(m. °C)]
$T_{r,in}$	Temperature of the resin at the injection gate [°C]
k_m	Thermal conductivity of the mold material [W/(m. °C)]
h	Natural convective heat transfer coefficient between air and mold [W/(m ² . °C)]
$T(k,i)$	Current temperature at any node [°C]
$T^{next}(k,i)$	Temperature at any node at the next time step [°C]
Δt	Time increment
$k_{z,eq,wet}$	Thermal conductivity of wet resin in z direction [W/(m. °C)]
$k_{z,eq,dryt}$	Thermal conductivity of dry resin in z direction [W/(m. °C)]
s	Saturation
$k_{z,eq,eff}$	Effective equivalent thermal conductivity of resin in z direction [W/(m. °C)]
A_{in}	Cross sectional area of the lineal injection gate [m ²]
A_{exit}	Cross sectional area of the lineal ventilation gate [m ²]
r	Stability parameter in finite difference analysis
b	All the terms related with the neighbour temperatures in finite difference analysis
T_o	Dry sensor temperature [°C]
θ	Normalized temperature
R_{sens}	Resistance generated by the polymer-fabric media between two electrodes
V_{sens}	Output voltage [V]
L_{wet}	Length of sensor wire covered with the resin [m]

Chapter 1

INTRODUCTION AND EXPERIMENTAL SET-UP

After an introduction to the RTM process, its issues, and available sensor systems for the flow monitoring and resin cure, in this study RTM process will be monitored using two alternative types of sensor systems.

1.1 Composite Materials

Composite materials are preferred to traditional engineering materials because of high specific strength, high stiffness, high energy absorption upon impact and high corrosion resistance. Composite materials are being used in industries including aerospace, marine, civil, automotive, military and sports goods [1].

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, sports goods such as racquet frames, bicycle bodies and hockey clubs.

A typical composite material is a combination of polymer and reinforcing fibers (see Figure 1.1 for a sample composite part). “Advanced” composite materials have continuous fibers (usually in the form of stitched or woven fabrics) and a surrounding matrix, which is usually a thermosetting cured polymer.



Figure 1.1 A typical composite part made in our research laboratory.

1.1.1 Fabric

Fabrics carry most of the structural loads acting on composite parts, and hence they provide strength and stiffness 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 1.2. Different types of fabric have different draping capability (being able to lay up over a tool surface without a formation of any wrinkle) and different mechanical properties. Fiber volume fraction ($V_f = 1 - \phi$, where ϕ is the porosity) is the ratio of fiber volume to the total volume. As V_f 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 due to its higher resistance to flow (or, lower permeability).

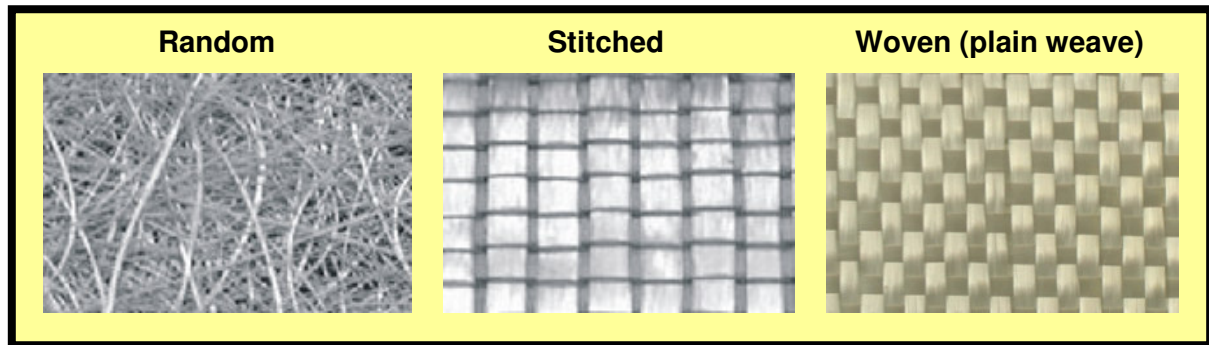


Figure 1.2 Different types of glass fabric.

Table 1.1 Modulus of elasticity and ultimate tensile strength for different materials [3].

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 (Aramid)	62 - 117	2800

In this study, both random and plain-woven e-glass fabrics were used in the experiments (see Figure 1.3). Random fabrics are highly isotropic, however, woven fabrics are generally anisotropic (i.e., their mechanical properties differ in different directions). This anisotropy also affects the flow front propagation of polymer through fabric preforms. For example, if an internal point injection gate is used, the in-plane flow front will be circular for an isotropic fabric, whereas it will be elliptical in the case of an isotropic fabric [2].

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 [3]. However, due to the weave structures and empty spaces between fibers, the fabric strength is either smaller than steels, or on the same order of magnitude compared to steels [2]. The overall strength of composite part will be dependent on the fiber volume fraction and structure of fabric. In Table 1.1, a comparison of modulus of elasticity and ultimate tensile strength for different materials is given [3].

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.

1.1.2 Resin

Resin, which is the second major component of composite part, is any polymer with the required curing agents added in it. After it cures, resin 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. It also transmits external forces to the reinforcing fibers. Thermoset polymers have a tensile strength of about 35-170 MPa which is much lower than that of steels (see Table 1.1).

There are two types of polymers used in composite materials manufacturing: thermosets and thermoplastics. Thermosets are in liquid phase at room temperature. Thermosets require a stage in which a chemical reaction of cross-linking between polymer molecules takes place.

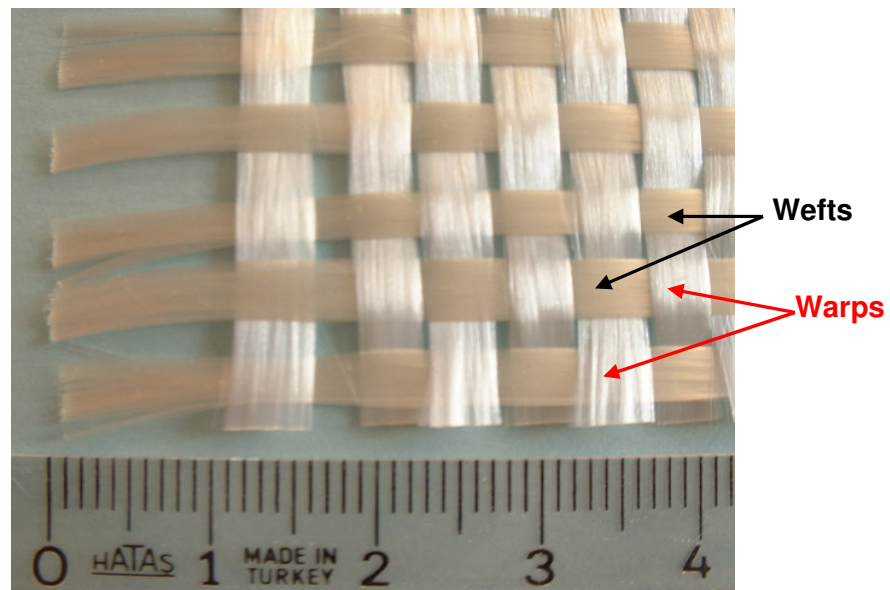


Figure 1.3 (a) Woven glass fiber bundles called wefts and warps.

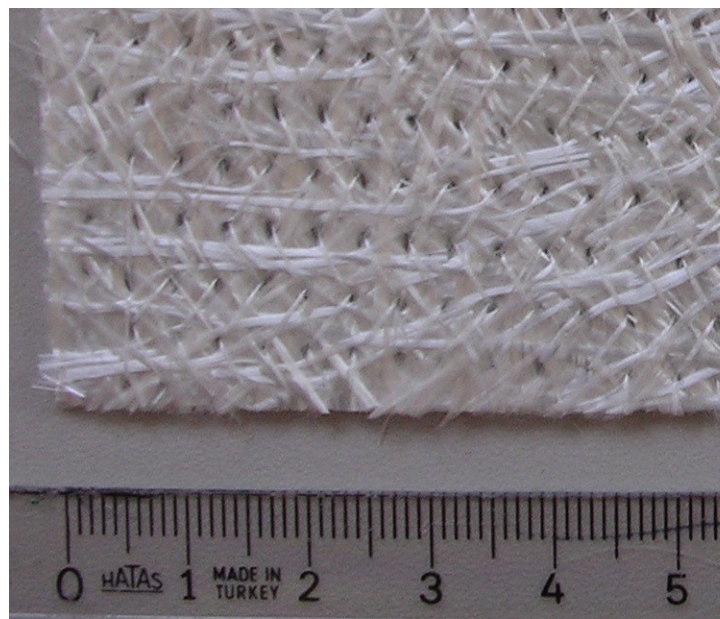


Figure 1.3 (b) Random e-glass fabric.

This stage is called *curing*. Due to strong covalent bond between the mers (unit cell molecules), processing of thermosets is an irreversible process. 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. After a pot life time, gelation starts and viscosity of polymer increases very sharply. As the process comes to an end, they solidify. Due to their relatively lower viscosity than thermoplastics, thermosets have the advantage of easy processing. The fraction of cure agents determines the pot life. For high volume manufacturing, pot life should be designed to be as short as possible. However, as we shorten the pot life, there is a risk that gelation might start before complete mold filling if polymer does not propagate as designed under desired conditions.

Thermoplastic resins have higher viscosity than thermosets, 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 much higher viscosity than thermosets, it is very difficult to make them flow through micro-scale empty spaces between fibers. They also show non-Newtonian flow characteristics. For a comparison, Table 1.2 shows some viscosity values for different materials [4]. As a summary, there are two major reasons to use thermosets instead of thermoplastics in manufacturing processes of “advanced” composite materials: (i) requirement of lower injection pressure due to lower viscosity than for thermoplastics; (ii) in general, thermosets have higher mechanical properties than thermoplastics.

Table 1.2 Viscosity values for different materials [4].

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}

1.2 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 relatively lower strength requirements might be manufactured with discontinuous fibers, which are less costly and easier to impregnate than continuous fibers. Discontinuous fibers may be in the form of chopped fibers compacted in random orientation.

Composite materials manufacturing techniques can be classified as (i) short (discontinuous) fiber composite manufacturing; and (ii) advanced composite manufacturing techniques [4]. 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 a highly viscous resin system and 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 impregnation of a preform fabric with thermoset resin. Since a thermoset resin is used, curing takes place. The processes following fall into this class: 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.

1.2.1 Resin Transfer Molding (RTM) Process

In this study, our focus will be on RTM process, which belongs to the group of LCM processes [4]. In LCM processes, the basic principle is to inject a liquid thermoset resin into a mold cavity with a previously placed stationary fabric perform, and saturate all gaps between the fibers with resin before the gellation of a polymer starts.

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

- High fiber volume fraction (V_f) which means parts with higher strength,
- High dimensional accuracy (low tolerances),
- Complex shapes,
- Good surface quality (low surface roughness).

With RTM, near net-shape manufacturing (little further processing is needed on parts) is possible. Parts with nonuniform properties can 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 1.4, there are five major stages of the RTM process [13]:

1. *Preform Manufacturing*: Fabric layers with certain dimensions are cut from a roll of fabric and then stacked together.

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*: As the mold is closed, the fabric preform is compacted between upper and lower mold parts. Fiber volume fraction might be as high as 65-70% if high strength is needed.
4. *Resin Injection and Cure*: Resin is injected into the mold cavity using an injection machine. Injection is 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.

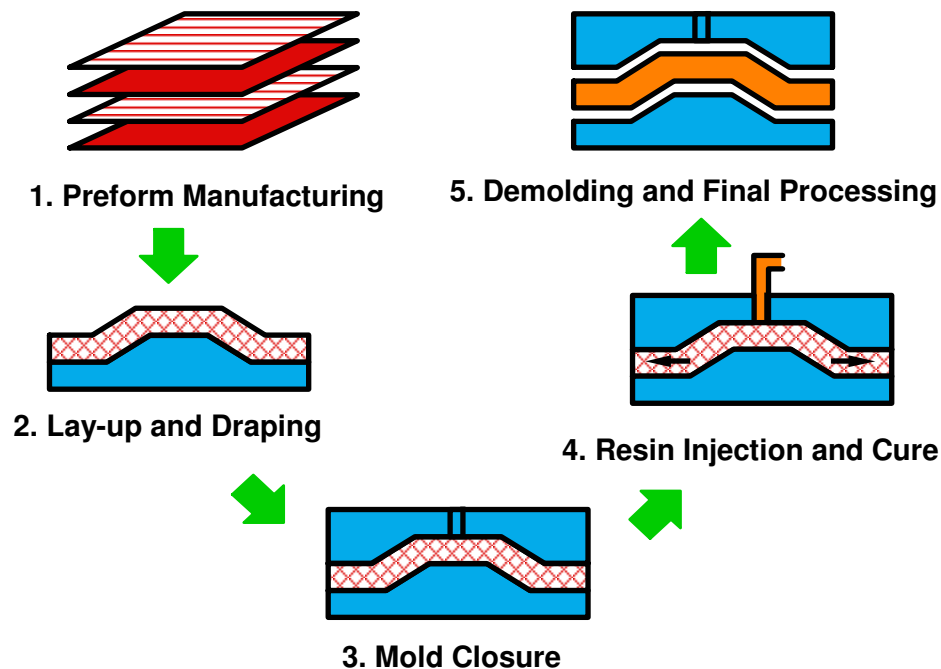


Figure 1.4 Stages of the RTM process [13].

1.3 Experimental Set-up and Mold Design

The modular RTM mold used in this study was designed and manufactured in TUBITAK, MISAG project [2]. A similar modular mold was originally used by Sozer et. al [5,6]. The mold enables production of rectangular panels with different dimensions. It is a modular mold that enables testing of different injection and control schemes. Figure 1.5 shows the major components of this RTM mold. The functions of mold parts can be described as follows:

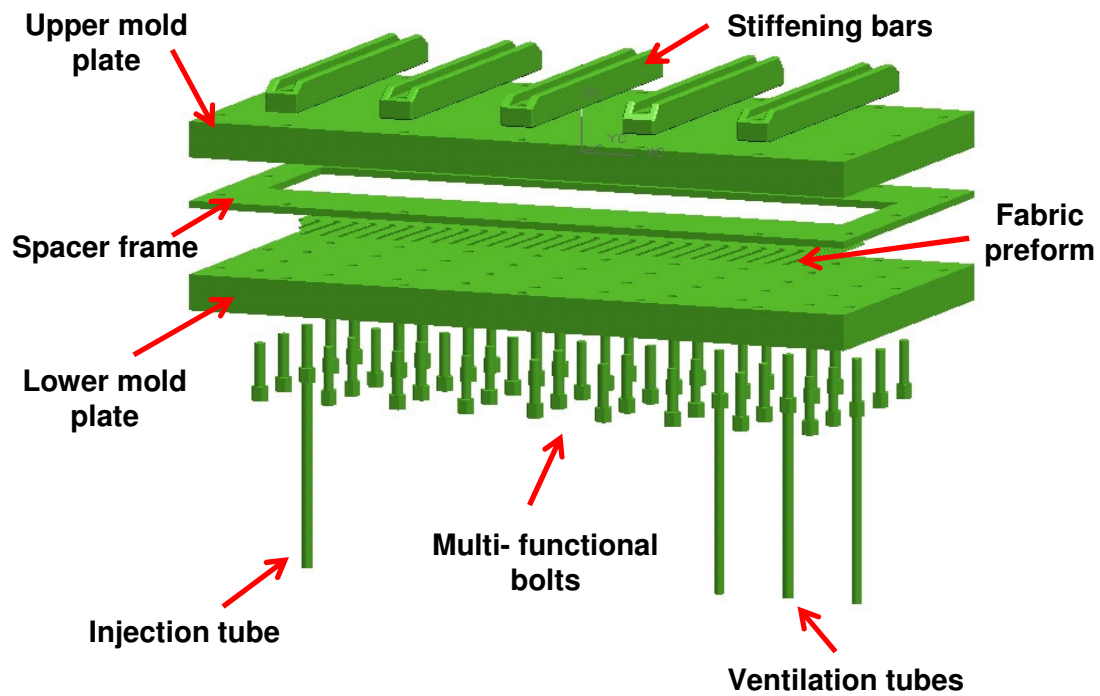


Figure 1.5 Modular RTM mold and its components [7].

1. Upper and Lower Mold Plates: When the mold parts are closed during the injection process, leakage of polymer must be 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.

In this study, compaction of fabric preform within the mold cavity is performed by screwing 16 bolts around the mold manually. The lower part of the mold is made of aluminum and mounted on a wheeled steel cart as shown in Figure 1.6. Two alternative upper parts are used: metal (aluminum) part, or transparent acrylic part. While the upper aluminum part provides higher stiffness and hence better compaction, the transparent acrylic part provides a visual access to the system and flow front propagation can be observed. Figure 1.7 shows the two configurations of RTM mold closed with alternative upper parts.

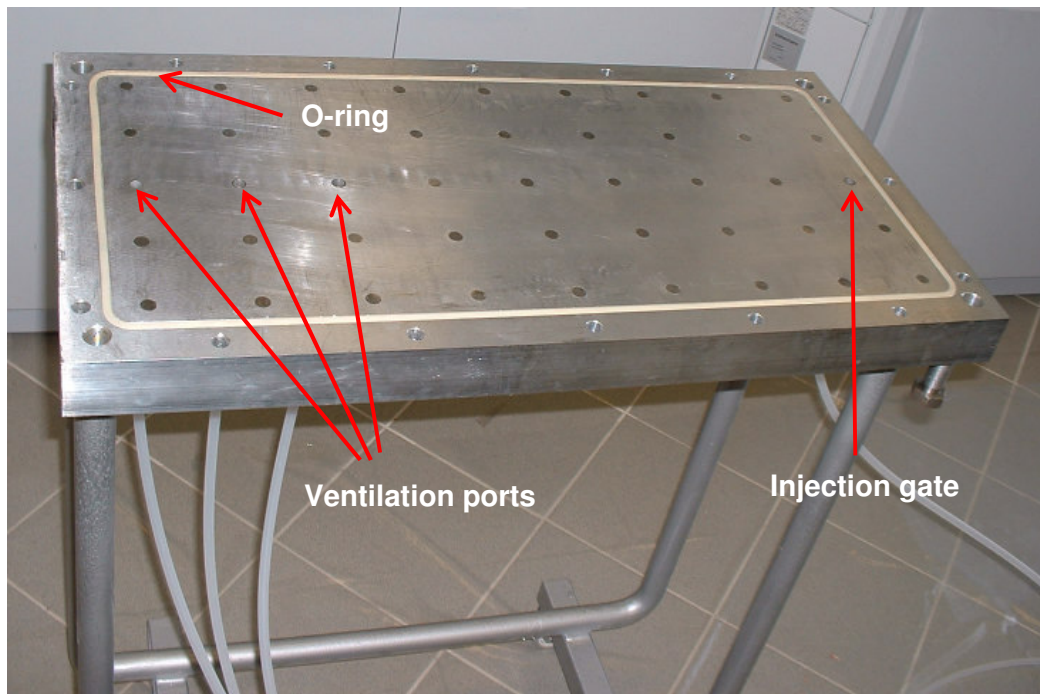


Figure 1.6 The lower part of RTM mold and wheeled steel table fixed to that.

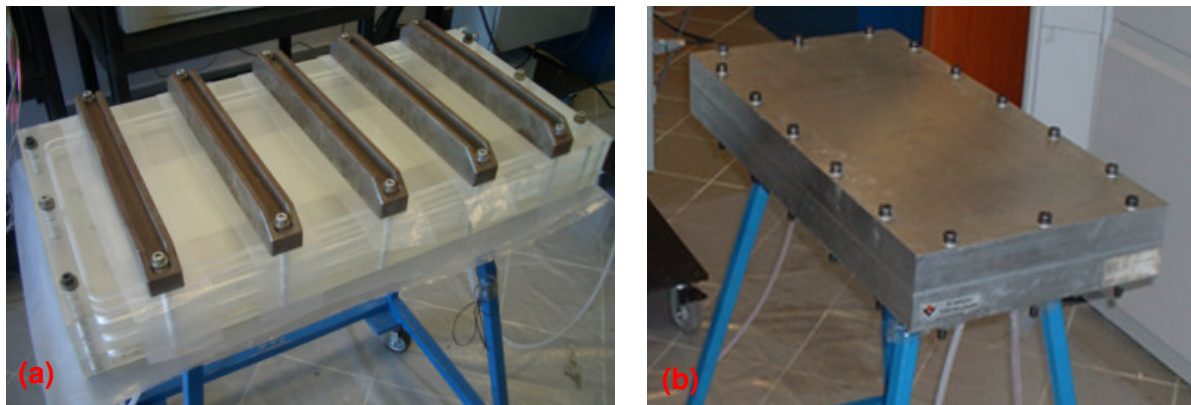


Figure 1.7 Alternative upper parts: (a) acrylic part (usually 3 pieces), and (b) aluminum metal part.

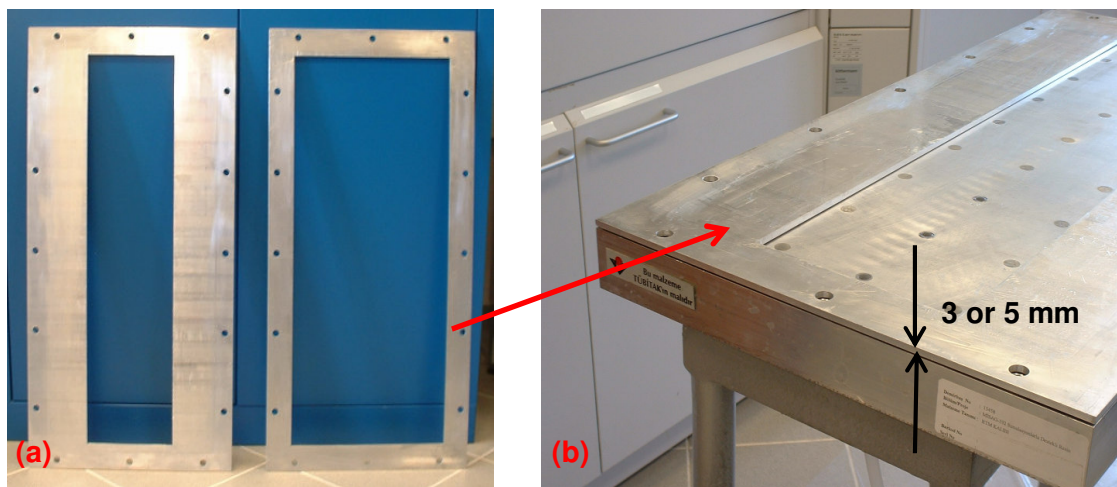


Figure 1.8 (a) Two of the six spacer frames, and (b) a spacer frame placed on lower mold part.

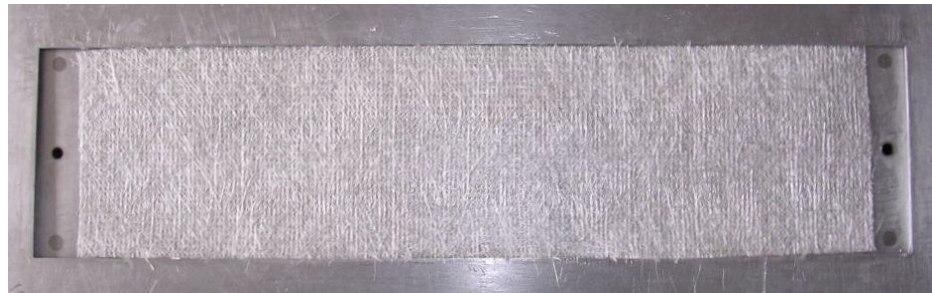


Figure 1.9 Random fabric preform placed into the mold cavity (top view of mold).

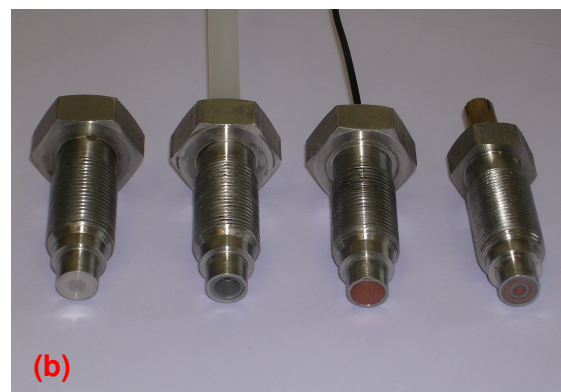


Figure 1.10 (a) Bottom view of the mold with 45 multi-function bolts; and (b) different uses of bolts.

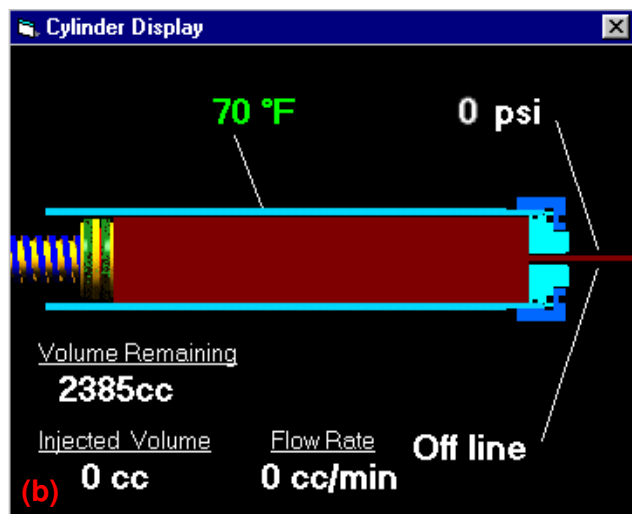


Figure 1.11 (a) Injection machine; and (b) display of Floware software.

2. *Spacer Frame*: Spacer frame determines the dimensions of the mold cavity, and thus the dimensions of the part to be manufactured. In Figure 1.8, two sample spacer frames are shown.

3. *Stiffening Bars*: They are used to ensure stiffness of mold plates against bending, and hence for better compaction of preform.

4. *Fabric Preform*: Fabric is cut from rolls to fit the interior dimensions of the spacer frame used. In our study, we mostly used random fabric. Figure 1.9 shows layers of random fabric placed into the mold cavity.

5. *Injection and Ventilation Tubes*: Resin is transferred from the injection machine to the mold through polyethylene injection tube(s) [8]. The number of injection and ventilation ports can be one or more.

6. *Multi-function bolts*: There are 45 multi-function bolts as shown in Figure 1.10(a). These bolts can be used as (i) solid (no function); (ii) injection gate; (iii) ventilation port; or (iv) a sensor for resin flow monitoring (Figure 1.10(b)).

1.4 Injection Machine

Resin is injected from the injection machine into the mold cavity through injection tubes. Two injection machines are available in the laboratory. They are from Radius Engineering Inc [9] (see Figure 1.11a). 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. The process parameters and variables can be monitored from the Floware display as shown in Figure 1.11(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.

1.5 The Polymer System and Fabric Used in the Experiments

Plain weave and random type of e-glass fabrics [10] 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.

Two types of thermosetting polymers were used in this study. The first polymer is a general-purpose polyester [11]. Some chemical agents are added to the polymer system to start cross-linking. These are Cobalt and Peroxit [12] which are used as an accelerator and as a curing agent, respectively. 3 grams of Cobalt and 3 grams of Peroxit are added into 2000 grams of polyester. The mixing ratio can be altered for different room temperatures or according to the desired curing time. The second type of polymer used in this study is Moravia Epoxy [13], which is a two-component epoxy system. The two components of epoxy are mixed with a ratio of two to one in volumes to start cure. Information about the viscosity and density values for the two polymers can be found in Appendix A.

1.6 Organization of the Thesis

In this study, we tried to monitor resin flow and cure in RTM process via different types of sensors. The study mainly discusses two types of sensor systems and analysis of them: (i) Thermocouples; and (ii) Point-Voltage Sensors. The organization of the chapters can be given as follows: A review of the literature about the sensor types and systems is given 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. The use of point-voltage sensors is described in Chapter 5. The conclusions of this study are summarized in Chapter 6.

1.7 Contributions Done in this Thesis

To fully automate the RTM process, in-situ mold filling should be monitored by integrating sensors with the mold and DAQ system. Experimental setup and two alternative types of sensor systems had been introduced in a previous study last year [15]. In this study, a mathematical model was developed based on 1D flow and 2D heat transfer between resin and mold walls to investigate the constraints of the thermocouple sensors. The experiments of the previously developed point-voltage sensors are performed and verification of these sensors are made by comparing the sensor data and visually recorded flow front. By discussing the issues of the sensor types, this study is expected to be a guide to select an appropriate sensor system for the flow monitoring in the RTM process.

Chapter 2

LITERATURE REVIEW OF SENSOR SYSTEMS

2.1 Literature Survey

Throughout the literature, the focus has been to understand the physics of the RTM process and to model it properly. Thus, many research studies were carried out to model and simulate the RTM process. Monitoring of resin flow and cure constitutes a significant portion of these studies. Researchers and engineers aim to overcome some potential problems commonly encountered in the RTM process and try to fully automate the process for the sake of (i) manufacturing high quality composite parts, and (ii) increasing the production rate.

In order to fully automate the process and manufacture parts having desired quality, the RTM process parameters such as injection pressure, injection flow rate, position of gates and vents should be set properly. 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.

Process monitoring plays a crucial role in the 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 two monitoring purposes, the most frequently used sensors are thermocouples, pressure

transducers, SMARTweave, dielectric, ultrasonic, fiberoptic and lineal voltage sensors [14]. The literature survey of different sensor systems was done by Goker Tuncol [15], and it will be summarized here as well.

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} in Figure 2.1) is a linear function of temperature [16].

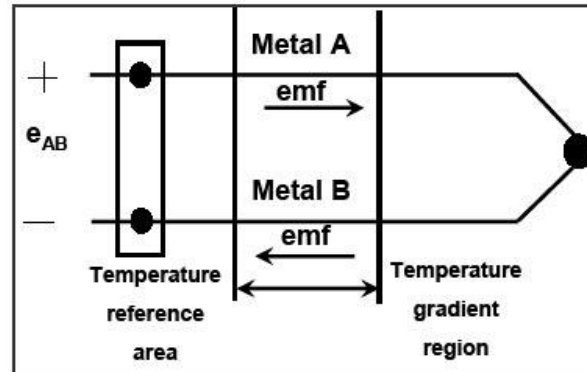


Figure 2.1 Thermocouple sensor [16].

Thermocouples are widely used in cure monitoring investigations. In order to predict the degree of resin cure by using thermocouples, one has to know the temperature history of the resin [17]. Besides being used for cure monitoring, thermocouples are used for resin flow monitoring as in [15] and our study. However, it is important that there should be a considerable amount of temperature difference between the mold 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 [15].

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 which is proportional to the pressure [18]. A melt pressure transducer (shown in Figure 2.2 [19]) is designed specifically for measuring polymer pressure. These transducers are not generally used for flow monitoring purposes since placing pressure sensors at many discrete positions inside the mold would be very costly. They are usually used to monitor the injection pressure only, as in our study.



Figure 2.2 A melt pressure transducer [19].

SMARTweave [67] was developed by the U.S. Army Research Laboratory for monitoring resin flow front progression and providing data for control of resin flow in large RTM fiberglass parts [14]. 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 (see Figure 2.3) [20]. 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. [22], and Don et al. [23] used SMARTweave in their resin flow and cure monitoring studies.

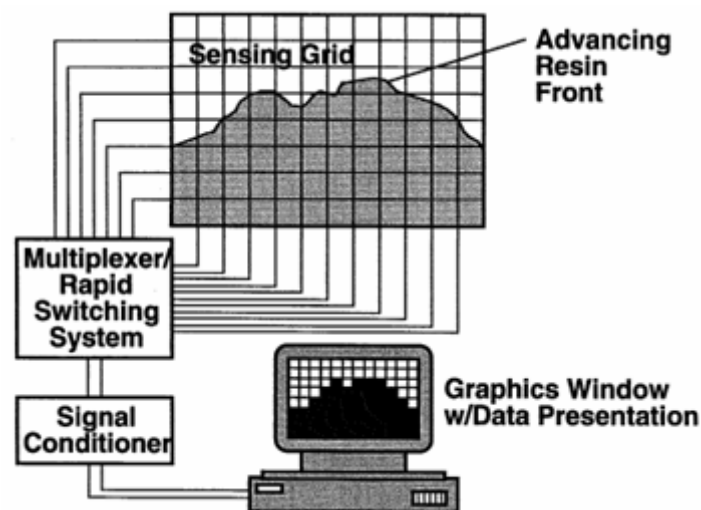


Figure 2.3 Schematic for the Smartweave system [20].

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 [14]. 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.

McIlhagger et al. [25] 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 properties such as conductance and 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. That is, activities on the molecular level, such as the ones in curing stage, strongly affect these electrical properties. They used ionic conductivity to make a direct 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. [26] 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 3mm x 3 mm, which was manufactured by etching a thin copper plate bonded onto an epoxy substrate. 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).

Kim et al. [27] 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. [28] used ultrasonic built-in sensors in a mold with on-line process control for monitoring both resin flow and cure. 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 do not 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 variables. During the curing process, an increasing sound velocity is detected by the ultrasonic receiver, which reaches a maximum value at the end of curing.

Rath et al. [29] 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 [30] used fiber-optic sensing to monitor three dimensional resin front location. They compared their results with numerical simulations 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, it is possible to monitor the resin flow front. Dunkers et al. [31] made use of fiber-optic sensors for resin cure monitoring as well.

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. [32] 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 and a resistance generated by the polymer-fabric media between the wires. Separate couples of wires can be placed at desired locations of the mold. A certain voltage is applied to each circuit's beginning. 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 about the lineal sensors and the point-voltage sensors developed in this study is given in Chapter 5.

Lawrence et al. [33] 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, and conducted several mold filling simulations by using LIMS (Liquid Injection Molding Simulation) [34]. 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. [35], Bickerton et al. [36] and Sozer et al. [37] as part of their control systems.

2.2 Most Recent Research on Sensors and Monitoring in RTM

Lee et al. [38] proposed a real-time simulation/control method to control the formation of air spots during mold filling. They used optical sensors for detection of the flow front in their study. Optical sensors in their study consist of an infrared LED and a photo-detector packaged in a single housing. A photo-detector is a device that generates voltage output proportional to the amount of light it absorbs. Before the flow front arrives, the reflected light from the fibers is high, generating a high voltage output at the sensor. When the resin reaches the sensor, the amount of reflected energy is reduced, and the voltage output decreases.

Advani et al. [39] used two types of sensors in their study for flow sensing and controlling the race-tracking disturbances: (i) dielectric sensors embedded in the mold surface and (ii) a pressure sensor. The dielectric sensors in their analysis consist of two copper wires embedded in mold surface. The pressure sensor is a pressure sensitive film consists of two thin, flexible polyester sheets, and in between the two layers, there is a thin semi-conductive coating which changes its local electrical resistance when different loads are applied. The pressure sensor enables to process the pressure data and display the flow front pattern in real time.

Hegg et al. [40] used dielectric sensors in their study to monitor the flow front position and the degree of cure of the resin as it is injected into the mold. The sensors are in the form of parallel plates and aligned parallel to the resin movement. They used a sinusoidal signal for generating an electric field between the sensors and the mold. The sensors react to the changes in capacitance and conductance of the resin due to the progress of flow front within the mold cavity.

Chapter 3

PROBLEMS OF THE RTM PROCESS AND THE NEED FOR A CONTROL SYSTEM

3.1 Problems of the RTM Process

Besides having advantages over other composite manufacturing techniques, Resin Transfer Molding (RTM) process has some potential problems. There are two common problems that may occur during an RTM injection: (i) incomplete mold filling (i.e., micro or macro scale dry spots in the composite part), and (ii) wash of fabric perform.

During an RTM injection, some parts of the fabric layers may move and change their initial position. This is called *wash* of fabric (see Figures 3.1 and 3.2). Possible reasons of this phenomenon are high pressure at the injection port and insufficient compaction of the fabric preform. Wash of fabric in Figure 3.2 actually started along the edges of the mold and eventually caused a large wrinkle in the mid-section.

Another major problem in RTM process is the incomplete filling of the mold cavity. The main reason behind this phenomenon is the occurrence of race-tracking channels (Figure 3.3) which are also called as ‘edge flow’ or ‘edge effect’. As it can be seen in the figure, there always stays a gap between the fabric preform and the mold walls. These gaps have a few millimeters width along the mold edges and corners; however, presence of these small channels might cause a significant change in the local permeability of fabric preform. Differences in the local permeability significantly change the flow pattern (see Figure 3.4). For example, although a line injection was intended in Figure 3.5, the flow front did not

progress as a line. Resin raced along the two race-tracking channels, and the flow front was like a U-shape.

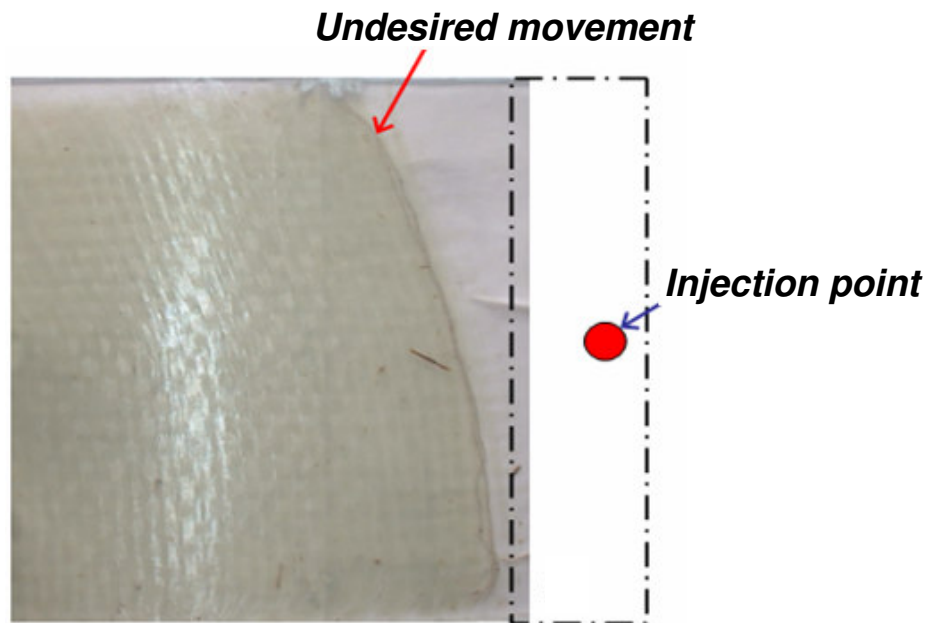


Figure 3.1 A close view of wash of fabric near an injection port [15].

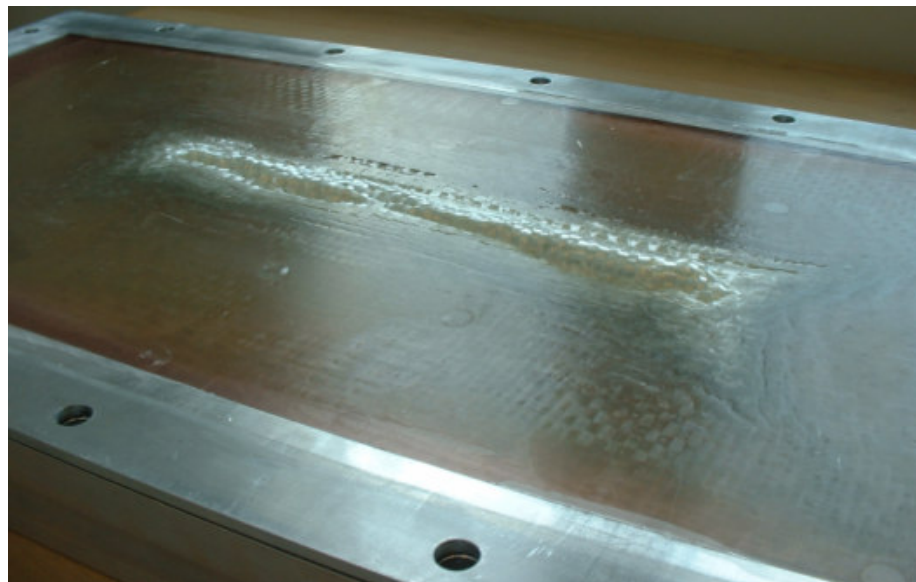


Figure 3.2 Wash of fabric in the mid-section of the mold [15].

Another major problem in RTM process is the incomplete filling of the mold cavity. The main reason behind this phenomenon is the occurrence of race-tracking channels (Figure 3.3) which are also called as ‘edge flow’ or ‘edge effect’. As it can be seen in the figure, there always stays a gap between the fabric preform and the mold walls. These gaps have a few millimeters width along the mold edges and corners; however, presence of these small channels might cause a significant change in the local permeability of fabric preform. Differences in the local permeability significantly change the flow pattern (see Figure 3.4). For example, although a line injection was intended in Figure 3.5, the flow front did not progress as a line. Resin raced along the two race-tracking channels, and the flow front was like a U-shape.

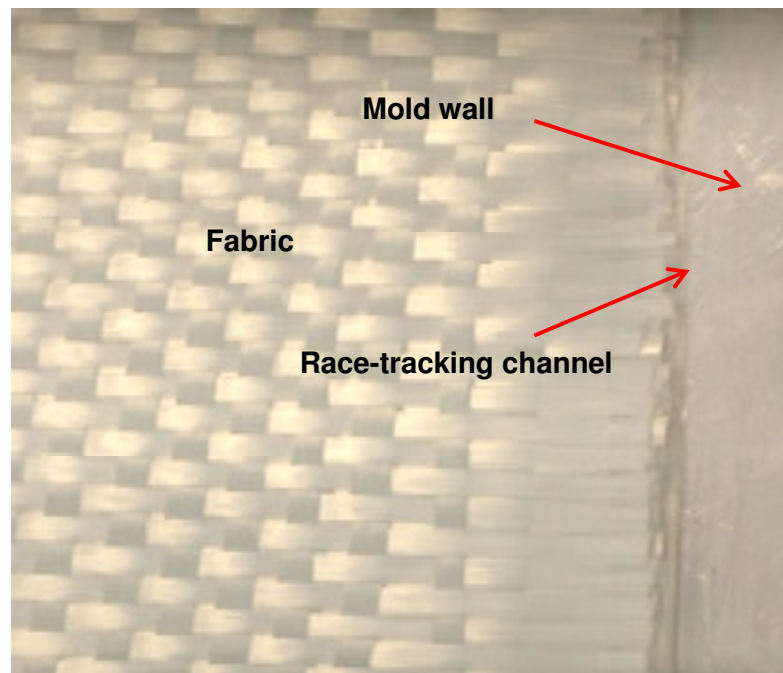


Figure 3.3 A race-tracking channel between the fabric edge and mold wall [15].

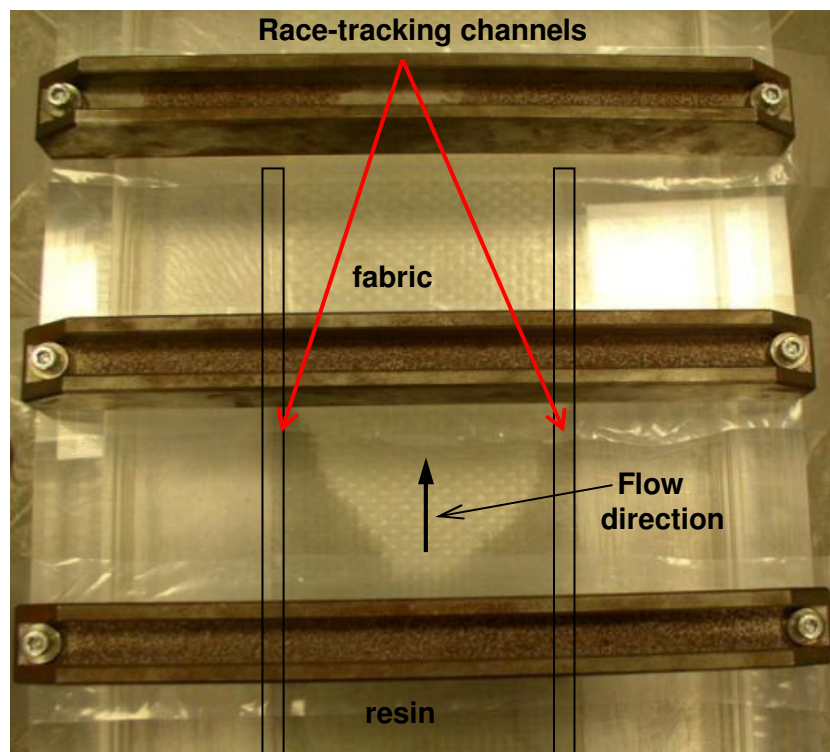


Figure 3.4 Effect of race-tracking channels on flow front [15].

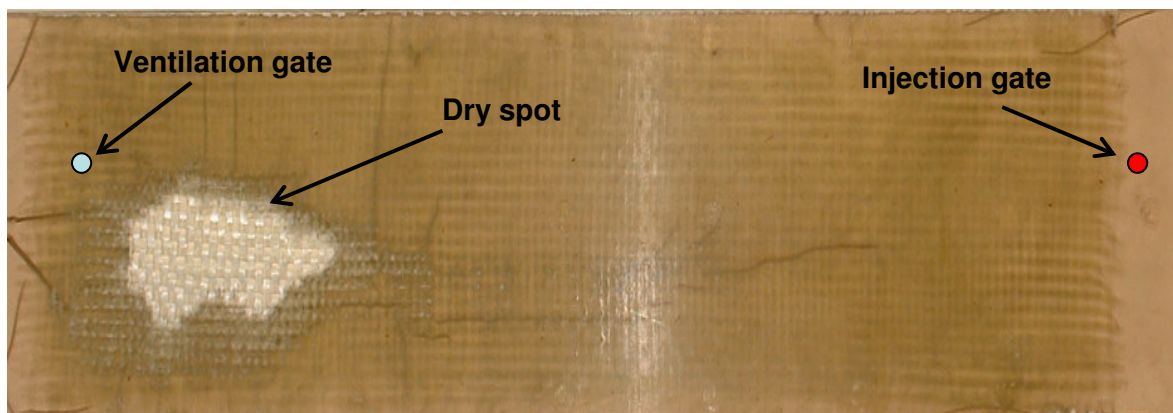


Figure 3.5 A composite part with a macro size dry spot (void) near a ventilation gate [15].

Dry spot (void) formation (see Figure 3.5) is a significant problem to pay attention during the mold filling stage. The size of the dry spots may be in macro and/or micro scale. If some amount of air is entrapped at a certain region, this prevents wetting of the fabric at that particular location, and a macro size dry spot occurs. Micro dry spots occur because of high injection flow rates. If a high flow rate is used in the injection, as the flow front of resin passes through fabric, it might not be saturated completely and micro size dry spots occur. This is the reason for using very low injection flow rates (100-200 cc/min) in this study. 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.

3.2 The Need For a Control System

Due to the issues mentioned above, a control system is needed (i) to manufacture void free parts; (ii) to decrease cycle time and cost; and (iii) to fully automate the process. Attempts and studies to launch such control systems have already been mentioned in Chapter 2. The ingredients of the control system are:

- Mold
- Injection Machine [9]
- Mold Filling Simulations (LIMS) [34]
- Sensors for (i) monitoring mold filling; and (ii) resin cure as well
- Data Acquisition System (LabVIEW software [41] and NI DAQ cards [42])

The key elements in the control system are flow-monitoring sensors. With an appropriate sensor system, flow and cure monitoring must be done and the system must be integrated for

full automation. Before going into the analysis of the sensor systems, some useful information about the DAQ system is given in the next section.

3.3 Data Acquisition System

The DAQ system for flow monitoring mainly works with the arrival times of the resin to particular sensor locations. Arrival of the resin is determined by using a proper threshold for the sensors. For the thermocouple sensors, this threshold is in terms of temperature, and for the voltage-point sensors, it is in terms of voltage. Whenever the reading of a particular sensor exceeds the default value by that threshold, the time is kept in an array. 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 orders of resin arrival times correspond to different *scenarios* [36,37]. For example, if only three sensors A, B and C are used, the possible scenarios can be listed as in Table 3.1. A parameter called *minimum time difference* is a parameter which determines the minimum time difference between any set of arrival time data to correlate them with scenarios. For any two or more sensors, if the difference between arrival time data, Δt , is smaller than the minimum time difference parameter, then the arrival times are considered to be practically equal to each other. Table 3.2 shows four sample cases and demonstrates the use of minimum time difference parameter for sensors A, B and C with arrival time data t_A , t_B and t_C . In the first two cases of Table 3.2, arrival times for the sensors A, B, and C are very distinct. In Case 3, the resin arrives at A and B simultaneously: $t_A = t_B$. However, Case 4 is difficult to evaluate. Mathematically speaking, $t_C < t_B < t_A$, and the resin arrival order corresponds to CBA, which is Scenario 6. However, $t_A = 50\text{s}$ and $t_B = 49\text{s}$, and the difference between them can be considered small if one compares it with the full duration of the mold filling. If hundreds of point sensors are placed in a mold cavity, one or two seconds

difference between t_A and t_B should be evaluated as $t_B < t_A$ for a more accurate and hence more detailed monitoring of mold filling. However, with rather limited number of point sensors, it is more reasonable to use the “minimum time difference” parameter, say $\Delta t = 2$ seconds or so. Thus, $|t_A - t_B| < \Delta t$, and the evaluation should be $t_A \approx t_B$ which corresponds to Scenario 8 of Table 3.1.

A detailed information about the LabVIEW code used in this study, analysis of the current DAQ system, information about the user interface, and information about the DAQ cards are given in Appendix B.

Channel number in our current DAQ system is limited to 16 when used as single-ended, and to 8 when used as differential. For a very detailed flow monitoring, one might need much more sensors especially when the composite part is large and complex. In order to increase the number of channels of the DAQ, a multiplexer prototype was developed (see Appendix B).

Table 3.1. Possible scenarios, sensor order and arrival time for three sensors A, B and C [64].

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 B] C	$t_A \approx t_B < t_C$
8	C [A B]	$t_C < t_A \approx t_B$
9	[A C] B	$t_A \approx t_C < t_B$
10	B [A C]	$t_B < t_A \approx t_C$
11	[B C] A	$t_B \approx t_C < t_A$
12	A [B C]	$t_A < t_B \approx t_C$
13	[A B C]	$t_A \approx t_B \approx t_C$

Table 3.2. Scenario assignment for some hypothetical cases of resin arrival times [64].

Case	Arrival Time (sec)			Sensor Order	Scenario #
	t_A	t_B	t_C		
1	50	60	70	A B C	1
2	50	40	30	C B A	6
3	50	50	40	C [A B]	8
4	50	49	40	C B A or C [A B]	6 or 8 ?

Chapter 4

THERMOCOUPLE SENSORS

As mentioned in the literature survey part, thermocouples are used for measuring temperature, and a thermocouple consists of two dissimilar metal wires connected together at one junction. This end is called the hot junction, and the other open end is called the cold or reference junction. The hot junction is attached to the media of which the temperature will be measured, and the reference junction is attached to a measurement device. When the hot junction is heated, a small voltage difference occurs between these two wires. This is called the thermoelectric effect, which is also known as the Seebeck effect in physics, and the voltage is a linear function of temperature [16]. If the reference temperature, T_{ref} is kept constant, the Seebeck voltage V becomes linearly proportional to the temperature of the hot junction, T_{hot}

$$V = \alpha (T_{hot} - T_{ref}) \quad (4.1)$$

where α is called the Seebeck coefficient [43]. Thermocouples are widely used in resin cure monitoring investigations. To predict the degree of resin cure by using thermocouples, one has to know the temperature history of the resin [17]. The curing reaction of a thermoset resin system is exothermic and thus, the temperature rise due to the heat release during cure is expected to be detected by the thermocouple sensors. It is also possible to monitor flow front propagation as well as resin cure if there is a considerable temperature difference between the resin and mold walls so that resin arrival can be detected. This applies under either one of these two conditions: (i) thermoset polymer is heated prior to injection while

the mold walls are kept at a lower temperature such as room temperature initially; or (ii) inlet thermoset polymer is at room temperature while the mold walls are heated. The former case was applied in our experiments owing to the injection machine's external heating capability.

4.1 The Need for Modeling of Heat Transfer between the Resin and the Mold during Injection

As observed in our early prototype RTM injection experiments with typical materials and process parameters, the hot resin's temperature dropped almost immediately to that of cold mold which did not allow resin arrival detection by the thermocouple sensors [15]. The rate of conductive heat transfer from the resin to the mold wall is suspected to be so high that the internal energy and hence the elevated temperature of inlet resin are not conserved during the injection stage.

In this section, a mathematical model will be developed for one-dimensional resin flow (in x direction) and two-dimensional heat transfer (in xz plane) between the resin and the mold walls. The aim is to study what range of critical injection parameters (temperatures of inlet resin and mold walls, and resin flow rate) and mold material can enable the use of thermocouple sensors for adequate resin flow monitoring.

Consider a mold cavity as schematically shown in Figure 4.1. Due to the narrow empty space around the injection gate, the injection gate is practically a lineal one, and the corresponding resin flow is one-dimensional.

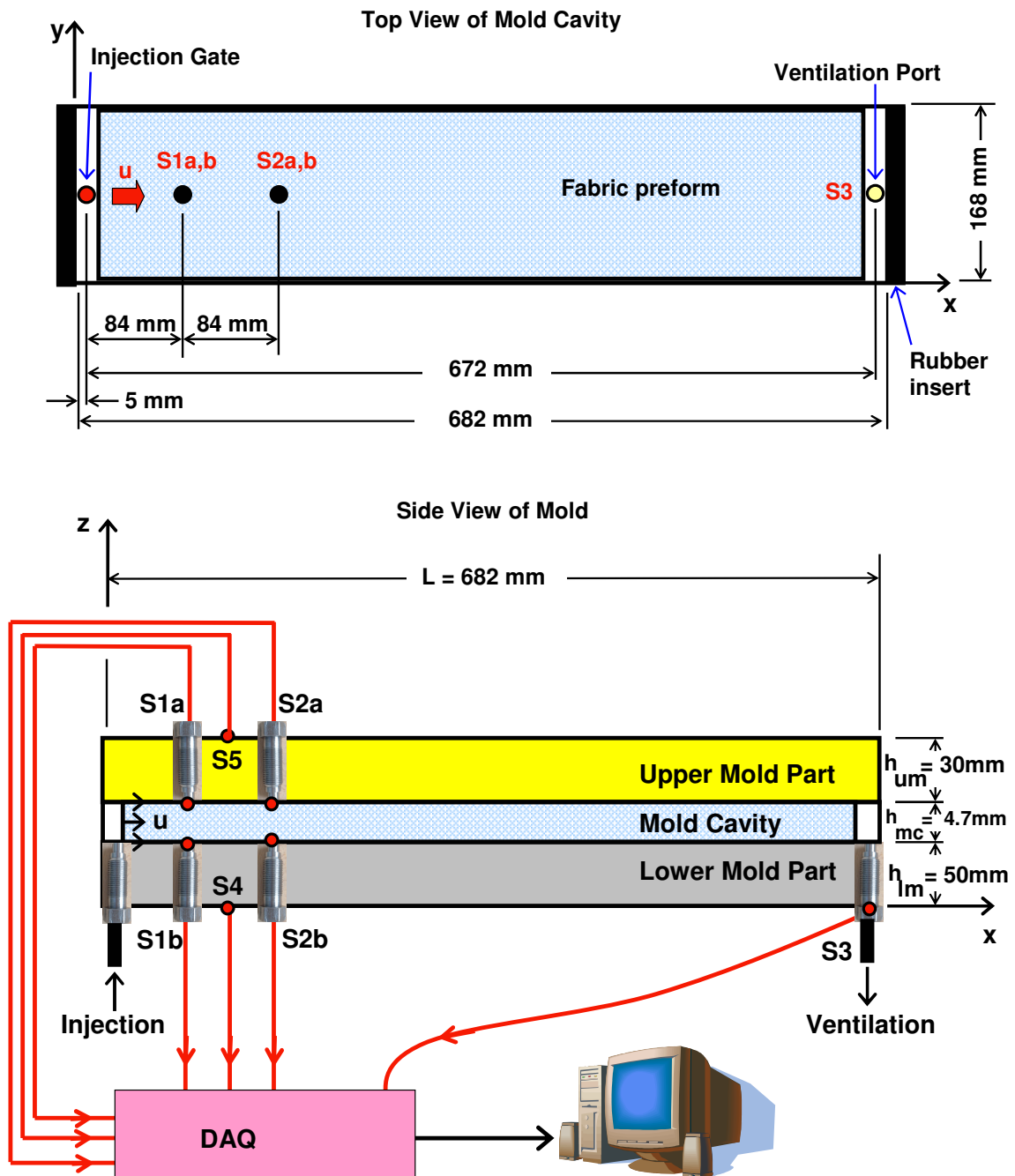


Figure 4.1. Monitoring of resin flow and cure using thermocouple sensors. Seven thermocouple sensors (S1a, S1b, S2a, S2b, S3 $\equiv$ Sexit, S4 and S5) are placed on mold walls [44].

A discrete mesh in xz plane was prepared, as shown in Figure 4.2. The increment, Δx in the x direction is uniform. However, because the mold cavity was very thin compared to the mold walls, different increments were used in the upper mold part, mold cavity, and lower mold part: Δz_1 , Δz_2 , and Δz_3 , respectively.

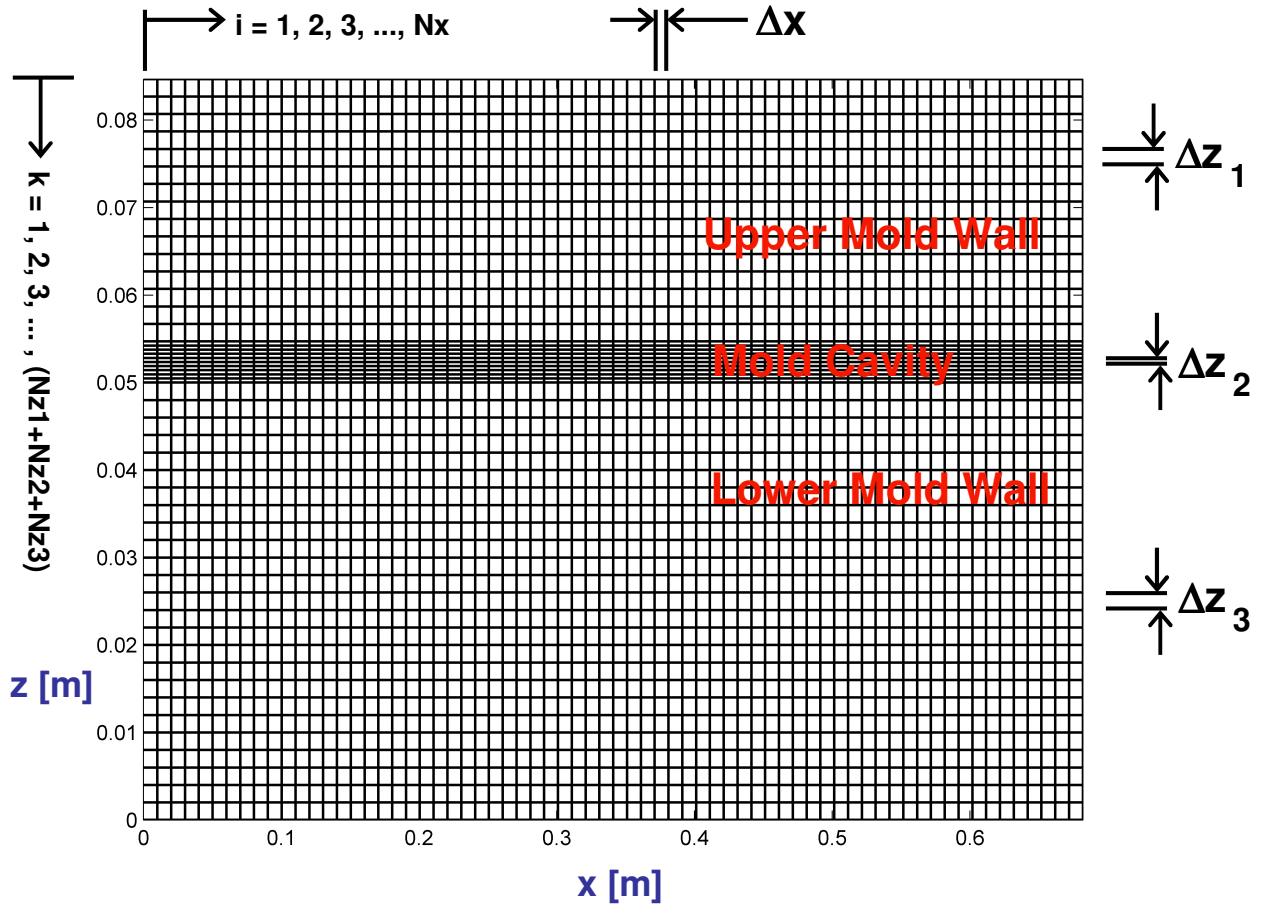


Figure 4.2. Mesh for the mold cavity and mold parts [44].

4.1.1 Governing Differential Equations (Conservation of Energy Equations)

Within the three domains (upper and lower molds, and mold cavity), unsteady energy equations will be used, and one-dimensional flow within the mold cavity will be considered. Assumptions made for this model are listed below:

- Flow of resin through the fabric preform is one-dimensional. Since the injections are performed at a constant flow rate, the corresponding velocity (averaged through the thickness direction, z) is given by $u = Q / A = Q / (w h_{mc})$. Here Q is the flow rate, w and h_{mc} are the width and thickness of the mold cavity, respectively. Assuming that the preform is a uniform porous media in macro scale, the flow front velocity is given by $u_f = u / \phi$, where ϕ is the porosity of the fabric preform.
- As a dimensionless analysis suggests, the conductive heat transfer in the mold cavity in in-plane directions is insignificant compared to the conductive heat transfer in transverse direction (z direction) since the thickness of the mold cavity, h_{mc} (on the order of millimeters) is much smaller than the in-plane dimensions (on the order of tens of centimeters). However, inclusion of the conduction in in-plane direction (x direction) does not bring a significant computational difficulty, and it will be included in this model.
- Assuming that the degree of cure is relatively low during the injection stage, the heat release due to exothermic cross-linking reaction is neglected.
- In typical RTM applications, the Brinkman number, $Br = (\mu u^2) / (k \Delta T) = (\text{viscous dissipation}) / (\text{conduction due to } \Delta T)$ is very low. Hence, we will drop the viscous dissipation term, $\tau : (\nabla U)$ in the energy equation of our model.
- The dry fabric and mold walls are at ambient temperature, T_∞ initially.

- Thermal dispersion is neglected assuming that (i) the Graetz number, $Gz = (u h^2)/(\alpha L) = (\text{convection in the flow direction})/(\text{conduction in the gapwise direction})$ is low; and (ii) $Pe/Gz < 1$, where the Peclet number $= Pe = (u d_p)/\alpha = (\text{convection on the microscale})/(\text{transport by conduction})$; α is the effective thermal diffusivity of the saturated fabric; and d_p is the fiber diameter [45].
- The temperature of the resin does not change as it travels from the injection machine to the injection gate through a plastic tube. In our experiments, this was achieved by using an electric heater sleeve that is controlled by the injection machine's software.

The mold cavity region is divided into two sub-regions. In the wetted region (the fabric preform saturated with resin) where $0 < x < x_f = u_f t = (u/\phi)t$, and $h_{lm} < z < h_{lm} + h_{mc}$, the energy equation is given by

$$\underbrace{[\phi \rho_r c_{pr} + (1-\phi) \rho_f c_{pf}]}_{\text{internal}} \frac{\partial T}{\partial t} = - \underbrace{\rho_r c_{pr} u}_{\text{convection}} \frac{\partial T}{\partial x} + \underbrace{k_{x,eq} \frac{\partial^2 T}{\partial x^2} + k_{z,eq} \frac{\partial^2 T}{\partial z^2}}_{\text{conduction}}. \quad (4.2)$$

In the dry region where $x_f < x < L$, and $h_{lm} < z < h_{lm} + h_{mc}$, there is no flow of resin ($u = 0$), and hence the convective term in energy equation drops out, resulting in the following form:

$$\underbrace{[\phi \rho_a c_{pa} + (1-\phi) \rho_f c_{pf}]}_{\text{internal}} \frac{\partial T}{\partial t} = \underbrace{k_{x,eq} \frac{\partial^2 T}{\partial x^2} + k_{z,eq} \frac{\partial^2 T}{\partial z^2}}_{\text{conduction}} \quad (4.3)$$

where ρ , c_p and k are the density, specific heat, and thermal conductivity of corresponding material. Subscripts $()_r$, $()_f$ and $()_a$ belong to the resin, fabric preform, and air in the mold cavity, respectively. If the injection is performed under vacuum, then the term $\phi \rho_a c_{pa}$ appearing in (4.3) should be dropped. The porosity of the mold cavity is given by ϕ , which varies between 0 and 1 depending on the compaction of fabric preform. $k_{x,eq}$ and $k_{z,eq}$ are the equivalent (or, also called effective) thermal conductivity of material (either “resin and fabric preform”, or “air and fabric preform”) inside the mold cavity in x - and z -directions, respectively. Different theoretical and empirical models have been used to calculate the components of equivalent thermal conductivity of a composite part in different directions [46]. *Parallel* and *series* configurations are commonly applied models. In this study, along the in-plane direction (x -direction), the solid (fibers) and fluid (resin or air) are assumed to be in *parallel* configuration; and along the transverse direction (z -direction), the solid and fluid are assumed to be in *series* configuration due to the placement of the multiple fabric sheets on each other in z -direction:

$$k_{x,eq} = \begin{cases} \phi k_r + (1-\phi) k_f & \text{in } 0 < x < x_f \\ \phi k_a + (1-\phi) k_f & \text{in } x_f < x < L \end{cases}$$

(4.4a)

and

$$k_{z,eq} = \begin{cases} \frac{1}{\left(\frac{\phi}{k_r} + \frac{1-\phi}{k_f} \right)} & \text{in } 0 < x < x_f \\ \frac{1}{\left(\frac{\phi}{k_a} + \frac{1-\phi}{k_f} \right)} & \text{in } x_f < x < L. \end{cases} \quad (4.4b)$$

If vacuum is drawn (not applied in this study), then ϕk_a term is neglected. Since the conductive heat transfer in the dry mold cavity region is much smaller in x -direction than in the transverse direction, instead of using Equation (4.3), one can simply use the assumption of $T = T_{f,initial}$ in this dry region, where $T_{f,initial}$ is the initial temperature of the dry fabric. However, in our study, we use Equation (4.3).

In the lower mold part ($0 < x < L$ and $0 < z < h_{lm}$):

$$\rho_{lm} c_{plm} \frac{\partial T}{\partial t} = k_{lm} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right). \quad (4.5)$$

In the upper mold part ($0 < x < L$ and $h_{lm} + h_{mc} < z < h_{lm} + h_{mc} + h_{um}$):

$$\rho_{um} c_{pum} \frac{\partial T}{\partial t} = k_{um} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right). \quad (4.6)$$

Subscripts $()_{lm}$, $()_{um}$ and $()_{mc}$ designate the lower mold part, upper mold part, and mold cavity, respectively.

4.1.2 Boundary Conditions

- At the inlet (injection gate) of the mold cavity:

$$T = T_{r,in}. \quad (4.7)$$

- Along the outer mold wall which is in contact with ambient air, a natural (free) convective heat transfer is assumed:

$$-k_m \frac{\partial T}{\partial n} = h(T - T_\infty) \quad (4.8)$$

where n is the outward direction on the mold wall; k_m is the thermal conductivity of the mold material which is equal to k_{lm} and k_{um} in the lower and upper mold part regions,

respectively; and h is the natural (free) convective heat transfer coefficient between air particles and horizontal mold parts.

- Along the two interfaces between the mold walls and the mold cavity, the temperature of the resin (also fabric and mold itself) is allowed to change as a function of x and t . These unknown temperatures of the interface nodes are going to be solved using an energy balance around the node. This approach is different from some other studies which assume constant temperature boundary condition (i.e., no variation with respect to time) [47-50]. At the interface of upper mold part and mold cavity, a boundary condition is derived by considering the unsteady conservation of energy at a control element around the node of (k,i) is driven (see Figure 4.3).

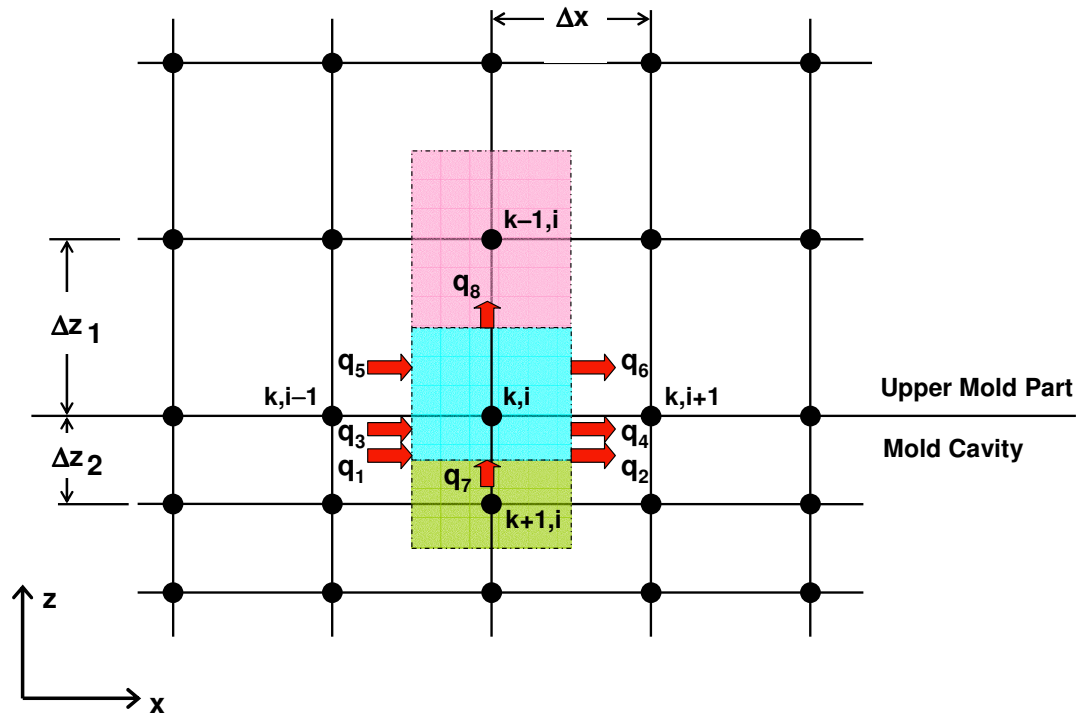


Figure 4.3. Heat fluxes from neighbor control elements to an element on the interface between the upper mold wall and mold cavity [44].

The conservation of energy equation is as follows:

$$\begin{aligned}
 \left(\begin{array}{c} \text{Rate of increase} \\ \text{of internal energy} \end{array} \right) &= (q_1 - q_2) + (q_3 - q_4) + (q_5 - q_6) + (q_7 - q_8) \\
 &= \left(\begin{array}{c} \text{Inflow Flux of} \\ \text{Heat Energy} \\ \text{by Convection} \\ \text{through} \\ \text{Mold Cavity} \end{array} \right) - \left(\begin{array}{c} \text{Outflow Flux of} \\ \text{Heat Energy} \\ \text{by Convection} \\ \text{through} \\ \text{Mold Cavity} \end{array} \right) \\
 &\quad + \left(\begin{array}{c} \text{Inflow Flux of} \\ \text{Heat Energy} \\ \text{by Conduction} \\ \text{in } x \text{ direction} \\ \text{through} \\ \text{Mold Cavity} \end{array} \right) - \left(\begin{array}{c} \text{Outflow Flux of} \\ \text{Heat Energy} \\ \text{by Conduction} \\ \text{in } x \text{ direction} \\ \text{through} \\ \text{Mold Cavity} \end{array} \right) \\
 &\quad + \left(\begin{array}{c} \text{Inflow Flux of} \\ \text{Heat Energy} \\ \text{by Conduction} \\ \text{in } x \text{ direction} \\ \text{through} \\ \text{UpperMold Part} \end{array} \right) - \left(\begin{array}{c} \text{Outflow Flux of} \\ \text{Heat Energy} \\ \text{by Conduction} \\ \text{in } x \text{ direction} \\ \text{through} \\ \text{Upper Mold Part} \end{array} \right) \\
 &\quad + \left(\begin{array}{c} \text{Inflow Flux of} \\ \text{Heat Energy} \\ \text{by Conduction} \\ \text{in } z \text{ direction} \\ \text{through} \\ \text{Mold Cavity} \end{array} \right) - \left(\begin{array}{c} \text{Outflow Flux of} \\ \text{Heat Energy} \\ \text{by Conduction} \\ \text{in } z \text{ direction} \\ \text{through} \\ \text{Upper Mold Part} \end{array} \right)
 \end{aligned} \tag{4.9}$$

or,

$$\begin{aligned}
& \left(\phi \rho_r c_{pr} + (1 - \phi) \rho_f c_{pf} \right) \frac{\partial T}{\partial t} \Delta x \Delta y (a \Delta z) + \left(\rho_{um} c_{pum} \right) \frac{\partial T}{\partial t} \Delta x \Delta y ((1 - a) \Delta z) \\
&= - \rho_r c_{pr} u \frac{\partial T}{\partial x} \Delta x \Delta y (a \Delta z) \\
&+ k_{x,eq} \frac{\partial^2 T}{\partial x^2} \Delta x \Delta y (a \Delta z) \\
&+ k_{um} \frac{\partial^2 T}{\partial x^2} \Delta x \Delta y ((1 - a) \Delta z) \\
&- k_{z,eq} \frac{\partial T}{\partial z} \Big|_{\text{in mold cavity}} \Delta x \Delta y + k_{um} \frac{\partial T}{\partial z} \Big|_{\text{in upper mold}} \Delta x \Delta y
\end{aligned} \tag{4.10}$$

where $\Delta z = (\Delta z_1 + \Delta z_2)/2$ and $a = (\Delta z_2/2)/\Delta z$. After dividing both sides with $\Delta x \Delta y \Delta z$, the following boundary condition is obtained:

$$\begin{aligned}
& \left[a(\phi \rho_r c_{pr} + (1 - \phi) \rho_f c_{pf}) + (1 - a) \rho_{um} c_{pum} \right] \frac{\partial T}{\partial t} \\
&= - a \rho_r c_{pr} u \frac{\partial T}{\partial x} + \left[a k_{x,eq} + (1 - a) k_{um} \right] \frac{\partial^2 T}{\partial x^2} - k_{z,eq} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in mold cavity}} + k_{um} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in upper mold}}
\end{aligned} \tag{4.11}$$

Similarly, the boundary condition at the other interface between lower mold part and mold cavity is obtained as follows:

$$\begin{aligned}
& \left[a(\phi \rho_r c_{pr} + (1 - \phi) \rho_f c_{pf}) + (1 - a) \rho_{lm} c_{plm} \right] \frac{\partial T}{\partial t} \\
&= - a \rho_r c_{pr} u \frac{\partial T}{\partial x} + \left[a k_{x,eq} + (1 - a) k_{lm} \right] \frac{\partial^2 T}{\partial x^2} + k_{z,eq} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in mold cavity}} - k_{lm} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in lower mold}}
\end{aligned} \tag{4.12}$$

where $\Delta z = (\Delta z_2 + \Delta z_3)/2$ and $a = (\Delta z_2/2)/\Delta z$.

Notice that, in the dry region where the resin has not arrived there yet, the boundary conditions become:

$$\begin{aligned} & \left[a(\phi \rho_a c_{pa} + (1-\phi) \rho_f c_{pf}) + (1-a) \rho_{um} c_{pum} \right] \frac{\partial T}{\partial t} \\ &= \left[ak_{x,eq} + (1-a)k_{um} \right] \frac{\partial^2 T}{\partial x^2} - k_{z,eq} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in mold cavity}} + k_{um} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in upper mold}} \end{aligned} \quad (4.13)$$

and

$$\begin{aligned} & \left[a(\phi \rho_a c_{pa} + (1-\phi) \rho_f c_{pf}) + (1-a) \rho_{lm} c_{plm} \right] \frac{\partial T}{\partial t} \\ &= \left[ak_{x,eq} + (1-a)k_{lm} \right] \frac{\partial^2 T}{\partial x^2} + k_{z,eq} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in mold cavity}} - k_{lm} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in lower mold}} \end{aligned} \quad (4.14)$$

When resin flow front is within the control area of the partially filled node, modified versions of differential equations (4.2), (4.13) and (4.14) are used. The equations (4.11) and (4.12) are also modified for the inlet elements at the interface (see Figure 4.4).

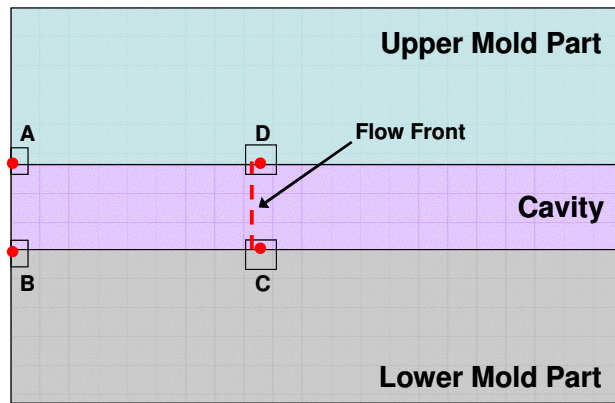


Figure 4.4. Schematic representation of the corner and the partially filled nodes.

For the four nodal points, the differential equations are derived as below:

For the control area at location A:

$$\begin{aligned} & \left[a(\phi \rho_r c_{pr} + (1-\phi) \rho_f c_{pf}) + (1-a) \rho_{um} c_{pum} \right] \frac{\partial T}{\partial t} \\ &= a \rho_r c_{pr} u \frac{\partial T}{\partial x} + k_{z,eq} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in mold cavity}} - k_{um} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in upper mold}} - k_{x,eq} a \frac{2}{\Delta x} \frac{\partial T}{\partial x} \Big|_{\text{in mold cavity}} - k_{um} (1-a) \frac{2}{\Delta x} \frac{\partial T}{\partial x} \Big|_{\text{in upper mold}} \end{aligned} \quad (4.15)$$

where $\Delta z = (\Delta z_1 + \Delta z_2)/2$ and $a = (\Delta z_2/2)/\Delta z$.

For the control area at location B:

$$\begin{aligned} & \left[a(\phi \rho_r c_{pr} + (1-\phi) \rho_f c_{pf}) + (1-a) \rho_{lm} c_{plm} \right] \frac{\partial T}{\partial t} \\ &= a \rho_r c_{pr} u \frac{\partial T}{\partial x} - k_{z,eq} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in mold cavity}} + k_{lm} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in lower mold}} - k_{x,eq} a \frac{2}{\Delta x} \frac{\partial T}{\partial x} \Big|_{\text{in mold cavity}} - k_{lm} (1-a) \frac{2}{\Delta x} \frac{\partial T}{\partial x} \Big|_{\text{in lower mold}} \end{aligned} \quad (4.16)$$

where $\Delta z = (\Delta z_2 + \Delta z_3)/2$ and $a = (\Delta z_2/2)/\Delta z$.

For the control area at location C:

$$\begin{aligned} & \left[a(s \phi \rho_r c_{pr} + (1-s) \phi \rho_a c_{pa} + (1-\phi) \rho_f c_{pf}) + (1-a) \rho_{um} c_{pum} \right] \frac{\partial T}{\partial t} \\ &= a \rho_r c_{pr} u \frac{\partial T}{\partial x} + a k_{x,eq,dry} \frac{1}{\Delta x} \frac{\partial T}{\partial x} \Big|_{\text{in dry mold cavity}} - a k_{x,eq,wet} \frac{1}{\Delta x} \frac{\partial T}{\partial x} \Big|_{\text{in wet mold cavity}} + (1-a) k_{um} \frac{\partial^2 T}{\partial x^2} \Big|_{\text{in upper mold}} \\ &+ k_{um} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in upper mold}} - k_{z,eq,eff} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in mold cavity}} \end{aligned} \quad (4.17)$$

where $\Delta z = (\Delta z_1 + \Delta z_2)/2$ and $a = (\Delta z_2/2)/\Delta z$.

For the control area at location D:

$$\begin{aligned}
 & \left[a(s\phi\rho_r c_{pr} + (1-s)\phi\rho_a c_{pa} + (1-\phi)\rho_f c_{pf}) + (1-a)\rho_{lm} c_{plm} \right] \frac{\partial T}{\partial t} \\
 &= a\rho_r c_{pr} u \frac{\partial T}{\partial x} + ak_{x,eq,dry} \frac{1}{\Delta x} \frac{\partial T}{\partial x} \Big|_{\text{in dry mold cavity}} - ak_{x,eq,wet} \frac{1}{\Delta x} \frac{\partial T}{\partial x} \Big|_{\text{in wet mold cavity}} + (1-a)k_{lm} \frac{\partial^2 T}{\partial x^2} \Big|_{\text{in lower mold}} \\
 & - k_{lm} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in lower mold}} + k_{z,eq,eff} \frac{1}{\Delta z} \frac{\partial T}{\partial z} \Big|_{\text{in mold cavity}}
 \end{aligned} \tag{4.18}$$

where $\Delta z = (\Delta z_2 + \Delta z_3)/2$ and $a = (\Delta z_2/2)/\Delta z$.

For the control elements at locations C and D, we have the effective conductive heat transfer coefficient in z direction calculated by considering the dry and wet sections:

$$k_{z,eq,eff} = \frac{1}{R_{z,eq,eff}} = \frac{k_{z,eq,wet} k_{z,eq,dry}}{s k_{z,eq,dry} + (1-s) k_{z,eq,wet}} \tag{4.19}$$

Also for the control elements at locations C and D, we have the term saturation (s), which shows whether the node is filled, partially filled or dry. For the filled nodes $s = 1$, for the unfilled nodes $s = 0$, and for the partially filled nodes it has a value of $0 < s < 1$.

At the ventilation port, where resin exits from the mold cavity, a boundary condition is obtained by considering the conservation of energy around a boundary control element with dimensions of $\Delta x/2$, Δy , and Δz :

$$\begin{aligned}
 (\phi \rho_r c_{pr} + (1 - \phi) \rho_f c_{pf}) \frac{\partial T}{\partial t} \left(\frac{\Delta x}{2} \Delta y \Delta z \right) = & \rho_r c_{pr} u \left(T \Big|_{x - \frac{\Delta x}{2}} - T \Big|_x \right) (\Delta y \Delta z) \\
 & + k_{z,eq} \left(\frac{\partial T}{\partial z} \Big|_{z + \frac{\Delta z}{2}} - \frac{\partial T}{\partial z} \Big|_{z - \frac{\Delta z}{2}} \right) \left(\frac{\Delta x}{2} \Delta y \right) \\
 & + k_{x,eq} \left(0 - \frac{\partial T}{\partial x} \Big|_{x - \frac{\Delta x}{2}} \right) (\Delta y \Delta z)
 \end{aligned} \tag{4.20}$$

where $\Delta z = \Delta z_2$. After dividing both sides with $\Delta x \Delta y \Delta z / 2$, the following boundary condition is obtained:

$$(\phi \rho_r c_{pr} + (1 - \phi) \rho_f c_{pf}) \frac{\partial T}{\partial t} = - \rho_r c_{pr} u \frac{\partial T}{\partial x} + k_{z,eq} \frac{\partial^2 T}{\partial z^2} - k_{x,eq} \frac{\partial T}{\partial x} \frac{2}{\Delta x}. \tag{4.21}$$

If the resin has not arrived there yet, then the boundary condition becomes:

$$[\phi \rho_a c_{pa} + (1 - \phi) \rho_f c_{pf}] \frac{\partial T}{\partial t} = k_{z,eq} \frac{\partial^2 T}{\partial z^2} - k_{x,eq} \frac{\partial T}{\partial x} \frac{2}{\Delta x}. \tag{4.22}$$

4.1.3 Numerical Solution of Temperature Distribution

The spatial derivatives in differential equations are approximated by using second order “central” difference equations as follows:

$$\frac{\partial T}{\partial x} \approx \frac{T(k, i + 1) - T(k, i - 1)}{2 \Delta x} \tag{4.23}$$

$$\frac{\partial^2 T}{\partial x^2} \approx \frac{T(k, i+1) - 2T(k, i) + T(k, i-1)}{(\Delta x)^2} \quad (4.24)$$

$$\frac{\partial^2 T}{\partial z^2} \approx \frac{T(k+1, i) - 2T(k, i) + T(k-1, i)}{(\Delta z)^2}. \quad (4.25)$$

The time derivative in differential equations is approximated by using first order “forward” difference equation as follows:

$$\frac{\partial T(k, i)}{\partial t} \approx \frac{T^{next}(k, i) - T(k, i)}{\Delta t} \quad (4.26)$$

where $T(k, i)$ and $T^{next}(k, i)$ are the temperature at any node, (k, i) at the current and next time steps. An Eulerian time-marching scheme is applied with an increment of Δt . Initially, the temperatures of all the nodal points (except the ones at the injection gate) are assigned to the ambient temperature, $T = T_\infty$.

The spatial derivatives in boundary conditions were approximated by using second order “forward”, or “backward” difference equations on the outer edge depending on the location of the node; and by using “central”, “forward”, or “backward” difference equations along the interface of mold parts and mold cavity. For example, for a nodal point on the top surface of the upper mold, the temperature gradient along the vertical direction is approximated as

$$\frac{\partial T}{\partial n} = \frac{\partial T}{\partial z} \approx \frac{-T(1, i) + 4T(2, i) - 3T(3, i)}{2 \Delta z_1}, \quad (4.27)$$

and when this expression is substituted in the boundary condition given in (4.8), it becomes

$$-k_{um} \frac{-T(1, i) + 4T(2, i) - 3T(3, i)}{2 \Delta z_1} = h[T(1, i) - T_\infty]. \quad (4.28)$$

At the simulation start time, $t = 0$, the control elements on the left edge of the mold cavity, where the lineal injection gate is located, are assumed to be just filled completely. That means, at $t = 0$ the saturation, $s = 1$ for the elements around nodes with index $i = 1$; and $s = 0$ for the elements around nodes with index $i \geq 2$.

The location of the flow front, x_f and what corresponding nodes are currently saturated with resin are computed as follows:

$$x_f = t u_f + 0.5 \Delta x$$

$$i_{x_f} = \text{ceil}\left(\frac{x_f}{\Delta x} + 0.5\right)$$

where $\text{ceil}(x)$ is a MATLAB's built-in function which rounds the value x to the nearest integer towards positive infinity.

To check the correctness of the numerical solution, it must be verified that the total energy of the system is conserved. The following rate of change of energy terms are calculated: rate of increase of internal energy for the upper mold part, $\dot{Q}_{\text{internal,top}}$; for the lower mold part, $\dot{Q}_{\text{internal,bot}}$; and for the mold cavity, $\dot{Q}_{\text{internal,cavity}}$; rate of decrease of energy from outer surfaces of the mold to the ambient air by natural convection, $\dot{Q}_{\text{convection}}$.

The rate of increase of internal energy in any of the three regions is calculated by using the first order difference equation for time derivative:

$$\dot{Q}_{\text{internal}} = \frac{\partial}{\partial t} \int_V \rho c_p T dV \approx \sum_{k,i} \rho c_p \Delta V_{k,i} \frac{T^{\text{next}}(k,i) - T(k,i)}{\Delta t} \quad (4.29)$$

where $\Delta V_{k,i}$ is the control volume around a nodal point. For three different sub-domains of the problem, the corresponding ρ and c_p of the related material are used in Equation (4.29).

$\dot{Q}_{\text{convection}}$ is calculated as follows:

$$\dot{Q}_{\text{convection}} = \frac{\partial}{\partial t} \int_A h (T - T_\infty) dA \approx \sum_{k,i} h \Delta A_{k,i} \frac{T(k,i) - T_\infty(k,i)}{\Delta t} \quad (4.30)$$

where $\Delta A_{k,i}$ is the control area around a nodal point on the outer boundary.

$\dot{Q}_{in,net}$ is the net rate of energy input to the entire mold cavity due to the inflow and outflow fluxes:

$$\dot{Q}_{in,net} = \rho_r c_{pr} (T_{r,in} - T_o) u A_{in} - \rho_r c_{pr} (T_{r,exit} - T_o) u A_{exit} \quad (4.31)$$

where A_{in} and A_{exit} are the cross sectional areas of the lineal injection gate and ventilation port, respectively. $T_{r,exit}$ is the volume-averaged temperature of the resin at the exit port. T_o is a reference temperature, and it is taken as the initial temperature of the mold and fabric. The second term on the right hand side of Equation (4.31) drops out if the flow front of the resin has not reached the ventilation port yet.

The conservation of energy requires the following equation to be satisfied:

$$\dot{Q}_{in,net} = \dot{Q}_{internal,top} + \dot{Q}_{internal,cavity} + \dot{Q}_{internal,bot} + \dot{Q}_{convection} \quad (4.32)$$

The numerical solution of the model is checked by calculating the percentage error as follows:

$$error = \frac{\dot{Q}_{in,net} - (\dot{Q}_{internal,top} + \dot{Q}_{internal,cavity} + \dot{Q}_{internal,bot} + \dot{Q}_{convection})}{\dot{Q}_{in,net}} \times 100. \quad (4.33)$$

4.1.4 Stability of Numerical Solution

Finite difference method yields the following form of evolution equation for an interior nodal point:

$$T_C^{t+\Delta t} = b + (1-r)T_C^t \quad (4.34)$$

where $T_C^{t+\Delta t}$ and T_C^t are the temperature of any central node (k,i) at times t and $t + \Delta t$, respectively; b contains all the terms related with the neighbor temperatures; and r is a dimensionless term: $r = \Delta t f(k, \rho, c_p) g(\Delta x, \Delta z)$ where f is a function of the material

properties, and g is a function of nodal spacing in x and z directions. For a stable Eulerian time-marching scheme, time step, Δt is chosen such that, $r < 1$, say $r = 0.8$. Since there are five evolution equations (one equation in each of the three regions, and two equations along the two interfaces), the smallest of the five critical Δt values is chosen for a stable numerical solution.

4.2 Experimental Setup

4.2.1 Mold

The general purpose mold mentioned in the introduction part is used in the experiments of this study. The dimensions of the mold are tabulated in Table 4.1

4.2.2 Thermocouple Sensors

With the idea of making a low-cost and practical detection system, J type thermocouples [51] are selected in which iron and constantan wires are used [52]. Thermocouple wires are placed inside a multi-functional hollow bolt as shown in Figure 4.4. A copper tip is machined on a lathe, and attached to the hot junction side of the thermocouple sensor. A plastic ring serves as a thermal insulator between the “copper + thermocouple” and “bolt + mold”. It also serves to seal the bolt and to prevent leakage of pressurized resin during RTM injections. The tip is made of copper for high thermal conductivity, and its dimensions are as small as possible to diffuse heat very rapidly. After the copper tip-plastic ring assembly is tightly fit into the hole of the bolt, silicon material is injected from the other open end of the bolt cavity to ensure sealing. Thermocouple sensors are placed at multiple discrete positions on the mold surface. An example configuration is shown in Figures 4.1, 4.6 and 4.7. A pair of sensors is placed at the same in-plane coordinate: one sensor (e.g., S1a) on the acrylic wall, and the

other sensor (e.g., S1b) on the aluminum wall. The aim is to study the effect of different mold material with different thermal diffusivity.

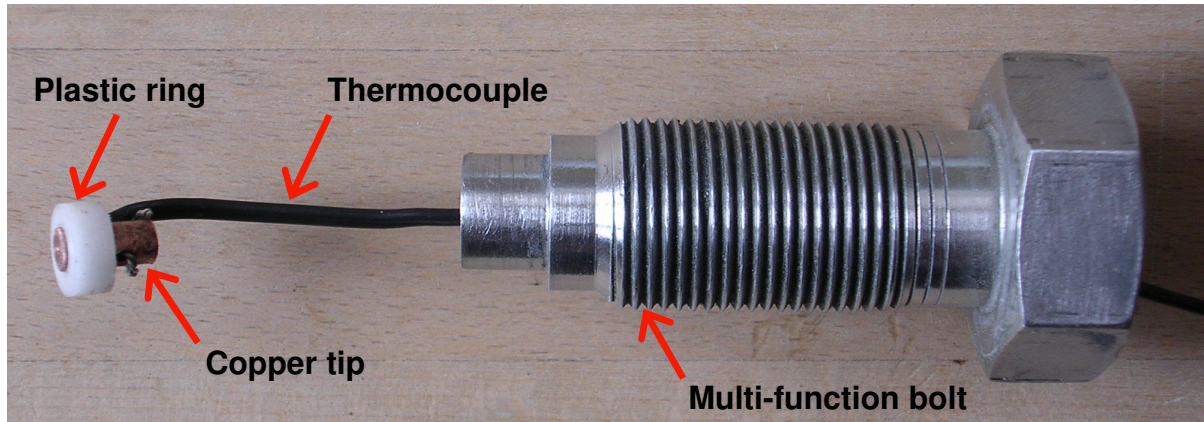


Figure 4.5. The unassembled thermocouple sensor with a copper tip [44].

Table 4.1. Dimensions of the mold [44].

Thickness of acrylic upper mold part, h_{um}	30 mm
Thickness of the aluminum lower mold part, h_{lm}	50 mm
Thickness of the mold cavity, h_{mc}	4.7 mm
Length of the mold cavity, L	682 mm
Width of the mold cavity, w	168 mm

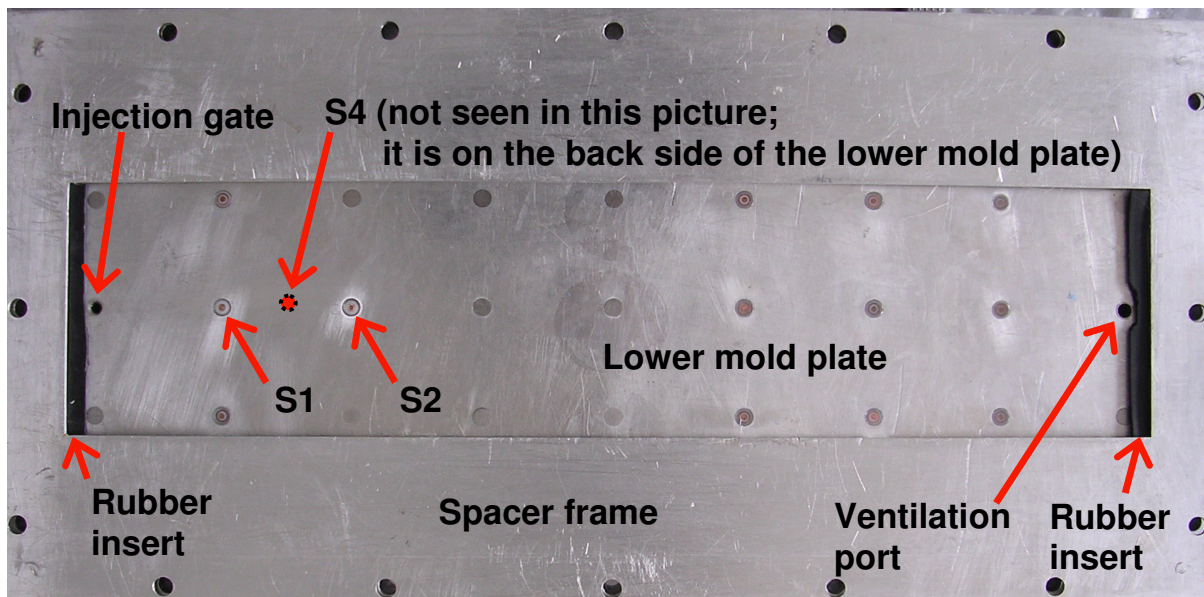


Figure 4.6. The thermocouple sensors located on the lower mold part [44].

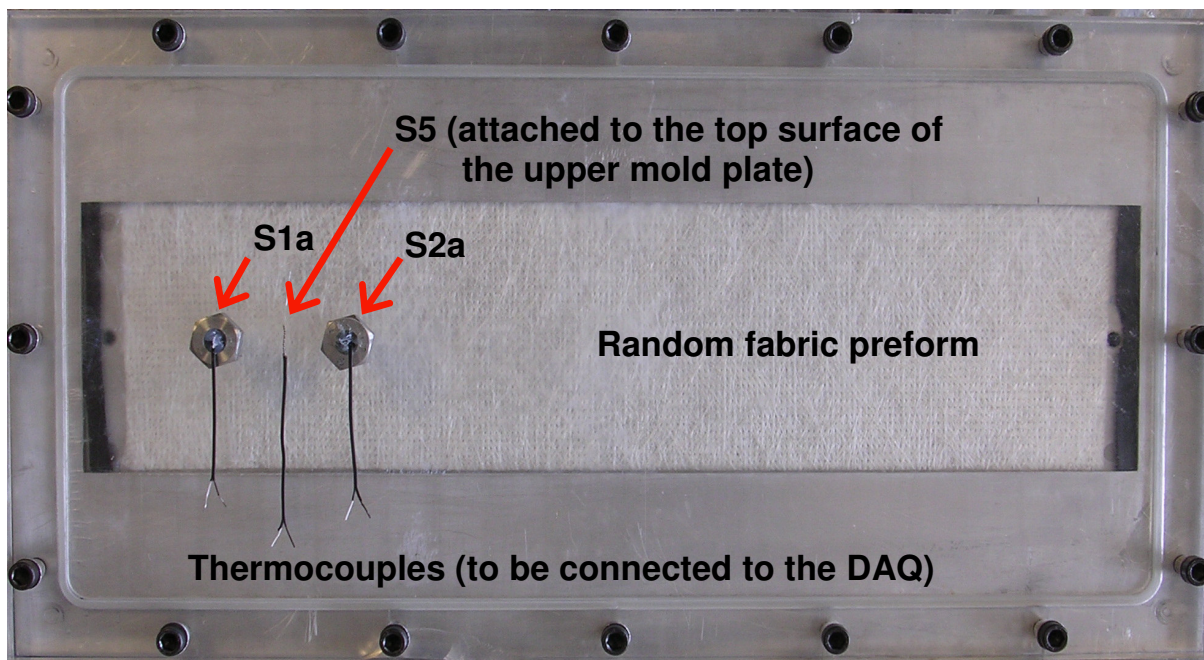


Figure 4.7. The thermocouple sensors located on the upper mold part [44].

Prior to injection, resin is heated up to a certain temperature above room temperature by using the injection machine's [9] built-in heating system. The injection machine has an electric heater jacket around the resin cylinder and a flexible heater sleeve around the connection tube between the machine and mold. The temperatures of these external heating units and resin flow rate are controlled by a computer connected to the machine. Heating the resin accelerates the curing action, and it 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 so that there is sufficient time to fill the mold completely before significant curing takes place.

The sensor configuration is shown in Figures 4.1, 4.6 and 4.7. On each side of the mold cavity, a narrow empty air channel is used to create lineal resin injection and ventilation so that one-dimensional flow can be obtained. Resin is transferred from the injection machine into the mold cavity through a polyethylene tube. An external heater sleeve keeps the temperature of the tube at the same temperature of the injection cylinder. Resin enters the cavity through an injection gate on the left side of the mold. It fills the empty channel before any significant impregnation of porous fabric. Hence, with this empty channel around it, the point injection gate acts like a lineal injection gate.

4.2.2.1 Sensitivity of the Sensor

In order to see how quickly this sensor responds upon resin arrival, just the tip of the sensor was contacted with mineral oil at different temperatures, and the normalized temperature was recorded as a function of time. Normalized temperature of the sensor is defined as $\theta = (T - T_o) / (T_{resin} - T_o)$ where T is the temperature measured by the thermocouple and T_o is the initial temperature of the dry sensor. One of the sample tests is shown in Figure 4.8 for $T_{resin} = T_{mineral\ oil} = 65^\circ\text{C}$, and dry sensor temperature $T_o = 26^\circ\text{C}$. In almost all tests, the sensor's normalized temperature rises from 0 to 0.5 in approximately 10-

12 seconds. Afterwards, the rate of change in temperature becomes smaller than the initial stage.

In order to investigate how much the copper tip delays the response time, plain thermocouple's hot junction alone (i.e., neither sensor's bolt nor copper tip was used together with the thermocouple) was contacted with hot mineral oil. The tests were carried out by dipping different lengths of the hot junction into mineral oil. When a long hot junction was dipped into the mineral oil, the response was very quick. One such test is shown in Figure 4.9 when 10 mm of hot junction is dipped in hot mineral oil. However, as the length was shortened, there was a significant delay. In order to compare with our sensor more fairly, only the tip of the plain thermocouple was contacted with mineral oil (by having a hot junction of less than 1 mm), and the response was plotted in Figure 4.10. The response rate of our sensor was about $d\theta/dt = 0.045 \text{ } 1/\text{s}$ in the initial stage, whereas it was $d\theta/dt = 3.2$ and $0.12 \text{ } 1/\text{s}$ for a plain thermocouple with a hot junction of 10 mm and less than 1 mm, respectively. The frequency of the data recording was 5 Hz in all these tests.

One might be in favor of dipping the thermocouple longer than a few millimeters to have a very high rate of temperature change. However, this approach has two major disadvantages: (i) the sensor's tip extended inward of the mold cavity disturbs the resin flow, and (ii) the sensor stays inside the composite part, which needs to be disintegrated from the composite part at the end of the manufacturing cycle, and this causes a deformed surface. Notice that our sensor system doesn't have these disadvantages since they are placed on the mold wall, i.e., they become a part of the mold wall as seen in Figure 4.6.

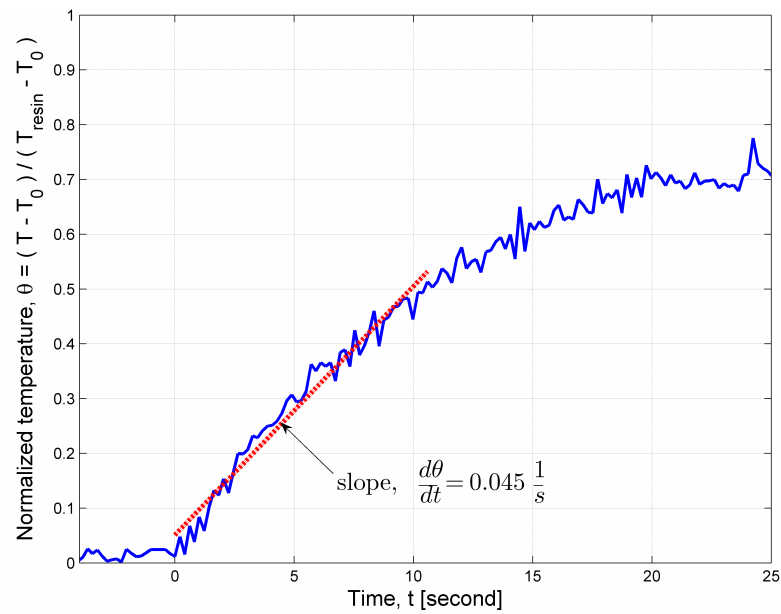


Figure 4.8. Response of a thermocouple inserted in a multi-functional bolt with a copper tip. In this sample test, $T_0 = 26^\circ\text{C}$ and $T_{\text{resin}} = 65^\circ\text{C}$ [44].

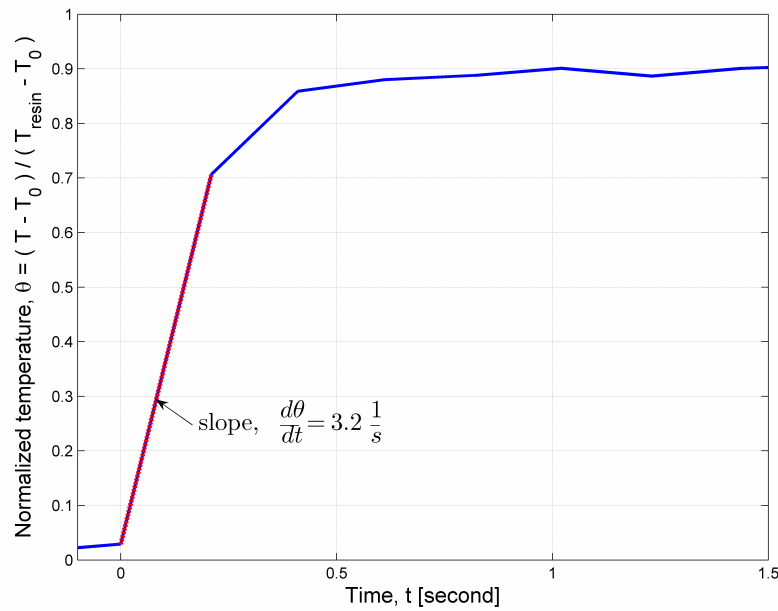


Figure 4.9. Response of a plain thermocouple alone, when 10 mm of the hot junction is dipped into the water. $T_0 = 26^\circ\text{C}$ and $T_{\text{resin}} = 65^\circ\text{C}$ [44].

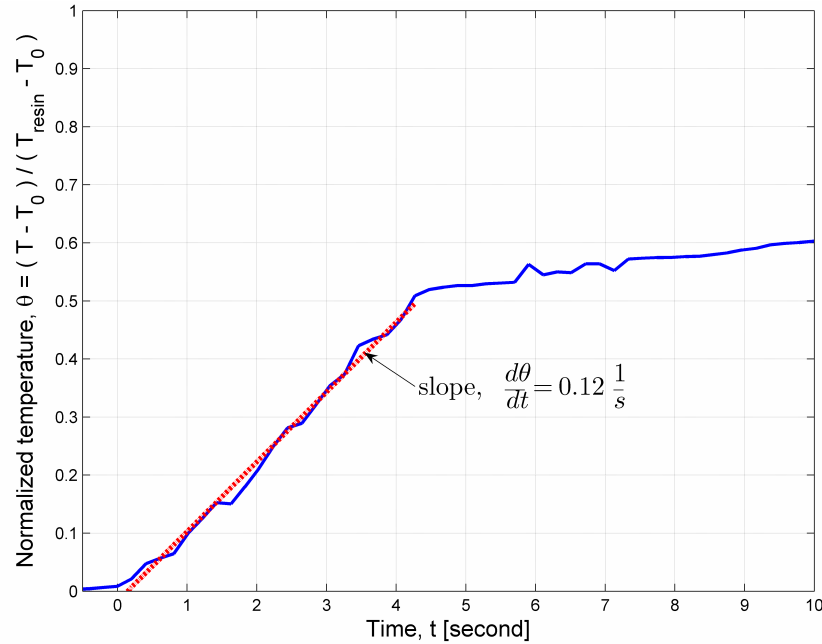


Figure 4.10. Response of a plain thermocouple alone, when only the tip of the hot junction is barely (less than 1 mm) dipped into the water. $T_o = 26^\circ\text{C}$ and $T_{\text{resin}} = 65^\circ\text{C}$ [44].

4.3 Experiments with Thermocouple Sensors

As it is mentioned in the introduction part, a general-purpose polyester [11] was intended to be used in the initial experiments of this study. It requires a curing agent (peroxide) and accelerator (cobalt), but no external heat supply is required for curing. However, in order to create an environment suitable for thermocouple sensor usage, the resin was heated by using the injection machine's heater.

In experiments, resin flow rate was set to a constant value so that flow front velocity was on the order of cm/s which is a typical value in RTM to eliminate any micro void entrapment between fibers. The threshold temperature for the detection of resin arrival is set to 1°C in the data acquisition program. In initial experiments, resin was heated 20°C above room temperature thinking, however, the outcome was very surprising. None of the sensors could

measure an increase in temperature of more than 1°C or so [15]. Even the first sensor that is the closest to the injection gate (at a distance of 9 cm) did not exceed the threshold value of 1°C. Indeed, we first suspected that there was something wrong with either the thermocouples or DAQ system; however, repeated experiments showed that they were working well. It is clear that these sensors fail to monitor resin flow with the selected set of RTM injection parameters.

A mathematical model was developed in the previous section to investigate the temperature fields in a mold cavity and mold walls around it. Its numerical solution will be detailed in the next section. The solution of this model verifies the experimental results: a large portion of the internal energy of the resin is transferred to the mold walls by conduction, thus causing a rapid decrease in temperature of resin just after it enters into the mold cavity.

The current polyester system became very unstable during the cure stage when its temperature was elevated above 40-50°C. The gelation time and corresponding viscosity of resin changed considerably from one experiment to another. Hence, in order to eliminate the effect of that variation from the problem, mineral oil (Castrol HT5 [53]) was used as a stable dummy resin in both experiments and model. At the end of this study, the model is used to design actual RTM injection parameters such as flow rate and material properties of resin and mold so that thermocouple sensor system can be used to monitor resin flow.

Five case studies were simulated using our mathematical model. Flow rate and material of the mold and resin are tabulated in Table 4.2. Density, specific heat and thermal conductivity of different materials involved in all of the case studies are tabulated in Table 4.3 by using the mean data collected from [53-59].

Table 4.2. Injection parameters and materials used in different Case Studies [44].

	Case Study 1	Case Study 2	Case Study 3	Case Study 4	Case Study 5
Injection flow rate, Q_{inj}	250 cc/min.	500 cc/min.	500 cc/min.	500 cc/min.	500 cc/min.
Upper mold part	Acrylic	Acrylic	Steel	Glass Fiber-Reinforced Composite	Acrylic
Lower mold part	Aluminum	Aluminum	Steel	Glass Fiber-Reinforced Composite	Aluminum
Resin	Mineral oil (dummy)	Mineral oil (dummy)	Polyester	Polyester	Mineral oil (dummy)
Fabric	Random e-glass	Random e-glass	Random e-glass	Random e-glass	Random e-glass
Fiber volume fraction, V_f	0.15	0.15	0.15	0.15	0.15
Velocity of flow front, u_f	6.2 mm/s	12.4 mm/s	12.4 mm/s	12.4 mm/s	12.4 mm/s
Resin inlet temperature, T_{inj}	80°C	80°C	80°C	80°C	26°C
Initial mold temperature, T_{amb}	26°C	26°C	26°C	26°C	80°C
Threshold temperature, ΔT	2°C	2°C	2°C	2°C	2°C
Experiment performed	Yes	Yes	No	No	No
Simulation performed	Yes	Yes	Yes	Yes	Yes

Table 4.3. Properties of materials around room temperature [53-59] used in simulations [44].

Material	Density, ρ [kg/m ³]	Specific heat, c_p [J/(kg.°C)]	Thermal conductivity, k [W/(m.°C)]
Polyester resin	1345	759	0.195
Mineral oil (dummy resin)	850	1860	0.133
Glass fiber	2580	803	1.15
Aluminum lower mold	2707	877	187
Acrylic upper mold	1170	1466	0.216
Steel (chrome-nickel)	8090	440	43
Air	1.18	1006	0.026

Injectons are made with a constant flow rate of 250 cc/min in Case Study 1, and 500 cc/min in Case Studies 2-5. In all of the case studies, a random glass fabric preform with a fiber volume fraction of 15% (four fabric layers in a mold thickness of 4.7 mm) was used. In Case Studies 1-4, resin inlet temperature was set to 80°C (54°C above the room temperature, 80°C). With these parameters, the aim is to obtain enough heat convection with moving resin so that the temperature of the flow front will be significantly above the initial mold temperature, and hence high enough temperature rise can be measured by thermocouple sensors.

Case Study 5 was simulated to show that our model can be also used for RTM applications in which cold resin is injected into a heated mold. It is essentially the same as Case Study 2, except that $T_{\text{resin}} = T_{\text{inlet}} = 26^{\circ}\text{C}$ (= room temperature) and $T_{\text{mold}} = T_{\text{fabric}} = 80^{\circ}\text{C}$.

S3 is a sensor located at the exit. As the schematic Figure 4.1 shows, this sensor is not on the mold wall, but it is inserted into the ventilation tube. Indeed, it crosses the entire inner diameter of the tube. Thus, S3 measures the volume-averaged temperature at the exit of the mold. On the other hand, S1a and S2a measure the temperature of the resin at the upper interface (= acrylic wall); and S1b and S2b measure the temperature of the resin at the lower interface (= aluminum wall).

4.4 Results and Discussions

4.4.1 Results of the Experiments

Repeated experiments of Case Studies 1 and 2 were performed. The results of two sample experiments are shown in Figures 4.11 and 4.12.

4.4.2 Results of the Numerical Model

By using increments of $\Delta x = 0.005$ m, $\Delta z_1 = 0.001$ m, $\Delta z_2 = 0.000235$ m, and $\Delta z_3 = 0.001$ m in the numerical model, temperature distribution was solved for Case Studies 1-5, and shown in the following figures at the end of injection ($t = 200$ s). The value of the time step, Δt was determined as explained in section 4.1.4. Sensor temperatures as a function of time, different terms of heat transfer rate and cumulated energy in different regions were also plotted in the same figures.

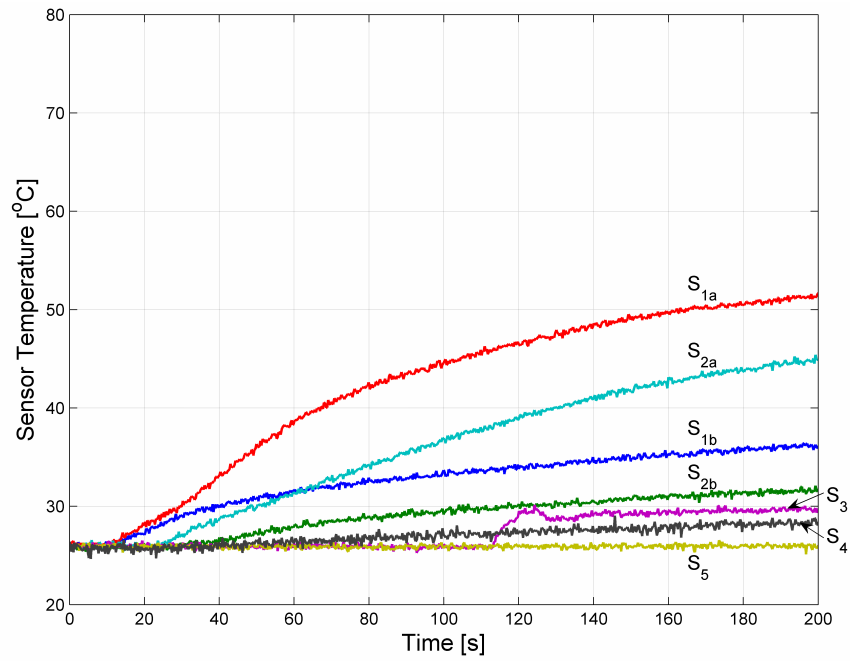


Figure 4.11. Experimental sensor temperatures in Case Study 1; $Q = 250$ cc/min, $T_o = T_{amb} = 26^\circ\text{C}$, and $T_{resin} = 80^\circ\text{C}$ [44].

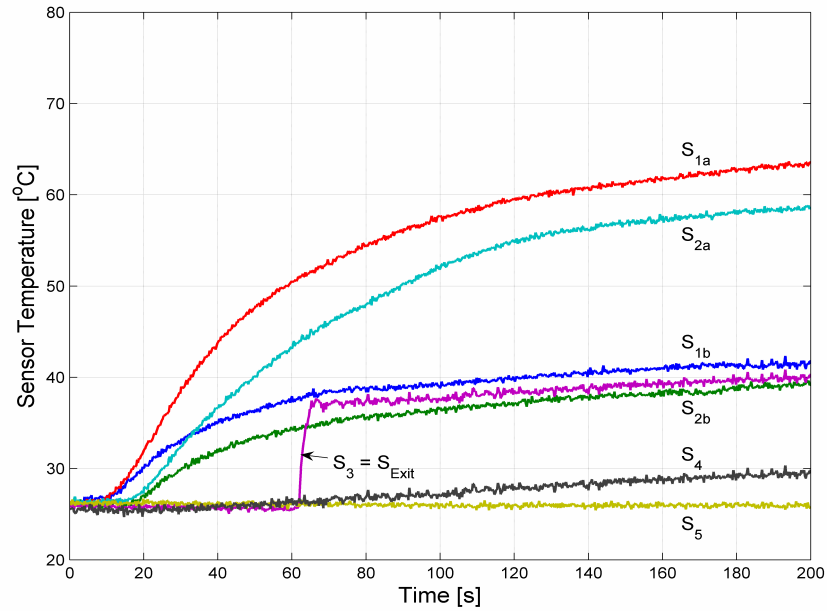


Figure 4.12. Experimental sensor temperatures in Case Study 2; $Q = 500$ cc/min, $T_o = T_{amb} = 26^\circ\text{C}$, and $T_{resin} = 80^\circ\text{C}$ [44].

4.4.2.1 Results of Case Study 1 (acrylic upper part – aluminum lower part)

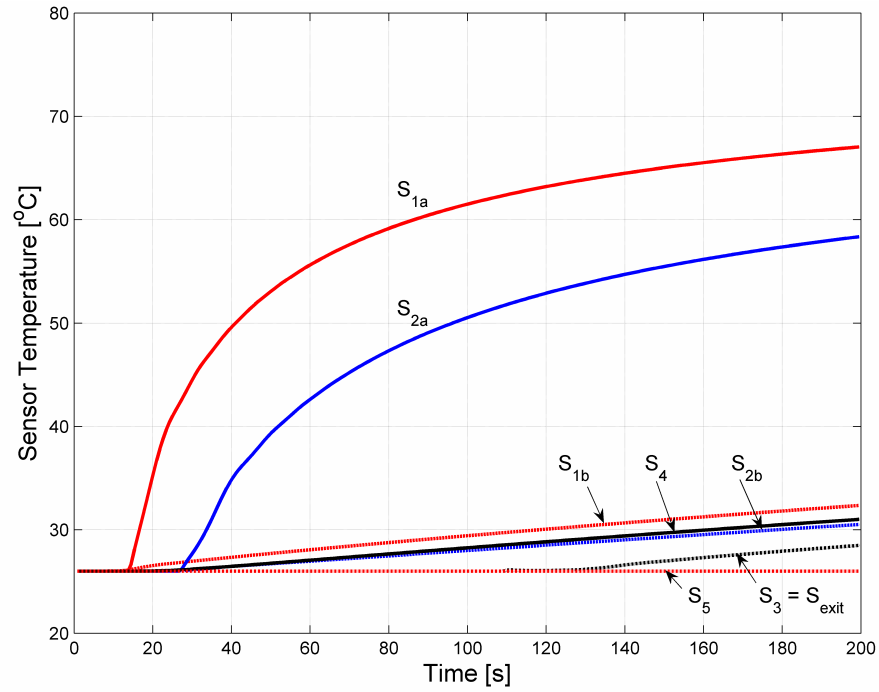


Figure 4.13a. The simulated temperature distributions in Case Study 1; the upper and lower mold parts are made of acrylic and aluminum, respectively; the dummy resin is mineral oil; $Q = 250$ cc/min, $T_{\text{resin}} = 80^{\circ}\text{C}$, and $T_{\text{amb}} = T_{\text{mold}} = T_{\text{fiber}} = 26^{\circ}\text{C}$.

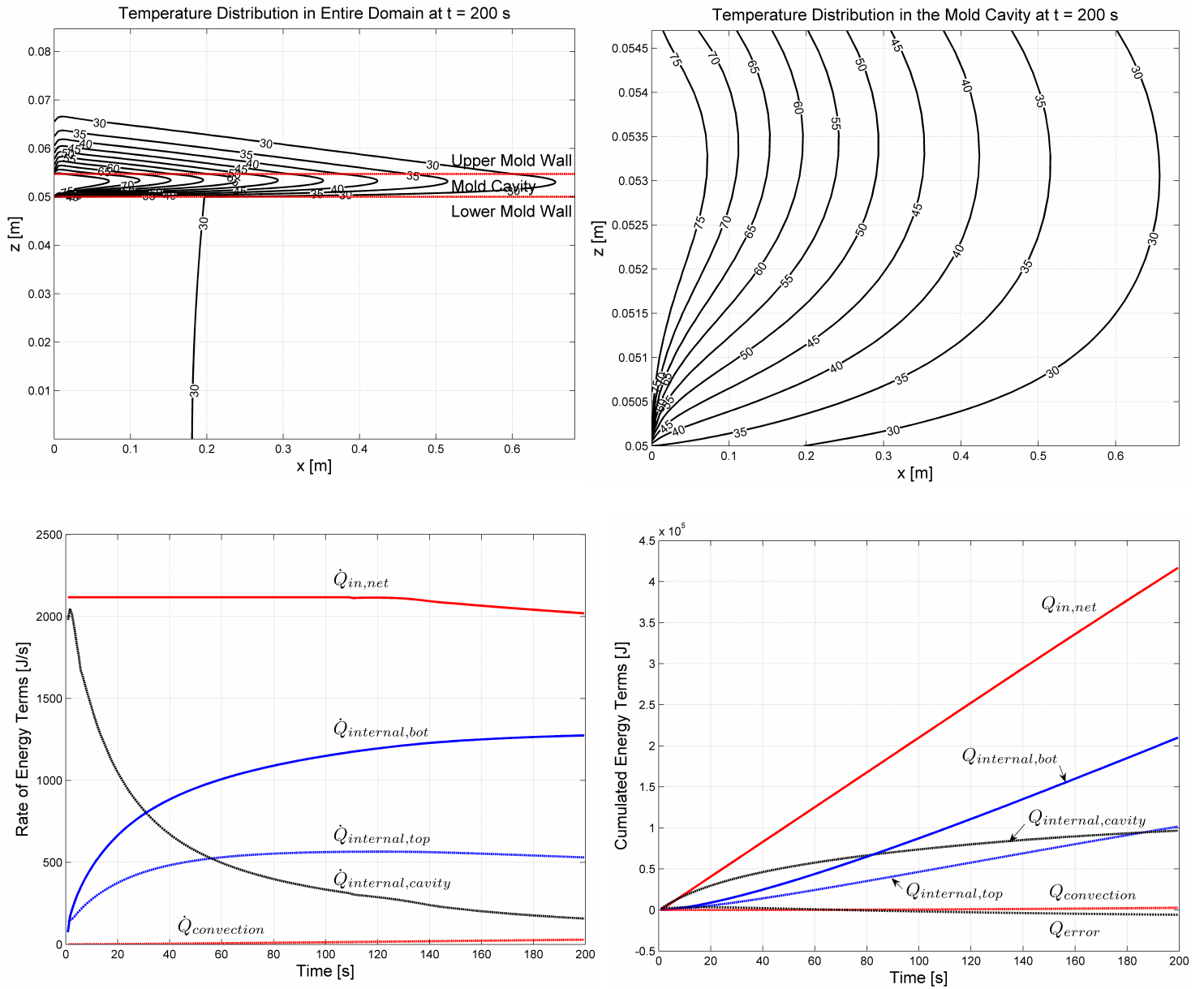


Figure 4.13b. The simulated results in Case Study 1; the upper and lower mold parts are made of acrylic and aluminum, respectively; the dummy resin is mineral oil; $Q = 250$ cc/min, $T_{resin} = 80^\circ\text{C}$, and $T_{amb} = T_{mold} = T_{fiber} = 26^\circ\text{C}$.

4.4.2.2 Results of Case Study 2 (acrylic upper part – aluminum lower part)

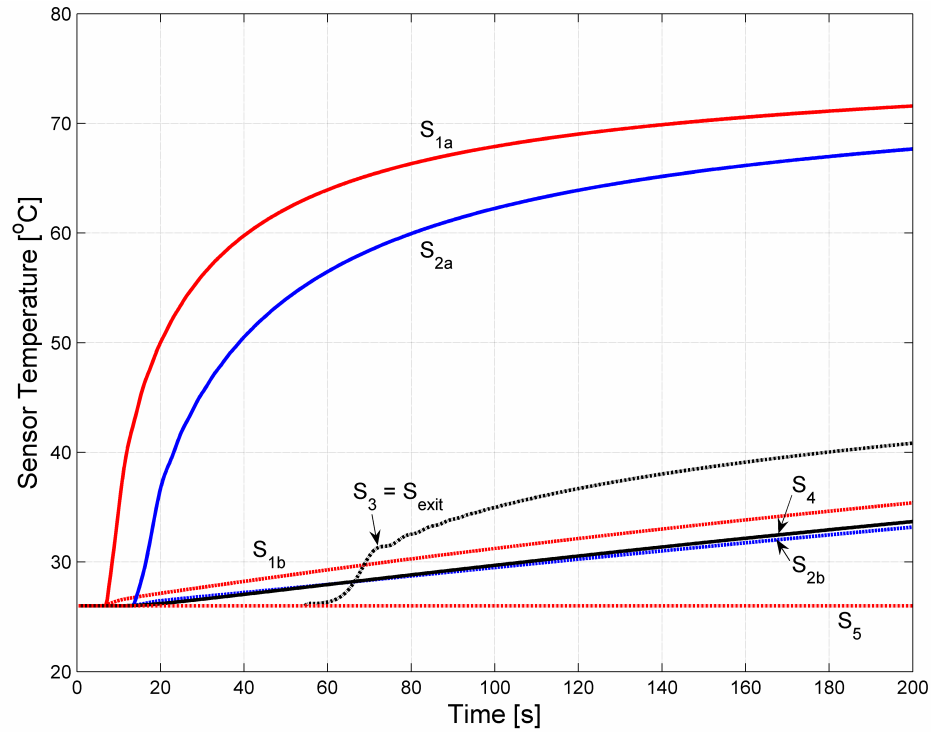


Figure 4.14a. The simulated temperature distributions in Case Study 2; the upper and lower mold parts are made of acrylic and aluminum, respectively; the dummy resin is mineral oil; $Q = 500$ cc/min, $T_{resin} = 80^{\circ}\text{C}$, and $T_{amb} = T_{mold} = T_{fiber} = 26^{\circ}\text{C}$.

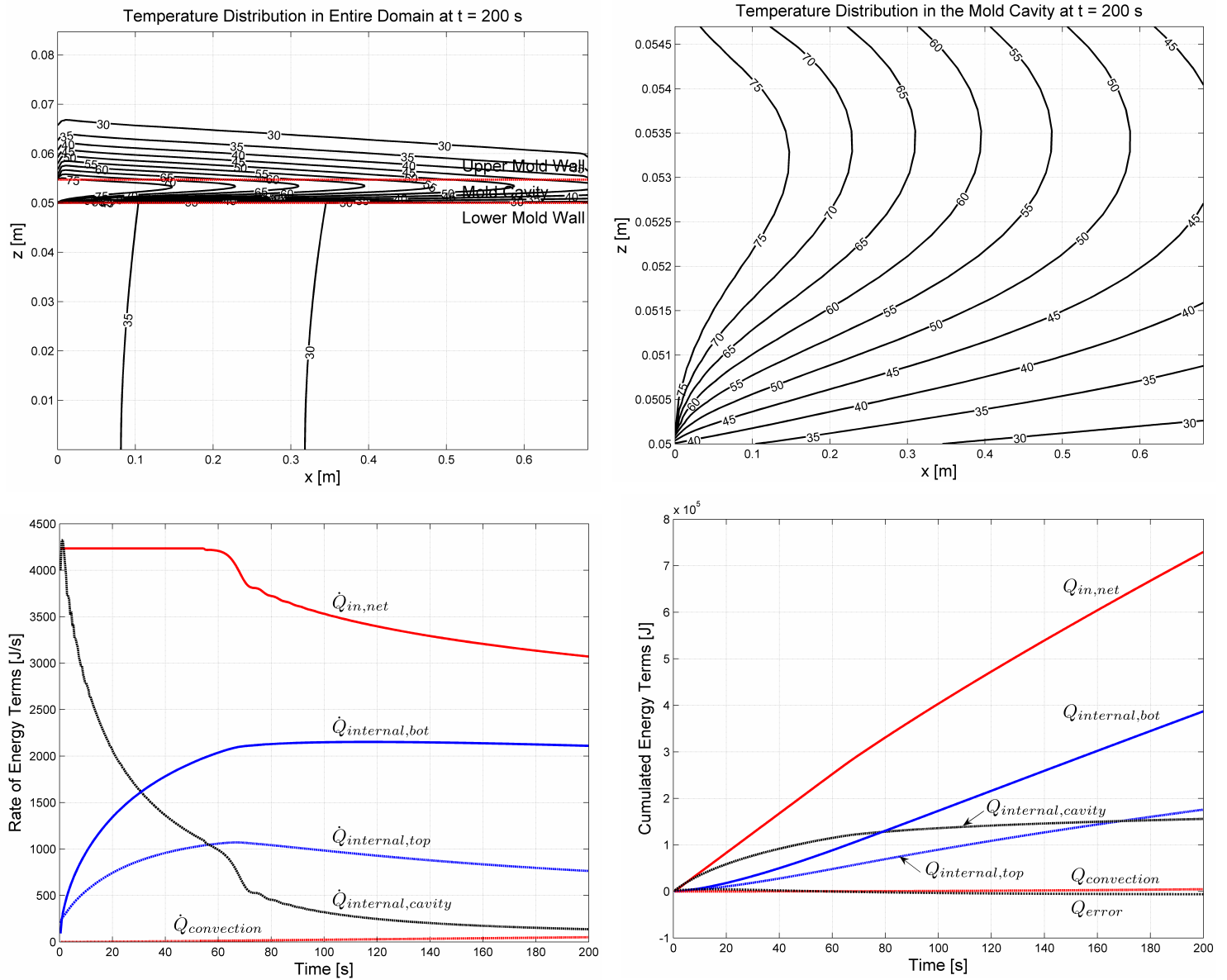


Figure 4.14b. The simulated results in Case Study 2; the upper and lower mold parts are made of acrylic and aluminum, respectively; the dummy resin is mineral oil; $Q = 500$ cc/min, $T_{resin} = 80^\circ\text{C}$, and $T_{amb} = T_{mold} = T_{fiber} = 26^\circ\text{C}$.

4.4.2.3 Results of Case Study 3 (steel upper part – steel lower part)

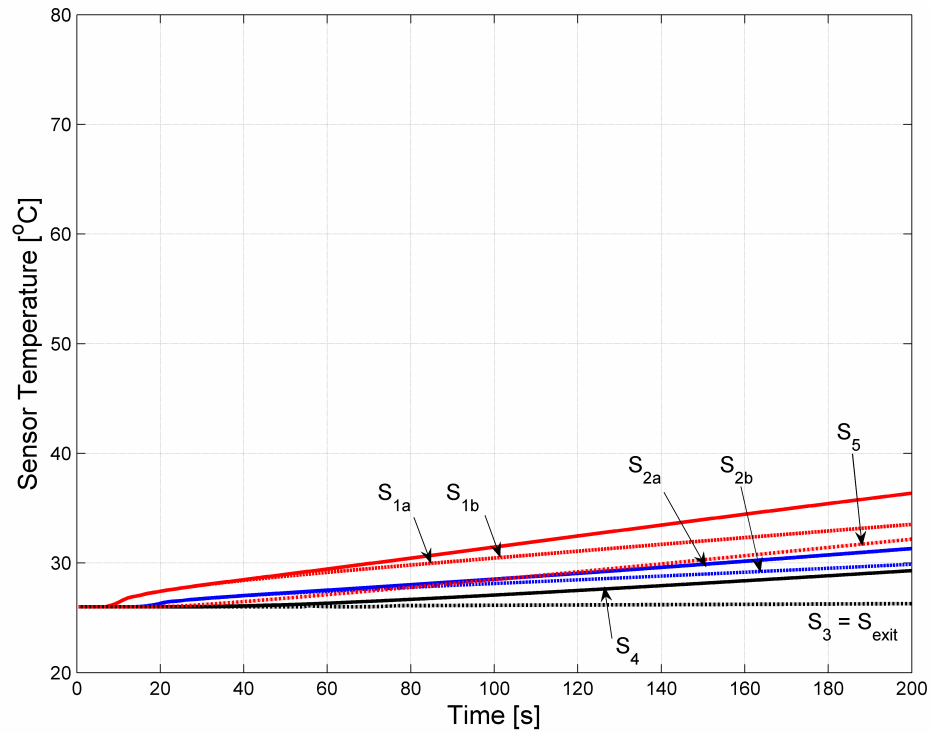


Figure 4.15a. The simulated temperature distributions in Case Study 3; both the upper and lower mold parts are made of steel; the resin is polyester; $Q = 500 \text{ cc/min}$, $T_{\text{resin}} = 80^\circ\text{C}$, and $T_{\text{amb}} = T_{\text{mold}} = T_{\text{fiber}} = 26^\circ\text{C}$.

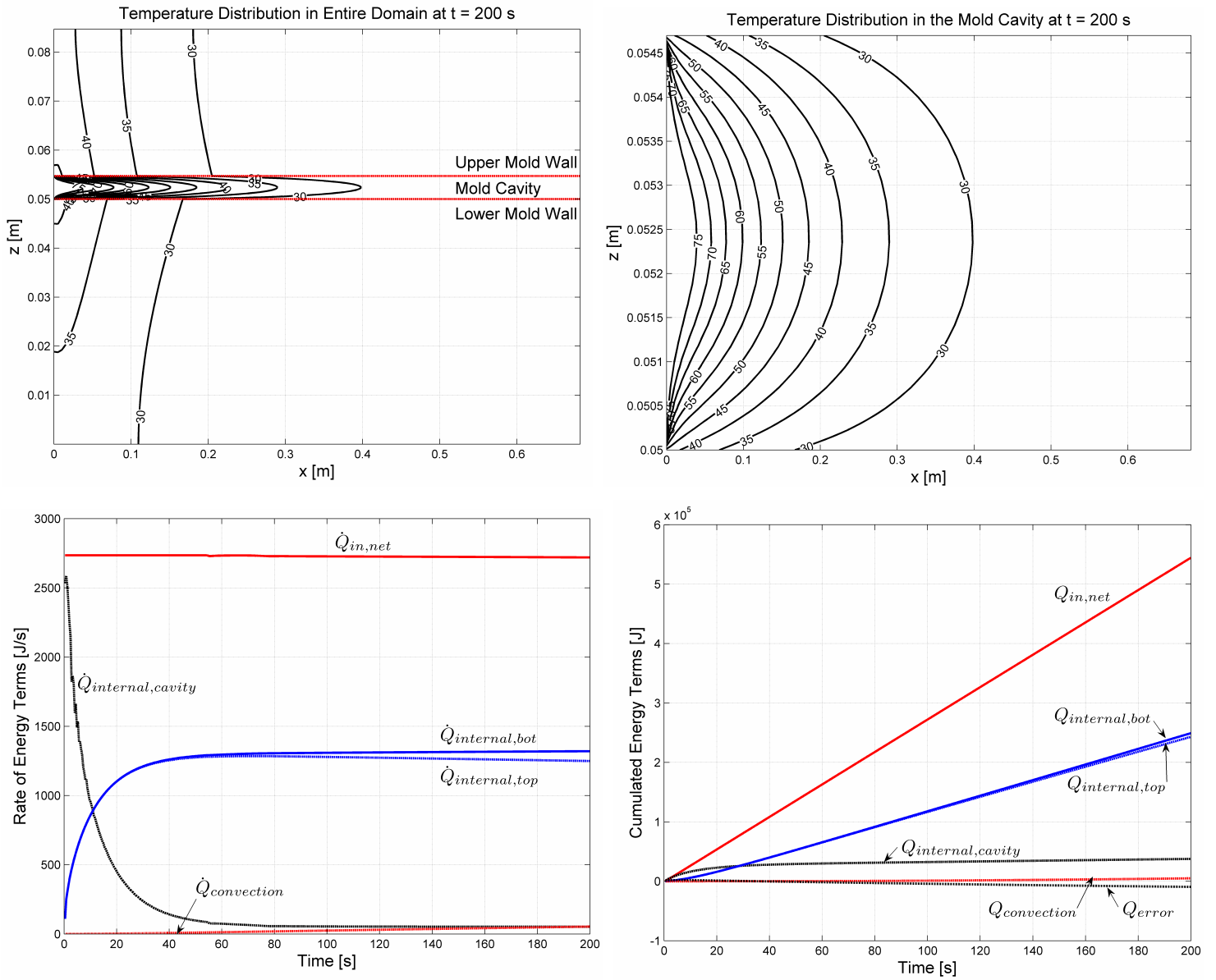


Figure 4.15b. The simulated results in Case Study 3; both the upper and lower mold parts are made of steel; the resin is polyester; $Q = 500$ cc/min, $T_{resin} = 80^\circ\text{C}$, and $T_{amb} = T_{mold} = T_{fiber} = 26^\circ\text{C}$.

4.4.2.4 Results of Case Study 4 (composite upper part – composite lower part)

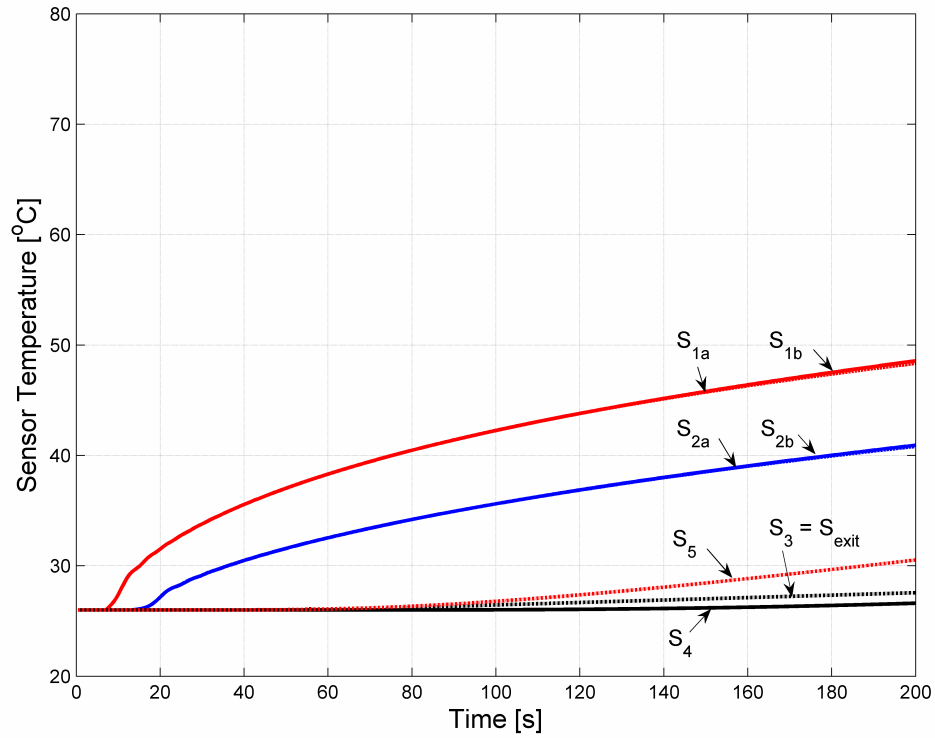


Figure 4.16a. The simulated temperature distributions in Case Study 4; both the upper and lower mold parts are made of glass-reinforced composite material; the resin is polyester; $Q = 500 \text{ cc/min}$, $T_{\text{resin}} = 80^\circ\text{C}$, and $T_{\text{amb}} = T_{\text{mold}} = T_{\text{fiber}} = 26^\circ\text{C}$.

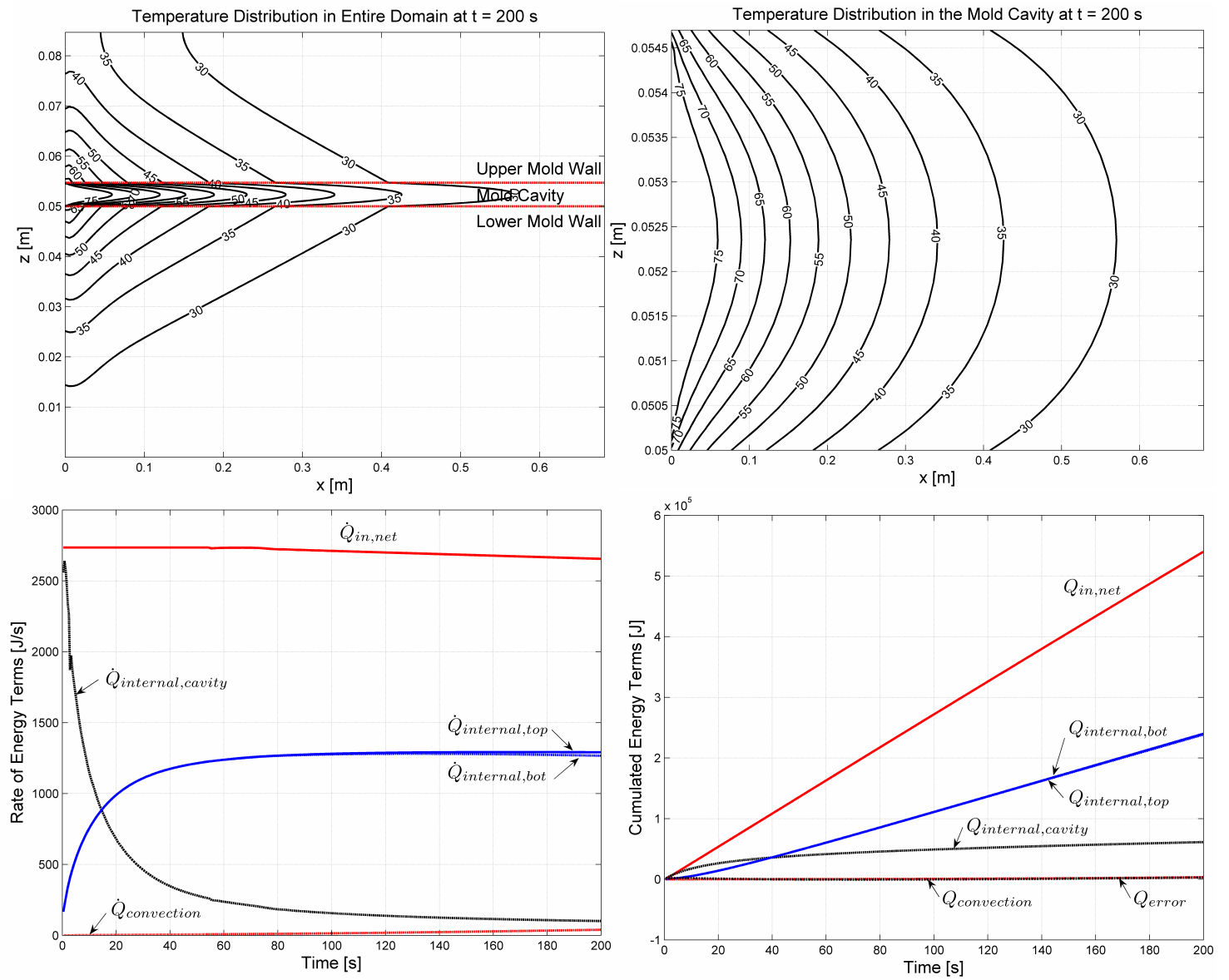


Figure 4.16b. The simulated results in Case Study 4; both the upper and lower mold parts are made of glass-reinforced composite material; the resin is polyester; $Q = 500$ cc/min, $T_{resin} = 80^\circ\text{C}$, and $T_{amb} = T_{mold} = T_{fiber} = 26^\circ\text{C}$.

4.4.2.5 Results of Case Study 5 (acrylic upper part – aluminum lower part)

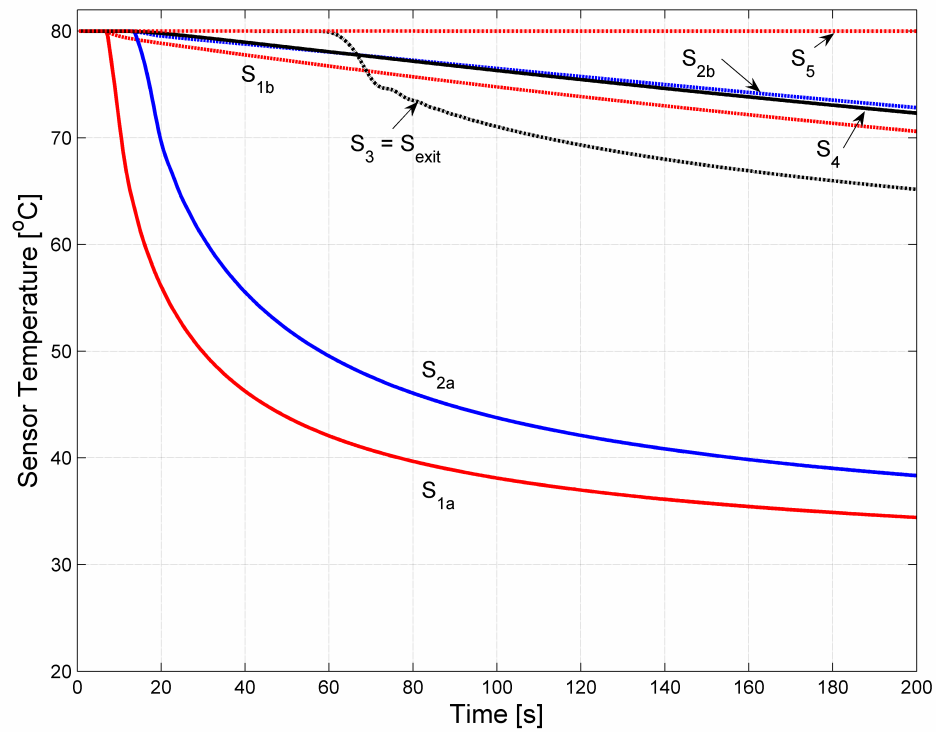


Figure 4.17a. The simulated temperature distributions in Case Study 5; this case study is equivalent to Case Study 2 except that the inlet resin is cold ($T_{\text{resin}} = 26^{\circ}\text{C}$) and the ambient and initial temperatures of the mold and fibers are hot: $T_{\text{amb}} = T_{\text{mold}} = T_{\text{fiber}} = 80^{\circ}\text{C}$.

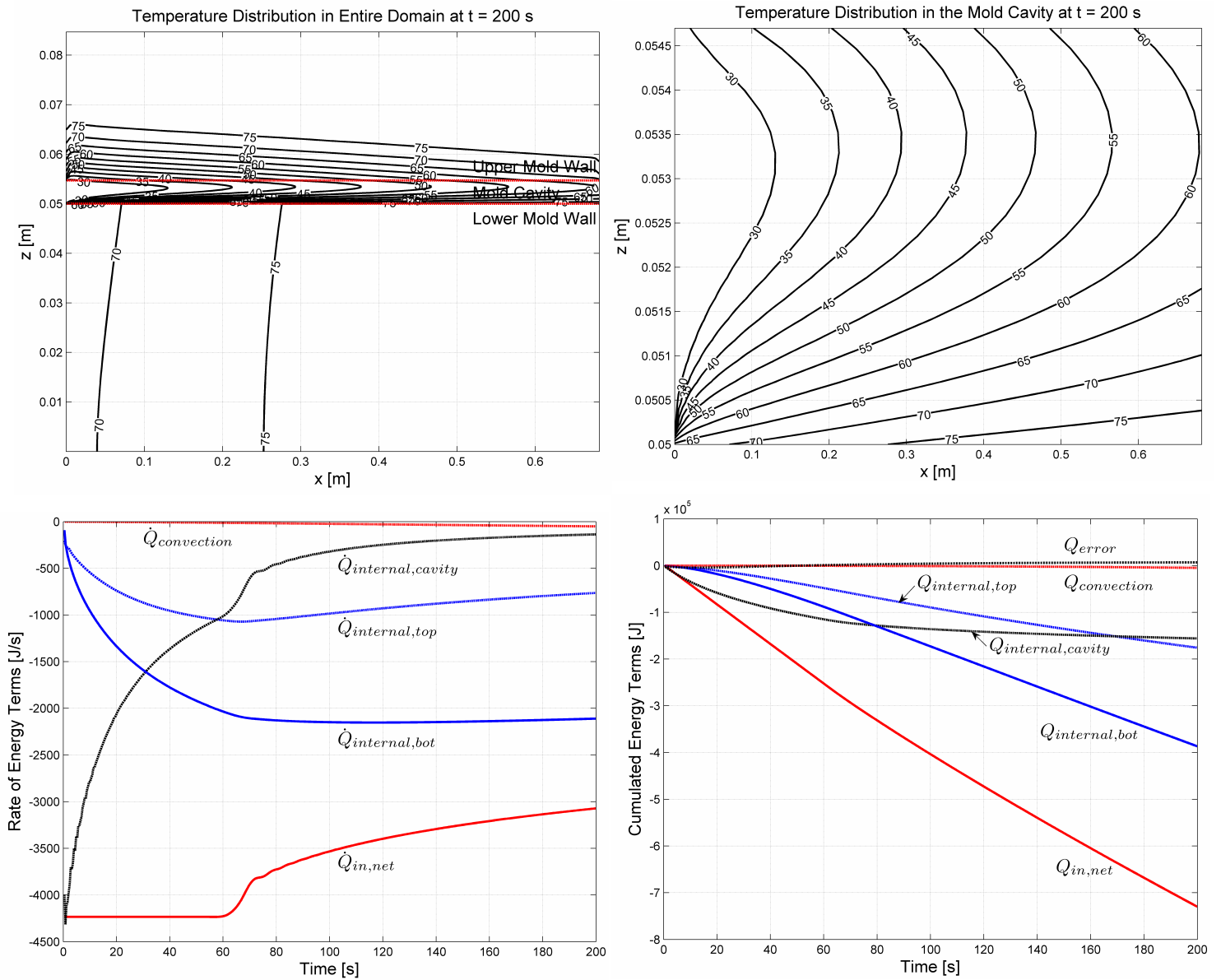


Figure 4.17b. The simulated results in Case Study 5; this case study is equivalent to Case Study 2 except that the inlet resin is cold ($T_{resin} = 26^\circ\text{C}$) and the ambient and initial temperatures of the mold and fibers are hot: $T_{amb} = T_{mold} = T_{fiber} = 80^\circ\text{C}$.

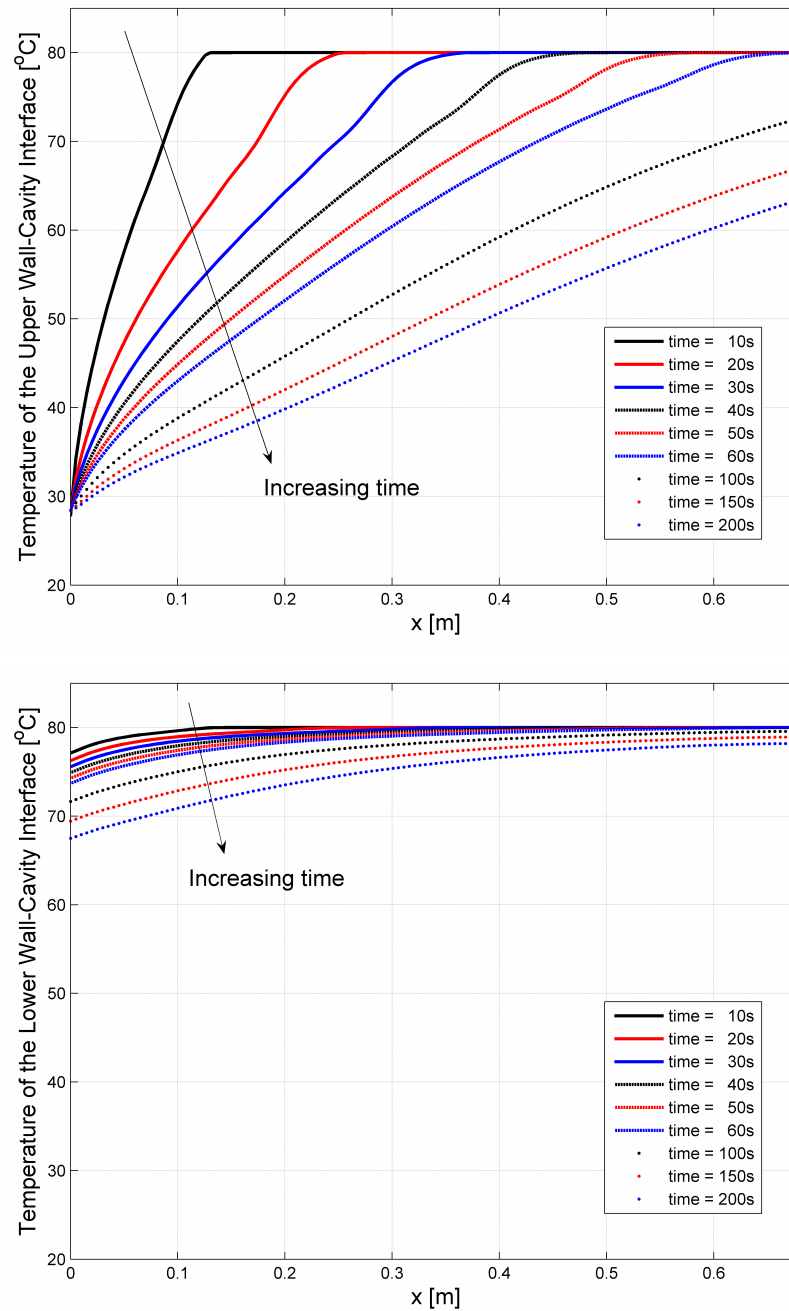


Figure 4.18. Simulated interface temperature distributions in Case Study 5. The top figure corresponds to the interface between the upper acrylic mold wall and the mold cavity; the bottom figure corresponds to the interface between the lower aluminum mold wall and the mold cavity.

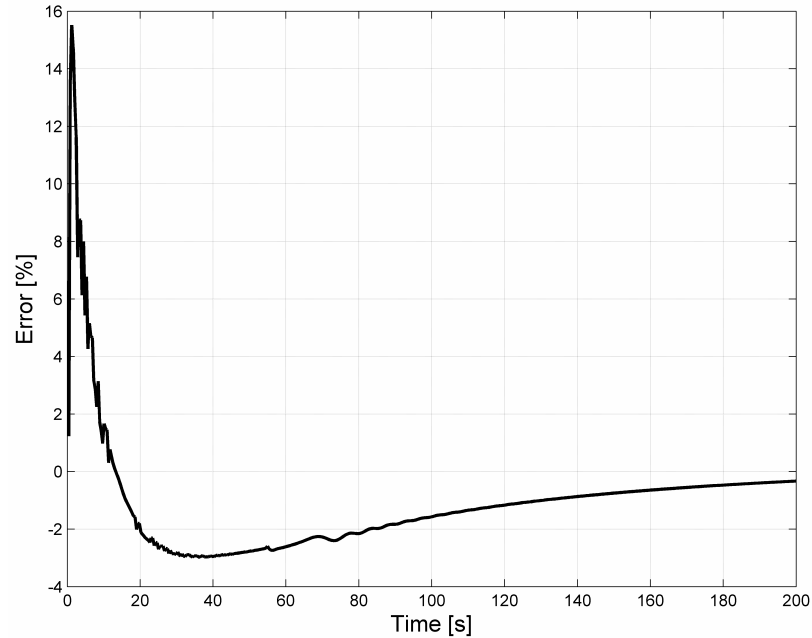


Figure 4.19. Numerical error for conservation of energy in Case Study 2.

4.4.3 Discussions

The comparison of the experimental and simulated response of the sensors adjacent to the mold cavity (S_{1a} , S_{1b} , S_{2a} , S_{2b} , and S_3) is summarized in Tables 4.4, 4.5 and 4.6. Although there exist some quantitative differences between the results of simulations and experimental sensor responses, the order and the general behavior are similar. However, the results indicate that this sensor system is not very adequate for an accurate monitoring of the mold filling due to its late response. This becomes worse if (i) the sensor is placed on a mold wall with a high thermal conductivity; and (ii) the location of the sensor is farther away from the inlet gate because the flow front of the resin does not conserve its initially high temperature.

When the temperature distributions of the experiments are observed (Figures 4.11 and 4.12), it is seen that on resin arrival, temperatures of two thermocouples S_{1a} and S_{1b} rise

simultaneously, but with different rates as expected from our model (Figures 4.13a and 4.14a). S_{1a} has a sharp increase, whereas S_{1b} has a gradual increase with a smaller slope than S_{1a} . For the second pair of sensors (S_{2a} and S_{2b}) too, these different behaviors of sensors are experimentally observed, and verified by the results of our model.

The change in thermocouple readings becomes steeper if flow rate is increased (from 250 cc/min in Case Study 1 to 500 cc/min in Case Study 2) due to an increased rate of convection of energy. This helps to have a flow monitoring with less trouble.

In the experiments, the mold cavity was filled at $t_{fill} \approx 115.1$ s and 62.7 s in Case Studies 1 and 2, respectively (see Table 4.5). In our actual injections, injection gate and ventilation port were kept open and injection was continued even after resin arrived at the ventilation port. This might be done in typical RTM process to ensure high saturation of fabric by eliminating micro size voids between fibers. Similarly, our simulations were done for injections lasting 200 seconds. The flow front arrived at the ventilation port at 110 s and 55 s in the corresponding simulations of Case Studies 1 and 2, respectively. There is a difference of approximately 5-8 s between the actual experiments and the ideal model for these case studies. The followings are the major causes of this deviation: (i) the control volumes around the nodes at $x = 0$ (i.e., $i = 1$) are already saturated with resin at $t = 0$ as an initial condition of the model; (ii) the thickness of the mold cavity was not exactly 4.7 mm everywhere due to the nonuniform compaction of the fabric preform and the spacer frame of the mold; (iii) delay of the response of a sensor to measure of a threshold value of 1°C .

Resin enters the mold cavity with a temperature of 80°C . At the end of actual experiments, resin exits from the ventilation port with a temperature of $T_3 \equiv T_{exit} = 29.7^\circ\text{C}$ (which is only 3.7°C above the initial mold temperature) in Case Study 1; and it exits with 39.8°C (which is 13.8°C above the initial mold temperature) in Case Study 2 (see Table 4.6). The simulated exit temperature is 28.5°C and 40.8°C in Case Studies 1 and 2, respectively. These values are close to the experimental temperatures.

The purpose of placing sensors S4 and S5 on the mold wall was not to monitor the flow, but to investigate the rates of heat diffusion in two different materials: aluminum and acrylic. When temperature distributions are examined, the two different behaviors of aluminum and acrylic can clearly be seen. The temperature of the acrylic side away from the interface with the mold cavity, did not change significantly, unlike in the aluminum side. T_5 stays almost constant during the whole injection indicating that no significant heat diffusion occurs in acrylic except within a narrow layer adjacent to the interface. As observed in experiments and also verified by our mathematical model, $T_{2b} \approx T_4$ in both Case Studies 1 and 2. This is not surprising as heat diffuses very rapidly in mold wall made of aluminum, which has a very high thermal diffusivity. Thus, thermocouple sensors on the aluminum mold wall might potentially mislead the user. The temperature of the mold wall increases gradually due to the diffusing heat. A regular thermocouple might have measured a temperature value greater than $T_{ambient} + \Delta T_{threshold}$ due to this diffused heat even before actual resin arrival. Recall that our sensor was developed to eliminate this potential problem by insulating the copper tip with a plastic ring. This way, the thermocouple sensors measure the temperature of the adjacent media (resin and fabric) in the mold cavity, not the mold itself.

When the percentage errors of the numerical simulations are analyzed, it is seen that the solution converges after a certain time (see Figure 4.19). However, the initial part of the solution is very sensitive on the values of Δx and Δz selected. The overall numerical solution is only a first order method by considering the first order Eulerian time integration used. Our numerical investigation indicates that the major reason of the initial sensitivity of the numerical solution is due to the sudden temperature change about $t = 0$, i.e., when hot resin suddenly enters the cold mold cavity. Initially, $T = 80^\circ\text{C}$ at $x = 0$, and $T = 26^\circ\text{C}$ at $x = 0 + \Delta x$ in the mold cavity. The finite difference approximation of the spatial derivative,

$$\begin{aligned}\frac{\partial^2 T}{\partial x^2} &= \frac{T(k, i+1) - 2T(k, i) + T(k, i-1)}{(\Delta x)^2} + O((\Delta x)^2) \\ &\approx \frac{T(k, i+1) - 2T(k, i) + T(k, i-1)}{(\Delta x)^2}\end{aligned}\quad (4.35)$$

has a relatively higher error than the other terms in the solution, and hence the solution has a relatively higher error in this initial stage. Although the error term in the initial stage is high, its effect on the overall temperature distribution is negligible. In all the simulations, a coarse mesh was used in the first run. Then, the mesh was made finer by doubling the number of elements in both directions, x and z , until a convergence criteria was satisfied ($\text{norm}(T_{\text{fine}} - T_{\text{coarse}}) < \text{tolerance}$) in the entire domain.

Between the start of the injection and resin arrival to the ventilation port, $\dot{Q}_{\text{in,net}} \approx 2120 \text{ W}$ in Case Study 1. It drops to 2020 W at $t = 200$ after the extended injection (see Figure 4.13b). However, in Case Study 2, $\dot{Q}_{\text{in,net}} \approx 4240 \text{ W}$ initially, but then drops to approximately 3070 W at the end of the injection (see Figure 4.14b). In Case Study 1 (in which the flow rate is half of that in Case Study 2), the fraction of convected energy is so low that its internal energy does not create a significant ΔT when resin reaches the ventilation port. Thus, $\dot{Q}_{\text{in,net}}$ does not decrease significantly after the resin starts exiting from the ventilation port.

Our mathematical model was tested by comparing the qualitatively close trends of the actual injections and the simulations for Case Studies 1 and 2 in which mineral oil was used not to degrade the surface of the acrylic upper mold part. Now that the mathematical model has been tested with a reasonably acceptable comparison between the experiments and the simulations, it is ready to be used for the design of parameters of mold and process that enables the use of thermocouple sensor system. Here, two of them are discussed very briefly. In Case Studies 3 and 4 (see Table 4.2), the same injection parameters of Case Study 2 were used, except that actual polyester was used instead of mineral oil, and steel and glass fiber-

reinforced composite mold parts were used in Case Studies 3 and 4, respectively (see Table 4.2). The results of Case Studies 3 and 4 are shown in Figures 4.15 and 4.16.

In Case Study 3 where the mold is made of steel, resin arrives at the sensor S1 at $t = 7.2$ s. Our model indicates that its temperature rises to 27°C at $t = 14.5$ s (which takes 7.3 s for a temperature rise of 1°C). This is not high enough for feasible on-line flow monitoring. The situation is worse for S2 than for S1. S2's temperature rises to 27°C at $t = 39.2$ s. After the actual resin arrival (at $t \approx 13.9$ s), it takes 25.3 s for the sensor S2 to measure a threshold temperature rise of 1°C . Thus, as a bottom line, this set of injection parameters (flow rate and $\Delta T = T_{\text{resin}} - T_o$) and materials selected for mold (= steel) and resin (= polyester) does not enable the use of thermocouple sensors for flow monitoring. This constraint on thermocouple usage can be explained by examining the plot at the bottom of Figure 4.15b. Almost one half of the cumulated net flux of heat, $Q_{\text{in,net}}$ is transferred to the upper mold part, and the other half is to the lower mold part. Only a very small portion of this energy is kept within the fabric and flowing resin as shown with the curve for $Q_{\text{internal,cavity}}$.

For low-volume manufacturing, a mold made of glass fiber-reinforced composite material can be used. It is preferred over a steel mold because of its lower cost and also relatively quicker manufacturing. Case Study 4 investigates this mold material and polyester resin. The sensors S1 and S2 detect resin arrival reasonably well if one examines the high rate of changes in T_1 and T_2 as shown in Figure 4.16a. However, one should always keep in mind that there is a time delay between the actual resin arrival and DAQ's "resin arrival" evaluation after an increase of $\Delta T_{\text{threshold}}$ is measured by the sensor. For example, resin arrives at S1 at $t \approx 7.2$ s, but T_1 changes from 26°C to 27°C (if $\Delta T_{\text{threshold}} = 1^\circ\text{C}$ value is used) at $t \approx 9.7$ s. Hence, there is a time delay of 2.5 s. The time delay gets longer as the sensors are located farther away from the injection gate. Resin arrives at S2 at $t \approx 13.9$ s, but T_2 changes from 26°C to 27°C at $t \approx 19.8$ s. The corresponding time delay is 5.9 s.

The results of Case Study 5 are shown in Figures 4.17a and 4.17b. This case study is the same as Case Study 2, except that the inlet resin is cold (at room temperature), and the mold

and ambient are hot (80°C) assuming that the mold is kept in an oven with natural convection. At the end of the mold filling ($t = 200$ s), the temperature of the interface between the lower mold part (made of aluminum) and the “resin + fabric” in the mold cavity is close to the initial temperature of the mold: $67.5^{\circ}\text{C} < T < 70^{\circ}\text{C}$ in $0 < x < 0.07$ m; and $70^{\circ}\text{C} < T < 78.2^{\circ}\text{C}$ in $0.07 < x < 0.682$ m. The temperature distributions along the two interfaces at different times are shown in Figure 4.18. The interface temperature on the aluminum mold wall is practically equal to the initial value of 80°C during the initial stage. Even much later, when the flow front arrives at the ventilation port at $t = 54.9$ s, the largest deviation from the initial temperature occurs at the inlet gate position with a value of only 6°C (i.e., the mold wall has a temperature of $T = 74^{\circ}\text{C}$ at that location).

Since there is no significant time-dependent variation of temperature at the lower interface, one might use an alternative and simpler boundary condition instead of our Equations (4.11)-(4.14) applied at this interface. A Dirichlet type (constant temperature) boundary condition was applied at the mold walls in [60] to calculate an approximate temperature distribution in the flow through a narrow gap with porous medium. Analytical solutions are available for linear and radial flows [61,62]. The gain of this simple approach is to have less computational effort. Our boundary condition based on energy balance within a control element at the interface boundary is especially needed for mold walls such as acrylic or glass-reinforced composite material with lower thermal conductivity than metals. As shown in Figure 4.48, the temperature distribution along the upper interface (between the acrylic mold wall and the mold cavity) changes very significantly as time progresses.

In the numerical solutions of all of Case Studies 1-5, the natural convective heat transfer coefficient, h is taken as $h = h_{\text{air,lm}} = 12.5 \text{ W} / (\text{m}^2 \text{ }^{\circ}\text{C})$, and $h = h_{\text{air,um}} = 12.5 \text{ W} / (\text{m}^2 \text{ }^{\circ}\text{C})$. This value is the average value between the lower bound of $2 \text{ W} / (\text{m}^2 \text{ }^{\circ}\text{C})$ and upper bound of $23 \text{ W} / (\text{m}^2 \text{ }^{\circ}\text{C})$ measured in [63]. To investigate the sensitivity of the numerical results on to this parameter, a sample case study (Case Study 2) was solved again two more times using

the lower and upper bounds of h . The results tabulated in Table 4.7 clearly indicate that free convection energy between the mold and the surrounding ambient air is very negligible compared with the energy cumulated in different parts of the mold.

Table 4.4. Expected resin arrival times to sensor locations considering (i) a uniform 1D flow assumption, and (ii) immediate response of the sensors upon resin arrival [44].

Sensor #	Resin arrival time [s]	
	Case Study 1	Case Studies 2-5
S_{1a} and S_{1b}	14.3	7.2
S_{2a} and S_{2b}	27.9	13.9
$S_3 (= S_{exit})$	109.9	54.9

Table 4.5. Experimental and simulated resin arrival times to the sensors considering an increase of a threshold temperature, $\Delta T_{threshold} = 1^\circ\text{C}$ in the sensor reading [44].

Sensor #	Case Study 1		Case Study 2	
	Experimental resin arrival time [s]	Simulated resin arrival time [s]	Experimental resin arrival time [s]	Simulated resin arrival time [s]
S_{1a}	15.8	14.7	11.4	7.4
S_{1b}	18.4	30.8	11.8	17.5
S_{2a}	31.3	28.7	18.5	14.4
S_{2b}	49.1	61.1	19.9	34.1
$S_3 (= S_{exit})$	115.1	150.8	62.7	63.7

Table 4.6. Experimental and simulated sensor temperatures at $t = 200$ s [44].

Sensor #	Case Study 1		Case Study 2	
	Experimental sensor temperature [°C]	Simulated sensor temperature [°C]	Experimental sensor temperature [°C]	Simulated sensor temperature [°C]
S_{1a}	51.68	67.04	63.61	71.58
S_{1b}	36.17	32.36	41.32	35.40
S_{2a}	44.81	58.35	58.41	67.66
S_{2b}	31.83	30.52	39.39	33.18
$S_3 (= S_{\text{exit}})$	29.73	28.49	39.82	40.84

Table 4.7. Sensitivity of simulated results of Case Study 5 on the natural (free) convective heat transfer coefficient, h_{air} , between the mold walls and ambient [44].

Process variables at $t = 200$ s	Natural (free) convective heat transfer coefficient, h_{air} [63]		
	Lower bound $h_{air} = 2 \text{ W/(m}^2 \text{ }^\circ\text{C)}$	Average $h_{air} = 12.5 \text{ W/(m}^2 \text{ }^\circ\text{C)}$	Upper bound $h_{air} = 23 \text{ W/(m}^2 \text{ }^\circ\text{C)}$
$Q_{\text{internal,cavity}}/Q_{\text{in,net}}$	0.2141	0.2137	0.2134
$Q_{\text{internal,top}}/Q_{\text{in,net}}$	0.2421	0.2410	0.2403
$Q_{\text{internal,bot}}/Q_{\text{in,net}}$	0.5356	0.5305	0.5255
$Q_{\text{internal,convection}}/Q_{\text{in,net}}$	0.0011	0.0066	0.0118
$Q_{\text{internal,error}}/Q_{\text{in,net}}$	-0.0071	-0.0082	-0.0090
$T_{S1a} [^\circ\text{C}]$	71.7104	71.5822	71.4990
$T_{S1b} [^\circ\text{C}]$	35.4884	35.3999	35.3131
$T_{S2a} [^\circ\text{C}]$	67.7415	67.6617	67.6093
$T_{S2b} [^\circ\text{C}]$	33.2386	33.1759	33.1146
$T_{S3} = T_{\text{exit}} [^\circ\text{C}]$	40.8618	40.8357	40.8152
$T_{S4} [^\circ\text{C}]$	33.7730	33.6874	33.6036
$T_{S5} [^\circ\text{C}]$	26.0007	26.0006	26.0006

Chapter 5

POINT-VOLTAGE SENSORS

5.1 Voltage Sensors

The simple electrical circuit shown in Figure 5.1 is used for both *lineal-voltage* [32] and *point-voltage* sensors [68]. It has two resistance elements: R is used as a voltage divider, and R_{sens} is the resistance generated by the polymer-fabric media between the two electrodes, A and B , of the circuit. In both point- and lineal-voltage *sensors*, the output voltage, V_{sens} is measured continuously to monitor (i) resin flow during mold filling and/or (ii) resin cure. Initially, the media between the two electrodes A and B is a compacted dry fabric perform, which is in contact with the sensor. In this study, random e-glass fabric layers were stacked to prepare fabric preform. The electrical conductance of this material is practically zero, therefore the output voltage, V_{sens} is practically zero. When the resin arrives at the sensor location, the resin makes contact with both electrodes, and hence the output voltage increases due to the conductance of the resin.

In a point-voltage sensor, the electrodes are very close to each other, and resin touches only the tip of the electrodes. Thus, a point-voltage sensor detects the arrival of resin at a point, namely the tip of the sensor, when the output voltage changes from zero to a terminal value almost instantaneously. For a detailed monitoring of flow and cure, many sensors should be used together.

In a lineal-voltage sensor (see Figure 5.2), the electrodes are a couple of parallel and long electrical wires, and resin flows over the length of the wires which are placed on the mold

wall. A lineal-voltage sensor detects what fraction of the sensor was covered with the resin by monitoring the ratio, $r(t) = V_{sens}(t)/V_{sens,max} = L_{wet}/L$ where L_{wet} is the length of the sensor wire covered with the resin, L is the length of the sensor wire, $V_{sens}(t)$ is the measured output voltage at time t , and $V_{sens,max}$ is the maximum voltage that can be read when the sensor is fully covered with the resin system used. For calibration purposes, $V_{sens,max}$ needs to be measured accurately before actual injections.

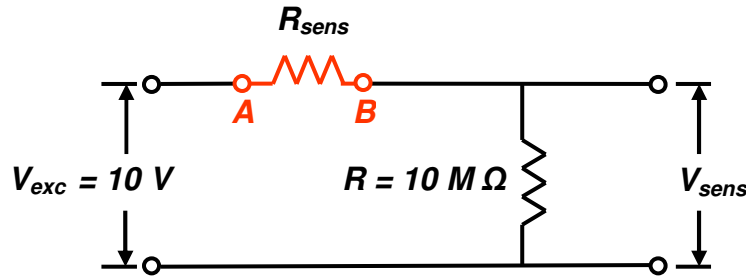


Figure 5.1. The electrical circuit of a lineal-voltage sensor [32].

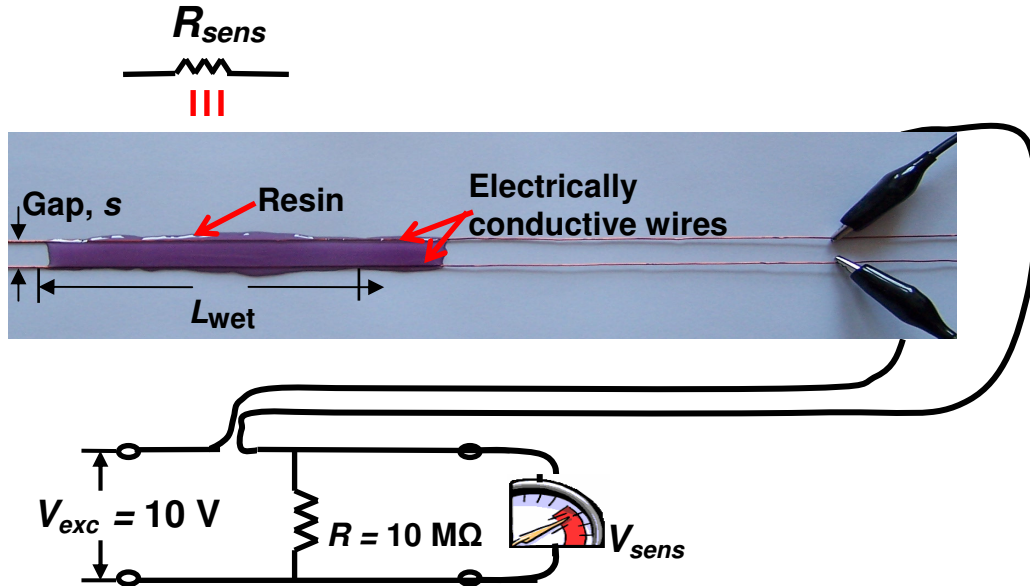


Figure 5.2. A lineal-voltage sensor [64].

5.1.1 Issues of Lineal-Voltage Sensors

To investigate the issues of lineal-voltage sensors, two copper wires with a diameter of 0.35 mm and a length of 200 mm are placed on an electrically insulated tape with a gap of 5 mm, and then connected to the electrical circuit as shown in Figure 5.2. To measure V_{sens} accurately, R should be chosen as close to R_{sens} (the resistance of polymer between the two wires) as possible. The order of magnitude of R_{sens} ranges between $M\Omega$ and $G\Omega$ for typical polymers of RTM in such a section. In this study, R is chosen as $10 M\Omega$; and the voltage of the power supply was set to $V_{exc} = 10$ Volts.

As Barooah et al. [32] and our experiments showed, R_{sens} is linearly proportional with $f(\rho, s)/L_{wet}$, hence V_{sens} is linearly proportional with $L_{wet}/f(\rho, s)$, where L_{wet} is the length of the resin layer, $f(\rho, s)$ is a function of the gap width, s between the two wires (see Figure 3), and ρ is the electrical resistivity of the resin.

Although a single lineal-voltage sensor enables more detailed monitoring of resin flow compared with a single point-voltage sensor, a lineal-voltage sensor has the following major disadvantages:

- It can detect only what fraction of the sensor was wetted by the resin instead of detecting what section(s) was wetted.
- *Disturbance* of resin flow: The wires are bonded on an electrically insulated tape and then placed on the mold wall. Even though the wires and the insulated film are very thin, they still cause a change in the empty-space-structure of the fabric preform. The effective permeability of the preform-sensor interface will be different from the bulk preform. As resin flows through this region, the flow is disturbed.
- The sensors can only be used once.
- Sensor removal from the part might be time-consuming and troublesome. The final surface has irregularities due to the detached sensors. Alternatively, the

sensors can be left embedded on the part surface, but they cause stress concentrations when the part is loaded.

The first item of the list is the most important issue for these sensors. If this limitation is not recognized, the in-situ sensor data that are input to the data acquisition (DAQ) system might be evaluated wrongly, and the outcome might mislead the user. Thus, for an accurate and reliable monitoring of the resin flow, one should be aware of this behavior. In this study, some experiments were performed to illustrate this behavior. Two of these experiments were shown in Figure 5.3.

In the first experiment shown in Figure 5.3a, resin covers only a single section of the sensor wires with a wetted length of 100 mm. In the second experiment, shown in Figure 5.3b, the resin covers multiple sections of the sensor wire with a total wetted length of 100 mm (at three separate locations with individual lengths of 40 mm, 20 mm and 40 mm). The output voltage reading, V_{sens} is tabulated in Table 5.1 for the two different resin systems used.

The results of experiments (a) and (b), which are equal to each other within experimental error, state that the output voltage is dependent on the “total” wetted length of the wire. It cannot distinguish whether the wire was covered with resin at only a single section or at multiple sections. Also, it cannot sense where the wetted section is on the wire, i.e., whether the sensor was covered with resin starting from the left or right end cannot be known.

Thus, if a lineal-voltage sensor is used, the user must be cautious about how to evaluate the in-situ sensor data. An assumption such as “the sensor must have been covered with resin starting from the end which is close to the injection gate since the flow front is first expected to arrive there” might lead to a false monitoring of mold filling. However, when $r(t) = V_{sens}(t)/V_{sens,max} = 1$, there is no possibility of making a wrong evaluation since the sensor data clearly mean that the sensor is *completely* covered with the resin, i.e., $L_{wet}/L = 1$.

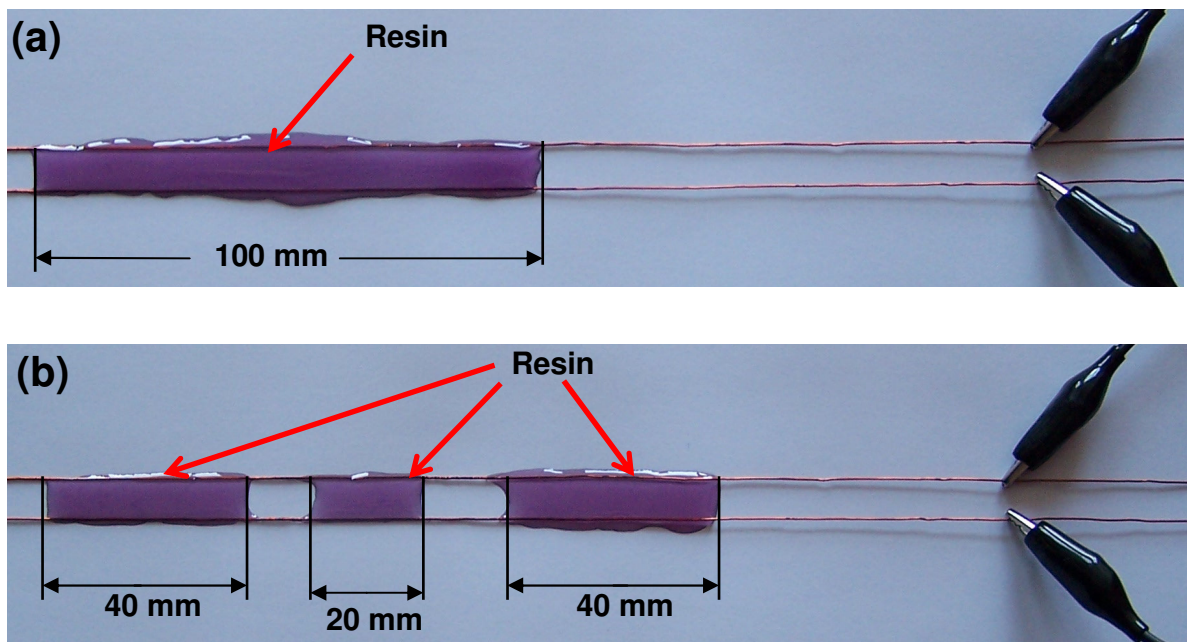


Figure 5.3. Wetting of a lineal-voltage sensor at (a) a single, or (b) multiple locations [64].

Table 5.1. Output voltage readings, V_{sens} when a single or multiple sections of a lineal-voltage sensor is covered by resin as shown in Figure 5.3. In all experiments, $V_{exc} = 10V$, and the total wetted length is 100 mm (which is the half of the sensor wire length) [64].

Resin	V_{sens} [V]	
	when only a single section is wetted (see Figure 5.3a)	when multiple (= 3) sections are wetted (see Figure 5.3b)
General-purpose polyester (Ilkester polyester 116 [11])	0.60	0.60
Epoxy (Moravia, two-component epoxy [13])	4.90	4.90

5.1.2 Point-Voltage Sensors

Being aware of the major issues of lineal-voltage sensors, we choose not to use them in our experiments. Two varieties of point-voltage sensors were developed and used in our experiments: (i) compact and wrapped lineal-voltage sensors, and (ii) point sensors with an amplification of the output voltage.

5.1.2.1 Wrapped Lineal-Voltage Sensor Compacted into a Point-Voltage Sensor

Resin covers only the tip of the poles (electrodes A and B in Figure 5.1) of a point-voltage sensor. The electrical resistivity of a typical RTM resin in such a region is very high. The corresponding output voltage, V_{sens} is only on the order of 0.1 V or less when the resin has a low conductivity. When the electrical noise of the DAQ system is considered, either this very small magnitude of V_{sens} needs to be amplified, or a different approach should be adopted.

First, we manufactured a variety of wrapped wires of lineal-voltage sensors compacted into a relatively small area. Some of these prototypes of printed circuit boards are shown in Figure 5.4. The unfolded lengths of the wires are shown in the figure. The electrical circuit of Figure 5.1 was connected to each of these prototypes, and V_{sens} was measured when two types of resins fully covered the wires. The measured V_{sens} values are given in the same figure. The output voltage, V_{sens} is about one order of magnitude higher for these wrapped sensors than the prototype with only concentric poles shown in Figure 5.4c. However, it is a difficult task to fit the sensors in Figure 5.4(a) and (b) into a reasonably small area on the mold wall. Another major issue of these new sensor types is the vulnerability of the thin printed wires to the high stresses of compaction and detachment of the sensors from the composite part at the end of the cycle. The thin wires of the printed circuit board are unlikely

to survive for more than a few injection cycles. Thus, these expendable sensors should be used one time only.

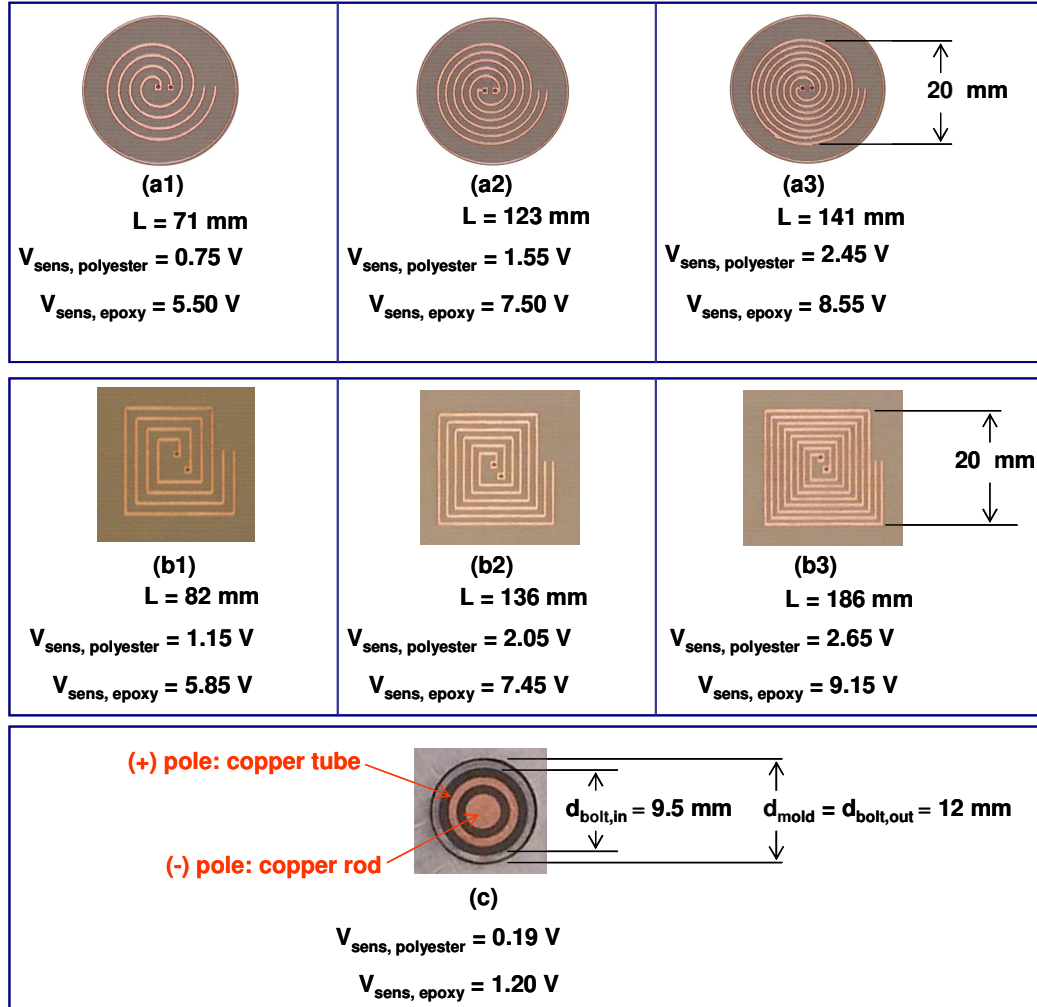


Figure 5.4. (a) and (b): Wrapped and compact lineal-voltage sensors printed on circuit boards. These sensors are designed to be used as point-voltage sensors. L is the length of the unfolded wire length. Each couple of wrapped wires are compacted within an area of approximately 20 mm x 20 mm. The gap between the wires, s , and the thicknesses of the wires are not constant in all prototypes. A single layer of random e-glass fabric was saturated with resin, and then placed on the wires to measure V_{sens} . V_{sens} values are the mean of repeated experiments. (c): Point-voltage sensor with concentric poles only; it fits into the hollow multi-function bolt [64].

5.1.2.2 Point-Voltage Sensor with Voltage Amplification

Due to the issues mentioned above, a new point sensor system was developed in this study and it is shown in Figures 5.4c, and 5.5. A copper tube and a copper rod are machined on a lathe and fitted concentrically into a multi-function bolt. Two plastic tubes made of delrin (a polyacetal polymer by DuPont) separate the copper tube and rod (see Figure 5.5b), and hence prevent any electrical conductance between them, or to the metal bolt. The copper tube and rod act as the electrodes of the circuit (poles *A* and *B* of Figure 5.1).

This sensor has the following characteristics:

Advantages:

- It is durable and resistant to resin contact, resin cure and part de-molding.
- It fits into the hollow multi-function bolt (which has an inner hole diameter of 9.5 mm).
- It is easy to manufacture; and it has a low cost.
- Sealing of the bolts is ensured, and hence resin leakage is prevented.

Disadvantage:

- It is more sensitive to the electrical noise in the data acquisition system than the former design of wrapped lineal-voltage sensors, since V_{sens} is hard to detect by DAQ if the resin system has low electrical conductivity. For this reason, the electrical circuit shown in Figure 5.1 will be modified as described in the next section.

The copper rod and tube, and hard insulating plastic tubes are tightly fitted into a hollow bolt for a fine sealing. Our repeated experiments showed that plastic tubes are not de-graded due to the contact of curing resin. The insulating plastic between the copper tubes should be chosen carefully. It must have a much higher resistance than the resin; otherwise the circuit

would already be closed in its initial un-wetted stage. The insulating plastic (delrin) used in this study meets this requirement.

5.1.2.2.1 Modified Electrical Circuit of the Point-Voltage Sensors

When the conventional electrical circuit (shown in Figure 5.1) is connected to the point-voltage sensor's poles, V_{sens} is measured 0.19 V if the resin is a general purpose polyester, and 1.2 V when the resin is a two component epoxy (see Figure 5.4). Experiments also indicated that, as long as the thickness of the resin layer on the sensor is on the order of mm, it did not affect these voltage readings significantly. The value of $V_{sens} = 0.19$ V corresponding to polyester resin is not high enough when one considers typical amplitude of voltage oscillations due to the electrical noise that exists in a typical DAQ system. Thus, these voltage readings have to be amplified before being evaluated by DAQ. The amplification process can be performed by a simple op-amp circuit. However, the input impedance generated by the $R = 10\text{ M}\Omega$ resistance and the resistance of resin (R_{sens}) are too high, and the voltage reading V_{sens} cannot be directly amplified. In order to enable amplification, an op-amp with high input impedance is needed to serve as a buffer to interface the high input impedance. After the buffering process, the DC voltage can be amplified by using a conventional op-amp. The circuit with this added feature of amplification is shown in Figure 5.6a, which includes two op-amps: one is used as a buffer, and the other is used as an amplifier.

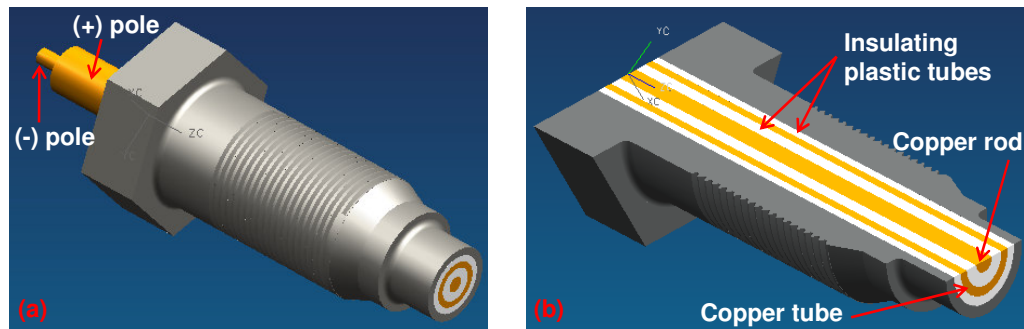


Figure 5.5. Point-voltage sensor developed: (a) solid model, and (b) cross-sectional view [64].

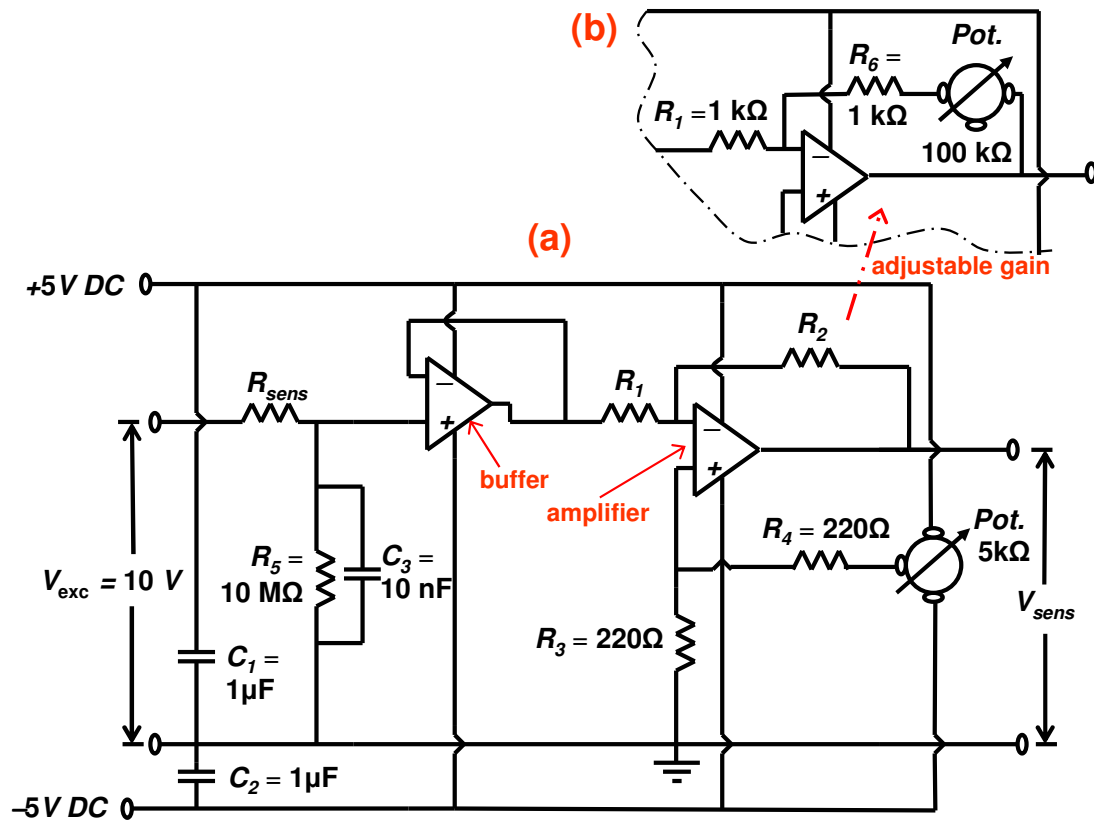


Figure 5.6. (a) The improved electrical circuit of a point-voltage sensor. In this circuit, the output voltage, V_{sens} is amplified to overcome the noise in the DAQ system; $R_1 = 1k\Omega$ and $R_1 = 100k\Omega$, hence the gain factor is 100. (b) An adjustable gain factor can be obtained using a resistor R_6 and a potentiometer together instead of using R_2 alone.

The elements of this circuit can be described as follows:

- Op-Amp (buffer): This is used as a buffering op-amp with high input impedance. It isolates the high impedance system and makes DC voltage amplifiable by a conventional op-amp. OPA655P [65] is used with an input impedance of $10^{12} \Omega$.
- Op-Amp (amplifier): This op-amp is used as the conventional inverting op-amp for amplification. An LM358P [66] is used for this purpose. In this study, amplifying ratio, $R_2 / R_1 = 100 \text{ k}\Omega / 1 \text{ k}\Omega = 100$ was taken. The advantages and disadvantages of this high ratio are discussed later in this study.
- Capacitors: Capacitors C_1 and C_2 are used in order to compensate for any fluctuations in the power source. Capacitor C_3 of 10nF is used to reduce the noise on the output signal.
- Potentiometer (POT): The potentiometer is used in order to offset the amplifying op-amp's output voltage when the circuit is open.

The circuit is manufactured on a PCB (Printed Circuit Board). Each PCB circuit is placed in a commercially available and low-cost plastic casing (box). Suitable connections are made for the integration of these boxes with multi-functional bolts that contain point-voltage sensors. The bolts are mounted on the mold wall at desired locations (where to monitor the mold filling and resin cure). Shielded cables carry power to these boxes and also receive DAQ signals from these boxes.

5.1.2.2.2 Response Rate of the Sensor System

Specifying a proper threshold voltage, $V_{threshold}$ is important. For either of the two polymer systems mentioned earlier, a typical $V_{threshold} = 1 \text{ V}$ is proper. This threshold value is high enough so that it eliminates the possibility of a false detection of resin arrival due to a typical electrical noise that still exists in the system. It is also low enough so that it can guarantee to detection of the actual resin arrival, since the typical voltage shift in V_{sens} is ~ 4

- 5 Volts when either of the two types of resin arrives at sensor location. V_{sens} increases as the fraction of the sensor's wetted tip area increases (see Table 5.2).

Using epoxy resin and modified electrical circuit in Figure 5.6a, output voltage was measured when $1/4$, $1/2$, $3/4$ and full of the tip area was covered by resin. When one considers the typical $V_{threshold} = 1$ V for the designation of the “resin arrival”, it is enough to wet a quarter of the sensor tip by epoxy resin. As seen from the same table, the thickness of the resin layer was not very significant on the output voltage value as long as it is on the order of mm.

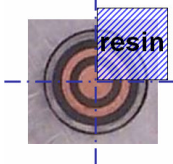
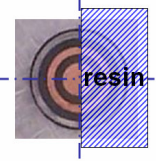
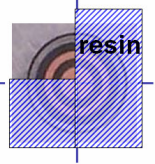
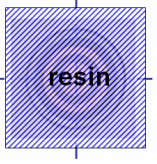
Figure 5.7 shows the voltage reading of a single point-voltage sensor during a sample experiment. Initially, $V_{sens} \approx 0$ since the tip of the sensor is touching a dry e-glass fabric preform. When the resin flows in the mold cavity, and eventually arrives at the sensor location at approximately $t \approx 216$ seconds, it covers the two poles of the circuit. This way, the electrical circuit shown in Figure 5.6 is closed due to the electrical conductivity of the liquid resin, and V_{sens} reaches a value close to 5 V. Even though the output voltage is amplified by a factor of 100, which is the gain (R_2/R_1) used in this study, V_{sens} cannot exceed the magnitude of the supply voltage (5 V) due to the working principal of the amplifier op-amp.

As seen in the figure, the voltage reading increased to ~ 5 V almost immediately considering the sampling frequency of the data acquisition system, which was set to 5 Hz in this sample experiment. It took only two data samples, which corresponds to 0.4 second, for this sharp increase of the voltage. For an injection process that is typically on the order of minutes, this response time is acceptable. Actually, the response of this new sensor system is much better than it looks, if one considers the flow dynamics of the problem. In this sample experiment, the flow rate was set to $Q = 60$ cc/min. By using the fiber volume fraction (0.24) and the dimensions of the mold cavity cross-section (168 mm x 3 mm), the velocity of the flow front is

$$V_{ff} = \left[(60,000 \text{ mm}^3 / \text{min}) (1 \text{ min} / 60 \text{ s}) \right] / \left[(168 \text{ mm}) (3 \text{ mm}) (1 - 0.24) \right] = 2.6 \text{ mm/s} .$$

Thus, the flow front covers only a small section of the sensor tip within 0.4 second since the two concentric poles are placed within the inner hollow bolt with a diameter of 9.5 mm. In other words, as the flow rate of the injection is increased, the response time of the sensor becomes even shorter than 0.4 second that was measured in the sample experiment.

Table 5.2. Output voltage readings, V_{sens} when the tip of the new point-voltage sensor is partially wetted by epoxy resin. The modified electrical circuit (shown in Figure 5.6) is connected to the poles of the sensor [64].

Thickness of the resin layer	V_{sens} [V]			
	when 1/4 of the sensor is wetted 	when 1/2 of the sensor is wetted 	when 3/4 of the sensor is wetted 	when full of the sensor is wetted 
≈ 1 mm	1.60	2.11	3.97	4.23
≈ 2 mm	1.60	2.21	4.59	4.62
≈ 3 mm	1.61	2.23	4.59	4.62
>> 3 mm	1.62	2.25	4.59	4.62

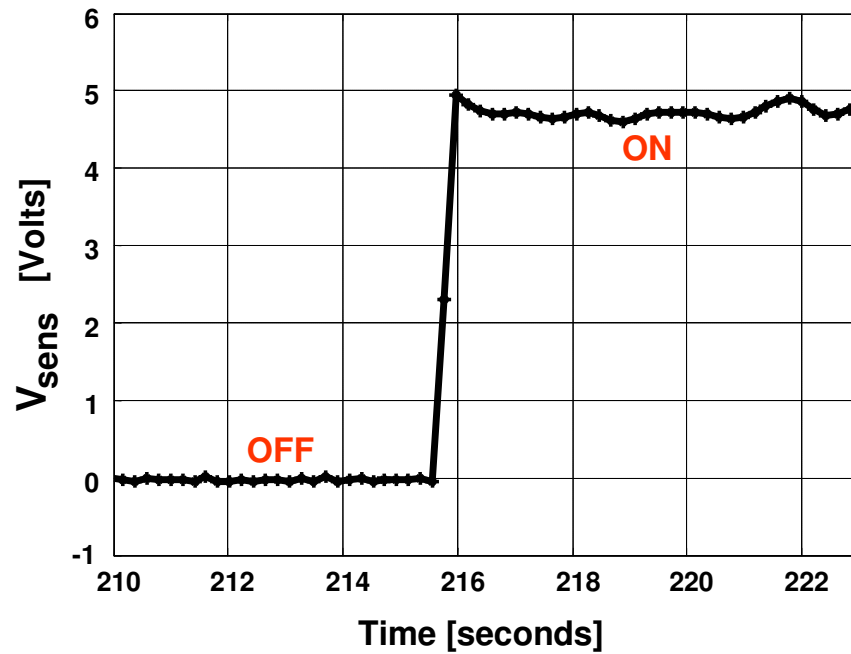


Figure 5.7. Response of a single point-voltage sensor when resin covers the poles of the sensor.

5.2 Experiments

A set of experiments were performed to test the accuracy and reliability of the sensor system developed. By using nine point-voltage sensors, monitoring of mold filling was achieved with success.

5.2.1 Configuration of the Sensors

In these experiments, nine point-voltage sensors (S1, S2, ..., S9) were placed on the bottom mold plate as shown in Figure 5.8. One advantage of these sensors is that, the bolts containing the sensors are parts of the mold, and thus they do not alter the mold cavity as some of the other sensor types do.

In this study, a frame with inner cavity dimensions of 704 mm x 168 mm x 3 mm, and four layers of random e-glass fabric is used. The corresponding fiber volume fraction is 24%. The empty channels on both sides of this cavity are used to generate lineal injection and ventilation. The sampling frequency of the data acquisition system is set to 5 Hz. Figure 5.9 shows the setup consisting of the mold and the sensors.

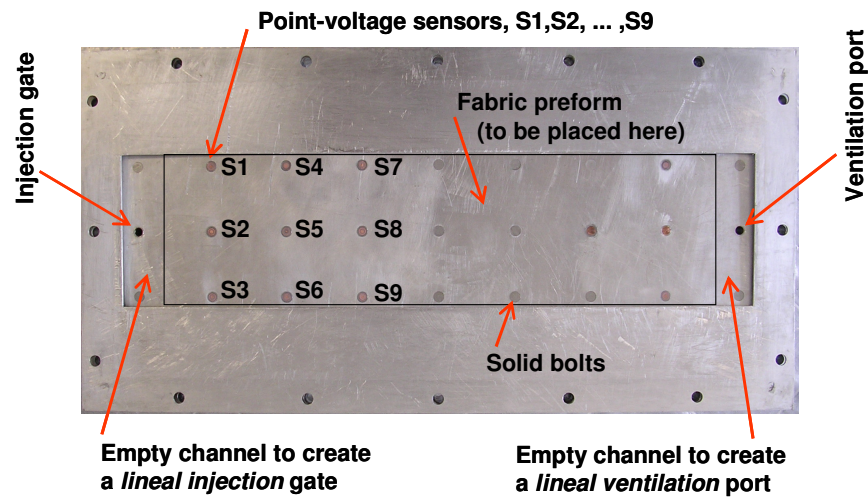


Figure 5.8. The configuration of nine point-voltage sensors on the lower mold plate [64].

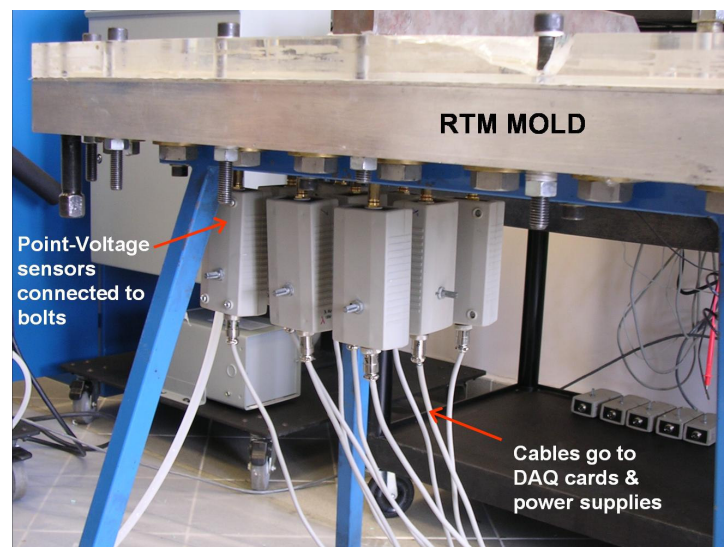


Figure 5.9. Mold and point-voltage sensors [64].

5.2.2 Results of a Sample Experiment during Monitoring of Mold Filling

In Figure 5.10, the times of resin arrivals at the nine sensor locations can be clearly seen with sharp jumps in V_{sens} . According to these results, the resin arrived at the three frontier sensors that are close to the injection gate with the following arrival order: S1, S3 and then S2 at $t = 64\text{s}$, 66s and 106s , respectively. The data suggests a U-shaped flow front, which is caused by the racetracking channels on both sides of the mold. Since $t_{S1} \approx t_{S3}$, this U-shaped flow front is expected to be almost symmetric around the mid-line of the mold, which passes through sensors S2, S5 and S8. As the resin further propagates in the mold cavity, the following can be predicted: (i) the concavity of the U-shaped flow front increases (by comparing t_{S6} and t_{S5}); and (ii) the flow front is not symmetric any more (by evaluating the data $t_{S4} \gg t_{S6}$ and $t_{S7} \gg t_{S9}$), hence the effects of the two racetracking channels on the shape of flow front are not equal.

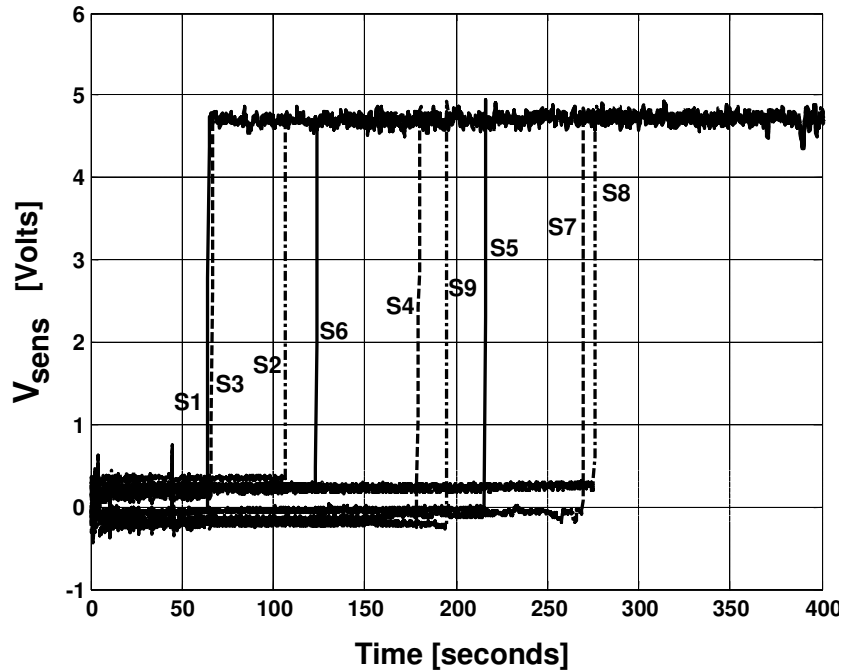


Figure 5.10. Experimental data during monitoring of the mold filling [64].

In order to verify the reliability of the sensor data, snapshots of the recorded experiment were taken at t_{S1} , t_{S2} , and so on, and shown in Figure 5.11. The visually recorded flow front location at t_{S_i} intersects closely the known coordinates, (x_i, y_i) of the i th sensor S_i .

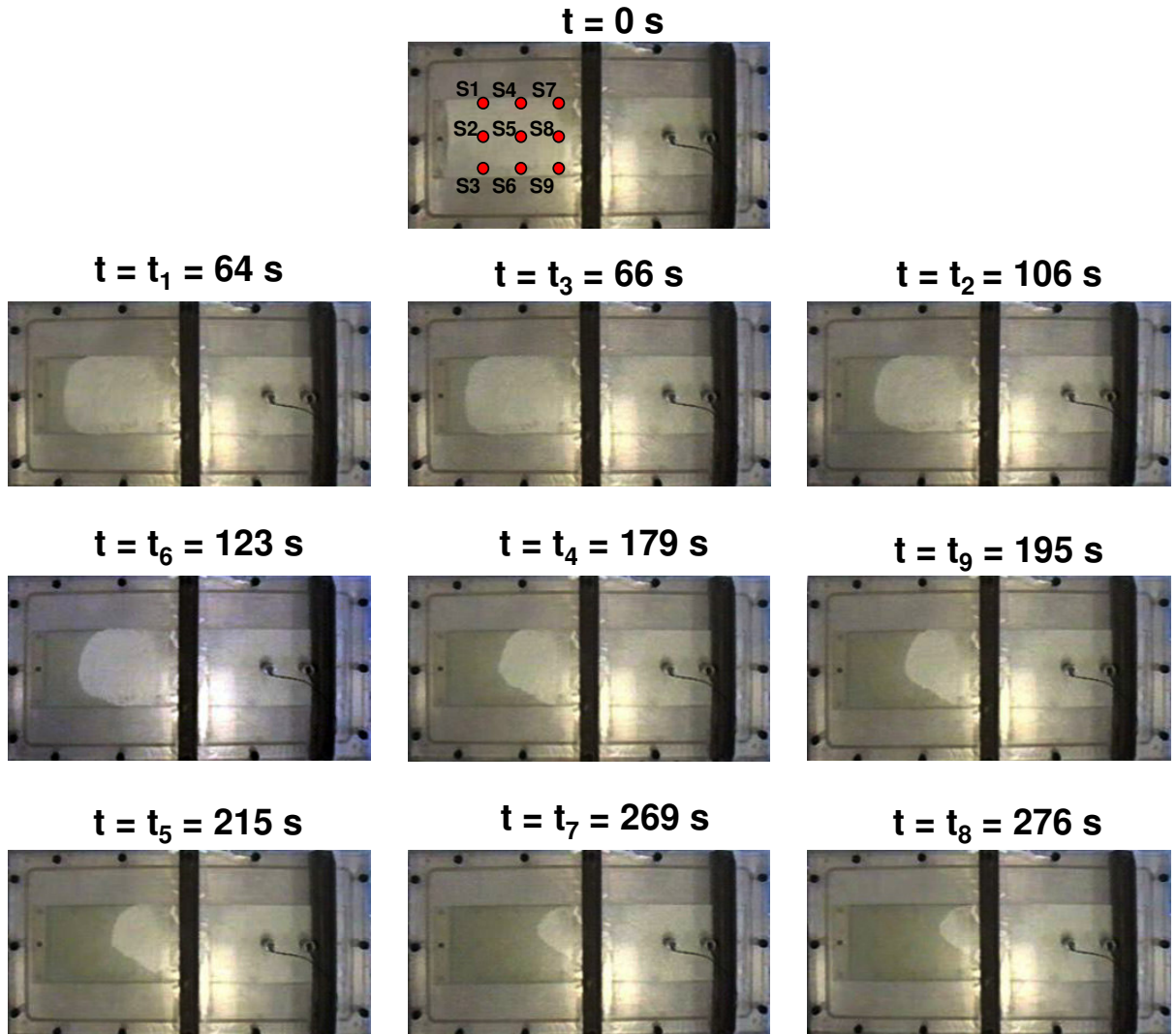


Figure 5.11. The flow front locations at $t = t_1, t_2, t_3, \dots, t_9$ (when the resin arrives at the sensors S1, S2, S3, ..., S9, respectively) [64].

One of these snapshots (corresponding to the resin arrival at S6) which is shown in Figure 5.12 shows a very close match of the flow front and the coordinate of the sensor. However, not all of the flow fronts of those nine snapshots intersect the coordinates of the sensors very closely. It is suspected that the flow front velocity profile is not uniform through the thickness of the mold cavity.

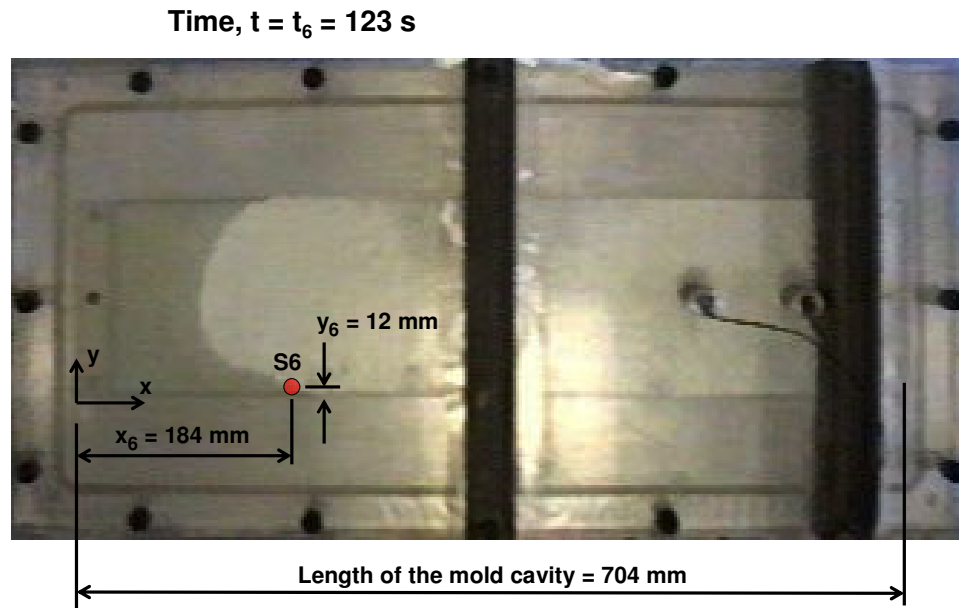


Figure 5.12. The flow front location at $t = t_6$ (when the resin arrives at the sensor S6) [64].

5.2.3 Results of a Sample Experiment during Monitoring of Resin Cure

During the injection stage of the manufacturing cycle, the degree of resin cure is intended to be kept very low so that the corresponding viscosity of the resin is at its low level. This is important for the sake of low injection pressure. This behavior of the resin is maintained by tailoring the resin system. In this study, the amounts of the additives (peroxide and cobalt) that are added to the polyester are adjusted so that no significant change occurs in the degree of cure and the viscosity of the resin during the first half hour approximately. The two-

component epoxy also has approximately 30 minutes of pot life at 20°C. Afterwards, the cure of the polymer changes the chemical structure and decreases the electrical conductivity of the resin. Then, the voltage readings gradually decrease and drop to the zero level when the full cure is achieved. Figure 5.13 shows the injection and cure cycles for the sample experiment.

By monitoring V_{sens} , one can determine the corresponding resistivity of the resin and decide when to open the mold. However, this needs to have a previously tabulated database that will relate the “green strength” of the composite part to the resin resistivity. After V_{sens} drops below the critical value corresponding to the green strength, one can de-mold the part safely ensuring no warp or deformation occurs on the composite part. Figure 5.13 shows the decrease in V_{sens} for all the sensors during the curing stage of the sample experiment. Our experience indicates that if the part is de-molded after V_{sens} drops below approximately 1 Volt, no significant warpage or deformation is likely to occur during the detachment of the part from the sticky mold surface. The only significant warpage is observed around the lineal injection gate and ventilation port where there are no reinforcing fibers. Since these sections are to be trimmed at the end of the cycle anyway, this warpage is not important. For an optimal de-molding time, one should do mechanical tests on the curing resin at different degrees of cure and find the electrical resistivity corresponding to the green strength. One can use a program such as PSpice to determine V_{sens} corresponding to the critical R_{sens} . In PSpice program [69], the electrical circuit of the new sensor system is drawn (see Figure 5.14); and the variation of V_{sens} as a function of R_{sens} is plotted in Figure 5.14

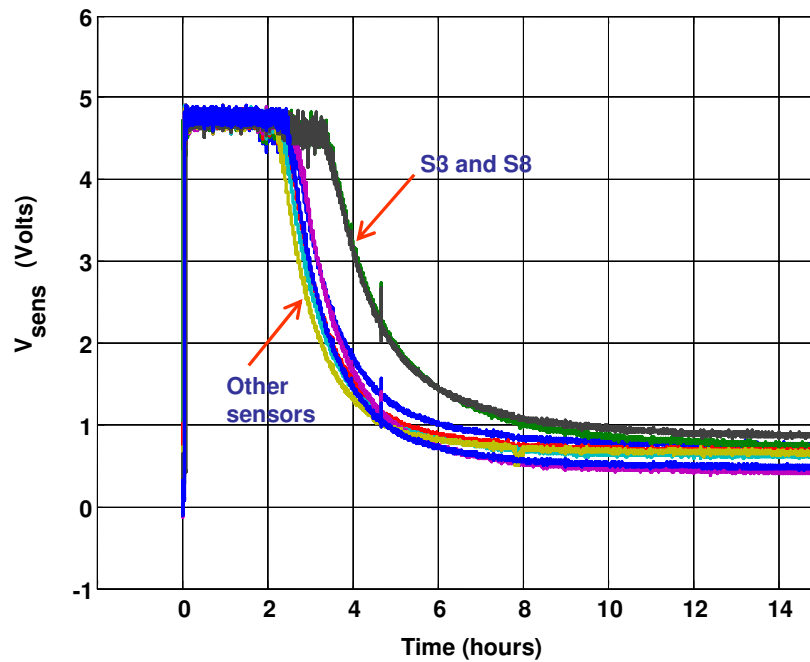


Figure 5.13. Experimental data during monitoring of resin (epoxy) cure [64].

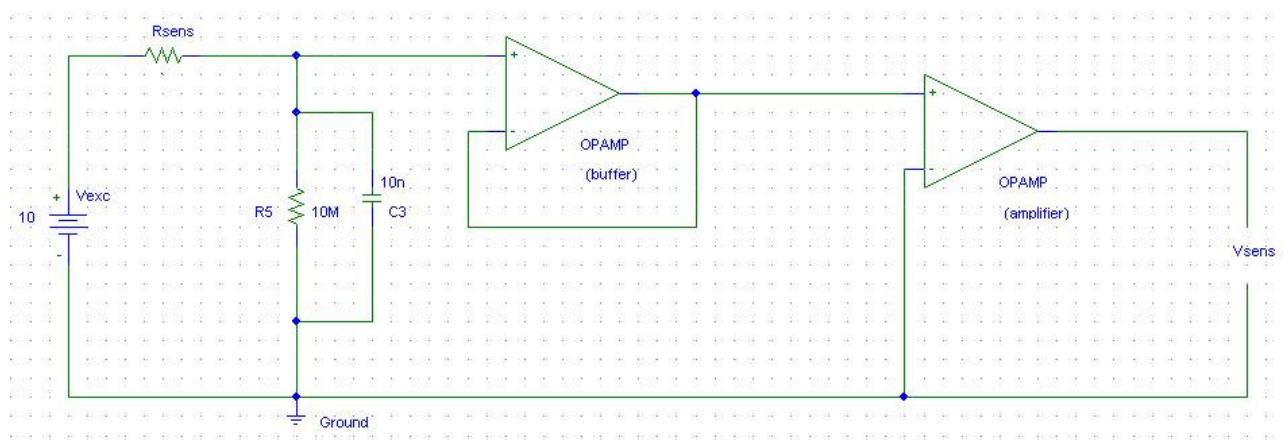


Figure 5.14. Analysis of the electrical circuit of the new sensor system (see Figure 8) using the PSpice program [69].

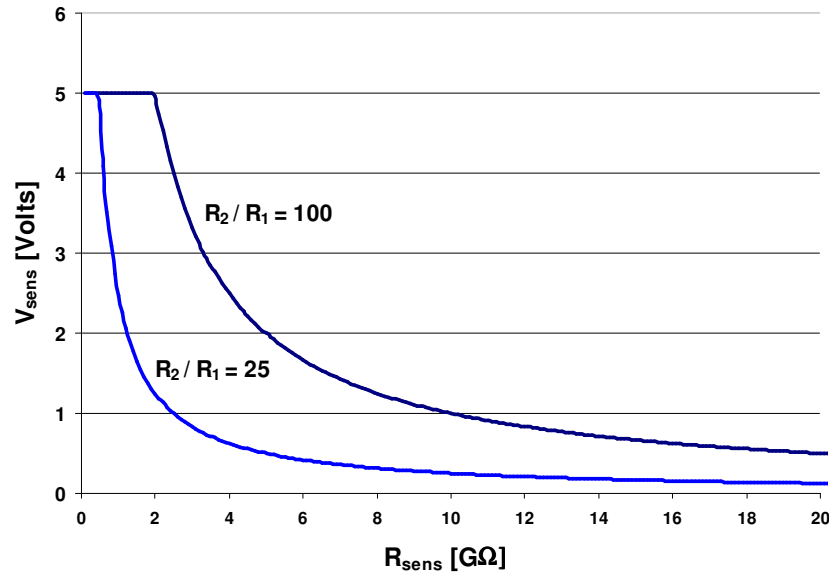


Figure 5.15. The variation of V_{sens} as a function of R_{sens} for two different gain, $R_2 / R_1 = 25$ and 100.

5.2.4 Importance of the Gain, R_2 / R_1

Figures 5.15 and 5.16 are important in investigating the advantage and disadvantage of setting the gain (R_2/R_1) to a very high value. For example, when R_2/R_1 is set to 100, the increase in R_{sens} (which occurs during the actual chemical reaction of resin cure) cannot be observed until $R_{sens} \approx 2 \text{ G}\Omega$. If the green strength of the resin matrix corresponds to $R_{sens} < 2 \text{ G}\Omega$, the user of the sensor will wait for a significant change in V_{sens} , which will occur later than the optimal de-molding time. Thus, the cycle time will be unnecessarily longer than the optimal one. On the other hand, if R_2/R_1 is kept low, the corresponding increase in V_{sens} might not be high enough to guarantee the detection of resin arrival during mold filling. To verify our findings about the R_2/R_1 ratio, an experiment was done by using two identical point-voltage sensors; except that one has $R_2/R_1 = 100\text{k}\Omega/1\text{k}\Omega = 100$, and the other has R_2/R_1

$= 25\text{k}\Omega/1\text{k}\Omega = 25$. The two sensors were placed on the lower mold plate, and general-purpose polyester was injected into the mold cavity. V_{sens} of the two sensors were plotted in Figure 5.16. No change was observed in $V_{\text{sens,gain100}}$ for approximately 1.5 hours. On the other hand, $V_{\text{sens,gain25}}$ started to decrease after $t \approx 15$ minutes due to the increase in R_{sens} during the resin cure.

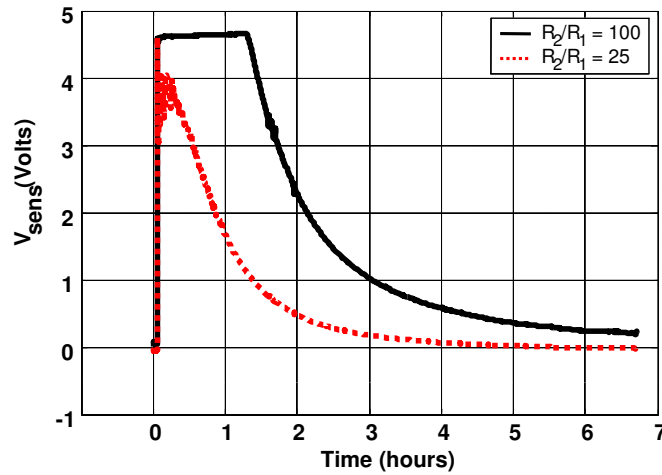


Figure 5.16. Monitoring of resin cure by using two different gain ratios, $R_2/R_1 = 25$ and 100.

A more robust point-voltage sensor can be developed with a variable gain, R_2/R_1 as shown in Figure 5.6b. In this modified design, a resistor R_6 and a potentiometer together replace R_2 . The sensor will have a gain spectrum of 1 – 100 if $R_1 = R_6 = 1\text{ k}\Omega$ and the adjustable resistance of the potentiometer can be set to any proper value of up to 100 k Ω by the user. During the mold filling, the resistance of the potentiometer is kept at its highest level for a guaranteed detection of resin arrival even if the resin has a very low electrical conductivity. If the same sensor system is going to be used for monitoring of resin cure after monitoring of the mold filling is completed, then the resistance of the potentiometer is adjusted to its lowest level to enhance the sensitivity of the circuit on the change in R_{sens} .

Repeated experiments show that our sensor system is accurate and reliable for flow monitoring by comparing the rapid sensor responses and the flow front images at corresponding times. On the other hand, if we want to use the same sensor system for the resin cure monitoring, an accurate database is needed to relate the followings as a function of cure degree and also temperature: (i) electrical resistivity of resin, and (ii) green strength and stiffness of the composite part. Currently, we cannot claim that our resin cure sensing is accurate since we do not have such an accurate material characterization database. However, when such a database is available, the optimal demolding should be done when the electrical resistance (and hence the output Voltage) corresponds to the desired degree of cure and mechanical properties. Time-dependent variation of viscosity and electrical resistance were measured for both resin systems used in this study. Both resin systems have approximately 30 minutes pot life which ends with a very sharp increase in the viscosity when the gellation starts. However, epoxy resin's exothermic cure reaction might cause a local temperature rise of more than 60 °C above the initial temperature even much before the gellation if the mold wall (or the container of the measurement) has low thermal conductivity. When aluminum mold wall is used, the released energy does not create such a big temperature rise in the resin since the heat diffuses in the metallic mold part at a high rate. Beacuse of these factors, one definitely needs the database mentioned above to claim for an accurate monitoring of resin cure and hence decision of the optimal de-molding time.

Chapter 6

CONCLUSION

In this study, two types of sensor systems (thermocouple sensors and voltage sensors) are analyzed for flow monitoring in the RTM process.

In thermocouple sensors analysis, experiments were performed using hot resin inlet and cold acrylic and aluminum mold parts. It is observed that, the sensors mounted on the acrylic part measured a predetermined increase of threshold temperature within a reasonably short time when resin arrived at the sensor location. On the other hand, due to the much higher thermal diffusivity of aluminum, the sensors on the metal part responded with a longer delay than the ones on the acrylic side.

A mathematical model was developed based on 1D flow and 2D unsteady energy equation to investigate these different levels of response rate and hence accuracy of the thermocouple sensors when they are mounted on mold parts made of different materials. Temperature of the resin particles and fabric adjacent to the mold walls at the interface nodal points were calculated using an unsteady energy balance equation, instead of using a constant temperature boundary condition. This approach for the interface boundary condition is shown to be needed for higher accuracy, especially when the mold parts are made of materials such as fiber glass-reinforced composites or acrylic, which have much lower thermal diffusivity than the metallic parts. Conducted heat energy diffuses at a lower rate in this mold part than the other metallic side. Along a very narrow region adjacent to the interface, the time-wise temperature change is higher than the metallic part. Thus, application of a constant temperature boundary condition at the interfaces was avoided in our model. The

rate of energy transfer between the resin and metallic mold wall is higher than the rate at the other interface. This causes a faster temperature change (decrease if hot resin enters in a cold mold; or increase if cold resin enters in a hot mold) for the resin particles adjacent to the metallic mold wall. Due to this low level of resin's internal energy and the response rate capability of our thermocouple sensor system, a longer delay occurs to measure the threshold temperature difference. To conclude, a thermocouple sensor should be used with caution for flow monitoring in RTM due to its limitations especially when metallic mold parts are used.

In voltage sensor analysis, experiments were performed with mainly two different types of sensors: point- and lineal-voltage sensors. The results of our experiments show that, although the in-situ data of a lineal sensor is more informative than the point-voltage sensor, it might mislead the user if the resin covers the wires at multiple sections, or resin covers the wires starting from an unexpected section. Because of this potentially false monitoring characteristic of lineal-voltage sensors, multiple (nine) point-voltage sensors were used in this part of the study.

Two prototypes were developed and tested: (i) a set of wrapped and compact lineal-voltage sensors acting as point-voltage sensors; and (ii) a point-voltage sensor with voltage amplification. The former prototypes have the advantage of higher than the latter. However, the following major issues of these prototypes must be overcome before actual manufacturing: they are not compact enough to fit in small sections of the mold wall, (which are the holes of multi-function bolts of our mold in this study); the thin wires of the printed circuit board are not very resistant to resin contact and detachment conditions.

The second prototype was manufactured by inserting a copper rod and tube into the hollow multi-function bolt. Some of the RTM resin systems, such as the general-purpose polyester used in this study, have very high electrical resistivity. When the poles are covered with such a resin system, the corresponding V_{sens} reading might be difficult to detect by the DAQ system. The simple electrical circuit of the conventional voltage sensor was improved

to amplify the output voltage, V_{sens} . The accuracy and reliability of this new sensor system was verified by comparing the in-situ sensor data with the visually recorded resin flow.

V_{sens} was shown to decrease during resin cure due to the increase in R_{sens} . However, a database is needed to relate R_{sens} of the resin system to its mechanical properties. Therefore, if the critical R_{sens} corresponding to the green strength of the resin matrix is known, the operator of the process can de-mold the part before a full resin cure is achieved to decrease the cycle time.

As a future work to this study, the following developments should be made:

- Creating a database that relates the green strength and the R_{sens} of the polymers for accurate cure monitoring.
- Design and manufacturing of more compact point-voltage sensors to increase the number of sensors per mold wall area for more detailed flow monitoring.
- Mold design and manufacturing for these new compact sensors.
- Develop the actual multiplexer from the proposed prototype, to acquire and process data with high number of channels.

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VITA

Murat Danişman was born in Ankara, Turkey on July 7, 1981. He received his B.S. degree in Mechanical Engineering from Middle East Technical University (METU), Ankara, in 2004. Since 2004, 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 the Resin Transfer Molding Process Developing Thermocouple and Voltage Sensors” project since September 2004. He is planning to continue his career as a Mechanical Engineer in the industry.

APPENDIX A

A1. Moravia Two-Component Epoxy [13]

Density: $\rho = 1.02 \text{ grams / cm}^3$ (at room temperature).

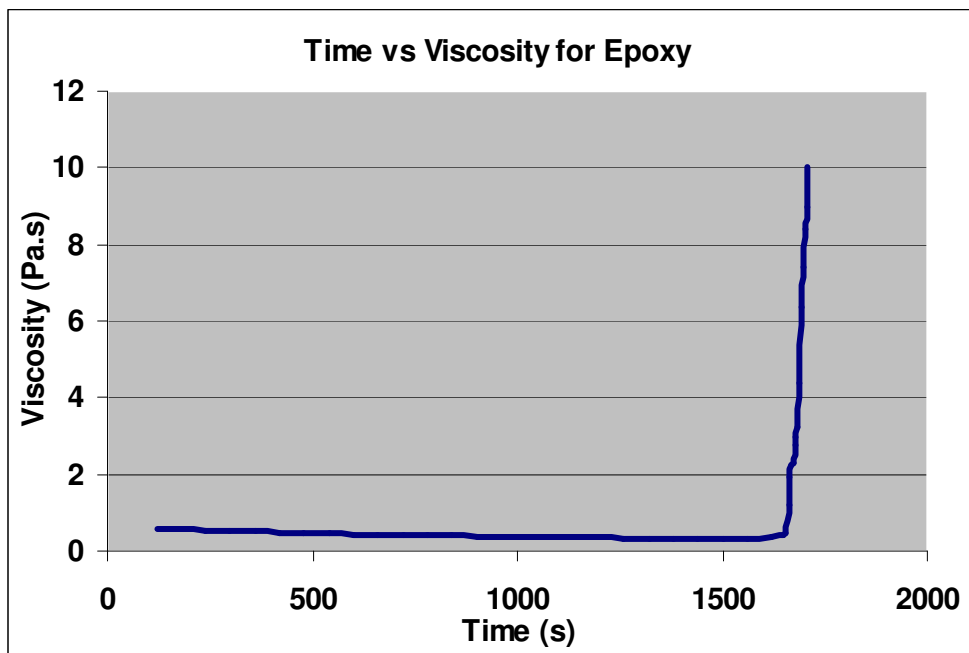
Mixing ratio (suggested by the supplier): 2 Volume A + 1 Volume B (hardener)

With this mixing ratio, the epoxy mixture has a pot life of 30 minutes at room temperature, which means the injection must be done within 30 minutes.

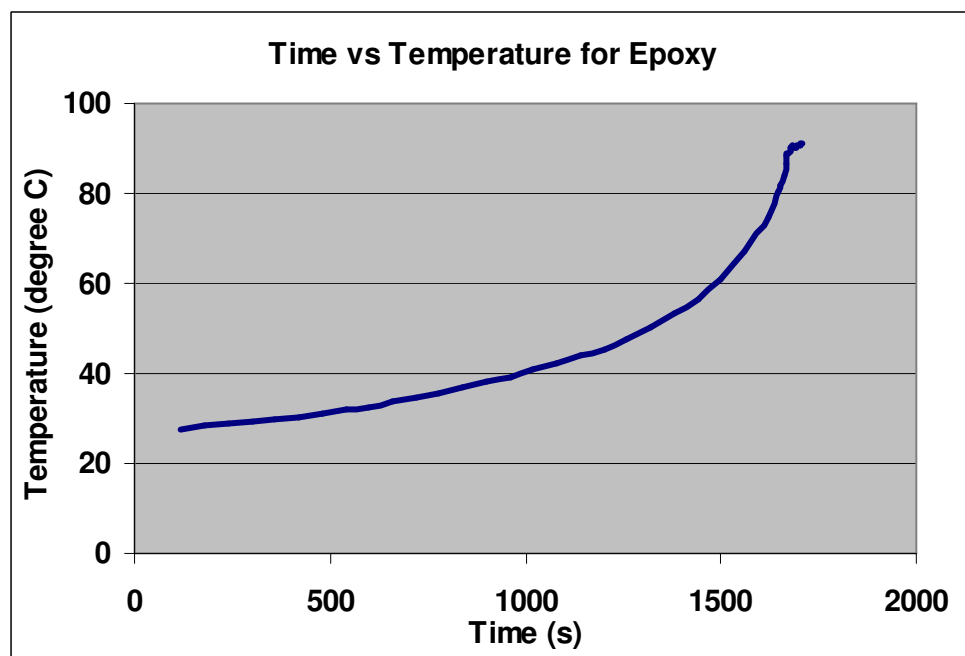
Viscosity:

Viscosity of the epoxy was measured by Brookfield DV-II + Viscometer (with spindle number 6, and a spindle rpm of 100) at room temperature (26°C). The viscosity and temperature values right after mixing up to 30 minutes are given below. The viscosity is ~ 0.6 Pa.s initially, and it decreases to ~ 0.3 Pa.s gradually. The decrease in viscosity is because of the increase in temperature. Since the curing reaction of the polymer is an exothermic one, the released heat causes temperature rise. After gellation starts at $t = 30$ minutes approximately, viscosity increases suddenly (see the figures on the next page).

Viscosity values after mixing:



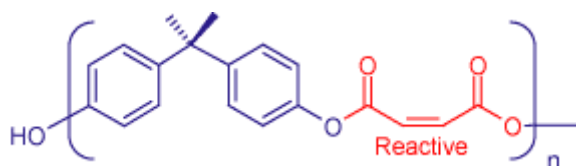
Temperature values after mixing:



A2. Polyester Resin [71]

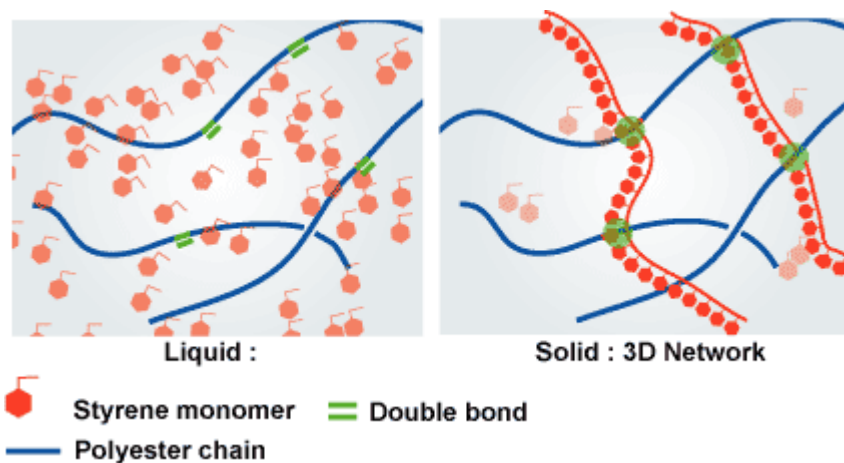
Chemical Structure of Polyester Resin

The unsaturated polyester resins refer to a large variety of chemicals which have reactive double bonds in the polymeric chain. Since it has reactive double bonds, it has the ability to crosslink in the presence of a monomer. Also, it has the ability to act as a diluent by a free radical mechanism.



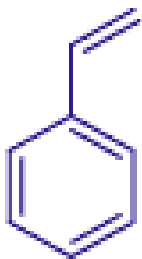
Example of chemical structure [71].

The general crosslinking mechanism is shown on the figure below.



Crosslinking mechanism of polyester resins [71].

The Crosslinking Monomer



In most cases the crosslinking monomer is Styrene introduced at concentrations between 25 and 45 wt%, but other monomers can also be used.

Curing Catalyst

To initiate the curing reaction a source of radicals is needed. In most of the cases organic peroxides are used.

- The first step is the decomposition of the peroxide.
- The second step is chain propagation reaction via styryl radical formation capable to react with a double bond.

The type of the peroxide used determines the kinetic of reaction and is also an important parameter for the "pot life". For cold curing, initiators such as amines or metallic salts are also introduced.

Families of Peroxides

The main families of organic peroxides used for curing unsaturated polyester are:

- Ketone peroxides
- Diacylperoxides
- Peresters
- Hydroperoxides
- Perketals

Ketone peroxides are generally used at room or mid temperature in combination with Cobalt salts(the one we use).

Diacylperoxides like Benzoyl peroxide can be used at room temperature, activated by tertiary aromatic amines, or without promoter at higher temperature (100°C)

Peresters are used at higher temperatures and are preferred in injection and compression molding processes.

Hydroperoxides are used at higher temperatures in injection and compression molding processes.

Perketals: same as peresters.

A3. 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

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 Range = -1.28 to 5.27 mV.

Physical Range = 0 to 100 °C
(corresponding to the end values of -1.28 and 5.27 mV, respectively).

B.2 National Instruments, 200 kS/s, 16-Bit, 16 Analog Input Multifunction Card (NI PCI 6035E) (Reference: <http://sine.ni.com/nips/cds/view/p/lang/en/nid/11915>)

The analog input card is used to record the sensor outputs. 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

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

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

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	0.1Ω 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

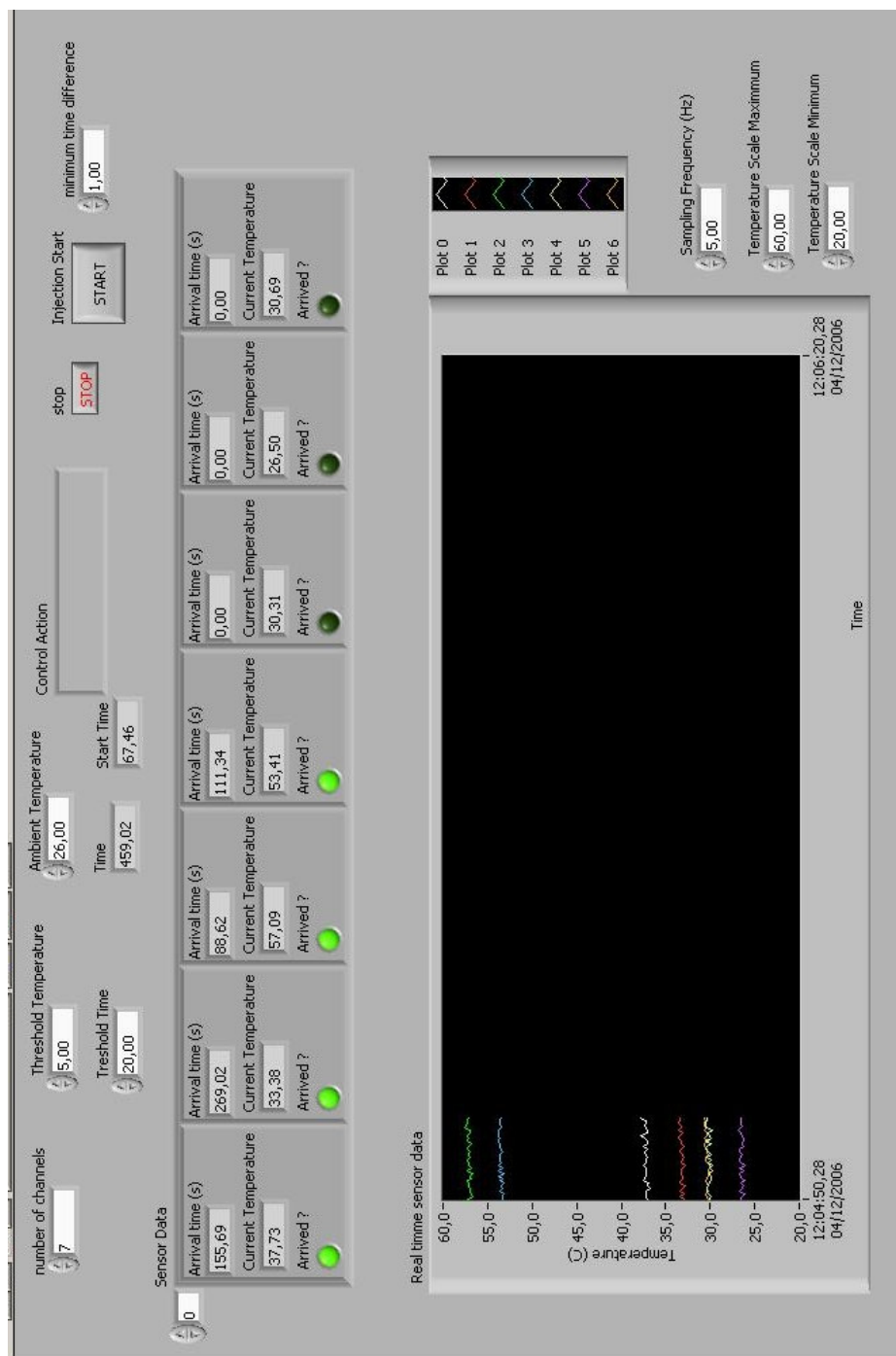
Digital I/O

Number of channels	8
Compatibility	TTL
Power-on state.....	Input (high impedance)

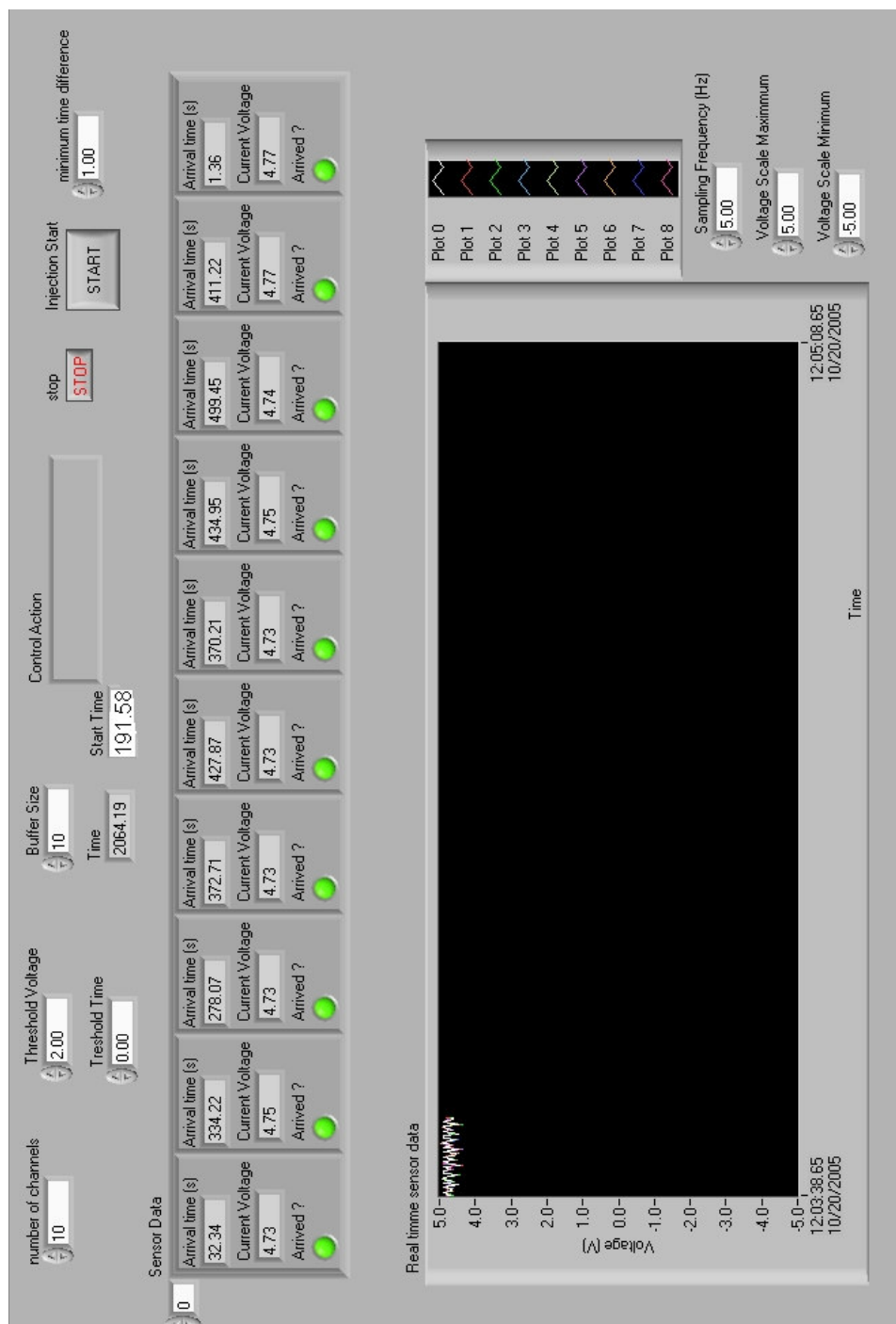
Digital logic levels

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

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



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



B.6 DETAILED INFORMATION ON DAQ PROGRAM

Basics of the Algorithm

The two programs work in the same logic in an on-off principle for the arrival times with a certain threshold. The sensor arrival monitoring and logging algorithms are the same for the two sensor systems. At every time step the program checks for all the sensors, whether the resin is arrived or not. An arrival signal means a value above threshold. This value is temperature for the thermocouples, and voltage for the point-voltage sensors.

However, there are some fundamental differences between the two programs. First of all, in National Instruments NI-6035E Multifunctional DAQ system, the calibration mapping for the J-type thermocouples, which actually returns a differential milli-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 point-voltage sensor configuration obviously does not have a calibration curve.

Another modification for the program is the necessity of getting rid of the noise in the system. The solution developed for this issue is software buffering. We could use the following alternatives for smoothing the signal:

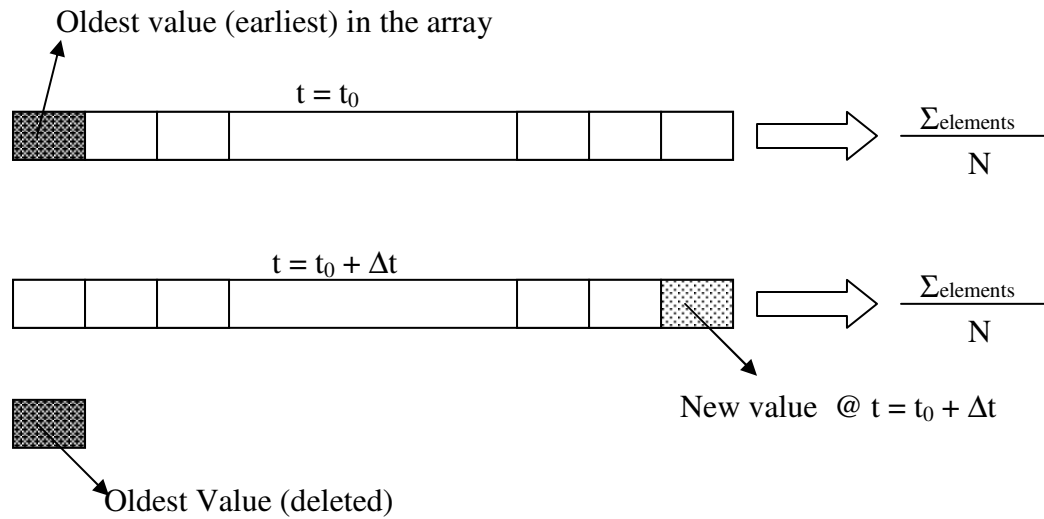
- Complicated analog band-pass filters.
- Digital filters based on frequency domain analysis.

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. A running average array is used to constantly average the samples with the past values. The newest value is

added to the last place in a dynamically allocated array, whereas the earliest value is popped out of the array.

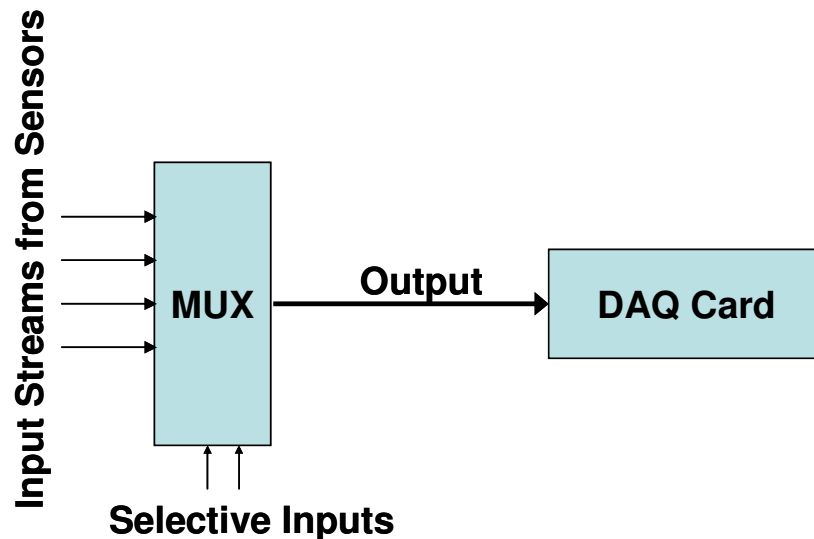
This algorithm is illustrated below:



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.

Multiplexer

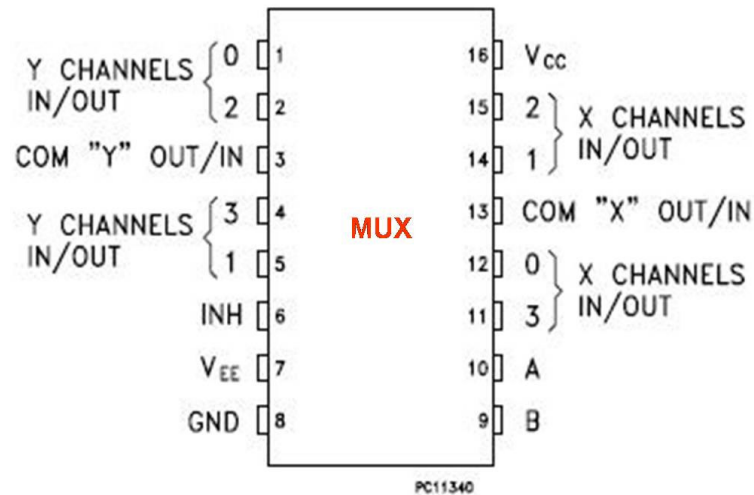
The current DAQ card has 16 single ended analog input channels. This limits the number of point-voltage sensors to 16 for simultaneous sampling. However, by using a 4-channel multiplexer one can increase the number of sensors to $4 \times 16 = 64$. In analog circuits, the multiplexer is a device that has multiple input streams and only one output stream. A 4 channel multiplexer for example, as used in this study, has 4 input channels and 1 output channel. It forwards one of the input streams to the output stream based on the values of one or more "selection inputs" or control inputs. Selective inputs are the inputs that you use to select which stream you want to send to the DAQ system (see Figure below). These inputs are digital inputs which can be sent from the digital I/O of the current DAQ system.



By using such a 4-channel multiplexer it is possible to increase the number of sensors to four times of the available channel number. Since the inputs can be sent to the DAQ card one at a time, there is a delay between the sampling times. The sensors are not exactly simultaneously sampled but the delay between them is insignificant when compared to the 5

Hz sampling frequency for sampling, ordering, displaying and recording the data. For the system with the multiplexer, the DAQ program for the point-voltage sensors is modified by using a sequence structure. The basic of this sequence algorithm depends on sending a selective input at the first sequence and collecting the corresponding sensor data in the second sequence.

As an analog multiplexer M74HC4052 [70] is used which is a dual 4-channel analog multiplexer/demultiplexer.



The above figure shows the pin connections of M74HC4052. V_{CC} and V_{EE} are the “+” and “-” poles of the supply voltage, which has an upper limit of ± 6 Volts. For operation as a digital multiplexer V_{EE} is connected to GND, but since we are dealing with analog signals GND is connected to common ground of the sensors and DAQ system in our case. Since this is a dual multiplexer we use one of the two choices among X or Y channels. If the X channels are to be used for example, the analog signals that come from the four sensors are connected to “X Channels In” pin, and the “Common X Out” pin is connected to one of the channels of the DAQ card. A and B are control inputs for selecting one channel out of four in

each section. The control inputs is sent from the Digital I/O of the NI PCI 6035E DAQ card. The DAQ card has 8 digital I/O lines, two of which can be used for this purpose. Digital outputs are TTL (transistor-transistor logic) outputs, which are either 0 or 5 Volts. The table below shows what control input corresponds to what channel to be sent to DAQ card.

INPUT STATE			ON CHANNEL
INH	B	A	
L	L	L	0X, 0Y
L	L	H	1X, 1Y
L	H	L	2X, 2Y
L	H	H	3X, 3Y
H	X	X	NONE

X: Don't care

The L and H means “Low” and “High” respectively, which represents 0 or 5 Volts for the digital inputs to pins A and B. By changing these values for pins A and B recursively using a “for loop”, every sensor signal is transferred to DAQ one at a time. The INH input in the table above is a switch that disable all the channels when “High”, but as long as you send TTL signals to pins A and B it always stays as “Low”.