Development of an Intelligent Injection System and its Application to Resin Transfer Molding

by

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Abstract

Resin Transfer Molding (RTM) is a procedure in composite material manufacturing in which resin and fibers are held apart until the last possible moment. In this way it can be contrasted with other manufacturing methods where the resin and fiber are combined prior to use. In RTM, unresinated fibers are held within a tool cavity and a differential pressure is applied to a supply of resin so that the resin flows into the reinforcement completely wetting it out. Reinforcements may be made of any fiber and the use of all forms has been reported, from unidirectional through woven or knitted cloths to needled and random mats and fully three-dimensional reinforcement preforms. The resin can be of a very wide range of chemistries and formulations, so long as the basic process requirements are met. Cure times can be from a few minutes to many hours. Resin injection machines vary widely, and production line design can be just as varied.

The focus of this project will be the development of an intelligent injection system and its application to RTM. In order to achieve this, the LabVIEW program will be employed to control pressure and flow rate—the two important parameters of RTM. This system includes an injector, computer, data acquisition boards, electric system and pneumatic system. A number of experiments have been performed to find the optimal application of this system. During the manufacturing of composite parts, all the processing parameters, such as temperature, pressure, flow rate and displacement with respect to time, can be written to a computer hard disk to be analyzed later. All the data acquired during the operation can help us to understand in depth the processing of composite materials and the relationship between process, quality and property.

Résumé

Le moulage par transfert de résine (MTR) est un procédé de fabrication de matériaux composites par lequel des résines et des fibres sont maintenues séparées jusqu'au dernier moment possible. De cette façon, on peut le distinguer des autres procédés de fabrications où la résine et la fibre sont combinées avant leurs utilisations. Lors du MTR, les fibres non traitées avec de la résine sont placées à l'intérieur d'un moule et une différente pression est appliquée à une quantité de résine pour que celle-ci circule dans la fibre. Certaines fibres peuvent être conçues à partir d'autres fibres et leurs utilisations sous toutes formes ont été documentée, du tissage ou tricotage unidirectionnel à différents types de textiles et aux fibres qui sont placées dans un moule dont la cavité intérieure est décrite en trois dimensions. La résine peut avoir différentes compositions chimiques si les exigences de base sont respectées.

Le projet portera sur le développement d'un système intelligent d'injection et son application au moulage par transfert de résine. Pour arriver à ce résultat, le programme LabVIEW sera utilisé pour contrôler la pression et le taux de circulation, deux paramètres importants du MTR. Ce système inclus un injecteur, un ordinateur, un panneau d'acquisition de données, un système électrique et un système pneumatique. Plusieurs expériences ont permis de trouver l'application optimale du système. Durant la fabrication des pièces composites, tous les paramètres d'opération comme la température, la pression, le taux de circulation et le déplacement par rapport au temps écoulé peuvent être envoyés au disque dur d'un ordinateur pour être analysés plus tard. Toutes les données d'opération sont acquises durant le procédé pour nous aider à comprendre en profondeur le processus du MTR et le lien entre les paramètres du procédé et la qualité des pièces résultantes.

Acknowledgments

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Chapter 1

1. Introduction

1.1 General discussion of the intelligent injection system

In recent years, considerable attention has been devoted to resin transfer molding (RTM) for producing low-cost, high quality, and geometrically complicated composite parts. The RTM process principally consists of two steps: the mold-filling step involves injecting a thermosetting resin mixed with a hardener into a net-shaped mold cavity containing a dry fibrous unit, called the preform. The resin-hardener mixture permeates the porous network formed by the fibers, resulting in a saturated preform. In the second step, the fiber-resin mixture is subject to high temperatures that harden the catalyzed resin around the fibers and form the composite part via a cross-linking chemical reaction called the cure process. In the RTM process, mold filling is regarded as one of the most complex and critical stages because it has a great impact on process performance and final part quality. A large number of variables related to the RTM process affect the process and product performance. Important design variables include pressure/flow rate, resin temperature, mold temperature, part geometry, material properties, gate and vent locations, and the number of vents. Major product and process performance measures include process cycle time and void content. The diverse combination of design variables makes the RTM process very complicated. The industrial production process as practiced in today's injection molding industry is based on the interactions between regulation technology, industrial handling applications and computer science [1]. The intelligent injection system is the combination outcome by which the processing parameters and production process are controlled by preinstalled software to achieve the quality requirements.

1.2 Literature review of the intelligent injection system

Research on intelligent injection systems has been diverse for several reasons: First, different processing methods have distinguished requirements on certain processing parameters; second, the diversity of software and the performing hardware; third, the diversity of controller architectures and mathematical numerical simulator models.

Shelesh-Nezhad and Siores [2] developed an artificial intelligent system for obtaining the magnitude of process parameters in the plastic injection molding operation. The system applies two techniques: case-based and rule-based reasoning. Case-based reasoning is used to derive the first trial setting of processing parameters, while the rule-based sub-system suggests a set of corrective actions to deal with possible corresponding variations in molding. This hybrid system reduces optimization time and human expert dependency. Mok, Wong and Lau [3] also developed an intelligent hybrid system, which is used to determine a set of initial process parameters for injection molding based on artificial intelligence techniques, case-based reasoning, hybrid neural network and generic algorithm. This system can determine a set of initial process parameters for injection molding, without relying on expert molding personnel, from which molded parts free from major molding defects can be produced.

Bozdana et al. [4] developed an expert system for the determination of injection molding parameters of thermoplastic materials. This system was developed to handle the relationships between these parameters in order to obtain an effective and rapid molding. The goal of the study was to develop a frame-based, modular and interactive expert system. The selection of the most suitable plastic injection molding machine and thermoplastic material for the given job were the main objectives of this study. In addition, the article provides a method to determine the optimal number of cavities according to the selection strategy used.

Prasad, Yarlagadda et al. [1] developed a hybrid neural network system for prediction of process parameters in injection molding. In their paper, they presented the attempts to develop an artificial neural network system for prediction of injection molding process parameters. Attempts have been made to determine the process parameters that could affect the injection molding process based on the equations governing the filling process. Then the parameters that require the use of trial and error methods or other complex software to determine the process parameters were researched. The two parameters that were predicted from the developed network are injection time and injection pressure. In Prasad's work, the training data were generated by simulation using C-MOLD flow simulation software. A total of 114 data were collected out of which 94 were used to train the network using MATLAB and the remaining 20 for testing the network. Two algorithms were used during the training phase, namely, the error-back-propagation algorithm and the Levenberg-algorithm. The accuracy of the developed network was tested by predicting the injection pressure and injection time for a few engineering components and it was found that the overall error is 0.93% with a deviation of 3.93%.

Nielsen and Pitchumani [5] developed a closed-loop flow rate control system for resin transfer molding using real-time numerical process simulations. Real-time feedback control of resin flow through a fibrous preform during the mold-filling step of resin transfer molding offers an effective means of eliminating fill-related defects in the composite products. This paper explores, for the first time, the use of on-the-fly finite-difference-based numerical solution of the partial differential equations governing the mold filling process in a closed-loop flow control. The numerical simulations are used to forecast system response in real-time, in order to determine the best combination of flow rates at the injection ports so as to steer the flow through target schedule during the process. Nielsen and Pitchumani [7] also conducted research on intelligent model-based control of preform permeation in liquid composite molding processes with online optimization. An artificial neural network trained to use data from numerical process models is used to provide rapid, real-time process simulations for the model-based control. A simulated annealing algorithm, working interactively with the neural network process model, is used to derive optimal control decisions rapidly and on-the-fly. Mogavero et al. [7] developed a nonlinear control method for resin transfer molding. In this paper, the two types of fluid injection that are commonly utilized, constant fluid pressure and constant fluid flow rate control, were analyzed and the focus was on the flow rate control. This paper presents a nonlinear control method for providing constant flow rate RTM processes with a pressure pot solely through the use of a regulator.

Computer simulations of the control examined the effect of various parameters on the ability to maintain constant flow rate. Rectilinear flow experiments were carried out to evaluate the theoretical development. Experimental results were in good agreement with the computer simulation; both computer simulations and experiments showed significant promise for the proposed control methodology.

Lee et al. [8] developed a monitoring and control system for resin transfer process. An advanced control technology in which sensor feedback and knowledge base are utilized was applied to the RTM process. This was accomplished through the development and feasibility demonstration of an intelligent RTM system. A DC-resistance measurement grid system was used to establish the resin state and flow front progression. The resin data was then processed in real time via a PC based controller. The ability for the system to perform control decision/actions, based on sensor data and a knowledge base, was developed into the system. Possibly control actions include variations in localized mold heating, vacuum, and resin flow location/rate/pressure. The feasibility of the intelligent control of the RTM process was demonstrated by experimental results.

1.3 Existing typical intelligent injection systems

1.3.1 The hybrid intelligent system

One of the typical intelligent injection systems is the hybrid injection system [2, 3, 4]. Shelesh-Nezhad and Siores [2] think that the main molding parameters in a thermoplastic injection molding are: melt temperature, mold temperature, injection time and required pressure. An expert chooses the molding parameters according to the material type and molding geometry and then implements them to assess the molding quality. If there is any variation, an iterative corrective action is performed to reach the quality requirements. Expertise and human expert reasoning in injection molding cannot be fitted totally into a Rule-Based Reasoning (RBR) format because experts can not always convert their experiences into a simple rule format. However, a hybrid system, Case-Based Reasoning (CBR) in conjunction with RBR, can more closely model the injection molding process because it is able to adapt previous solutions to current problems. CBR has yielded successful results in different engineering applications, including assembly sequence planning, manufacturing system design, process planning and model-based diagnosis. An expert in injection molding often goes through his previous works to find a molding design similar to the current molding and uses successfully tested molding parameters with intuitive adjustments and modifications as a start for a new molding application. A CBR system performs the same task by retrieving the most similar case to the new case from the case library and uses the modification rules to adapt a solution to the new case. Therefore, a CBR system can simulate human expert strategy in injection molding process design. The sequence of operations in a CBR system is illustrated in Figure 1.1.

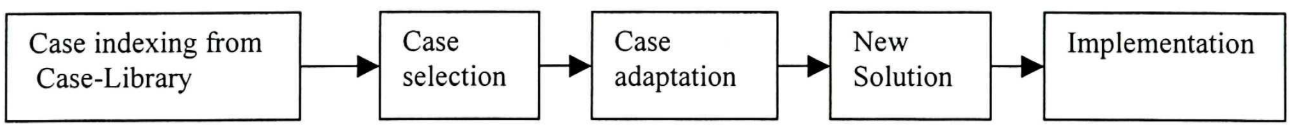

Figure 1.1 The Sequence of operations in a CBR system [1]

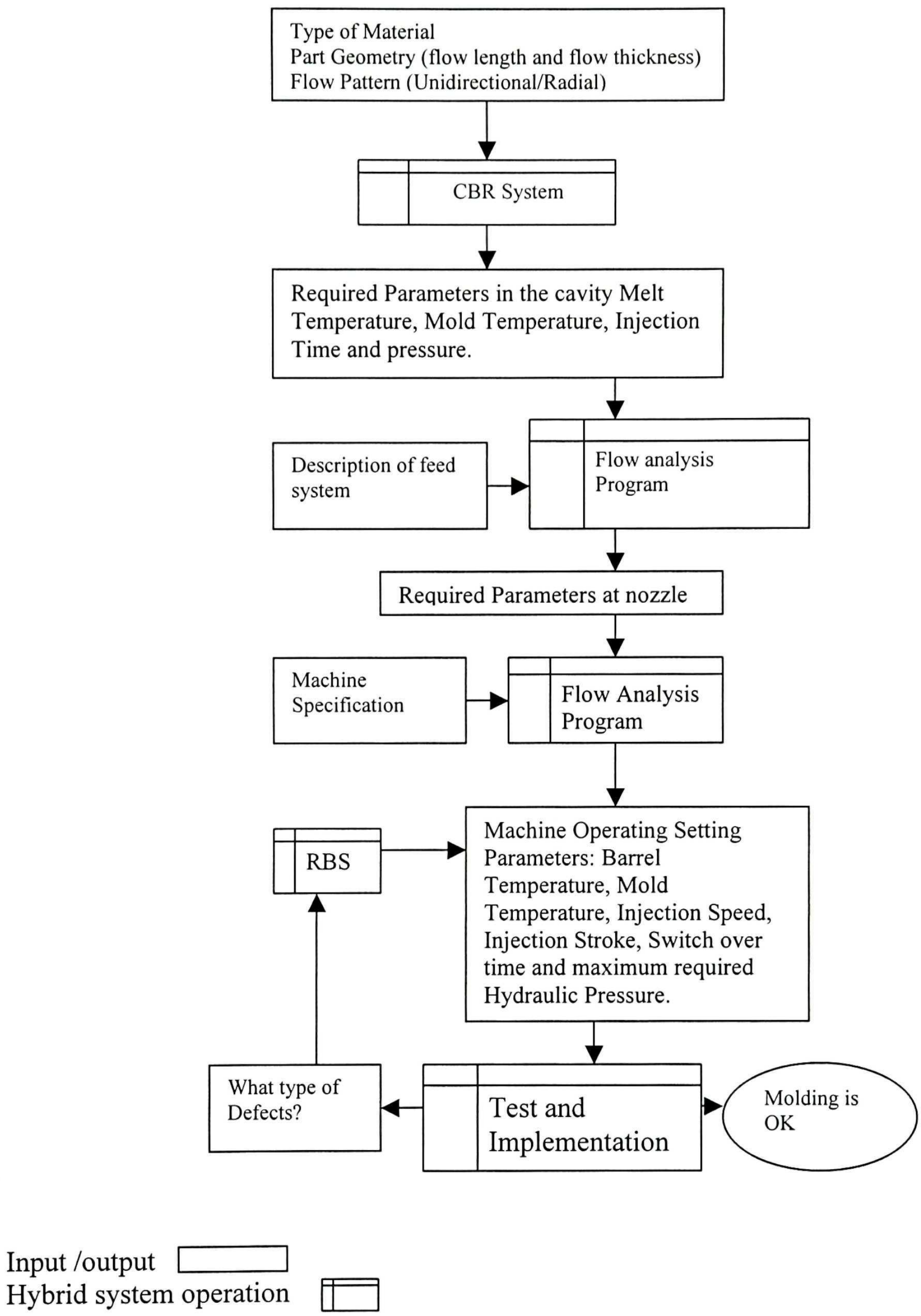

Figure 1.2 Expert System Architecture used for Plastic injection molding [2]

Expertise in injection molding can be formulated into a hybrid system encompassing both RBR and CBR sub-systems. The hybrid system can be used interactively as depicted in Figure 1.2 and includes the following modules: The Case-Based Reasoning sub-system is used to derive the optimum magnitude of process parameters in the cavity according to the type of processing material, flow type and cavity geometry; the flow analysis sub-system is employed to calculate the pressure drop and temperature difference in the feed system to determine the required magnitude of parameters at the nozzle; the post-processor converts the molding parameters into machine setting parameters; the Rule-Based sub-system derives what combination of process parameters must be changed during optimization and deals with possible variations.

1.3.2 Mold based close-looped flow control system in Resin Transfer Molding using real-time numerical process simulations [5, 6, 9]

Nielsen and Pitchumani [5] think that the molding process principally consists of two steps. First, the mold filling step involves injecting a thermosetting resin mixed with catalyst and initiators into a net-shaped mold cavity containing a dry fibrous unit, called the preform. The second step, the fiber-resin mixture is subject to high temperatures that harden the catalyzed resin around the fibers and form the composite part, via a cross-linking chemical reaction, called the cure process. The mold-filling step is critical from the viewpoint of quality of fabrication.

1.3.2.1 Real-time process controller [5]

The closed-loop process controller architecture and its integration with the RTM process is shown schematically in Figure 1.3. At any time t during the process the controller receives as input the actual flow front location, $Y_{act}(t)$, from an online flow sensor and the flow front location, $Y_{des}(t+\Delta t)$, desired at the end of the control interval, $t+\Delta t$. The goal of the controller is to determine the best possible flow rate, q_1, q_2, and q_3 to use at the injection ports of the RTM mold within the control interval time so as to progress the flow front to $Y_{des}(t+\Delta t)$.

1.3.2.2 Implementation of the controller architecture [5]

The closed-loop controller architecture was implemented by Nielsen and Pitchumani [5] on a Lab-scale RTM set up, as shown schematically in Figure 1.3. The injection system used consisted of three Cole-Parmer peristaltic pumps and three lab-built motor controllers to drive the pumps. Each pump was able to provide individually controlled flow rates (q_1, q_2, and q_3) in the range of 0-80 ml/min to the corresponding injection port on the mold. The 203x203 mm (8x8 inch) mold has a 3.2 mm (1/8 inch) thick cavity, and in addition to the three inlet ports, there are two outlets. Plexiglas is used for the top of the mold so that flow front position can be acquired through image analysis. Glycerin was used as the injection fluid in the experiments and its viscosity was determined to be 1100 cps. A CCD video camera placed above the mold and a National Instrument's IMAQ frame grabber card were used to capture images of the mold during the process, as shown in Figure 1.4. The controller architecture was implemented within the LabVIEW environment, while the numerical process model and flow rate determination was carried out in a separate Windows executable program. The entire system was run using a personal computer.

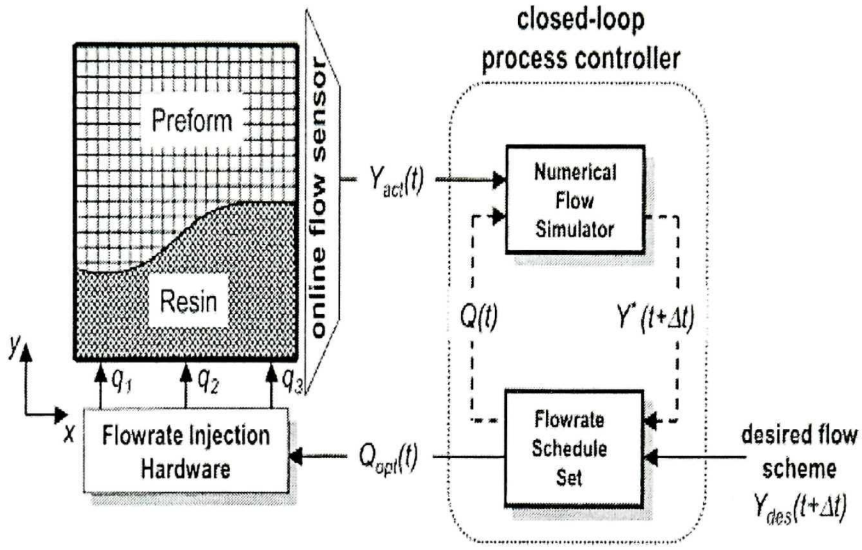

Fig. 1.3 Closed-loop process controller architecture and its integration with the RTM process [5]

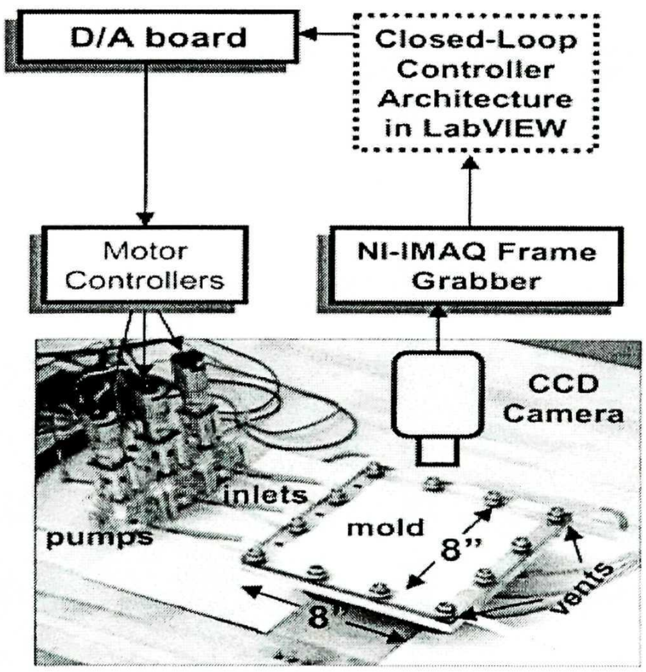

Fig. 1.4 Schematic of the experimental set up used in the controller validation studies, including a photograph of the RTM mold [5]

1.3.3 The nonlinear control method for Resin Transfer Molding [7]

Mogavero et al. [7] think that RTM is a versatile and attractive process for the high volume, high performance, and low cost manufacturing of polymer composites that is gaining prominence in industry. Process control is relevant to several facets of RTM. In most cases, two issues of concern are resin injection and curing. The ability to monitor and react to the changes in mold conditions would greatly reduce the cost associated with the trial and error inherent in RTM.

1.3.3.1 Non-linear injection system set up [7]

Figure 1.5 shows the setup of a RTM system used in the study [7]. The test fluid is placed in a pressure pot, which holds up to seven liters of fluid. For the experiments, the test fluid consists of a mixture of corn syrup, water, and clothing dye, which exhibits very Newtonian behavior. A tube runs from this pot through an in-line flow meter and pressure transducer, and then to the inlet of the mold. The flow rate and inlet pressure are measured along the way. The flow meter and transducer are connected to a computer data acquisition system, which records their responses and also controls the process. A closed-loop control system is then established to provide a constant flow rate by varying the pot pressure. A digital pressure regulator is used to control the pressure in the pot.

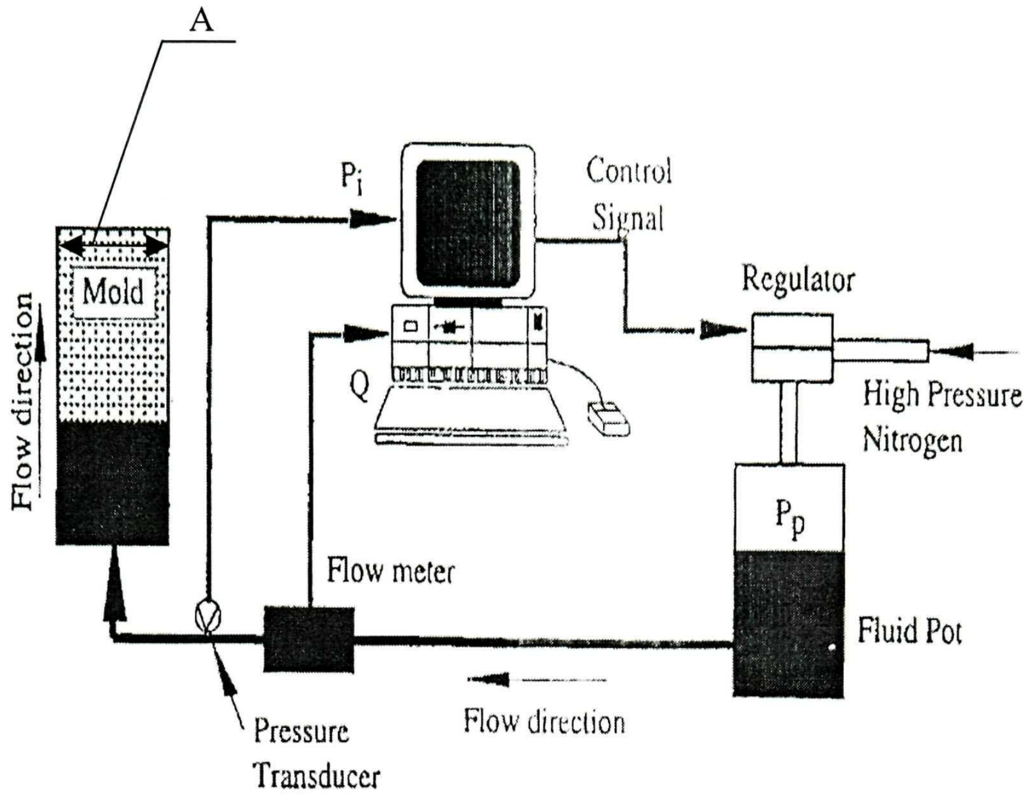

Figure 1.5 Experimental setup [7]

1.3.3.2 Control strategy formulation [7]

In order to utilize the regulator to control the flow rate, an algorithm needs to be developed based on the governing equations of the rectilinear flow experiments. These equations, given below, include Darcy's Law for one-dimensional flow, Poiseuille flow through a tube, and the relationship between the flow rate and the flow front advancement in porous media:

$$Q = \frac{KA}{\mu x}(p_i - p_a) \qquad (1)$$

$$\Delta P = P_p - P_i = \frac{8\mu\Delta z}{\pi R^4} Q \quad (2)$$

$$Q = \frac{dx}{dt} A\Phi \quad (3)$$

Where Q is the flow rate, K is the preform permeability, A is the cross-sectional area of the mold, p_i is the inlet pressure to the mold. p_a is the ambient pressure, μ is the fluid viscosity, x is the length of the flow front through the preform, Δ_P is the pressure drop along the length of the tube, *Pp* is the pot pressure, *R* is the inner radius of the tube, Δz is the length of the tube, and Φ is the preform porosity.

1.4 Discussion of the typical intelligent injection systems

The hybrid intelligent system has the ability to simulate human expert strategies by using and adapting previous experiences. However, several drawbacks of this system have been described by Shelesh-Nezhad and Siores [2]. First, it is an off-line system. The processing parameters recommended by the system cannot be outputted to the injection-molding machine, so it is not efficient and effective. Second, no experimental work was presented in the article to demonstrate its effectiveness, so the reliability of the mathematical model is doubtful as the author assumes that the operating parameters exhibit a linear relationship with the flow length and thickness dimensions. In another typical study [5], the closed-loop flow control in resin transfer molding using real-time numerical process simulations realized the capability of controlling resin permeation in RTM using numerical simulations within the framework of the closed-loop controller architecture. In contrast to previous simulation-based control techniques, such as the neural network model and off-line numerical control architectures, the control architecture presents some fundamental simplicity in design and actual implementation. First, there is no need for proxies to the numerical simulation. Secondly, the framework may be readily applied to other RTM setups and simulation models. Furthermore, the controller derives injection design parameters in real time without the need for off-line process simulations. However, as implied by the title, this system is mostly suitable only for flow rate closed-loop control. In case of the pressure control or a combination control, this system cannot meet the processing requirements. During the cure stage, the system cannot provide the backpressure required during the curing process. With the requirement of thick transparent Plexiglas for the video analysis, this system cannot be used in the manufacture of complex composite parts. All these limitations restrict this system significantly.

Mogavero et al. [7] introduced a nonlinear control method for Resin Transfer Molding. This nonlinear control method was developed to provide constant flow rate RTM processes with a pressure pot solely through the use of a regulator. However, this mathematical model was based on a mold with constant section area, and the author did not mention whether the numerical simulation is still reliable when the model is applied to complex geometrical parts where the section area would be a complex function of flow length.

1.5 Objective of this thesis

As described in the forgoing sections, all of the three typical intelligent injection systems have their advantages and disadvanges and cannot be widely used in the manufacturing process of composite materials. As the first objective of our research, the system should be accurate and flexible; for example, the system should be able to perform pressure control and flow rate control in one process as the manufacturing process requires. Secondly, this system should be able to work with 'real' parts, i.e., independent of mold type, regardless of whether the molds are with or without a transparent cover and how the mold section varies in length. The software LabVIEW demonstrates powerful functions in both numerical simulation and system control as Nielsen and Pitchumani's study [5], and it will be used in this research. The nitrogen pressure regulating method analyzed by Mogavero et al. [7] will be used in this research for its flexibility and easy parameter control. The whole system design must be comparable to those found in the literature. In the following sections, the design of our intelligent injection system will be discussed. All the previously mentioned systems will be considered, and a new LabVIEW control panel and an improvement of conventional flow rate control method will be proposed. After the whole system was developed, the system's applications to Resin Transfer Molding was tested with liquids including water, corn syrup, and two kinds of resin.

Chapter 2

System development

2.1 Theoretical background—Darcy's law

The Darcy's law is the basic equation on which most of the currently available simulation software is based [5,6,7,9]. It was first stated by the French physicist Darcy in the middle of the 19th century while he was studying the flow of water through porous sand beds. The law relates the fluid velocity to the applied pressure gradient:

$$v = -\frac{k}{\mu}\frac{\Delta P}{\Delta L} \qquad (1)$$

where v is the superficial fluid velocity (m/s); k the permeability of the medium (m^2); μ is the fluid viscosity (Pa s); ΔP the pressure difference (Pa) and ΔL the length of the porous specimen (m).

In RTM simulations, the flow of a resin through a fiber bed is then modeled as the flow of a fluid through a porous medium by Darcy's Law. Although the law was formulated for saturated flow in which the fibrous preform is already impregnated with the test fluid and 'new' fluid replaces the already present one as it flows through the material, it has already been successfully applied to mixed saturated-unsaturated flows as well. The main restrictions for the applications of Equation (1) and Equation (2) are that the fluid has to be Newtonian and the Reynolds number of flow has to stay low (low fluid velocity). However, the fluid velocity must not be allowed to become too low. Because in that case the capillary pressure can become more important than the applied pressure gradient.

In general the law is expressed in 3D as

$$\bar{v} = -\frac{[k]}{\mu}\nabla P \quad \text{or} \quad \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = -\frac{1}{\mu}\begin{bmatrix} K_{xx} & K_{zy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}\begin{bmatrix} \partial P/\partial x \\ \partial P/\partial y \\ \partial P/\partial z \end{bmatrix}$$

(2)

where $\bar{v}$ is the velocity vector (m/s); is the permeability tensor (m^2); ∇P is the pressure gradient (Pa/m); is the resin's viscosity.

The Darcy's Law has two important constants k and μ which cannot be controlled [19]. What we can control is the ∇P and flow rate. According to Darcy's Law, in order to increase fluid velocity v, the pressure difference, ∇P, must be increased and in the opposite case, the pressure difference should be reduced. In our research, this relation between pressure difference and fluid velocity is used to control the resin velocity, i.e., the resin flow rate.

2.2 Open-looped pressure controller architecture

The cavity pressure during injection molding is an important variable that affects the final product properties such as shrinkage, warpage, and final dimensions. Adaptive control, as discussed by Gao et all [10], are widely used to control this pressure in the process of injection molding. Adaptive control can be divided into two groups: self-tuning control, and model following control. The model following control for characterizing accurate pressure control was selected in this project.

The pressure controller architecture is shown schematically in Fig. 2.1.

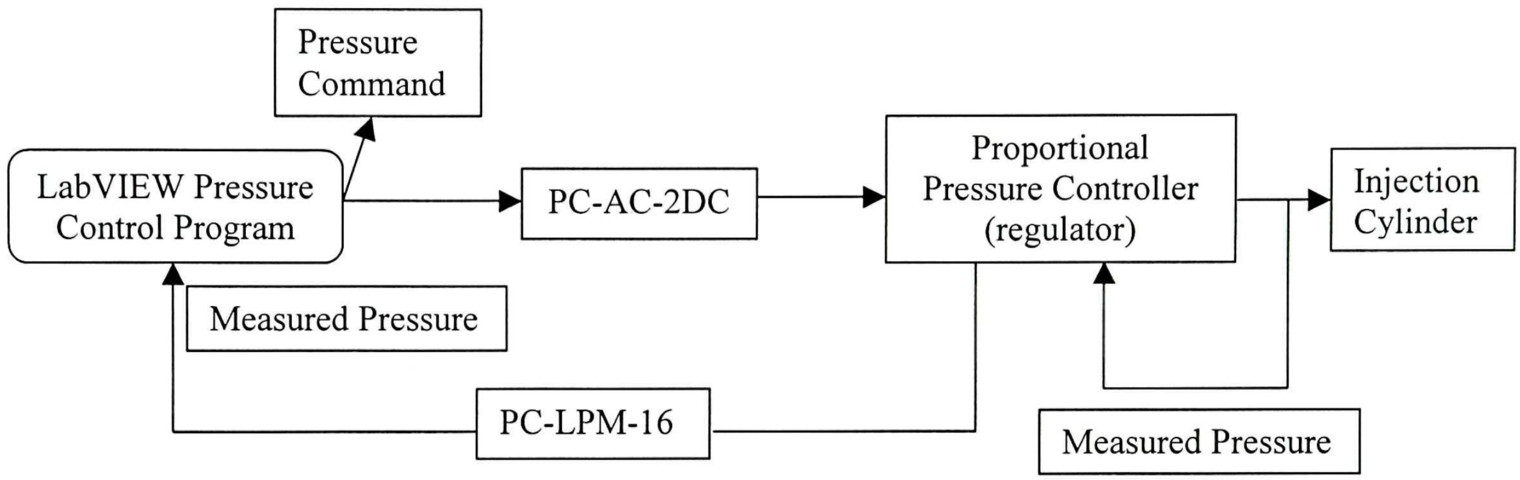

Figure 2.1 Diagram of the Pressure Control Process

In the pressure control model, the pressure value will be output linearly or according to whatever mathematical model the user input into the program from initial value to final values to a PPC valve to regulate the air pressure exerted on the injector piston.

As can be seen from the flow chart of Figure 2.1, the pressure exerted on the cylinder piston can be varied flexibly by a pressure command. However, if pressure is integrated with the flow rate controller, the user would not have to reply on the experts' experience, because the flow rate control will automatically adjust the pressure based on the needs of the required flow rate and display the real time pressure value during the operation.

2.3 Close-looped flow rate controller

2.3.1 Literature review of flow rate control

The flow rate controller adopted by previous researchers can be divided into three classes depending on their corresponding setup. The first is the off-line controller used in the expert system, as used in [1,2,3,4], which is used mostly for deciding the initial parameters. Then those optimized parameters are entered into the injection system as the processing parameters. From this point, real time control cannot be achieved. Moreover, the accuracy of these systems is dependent on the system database. As discussed before, the injection molding process is a very complex process, and it is very difficult to establish the correct relationships between the process parameters. Little convincing evidence has been shown in the articles previously published with this system [1,2,3,4].

The second controller is the intelligent mold-based closed-loop flow control [5,6]. In contrast to the preceding expert systems, the control architecture in [5,6] presents certain fundamental simplicities in design and actual implementation. There was no need for proxies to the numerical simulation, and the controller was shown to derive injection parameter designs in real time without the need for off-line process simulations. However, this system does have a strict requirement for the layout of the mold and all the experiments have been based on a special case: a 203x203 mm (8x8 inch) transparent plate mold with 3 inlets. The cover of the model must be transparent so that the flow data can be acquired from a camera and then analyzed by numerical simulation software. If the mold section is non-regular or without transparent cover, then the system will not be practical. This kind of cover usually has a relatively low bending stiffness. This can lead to a non-uniform cavity thickness, and thus to incorrect measurements. To counter this problem a metallic frame is often used and is placed on top of the transparent half to enhance its bending stiffness. However, this frame will partially obstruct a clear view of the flow front, and thus makes data reduction more difficult. Another disadvantage of the traditional 2D set-up is the fact that the actual data processing takes a lot of time. The pictures taken from the camera have to be digitized and transferred to a computer.

The set-up in [6] adopted a sensor plate to detect the flow front (Figure 2.2). The sensors are located on straight lines at 0, 22.5, 45, 67.5, 90, 180, 270. In the middle of the plate the injection gate can be seen. All the sensors and pressure transducers are connected to a Windows NT based Pentium 233 MHz PC by means of a data acquisition system that consists of National Instruments interface cards.

The third class features a nonlinear control method [7]. In order to utilize the pneumatic regulator to control the flow rate, an algorithm was developed based on the governing equations of the rectilinear flow experiments, which include Darcy's Law for one-dimensional flow, Poiseuille flow through a tube, and the relationship between flow rate and the flow front advancement in porous media as discussed in the introduction. For this system, computer simulations of the algorithm were done to examine the effect of various parameters on the performance, and rectilinear flow experiments were carried out to validate the theoretical development. The experimental results agreed with the general trends that were discovered in the computer simulations. This initial study showed that a constant flow rate could be maintained through the use of a computer controlled pressure regulator. However, this mathematical model is based on very simple cavity with non-variable section. As shown in Figure 1.5, if the cross section A of the mold varies with mold length, the dynamic modeling has to be changed in order to apply to a different mold. It would be more difficult when the cross-section to length function is unknown.

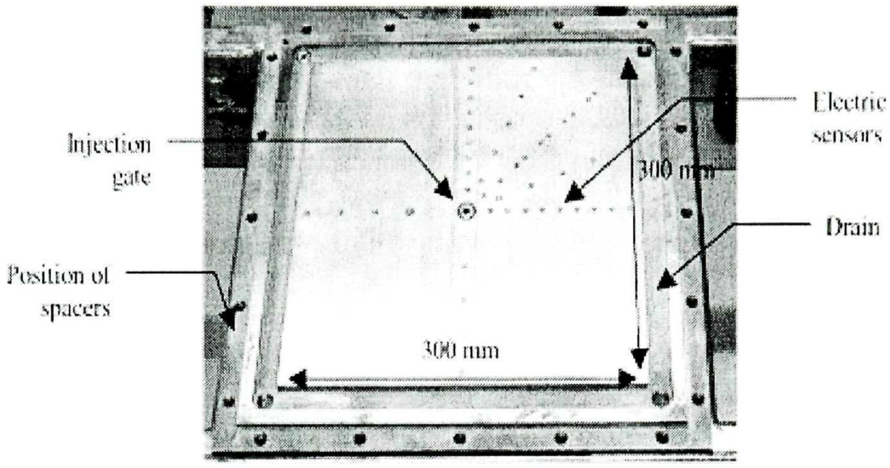

Figure 2.2 Sensor plate used by Hoses et al. [11]

2.3.2 The flow rate controller in this research

The requirements for the flow rate controller in this research include three important factors. First, the controller should be adapted to most molds currently used in the laboratory, regardless of whether they are with or without a transparent cover and how the mold section varies in length. Second, the system with the flow rate controller should be as flexible as possible. For example, the system can toggle between pressure control and flow rate control so that the pressure control can be exerted whenever necessary, such as the packing pressure needed during the curing period. Third, the achieved flow rate control should be as close as possible to the desired flow rate.

In our research, flow rate control is achieved by controlling the air regulator of the pneumatic system according to the comparison result of achieved flow rate and desired flow rate set before operation or during operation. Please refer to Figure 2.3 for a diagram of the control process. The flow rate will be linearly output from initial value to final value with respect to the time during each time interval. The output flow rate will be compared to actual flow rate value calculated by flow rate calculation module. The comparison of results will be used to increase or reduce pressure at the set rate on the control panel.

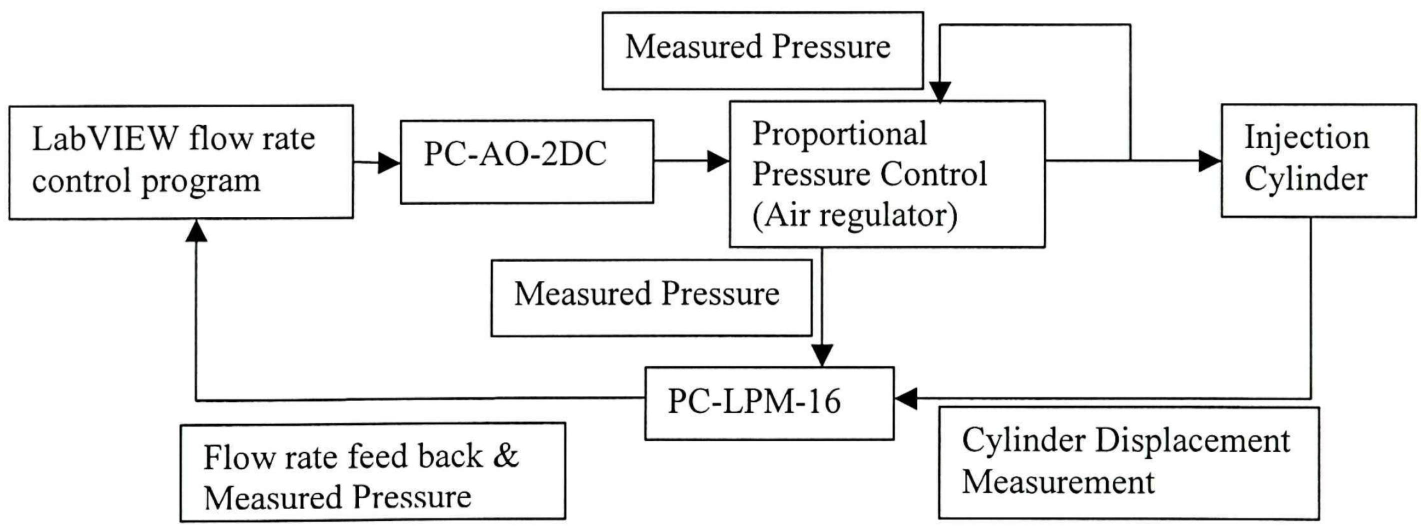

Figure 2.3 Block Diagram of the Flow Rate Control Process

2.4 Software development

LabVIEW is a graphics programming language that has been widely adopted throughout industry, academia, and government labs as the standard for data acquisition, instrument control software, and analysis software. As noted in the controller architecture in Figure 1.4, experimental setup [5], at every step during the control, the numerical flow simulation model was used to explore different combinations of flow rates at the inlet ports, and based on their simulations, the best flow rate combination was chosen for steering the flow front during the control interval. The controller architecture was implemented within the LabVIEW environment, while the numerical process model and the flow rate determination were carried out in a separate Windows executable program. LabVIEW streamed the present and desired flow front to the executable program, and after the simulations were completely stopped by the t_{max} condition, the executable streamed back the best combination of flow rates to use in the process.

Programs in LabVIEW are called 'virtual instruments' because they are designed to appear as actual instruments. A VI has two views: a 'front panel' and a 'block diagram'. The front panel acts as the user interface. The buttons, digital controls, indicators, and graphs are shown on the front panel as the physical instrument. The diagram shows the actual executable program, written in LabVIEW's graphics programming language, 'G'. Unlike languages such as Fortran or C++ that use lines of text, G uses icons and flow chart wiring to evaluate equations, execute loops and control data manipulation. Due to its visual nature, G is very user friendly.

The control software in our project is programmed with LabVIEW. The front panel in this program is called the "Injection Control Panel".

2.4.1 The Injection Machine Control Panel structure

Please refer to Figure 2.4 for 'Injection Control Panel'. The upper part of the "Injection Control Panel" on the monitor is divided into three boxes. The left upper box show the processing parameters set by the operator. The extreme left number represents the processing stage sequence by which the program reads sequentially the process parameters from the control panel. The parameters at each stage can be set by the user before manufacturing, and they can also be reset during the manufacture process as long as the program still has not completed the stage before which you are wishing to reset the parameters. The Boolean switch in the second column controls the process nature of this stage, i.e., whether the system will perform a pressure control or a flow rate control. The corresponding initial value and final value of pressure control or flow rate control in this stage should be entered in the next two columns. In the last column, the duration time of this stage is entered to control the processing time. The program will implement stage by stage under the control of the parameters set by the operators. When the last stage is finished, the program will stop automatically, indicating the sign 'TEST COMPLETE' in the left lower control box.

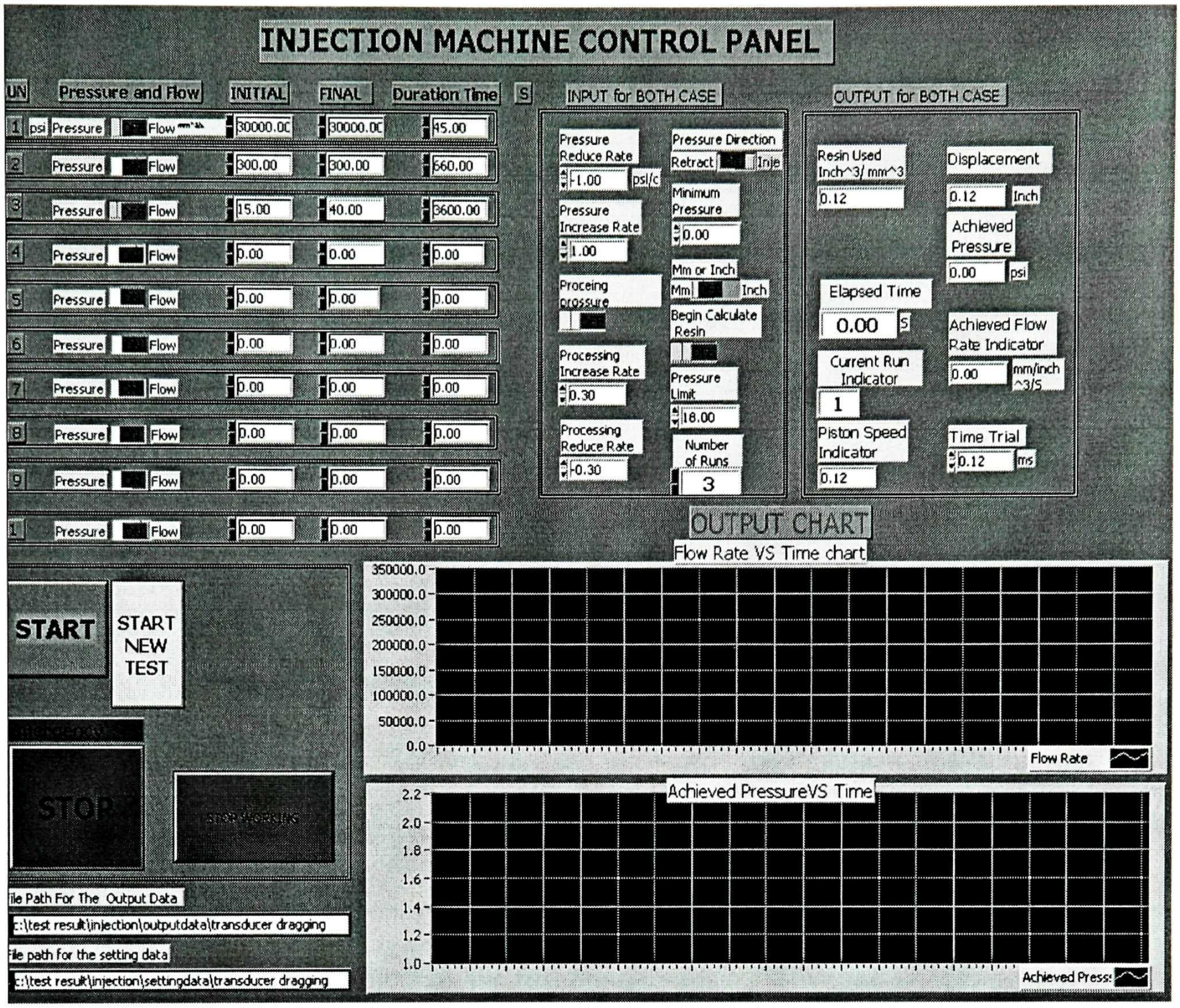

Figure 2.4 Injection Machine Control Panel

In the upper middle box are the input parameters that are essential to the material processing. The pressure reduce rate and pressure increase rate controls the pressure increment during every control interval. For flow rate control, if the achieved flow rate is smaller than the desired flow rate, then the pressure will be added up to an increment described as the pressure increase rate. The reverse is also the case. The lower two parameters in this column, processing increase rate and processing reducing rate, have the same physical meaning as the two upper parameters except that they usually have a relatively smaller value. The smaller values generally produce a smooth flow rate change, however, a longer time to reach the desired flow rate. These four pressure-changing rates can be set before operation or during operation by pushing the arrow button or entering a new value on the keyboard. When the 'Processing pressure-changing switch' is toggled to the 'on' position, the processing changing rate will take effect at the next control interval. The processing pressure changing rate can be adjusted to make the balance between the speed to achieve the desired flow rate and changing the flow rate more smoothly.

The first switch in the second column in the upper middle box is used to control the piston moving direction when there is no manual control level. A minimum pressure parameter is set before or during the operation to provide the system with a minimum pressure to assure the initiation of the process, especially in pressure control. For example, when the set pressure is low and cannot even move the piston, the minimum pressure can be set to start injecting the resin into cylinder. When the system pressure is less than the given minimum pressure, a red sign will be trigged in the upper right box. Conversely, the maximum pressure parameter is set to protect the experiment from a pressure limit. For example, during a flow rate control, the system increases the pressure to achieve the desired flow rate; however, the pressure can warp the fibers at a certain pressure point. With the maximum pressure parameter, the pressure will not continue to increase when it gets to the maximum pressure point, instead the process comes under constant pressure control at the value of maximum pressure at this stage. The 'mm or inch' switch button is toggled according to user requirements to have the experiment results in Metric or Imperial units. The 'Number of Runs' digital control is used to stop the whole process after the stages set by the user has been completely finished. The horizontal switch 'begin calculate resin' button is used to calculate approximately the amount of resin used in the experiments and the button should be clicked by user observation as soon as the resin flow leaves the cylinder.

The digital indicators and control LED in the upper right box are used to show the process progression. 'Resin Used' digital indicator in the left column is used to display the approximately amount of resin used in the experiment. The minimum control LED shows a signal if the Minimum pressure is triggered, i.e., if the processing is in the state of minimum pressure control. This case may also be inferred from the experimental results. The elapsed time shows the real system time since the 'start' button was pushed. The time indicator helps one to record and understand the results of the experiment. The 'Current Run Indicator' shows at which stage the program is so that the operator can adjust some of the parameters by hand according to the actual processing case. For example, the operator may wish to switch the 'processing pressure changing rate' button when the program progresses from the flow rate increasing stage to the flow rate stable stage to achieve a steady flow rate. 'Piston Speed Indicator' shows a real time piston speed. The 'Displacement' indicator shows exactly the real time piston position. In the last stage, the displacement indicator can help the operator to decide where to exert the packing pressure by clamping the resin exit line. 'Achieved pressure' indicates the real time pressure in the system. The 'Achieved flow rate' shows the user the achieved real-time flow rate value in the experiment. The 'Time Trial' is actually an input parameter, which is located here for the reasons of space and layout of the control panel.

The key control buttons and indicators are located in the lower left box, which includes the 'START' button, 'EMERGENCY STOP' button, 'STOP WORKING' button, 'START NEW TEST' button and two square LED indicator ('Pressure Limits Exceeded' and 'Test Complete'). The 'Emergency stop' button will stop all the program model inside the extreme outset While loop within a control interval and restore the PPC output pressure to 0 immediately. The 'START' button is used to start the program. 'STOP WORKING' and 'START NEW TEST' are a couple of button with opposite function. After one process is finished, 'STOP WORKING' button can be clicked to stop the whole program including the extreme outset While loop; however, 'START NEW TEST' button can be clicked to start a new process. After 'START NEW TEST' button is clicked and the processing parameters are re-entered, click on the 'START' button to start a new process. The lower part below this box comprises the three file names and their paths to which the processing data will be written. Five processing parameters are written to 3 files and the file names should be set for every experiment. All of the files can be opened and processed by Microsoft Excel and analyzed later.

The lower right area is the chart display area for the real time flow rate track, achieved pressure, piston displacement, and piston speed, so that the operator can monitor the real time process and make processing modifications correspondingly.

2.4.2 Introduction to the program

The whole program is constructed inside a While loop which keeps running until the Boolean value wired to its conditional terminal is 'FALSE'. The next inside layer is a sequence structure that executes subdiagrams sequentially. The first structure is in a ready-to-run state once the program is opened. The program proceeds into the second structure as soon as the 'START' button is pushed. The second structure is the main structure of the program. A While loop just next close to the second structure is used to contain most functional modules, which include the flow rate calculation module, the pressure control module, the flow rate control module, the elapsed time module, and the used resin calculation module. The iteration terminal of this While loop records the number of times the loop has executed so that the program can be finished automatically. The modules which will be called by the main program but not included in the second layer structure include Global Variable module, Displacement module, Value PPC to 0 module and Calibration module. These are described in the next sections.

2.4.2.1 Calibration module

The calibration program is an independent subprogram and has been developed to allow the user to easily calibrate or recalibrate an injection system. This subprogram provides the necessary parameters to calculate displacement in the Displacement module. When running this subprogram, the user is prompted to set the piston at an arbitrary position and press OK. At this stage, the voltage signal is written to constant 1. The recommended piston position is the piston start point inside the cylinder, i.e., the zero position. The user is then prompted to displace accurately the piston to a known distance, enter the distance and press OK again. At this stage, the voltage signal is written to constant 2. This gives the program a second position and a displacement. The recommended position is when the outer face of the piston is at the same level with the edge of the cylinder, so that the displacement used in the calibration can be easily and accurately measured. Then the user is prompted to set constant 3. In this program, constant 3 is equal to constant 1. This calibration method can be used to measure all the displacement by the voltage signal from the linear resistance transducer (LRT).

Note: to change calibration settings so that they become the default when the test program is started, the changes must be saved.

2.4.2.2 Global variable module

The Global Variable module is simply a window to or from which the global variables can be written or read. Constants 1, 2, and 3 are used by the Displacement module to calibrate the reading of the piston's movement.

2.4.2.3 Displacement module

Displacement module is an independent subprogram that will be called flow rate calculation module and provide real time piston displacement. The program receives the voltage signal of an LRT and the signal is converted to the piston displacement by a formulation based on the embedded formulation. The piston displacement is calculated with the below equation:

$$PD = \frac{DS - C_3}{C1 - C2} \times DC$$

where, PD is the calculated piston displacement, DS is the displacement voltage signal from displacement transducer, DC is the displacement constant corresponding to the displacement signal difference between C_1 and C_2. C_1, C_2 and C_3 are voltage signals representing constant 1, 2, 3, whose physical meaning have been described in Section

2.4.2.1 Calibration Module. The output unit can be toggled between metric and imperial by pushing the switch on the control panel.

2.4.2.4 Value PPC to 0 module

This subprogram is an independent program and is used to restore the PPC output pressure to zero by outputting a single value zero to an analog output channel to control the PPC valve at any case.

2.4.2.5 Elapsed time calculation module

This module is designed to calculate the elapsed time since the program has begun to run. It provides a timer to allow the user to monitor the whole process. For example, the user can know the exact time and stage at which the program is running by reading the time and the current running number control indicator on the control panel.

2.4.2.6 Flow rate calculation module

The flow rate is surrounded by a While loop just next to the second sequential structure (see Figure 2.5). With Emergency Stop and Synchronous local variable, this module can be held synchronous with the other subprograms. Flow rate has the same physical meaning as the piston speed except for the multiplying factor of the piston section. Therefore, the calculation of flow rate is based on the calculation of piston speed. The piston speed is the displacement difference divided by the time difference during a data acquisition interval for this module inside the while loop.

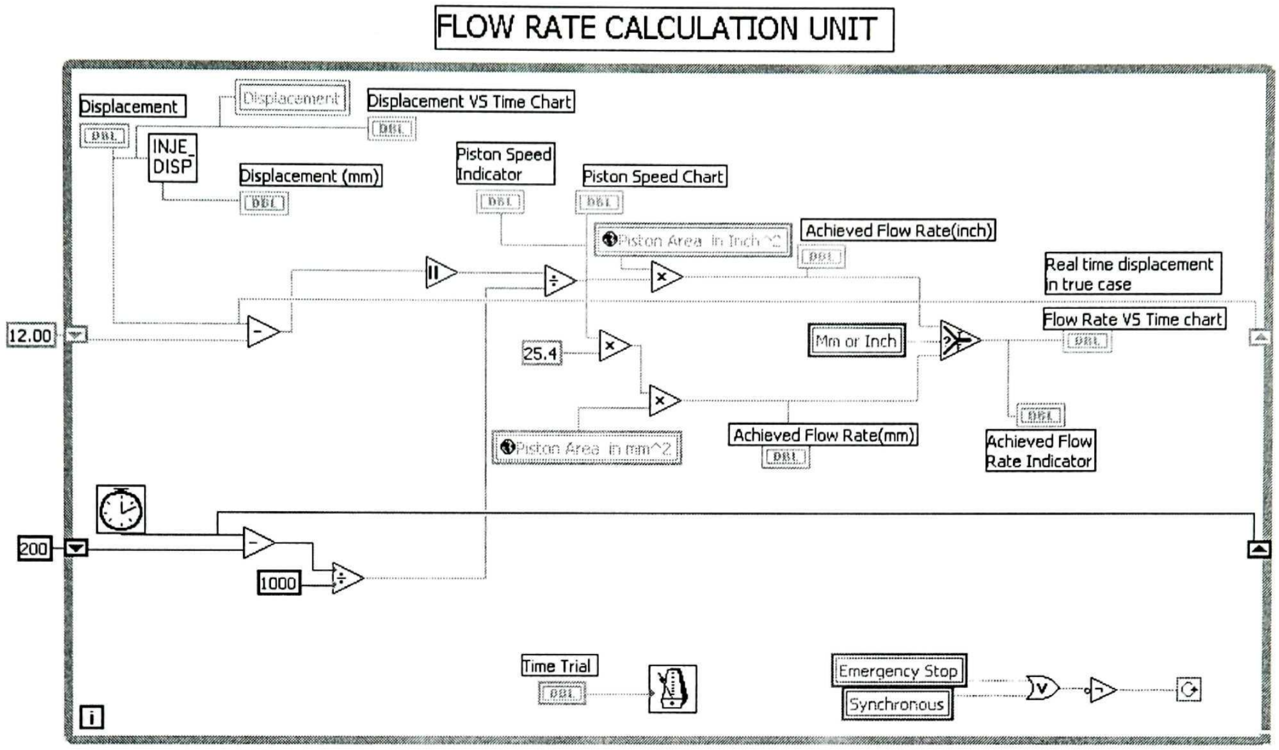

Figure 2.5 Diagram of flow rate calculation module

The flow rate calculation module provides the flow rate data for the data comparison in the flow rate control module and for the flow rate chart on the Front Panel during the whole process.

2.4.2.7 Pressure control module

The Pressure control module and the flow rate control module are two cases of the case structure inside the While loop just next to the sequential structure. The pressure control module is at the same level as the flow rate calculation module; however, the achieved flow rate data is calculated by the flow rate calculation module, then sent to local variable, and then read by pressure control model. There is one subprogram surrounded by a While loop representing pressure control and flow rate control module separately (See Figure 2.6 and 2.7).

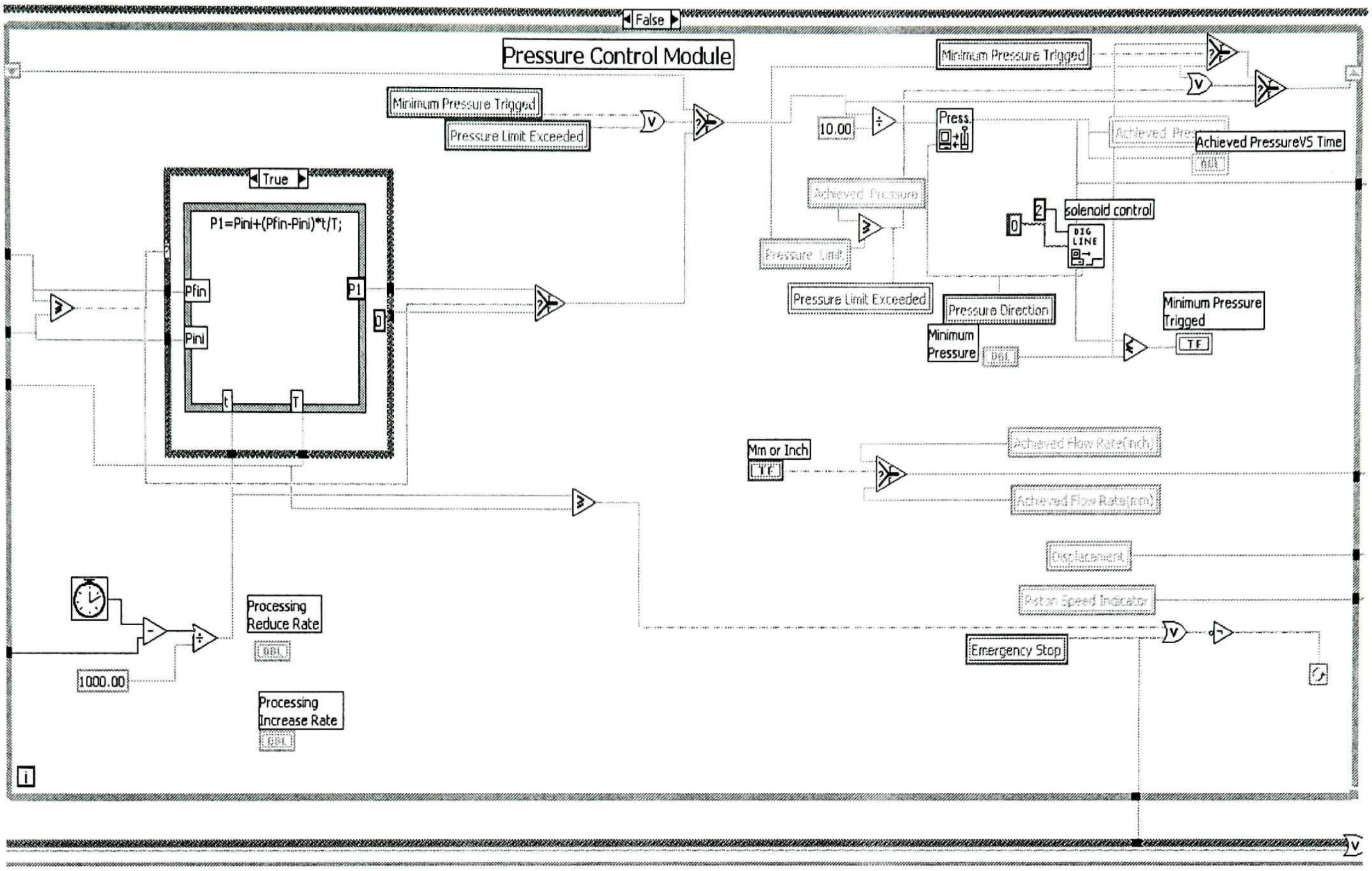

Figure 2.6 Diagram of Pressure Control Module

The pressure control module is the false case of the case structure inside the sequence structure. During this stage, the initial value, final value and duration time are inputted into the formulation node, where the pressure value will be linearly output with respect to time from initial value to final value. The outputted values are then sent to the PPC valve to regulate the air pressure. When the pressure is less than the minimum pressure, the output pressure value will be toggled to the minimum pressure. When the pressure is larger than the maximum pressure, the outputted pressure value will be switched to maximum pressure.

2.4.2.8. Flow rate control module

The flow rate control module is the true case of the case structure. When the Boolean value in the second column in the upper left box was set as true at one stage, the program will be in a flow rate control module. The initial value and final value of flow rate and the time duration are read into the case structure. The flow rate will be linearly output from initial value to final value with respect to the time during the set time duration. The outputted flow rate will be compared to actual flow rate value calculated by flow rate calculation module during every control interval. The compared result will be used to increase or reduce pressure at the set rate on the control panel to reach the desired flow rate. The maximum pressure and minimum pressure have the same function as in the pressure control module.

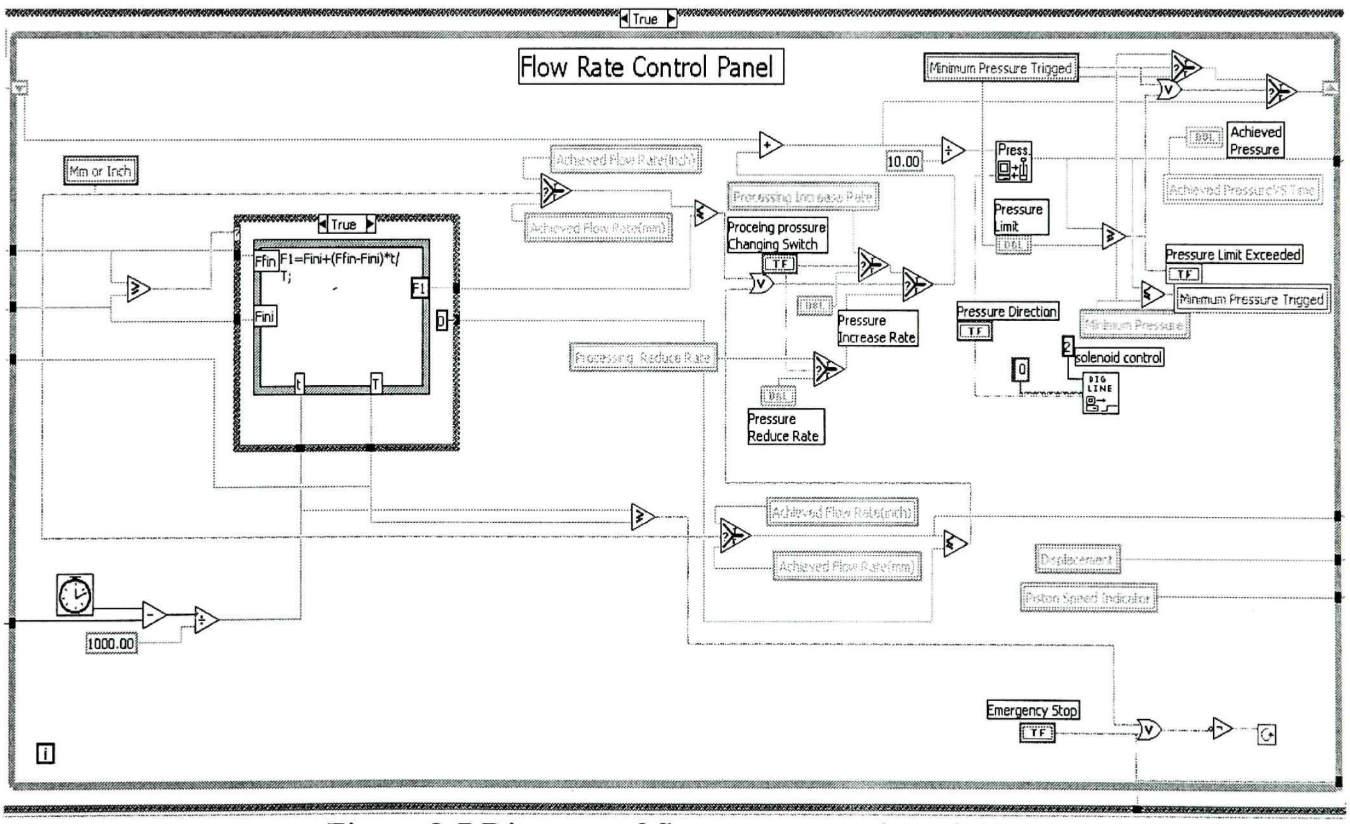

Figure 2.7 Diagram of flow rate control module

2.4.2.9 Used resin calculation module

This module is placed outside of the case structure and is at the same level as the case structure, so that the used resin volume can be calculated during the whole operation (See Figure 2.8). The used resin volume is the displacement of the cylinder multiplied by the inner section of the cylinder. This module begins to calculate as soon as the appropriate button is pushed on the control panel.

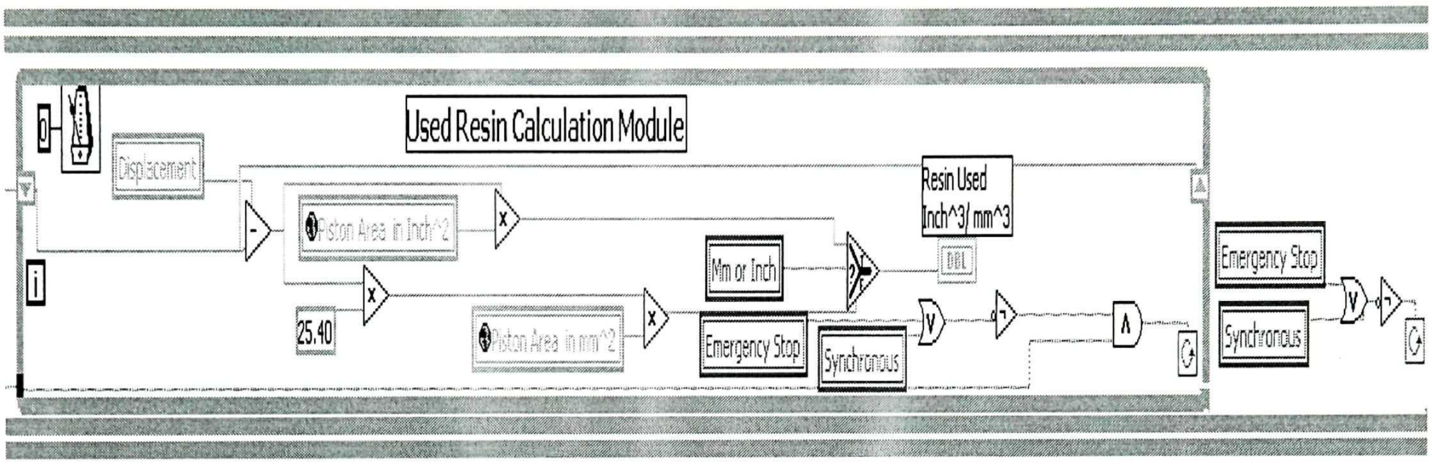

Figure 2.8 Diagram of used resin calculation module

2.5 System hardware units

The intelligent injection system integrates the Radius 2100 injector with an air pressure control system of a testing device for bicycle component made by Leong [16]. Modifications have been conducted to make the air pressure control and data acquisition system work with two sets of apparatus.

2.5.1 Radius 2100cc RTM Injection Cylinder

The Radius 2100cc RTM injector is a pressure controlled system (maximum pressure of 8.75 kg/cm2 (125 psi), designed to inject single component or pre-mixed multi-component resin systems. Displacement of resin from the delivery cylinder is achieved by a pneumatically actuated piston. The resin delivery cylinder is wrapped with a silicon pad heater capable of achieving temperatures up to 350° Fahrenheit. All components that come into contact with the resin are constructed from aluminum that is hard anodized to improve durability. Additional components of the injector include a cylinder heater jacket and injection line heater. The main power control, heater controls, and temperature monitors and the delivery cylinder remaining volume indicator are housed in a control box. Separate illuminated heater on/off switches provide power to the heater jacket and injection line heater via PID controllers which monitor and regulate temperature. Control of the delivery cylinder is through a 4-way, lever operated, pneumatic valve mounted on the cylinder trunnion block.

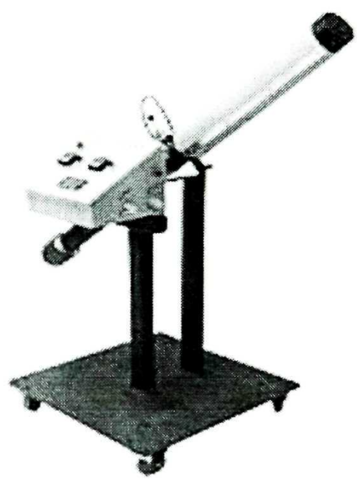

Figure 2.9 The Radius 2100cc Injector

2.5.2 The pneumatic element

The pneumatic element is responsible for converting the electronic requests from the program into applied forces acting on the resin inside the cylinder. This element comprises a solenoid valve, a small reservoir, a proportional pressure controller (PPC) and a filter-lubricator-regulator (FLR). Please refer the "A Testing Device For Bicycle Components" [17] for the details of the pneumatic element.

2.5.3 Electronic element

The electronic element is responsible for control and data acquisition (DAQ). It is based upon programs written in National Instruments' LabVIEW software running on a Windows platform. All necessary boards and signal conditioners are supplied by National Instruments Company. Data is sent and received via two data acquisition cards installed in the computer. The PC-AO-2DC card has two channels of analog output that are responsible for sending the pressure requests to the PPC via a zero to ten volt differential signal. The PC-LPM-16 is a multifunction input/output (I/O) card with both analog and digit capabilities split between 16 channels. It controls the position of the solenoid via digital transistor-transistor logic (TTL) signal and receives the zero to ten volt analog feedback signals from the PPC and the linear voltage transducer. Between the computer DAQ cards and the control components are two NI CB-50 connector boards, an NI SC-2055 connector board and a 70-RC-K8 eight-channel back plane with an SSR-ODC-5 signal-conditioning module. The roles of the connector boards are to cleanly convert and distribute the signals communicating between the 50-pin ribbons from the computer and the individual cables from the control components. The back plane and signal-conditioning unit act to amplify the input to the solenoid valve. In the design for "A Testing Device for Bicycle Components" [17], there is a poor match between SSR-ODC-5 and PC-LPM-16, because the output modules like SSR-ODC-5, does not work with the extended digital I/O lines of E Series devices. In order to make the solenoid valve work, a new board and relative accessories that works with SSR-ODC-5 must be chosen and installed in this system.

2.5.4 Rewiring modifications

The rewiring work was motivated mainly to remove noise from the current activating the PPC valve and making the system work with both the testing device for bicycle components and the intelligent injection system. After rewiring the system, the displacement signal no longer passes through the pneumatic box where the PPC valve is installed and driven to regulate the air pressure; the solenoid control signal cable and PPC control cable are also connected separately and directly to the electric box. An adapter cable (See Figure 2.10) between the displacement transducer cable on the test device for bicycle components and the displacement signal socket on the electric box was made in order to make sure the system works for both systems (Please refer to Figure 3.4). After rewiring, the schematic diagrams of the electric system are shown in Appendix 13.

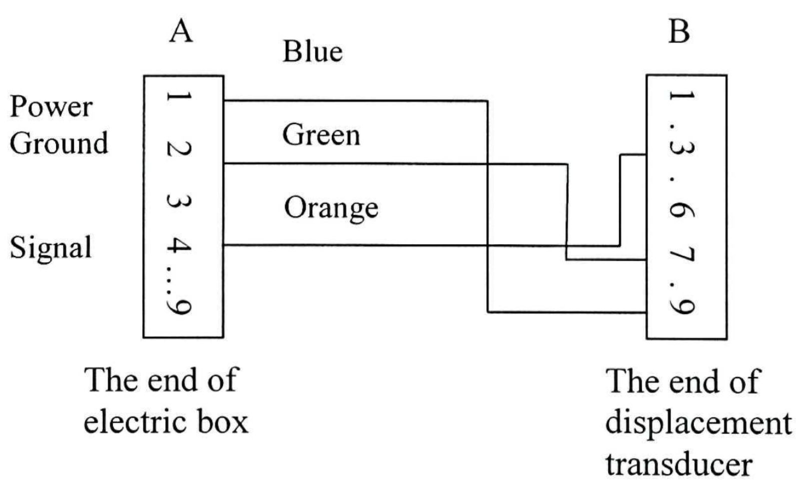

Figure 2.10 Block diagram of adapter cable

Chapter 3

Experiment implementation

In this system, LabVIEW software was programmed and integrated with computer boards, sensors, electronic and pneumatic hardware and an injection machine to control injection pressure and resin flow rate and acquire all the processing parameters. These include pressure, flow rate, piston speed, displacement, and experiment data settings. The system is also extendable to control temperature and acquire relative data. A number of experiments have been performed to test the system. Among the tests, controlled applications of Resin Transfer Molding were developed from tests with water, corn syrup, and two types of resin. Finally, an experimental manufacturing process with this intelligent injection system for square plate composite parts, resin with fiberglass reinforcement, has been developed.

3.1 Mold setup

A former Master's student, Alvarez [20] designed the mold that was used in the experiments. In order to achieve a flow rate graph that varies clearly with time, the mold cavity was shaped with rubber inserts as illustrated in Figure 3.1. Please refer to [20] for the details of mold setup.

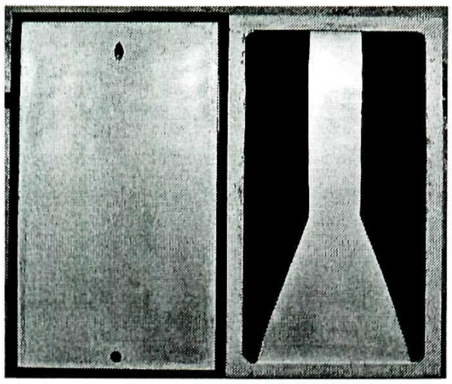

Figure 3.1 Square mold with rubber inserts (shown in black)

3.2 Preparation of test fluids

Figure 3.2 shows the setup of the RTM system for this study. The test fluid is placed in the injection cylinder, which holds up to 2.5 liters of fluid. For the experiments, three types of test fluid have been used which include water, a mixture of corn syrup and water, and two types of resin: Epoxy and Polyester. Hoes et al. [11] have given a thorough analysis of how to choose the test fluid. In their experiments, an important property of the test fluid that is described in the test set-up is its electrical conductivity. Further requirements are Newtonian behavior in the range of shear rates common to this type of injections, chemically non-aggressiveness towards the samples and set-up, low and preferably adjustable viscosity, and low cost and ease of cleaning and disposing. The resins that are actually used in a production cycle are expensive and difficult to clean and hence are not suitable on a regular basis in a test set-up. Many researchers use mineral oils as model fluid because they exhibit most of the aforementioned requirements. However, since oils are electrical insulators, they cannot be applied in the molds embedded with sensors. In order to get the experimental results for molds embedded with sensors, dark corn syrup has all the desired properties and was thus chosen as test fluid. This natural sugar solution has a very high starting viscosity, but can easily be diluted with water to obtain the desired viscosity. In our experiment, an approximate dilution of 20 wt% water is used, which brings the viscosity down to about 0.15 Pas at room temperature [11]. Water is used as a test fluid mainly because it makes it easy to clean the mold and the experimental results can be referred for further researches.

3.3 Experimental setup

This schematic diagram (Figure 3.2) shows the setup of the RTM system. The test fluid is placed inside the injection cylinder, which holds up to around 2.5 liters of fluid.

When the system is in operation, measured pressure and displacement signal are fed back to a computer data acquisition system passing through the electric box. At the same time, the achieved flow rate is calculated in the program from the acquired displacement data. The pressure command is used to regulate high-pressure air by controlling the PPC valve. The regulated air is exerted on the cylinder piston. The fluid travels through the pipeline from the cylinder to the mold. The displacement and pressure are measured at all times during the operation. The solenoid valve is used to control the cylinder piston movement direction. The displacement transducer, installed at the bottom of the cylinder, sends the displacement signal to the electric box. A closed-loop flow rate control system is thus established to provide the desired flow rate by varying cylinder pressure.

Please refer to Appendix 14 for detailed operation instructions.

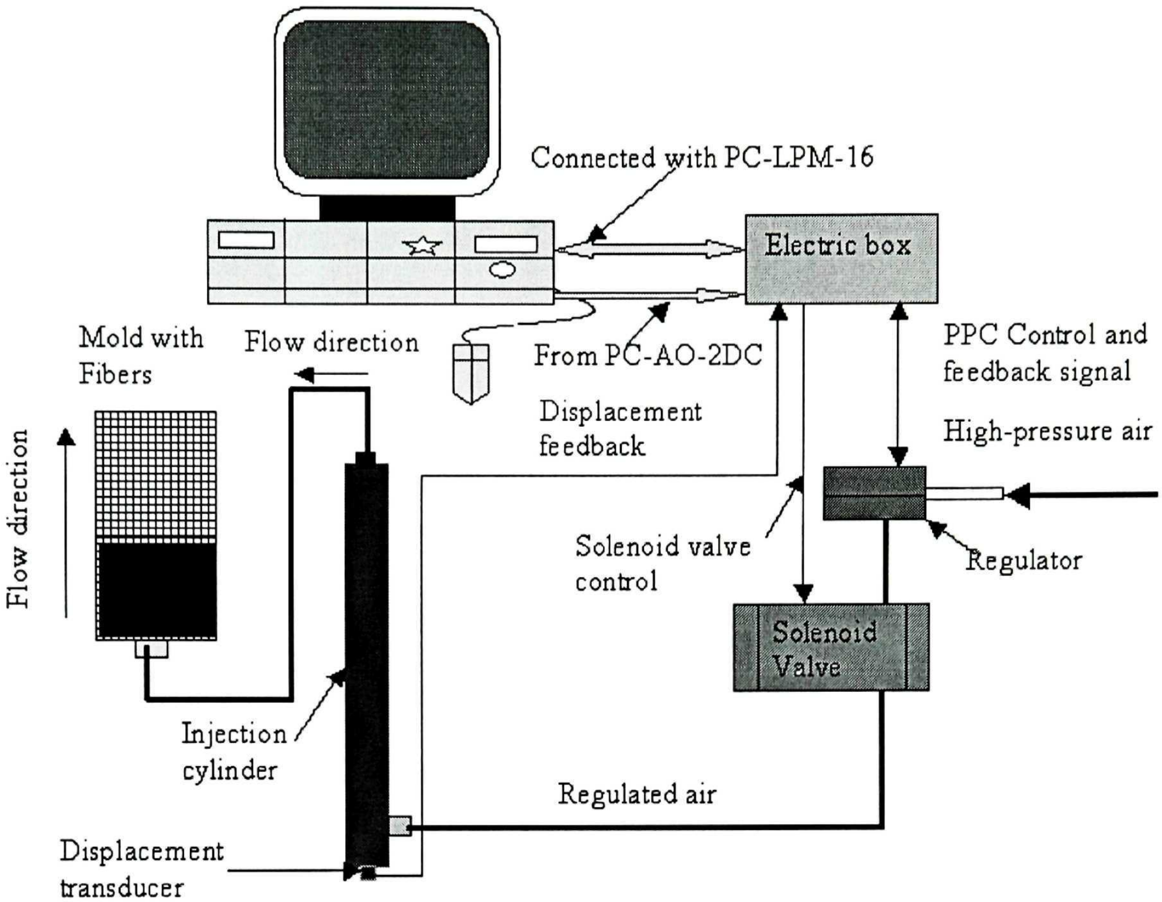

Figure 3.2 Experimental setup

Chapter 4

Control System for Resin Transfer Molding

The system developed in this research is designed to achieve pressure control, flow rate control, and integrated control with data acquisition. Under pressure control, the system pressure will be linearly regulated from initial value to final value and the injecting pressure can be set according to manufacture recommended requirements before the operation. The pressure can also be set during the operation to achieve real time pressure control. For flow rate control, the appropriate flow rate will be estimated for a certain manufacturing process or by experience and then this value will be assigned to the system. The intelligent system will adjust the pressure with the given pressure increment to achieve a resin flow rate that will be as close to the given flow rate as possible. However, at a certain point in the injection molding stroke, for example, when the mold is almost full or when the gate freezes, the resistance to flow becomes very high and it becomes unrealistic to expect the cylinder to maintain the desired rate. At this point the control is shifted from being flow rate controlled to being pressure controlled. This point is known as Velocity Pressure Transfer or VPT. In RTM, this point is also set as maximum pressure to protect the fiber from being warped by high pressure. For the integrated control, both pressure control and flow rate control will be integrated and optimized together in one manufacturing process to achieve a high quality part.

4.1 Pressure Control

Pressure is an important processing parameter in Resin Transfer Molding. It is related to product quality in many ways, such as reducing shrinkage. Pressure also affects other parameters such as temperature and filling time. Pressure control is the basic function of this intelligent injection system. During the mold filling stage of the molding cycle, high injection pressures may be needed in order to maintain the desired mold filling speed. Once the mold is full then this high pressure may not be necessary or even desirable. In many cases, a high first stage pressure may therefore be followed by a lower, second stage pressure. When molding some semi-crystalline, thermoplastics materials, for example nylon and acetal, the use of second stage pressure may not be required, as abrupt changes in pressure can cause undesirable changes in crystalline structure. To decrease the level of orientation in the part it is important that the mold be filled as quickly as possible and that the plastics melt not is sheared while it is being cooled - what is called cold, creeping flow. Such an undesirable situation could result if the VPT point were set to the wrong level, for example, if control were handed over, from velocity to pressure too soon. If the gate was still open, and if the packing pressure was only high enough to give slow filling, then a high level of internal stress in the part would result: this is because the level of retained crystalline orientation is being maximized by cooling the mold while filling slowly. In such a case it would be better to increase the packing pressure so as to increase the mold-filling rate. Changeover at the

VPT may be set before and during the operation by the operator on the Control Panel through adjusting the given value of maximum pressure or triggered while the program is operating. VPT is also set according to the experience whereby a pressure is avoided at which the fiber would be warped. Backpressure is the pressure that the cylinder must generate, and exceed, before it can move back. In our program, the backpressure can be set on the control before or during the operation. The displacement display on the right corner of Control Panel can help the operator clamp the outlet pipeline while keeping a little resin inside the cylinder to avoid air bubbles from getting into the mold. Below are the three summarized typical applications of pressure control.

4.1.1 Simple pressure control

Please refer to Appendix 1 for tables and graphs.

Overall, the tables and graphs in Appendix 1 suggest that the intelligent injection system works as it was designed to do. Table 1, and Graphs 1, 2, 3 and 4 are the data acquired during the test of a simple pressure control model of the intelligent injection system. Table 1 shows the settings data, Graph 1 shows the pressure tracking during the whole test under the command of the settings data, Graph 2 shows the displacement with respect to time, Graph 3 shows the flow rate with respect to time, and Graph 4 shows the piston speed with respect to data acquisition time. Graphs 3 and 4 are necessarily exactly the same shape except for a multiplying factor.

In the settings data, the pressure is required to change consecutively in five stages. As revealed from the data trend in Graph 1, pressure changes as required by the settings data. As can be seen in Graph 2, the piston does not move until the pressure reaches 1.19

kg/cm2 (17 psi). This demonstrates that the piston needs a higher pressure to initiate movement (overcome static friction) than the pressure it needs during movement (sliding friction). The displacement shown in Graph 2 continues to increase until it reaches the upper limit, at which the displacement is around 541.5 mm (21.32 inches) (the maximum stroke of the piston). Different increasing displacement slopes can be seen as the pressure changes as required by the settings data. As can be seen in Graph 3, the flow rate increases sharply to around 60,000 mm^3/sec and remains steady at around 50,000 mm^3/sec while the pressure is kept at 1.19 kg/cm2 (17 psi). As the pressure reduces from 1.19 kg/cm2 (17 psi) to 0.74 kg/cm2 (10.5 psi), the flow rate reduces to around 30,000 mm^3/sec. When the piston reaches the end of the cylinder, the flow rate falls steeply to zero. As can be seen from the data in Graphs 3 and 4, the piston speed has the same physical meaning as the flow rate, thus the piston speed has the same characteristics as the flow rate.

The flow rate before the piston moves and after the piston reaches the end of the cylinder is supposed to be zero. The difference between expected and obtained results would seem to stem from two possible sources: pressure impact and magnetic field. In order to remove the noise from pressure impact, a 200 ms time trial has been adopted to reduce the noise from non-consecutive changing pressure. However, to what extent the time trial affects the noise from the pressure impact is unknown. Nevertheless, a significant difference can be seen from the comparison of the test with the time trial and without the time trial. The remaining noise comes mainly from the magnetic field caused by the varying PPC control current. The random noise causes an accuracy problem in the data acquisition. As can be seen, the noise is mostly less than 20, 000 mm^3/sec in this case, so an accurate flow rate control cannot be achieved according to this result if the setting flow rate is less than 20,000 mm^3/sec in most cases.

Noise is a big problem in the Intelligent Injection System. It not only contributes inaccuracy to the data acquired to be analyzed later, but also affects the feedback control based on the acquired data. In this system, the noise mainly comes from two sources. The first is the pneumatic impact by the PPC valve. PPC is the abbreviation of Proportional Pressure Controller, an innovative product that converts an electrical signal into a proportional pneumatic output. The PPC controls output pressure by constantly measuring its output and comparing it to the command signal. If a higher pressure is commanded, the PPC quickly responds by actuating the fill valve until the output pressure is equal to the pressure represented by the command signal. The opposite is also the case. When the PPC valve works under the demands of the program, the pressure outputted by the PPC valve will not be continuous, which will cause impact on the piston responsible for pushing the resin. As a result of this impact, the piston speed and flow rate will be affected dramatically as analyzed by Musa et al [21, 22]. Actually, flow rate and piston speed are directly proportional by a multiplying factor. The second reason for noise is the external noise from the PPC control circuits. During the experiments, a phenomenon was found that whenever the PPC valve was operating, there was random noise in the data of flow rate or piston speed acquired during the operation. When the PPC stopped working or pressure was kept at a certain value, the external noise was much less significant or disappeared. This phenomenon was clearly demonstrated by the experiments.

In order to deal with the first source of noise, several methods were tried. A function that sets a longer data acquisition time was added to the program. In the model of flow rate calculation, a "wait until function" tick timer was added to control the time distance between two consecutive data acquisitions. With a slightly longer data acquisition time interval, the acceleration effect of pneumatic impact on the flow rate or piston speed was reduced. However, it was difficult to get a numerical result, i.e., it was hard to say for a certain time interval, how much noise has been removed from the system. The specific case depended on the viscosity of the resin being used and other factors.

For the second source of noise, external noise from the PPC control circuit, a great deal of work was done. However, little positive effect was achieved, although the specific reasons became more clear. In the design for a fork testing station [17], the displacement signal is passed through the pneumatic box inside which the PPC valve is installed before it is input into the block inside the electric box. This is done in order to exclude the possibility of the displacement signal being affected by the coil inside the PPC valve. After rewiring, the displacement signal goes directly from the injection machine to the electric box. However, the noise is almost the same as before rewiring. Because the noise comes directly from the PPC control current, shielding would be the most effective way to reduce it. Shielding is a method of preventing interaction between circuits by surrounding the circuits with metal plates. Some shielding work has been done by rewiring work in shielding the wire transferring the PPC control current, but there is still no significant effect. Further work in shielding would be to separate the blocks inside the electric box shared by displacement and the PPC control current transferring wires. A new redesign scheme has been proposed, but more parts will be needed, including a new board and other corresponding parts. It remains to be seen whether the new redesign plan will remove the noise.

Appendix 2 shows another example of simple pressure control, this time using corn syrup as the injecting fluid. The table and graphs also suggest that the intelligent injection system works as it was designed to do. The table and graphs are the same as those in Appendix 1 except that Appendix 2 does not the have graph 4, as the graphs 3 and 4 have the same physical meaning. The flow rate achieved in Appendix 2 is much lower than that in Appendix 1, because the viscosity of corn syrup is much higher than that of water.

Rubber inserts shown in Figure 1 are used to shape the mold cavity, however, the obtained results do not coincide with the expected results. The difference between expected and obtained results is probably due to the big flow rate and the relatively small mold cavity volume. When the test is performed with water, the cavity can be filled in less than 2 seconds (overlapping with the overshoot periods). When the test is performed with corn syrup, as can be seen in graph 2 in Appendix 2, the pressure is increased from 0 kg/cm^2 (0 psi) to 4.2 kg/cm^2 (60 psi) in 10 seconds, and then the pressure is kept at 4.2 kg/cm^2 (60 psi). During this period, a clear flow rate trend cannot be distinguished from the graph because a large pressure is needed to overcome the resistance from viscosity so that the resistance change caused by section change is not evident.

4.1.2 Flow rate simulation under pressure control

Please refer to Appendix 3 for flow rate simulation under pressure control (FRSPC) and Appendix 6 for quick flow rate control. FRSPC is nothing but pressure control but with the intention of simulating flow rate control.

This application is designed for the manufacture of regular section parts using the experience obtained from the flow rate control injection molding process. As can be seen from the table and graphs in Appendix 6, the data analysis of quick flow rate control with water, a flow rate of 30,000 mm^3/sec can be achieved when the pressure is kept at 0.74 kg/cm^2 (10.5 psi). In order to simulate this process to achieve an approximate flow rate control for this square plate part, in the experiment represented by Appendix 3, we increase the pressure from 0 kg/cm^2 (0 psi) to 1.19 kg/cm^2 (17 psi) in 6 seconds to initiate the piston movement and then reduce pressure from 1.19 kg/cm2 (17 psi) to 0.7 kg/cm^2 (10 psi) in 4 seconds and keep the pressure there for about 100 seconds. During the constant pressure period, the flow rate remains around 30,000 mm^3/sec until the piston reaches the limit of the cylinder. One point should be mentioned here, some small defects on the inside wall of the injection cylinder may cause a friction change which could affect the flow rate. This case is sensitive when doing experiment with water, because of the relatively small pressures required. As can be seen from the displacement graph and flow rate graph in Appendix 3, the piston inside the cylinder met greater friction at the positions of 419.1 mm (16.5 inches) and 482.6 mm (19 inches) from the bottom of the cylinder. When this application is applied to parts with gradually changing sections, the pressure applied could be linearly changing based on experiences obtained in flow rate control. Linearity, an important property of PPC valve, is made full use of in the design of this system.

4.1.3 Real time pressure control

Please refer to Appendix 4 for the data acquired from the real time pressure control experiment. As can be seen from Appendix 3, the table and graphs suggest that the intelligent injection system works as it was designed to do during real time pressure control.

This Real time pressure control will be used for those cases in which the pressure needs to be reset or adjusted during the operation. This function can be achieved by the combination of the maximum pressure button and minimum pressure button. The arrows on these two buttons can be pushed to change the values to meet practical requirements during the manufacturing process. As can be seen in Appendix 4, with the settings data the pressure is increased from 0 kg/cm^2 (0 psi) to 0.84 kg/cm^2 (12 psi) in 6 seconds and then reduced to 0.56 kg/cm^2 (8 psi) and kept at 0.56 kg/cm^2 (8 psi); however, the piston did not move as the operator expected. In order to continue this experiment and achieve a desirable flow rate, the abrupt pressure was reset to 1.19 kg/cm^2 (17 psi), 0.56 kg/cm^2 (8 psi), 0.7 kg/cm^2 (10 psi), 0.91 kg/cm^2 (13 psi), 1.05 kg/cm^2 (15 psi) and then 0.56 kg/cm^2 (8 psi) separately. After the desired pressure has been set by clicking the arrows on the buttons or direct input on the keyboard, a click on the blank space is needed to put the procedure into effect. During the last stage, the minimum pressure is set to 0 kg/cm^2 (0 psi), the operation is put back under the control of the initial settings data, then a smooth change in pressure can be seen, as required. Care must be taken to observe that a quick number change is required, because during the changing period, the pressure is controlled by the preset data in the program.

4.2 Flow Rate Control

Flow rate is the injection speed that refers to the velocity of mold filling. When molding thin-sectioned components, high injection speeds are essential in order to fill the molding before cure occurs. However, a better surface finish is obtained on molds with thicker sections and by using a slower speed [18]. Thermoplastics and thermoset resins differ widely in their viscosity, or ease of flow, and the problem is made more difficult by the fact that each material is available in a range of forms (with different permeability), each of which also has a different flow behavior. The situation is made even more complicated by the fact that the flow properties are non-Newtonian and so there is no linear relationship between pressure and flow [19]. During the operation of this system, the pressure will be increased or reduced at a certain rate, depending on whether the achieved flow rate is lower or higher than the required flow rate. In this way, the complicated problem can be solved in a simple way. Many molding problems, for example jetting and air trapping, may be avoided by using a range of speeds (that is, programming the injection speed) during the mold filling stage.

In our intelligent system, we designed a closed loop control system to achieve this function. A sensor installed at the end of the cylinder is used to track the piston position, the data of which with respect to time is written to a hard disk. The information from the displacement sensor is converted into flow rate and fed to a controller where the achieved flow rate is calculated and compared with the set flow rate. In order to reach a given flow rate, the pressure will change at the set pressure increment until VPT is achieved.

The flow rate control is divided into two-applications: simple flow rate control and quick flow rate control. Experiments have been done with water and corn syrup. All the acquired data can be referred to for practical manufacturing.

4.2.1 Slow flow rate control

The table and graphs in Appendix 5 demonstrate how the flow rate is achieved when it is required to perform a simple flow rate control application. As shown in Table 1, the flow rate is required to increase from 0 to 30,000 mm^3/sec in 30 seconds, then is kept at 30,000 mm^3/sec for 30 seconds, then is required to increase from 30,000 mm^3/sec to 50,000 mm^3/sec, and then is reduced to zero. Graph 1 in Appendix 5 shows that the achieved flow rate performs as it is required to do. Graph 2 shows how the pressure is changed to reach the desired flow rate. Graph 3 indicates how the piston displacement changes with respect to time. However, as revealed by graphs 1 and 2, in order to initiate the piston movement, a much higher pressure is required than the piston needs during the moving phase (after overcoming static friction). As a result, the piston overshoots at that moment and the flow rate rises sharply to 60,000 mm mm^3/sec and then falls off to around 30,000 mm^3/sec as required by the program. As can be seen from the data in the table, the flow rate is required to increase over a period, and after it reaches the peak at the beginning of the piston movement, the flow rate changes slowly and smoothly. Compared with the settings data, the discrepancy in the time to reach a flow rate of

30,000 mm^3/sec can be attributed to the small pressure increment; so in this experiment, the smoothness is achieved at the expense of time.

4.2.2 Quick flow rate control

The difference between the slow flow rate control and quick flow rate control lies in the initial set flow rate value and the set increment. When a 30,000 mm^3/sec flow rate value is given as the initial and final value at the first stage, the required flow rate value will always be larger than the achieved value, even when the noisy flow rate and overshoot are counted. In this way, the pressure is kept in an upward trend at a larger increment, so the piston can start to move in a shorter time and at smaller pressure due to the bigger air impact caused by the bigger pressure increment. However, the flow rate in this application does not change as smoothly as it does in slow flow rate control. This application has been demonstrated with water and corn syrup in four experiments with different required flow rate values.

Please refer to Appendix 6 for the experiment with water. The table and graphs in Appendix 6 show that the flow rate changes as required in the settings data. It is obvious that the flow rate is not changing as smoothly as it does in slow flow rate control and the flow rate reaches a value of 67200 mm^3/sec when the pressure increases to 1.26 kg/cm^2 (18 psi) and then levels off at 30,000 mm^3/sec quickly. Because the piston starts to move much earlier than expected, the piston gets to the end of the cylinder just when the set data requires increasing the flow rate to 50,000 mm^3/sec. Although the pressure keeps increasing to 2.1 kg/cm^2 (30 psi), the maximum pressure set in this experiment, all the flow rate data after that are noise. Another implication of this test is that the processing parameters should be set carefully by experience.

The experiment represented by Appendix 7 is a quick flow rate control application done with corn syrup. Table 1 and Graphs 1, 2, 3 show that the flow rate is regulated as required by the set data. Please refer to Graph 3 for the plot of displacement with respect to time. The piston has a sharp rise from 0 to 127 mm (5 inches) when the pressure gets to 2.24 kg/cm^2 (32 psi) due to the vacancy inside the injection cylinder. Because of the overshoot of the piston cylinder, a very large flow rate is achieved during a short time. Then the pressure continues to increase to meet the requirement of the 30,000 mm^3/sec flow rate. However, because of the high viscosity of the corn syrup used in the experiments, the required flow rate is not achieved during the whole experiment, even though the pressure increases to 6.09 kg/cm^2 (87 psi), as illustrated in graph 2. After the peak pressure value, the pressure falls off as required by zero value of flow rate. The pressure's declining rate is controlled by the given pressure increment in this application, and the comparison results between the required flow rate and achieved flow rate. During the whole experiment, a relative small noise level is observed because of the weak effect of air impact on corn syrup with high viscosity.

The table and graphs in Appendix 8 show the experimental results when the given flow rate is less than 10,000 mm^3/sec. As can be seen in Graph 3, the piston does not move at all because of confusion in the comparison between the noise and the required flow rate value; the pressure does not increase as expected and the piston does not move at all. The values shown in Graphs 1 and 3 due to the noise acquired during the operation. From the data shown in Graph 1, a flow rate of less than 20,000 mm^3/sec could not be achieved in this case because of the noise.

A longer time duration was tried in the experiment shown in Appendix 9. The highest flow rate is achieved between 5500 mm^3/sec and 6600 mm^3/sec when the pressure is increased to 6.65 kg/cm^2 (95 psi). This flow rate remains steady until the flow rate is required to decline to zero. The question here is why did the noise tend to disappear or became very small when the pressure reached the PPC valve's pressure limit. This implies, once again, that the noise comes from the PPC valve. In order to exclude this possibility, rewiring work was done. The displacement transducer signal wire was connected to the electronic box directly to avoid being affected. However, the noise was almost the same as before rewiring. The only possible reason for the noise is that it comes into the circuit from the electronic box or the computer board inside the computer as a result of the magnetic field.

4.3 Integrated Control

The process of integrated control includes both flow rate control and pressure control; however, it is not a simple combination of flow rate control and pressure control. It implies a philosophy to achieve good part quality with optimal processing parameters. Two applications of integrated control are introduced here and far more integrated controls can be explored by the users of this system.

4.3.1 Simple Integrated Control

Table 1 and Graphs 1, 2, and 3 in Appendix 10 show how the system works well under a pre-set processing procedure. The pressure is increased from 0 to 0.84 kg/cm^2 (12 psi) in 6 seconds in the first stage, and then the process moves into the second stage with flow rate control at a given flow rate of 30,000 mm^3/sec. During the second stage, the pressure and flow rate rise and decline smoothly because of the given small pressure increment. The piston reaches the end of the cylinder during the second stage; however, the pressure goes up to achieve the required flow rate until the third stage of pressure control. As can be seen from the table and graphs in Appendix 10, the whole control process is flexible, smooth, but with slow response time.

4.3.2 Optimal Integrated Control

Table 1 and Graphs 1, 2, 3 in Appendix 11 show how the process of optimal integrated control is under the command of the operator's pre-set data. The optimal integrated control is somewhat like flow rate simulation pressure control inasmuch as it is based on experience, except it is much more flexible and less experience is required. As already known by experience that the piston starts to move at around 1.19 kg/cm2 (17 psi) and remains steady at a flow rate of 30,000 mm^3/sec when the pressure is kept at 0.74 kg/cm^2 (10.5 psi), so pressure is increased from 0 to 1.19 kg/cm^2 (17 psi) in 6 seconds and then reduced to 0.74 kg/cm^2 (10.5) in 4 seconds. In the third stage, flow rate control at 30,000 mm^3/sec is applied. In this way, flow rate control can be achieved and come to steady state quickly and smoothly.

It is difficult to say whether the optimal integrated control is the best option. The appropriate processing parameters should be chosen by the specific case according to the operator's experiences. However, optimal integrated control does make full use of the advantages of both flow rate control and pressure control.

4.4 Summary of control schemes

From the above analysis, all the control schemes have their advantages and disadvantages. In order to achieve the quality requirements for the resulting parts, the processing parameters and production process are controlled by preinstalled software and the processing parameters and production process are decided by the important design variables including pressure, flow rate, resin temperature, mold temperature, part geometry, material properties, gate and vent locations and the number of vents. In order to help the users of this intelligent injection system, the control schemes are summarized based on the four aspects: response speed, experience required, ease of use and overall

Control schemes		Response speed	Experience required	Ease of use	Overall accuracy
Pressure Control (PC)	Simple PC	High	Low	No	High
	Flow rate simulation PC	High	High	Yes	High
	Real-time PC	High	Low	No	Low
Flow rate control (FC)	Slow FC	Slow	High	Yes	Medium
	Quick FC	Medium	High	Yes	Medium
Integrated Control (IC)	Simple IC	High	Medium	Yes	Medium
	Optimal IC	High	Medium	Yes	High

accuracy.

Response speed is an important factor describing the system's performance to respond to pressure requirements. Firstly, high response speed is important for materials with short curing times like polyester resins. Secondly, high response speed can help to reduce process cycle time and improve production efficiency. Thirdly, high speed helps to reach good quality of resulting parts relying on a strict production process. The extent of experience required is evaluated by the parameters setting of flow rate, pressure, pressure changing rate and VPT (velocity pressure transfer). The extent of ease of use is evaluated by how much work the operator is required to do like setting of maximum or minimum pressure and toggling the pressure rate during operation. The overall accuracy is a factor evaluating the combination of linearity and hysteresis in achieving the desired pressure or flow rate. Obviously, flow rate control is not achieved linearly. The operator will have to play with this system to know how a high quality part can be achieved.

Chapter 5

Conclusions and Future Recommendations

5.1 Conclusion

In this research, the intelligent injection system has been successfully developed and the system's application to Resin Transfer Molding has been developed from the experiments. For this system, pressure control and flow rate control can be achieved separately or as an integrated control scheme. Pressure control can be achieved linearly and accurately making use of the PPC's Linearity. Simple pressure control, flow rate simulation pressure control, and real time pressure control have been developed as the typical pressure control applications. Flow rate control presented a good trend in achieving the required flow rate. Slow flow rate control and quick flow rate control have been developed as the typical flow rate control methods. The application of integrated control includes simple integrated control and optimal integrated control. Overall, the experiment results presented in this thesis proved the feasibility and power of the intelligent injection system developed in the environment of LabVIEW.

The system is now ready to use for composite material resin systems in order to develop optimized RTM processes. All the processing data acquired during the operation can help us to understand in depth the process of RTM and relationship between process parameters and quality of resulting parts and eventually improve the RTM process.

5.2 Major Accomplishments of this thesis

- Developed an intelligent injection system that integrates injector, computer system, control system, pneumatic unit and a LabVIEW program.
- Experimented with the Resin Transfer Moulding process for a composite plate using the intelligent injection system.
- Performed manufacturing experiments with the intelligent injection system and summarized its application to Resin Transfer Molding.

5.3 Future recommendations

- Verify what causes the noise in the displacement signal. Study the effect of common power supply and magnetic field on the noise in the system.
- Attempt to further understand the program structure in order to increase the running speed that will improve the flow rate control quality.
- Linking the hybrid expert system [2] with the LabVIEW simulation program to reduce expert's dependency.
- Try the system with a faster computer and new computer data acquisition boards with higher sampling rate.
- Attempt to use flow meter between the injector and mold to acquire accurate flow rate feedback.

- Numerical simulation software like Matlab can be embedded in LabVIEW so that it can work with complicated mathematic model to achieve accurate control.
- Install a pressure transducer near the inlet of mold to achieve accurate pressure feedback of mold temperature.

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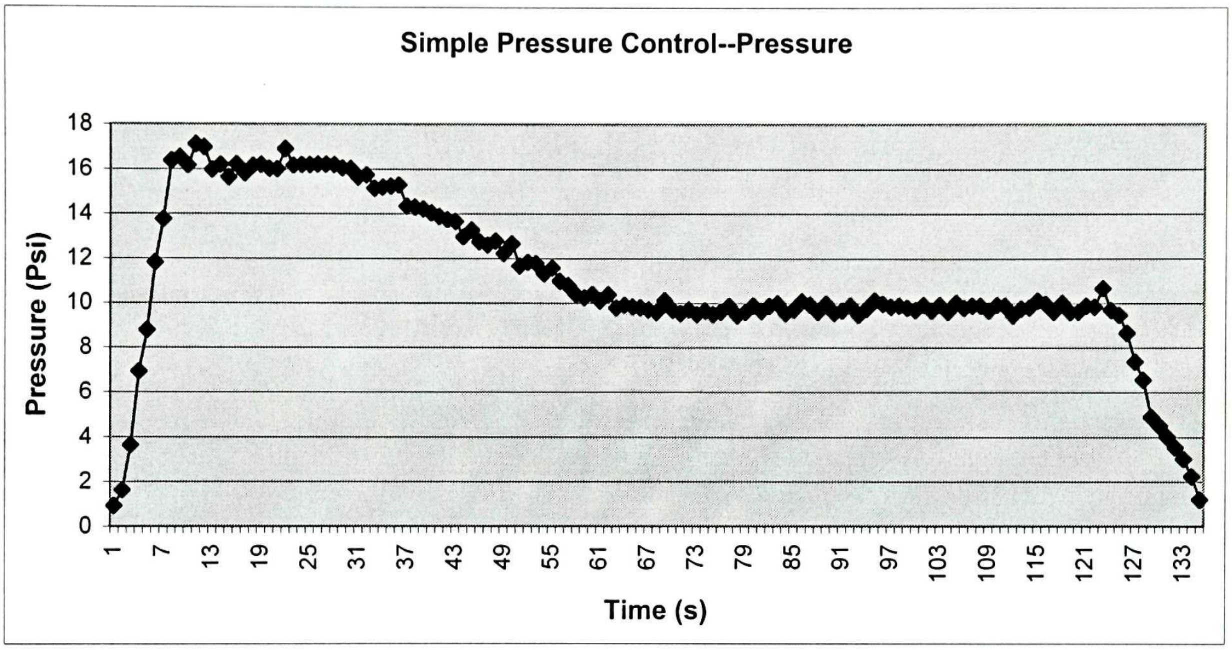
Appendix 1

Simple Pressure Control Date With Water Data Summary

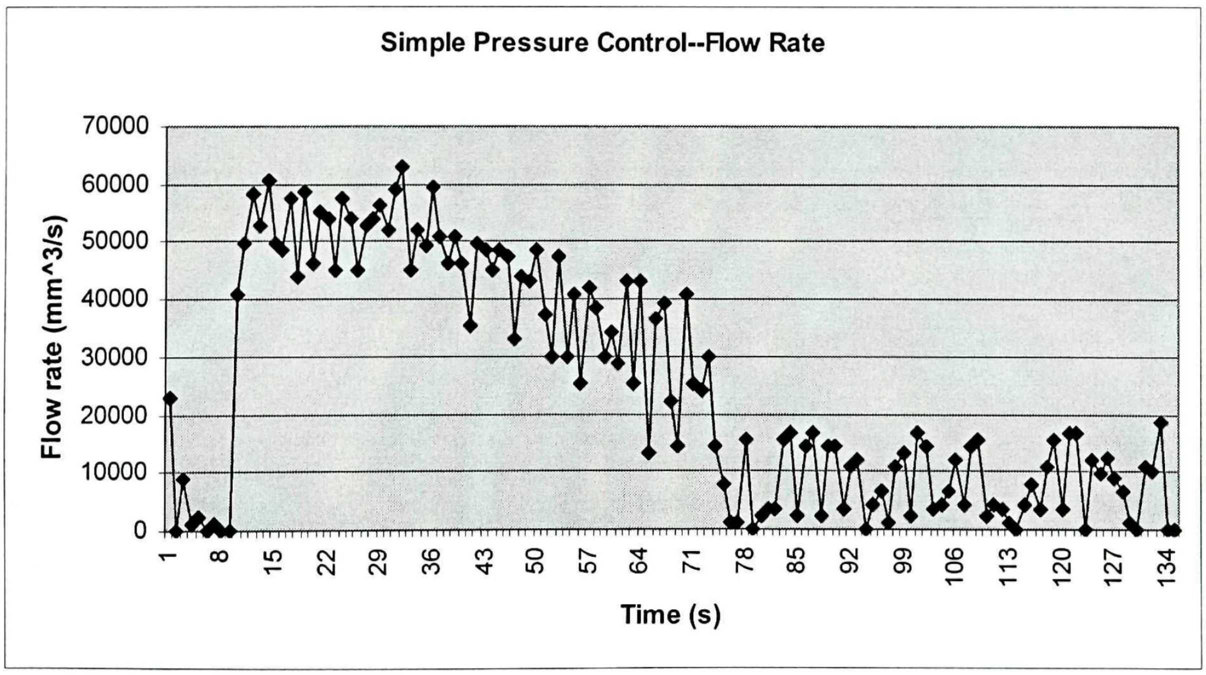
Resin: Water Simple pressure control setting data

Simple PC	First stage	Second stage	Third stage	Fourth stage	Fifth stage
PC(0)or FC(1)	0	0	0	0	0
Time duration	6s	15s	30s	50s	10s
Initial value	0 psi	17 psi	17 psi	10.5 psi	10.5 psi
Final value	17 psi	17 psi	10.5 psi	10.5 psi	0 psi

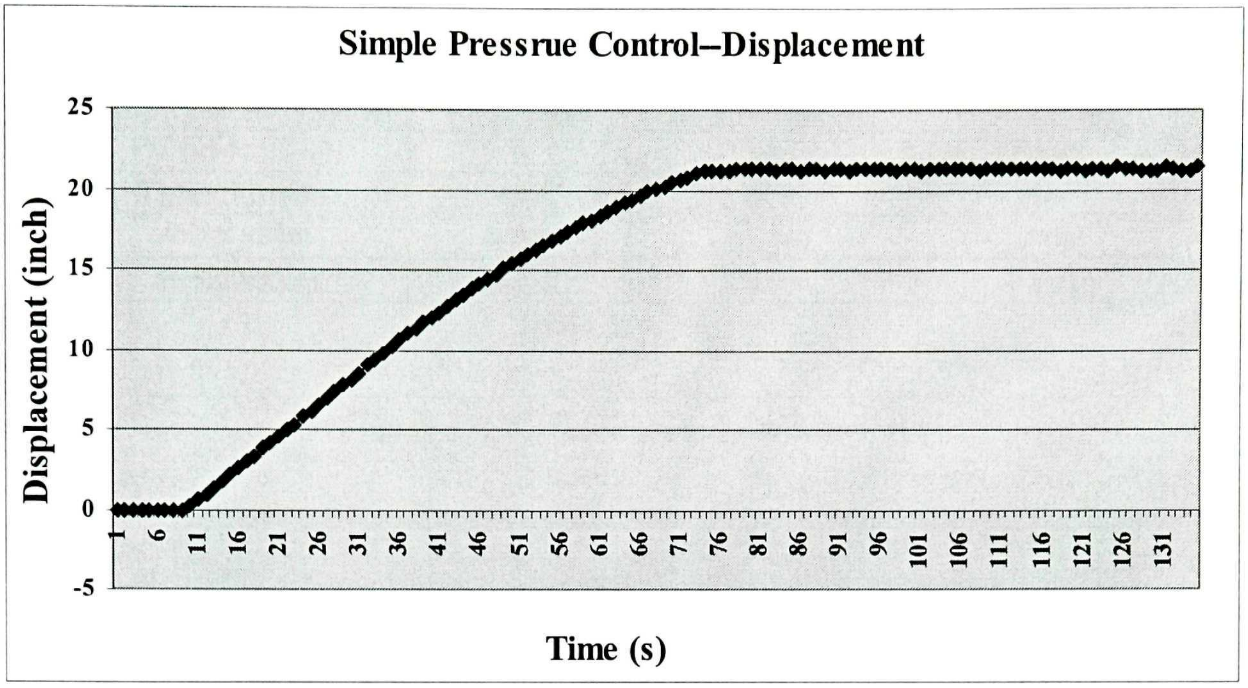
Table 1



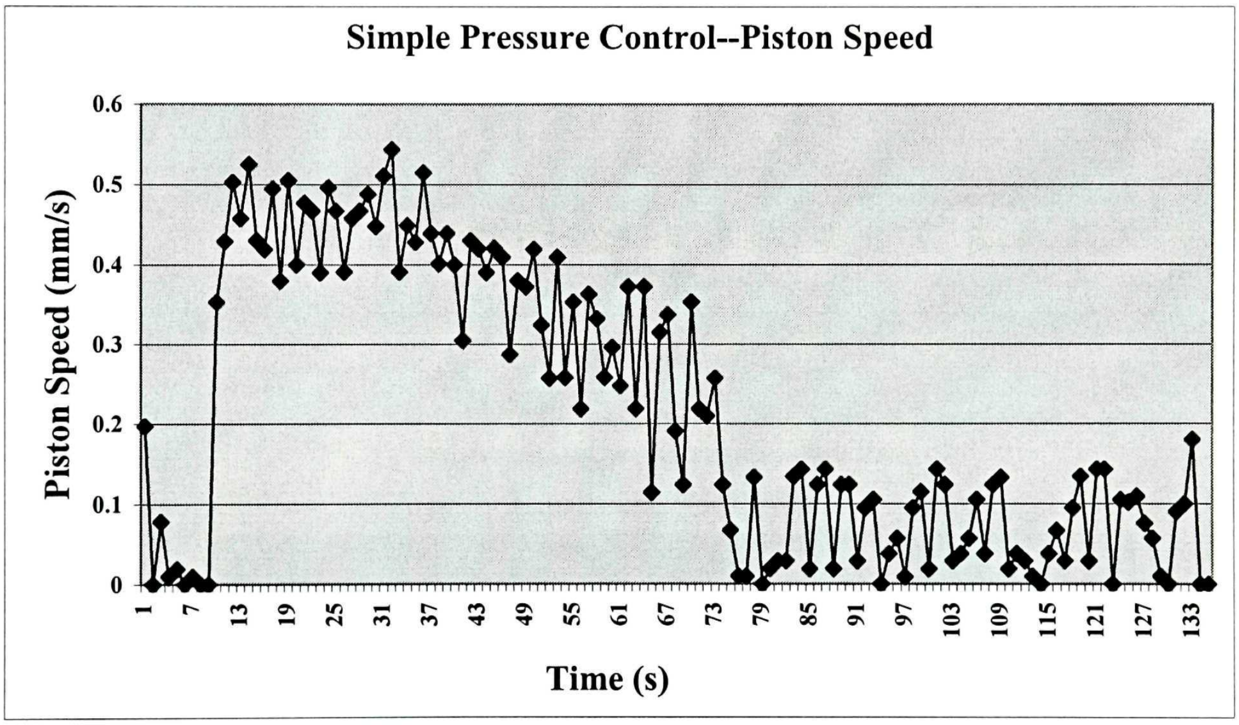
Graph 1



Graph 2



Graph 3



Graph 4

Note:

1. Time trial is a parameter set to control the time interval for displacement data acquisition in flow rate calculation module. It was set as 200 ms in all the experiments referred in this thesis to reduce the effect of air impact.

2. Resin volume used: 2450832 mm^3 (this value demonstrates that the length calibration is right).

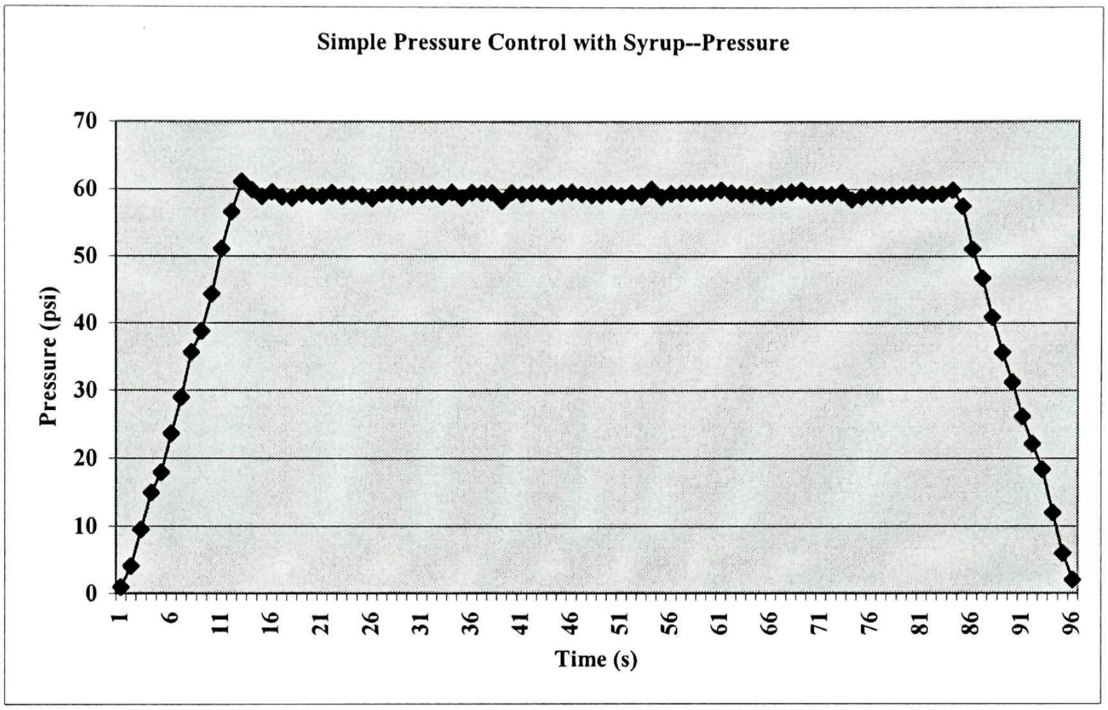
ppendix 2

Simple Pressure Control with Syrup Data Summary

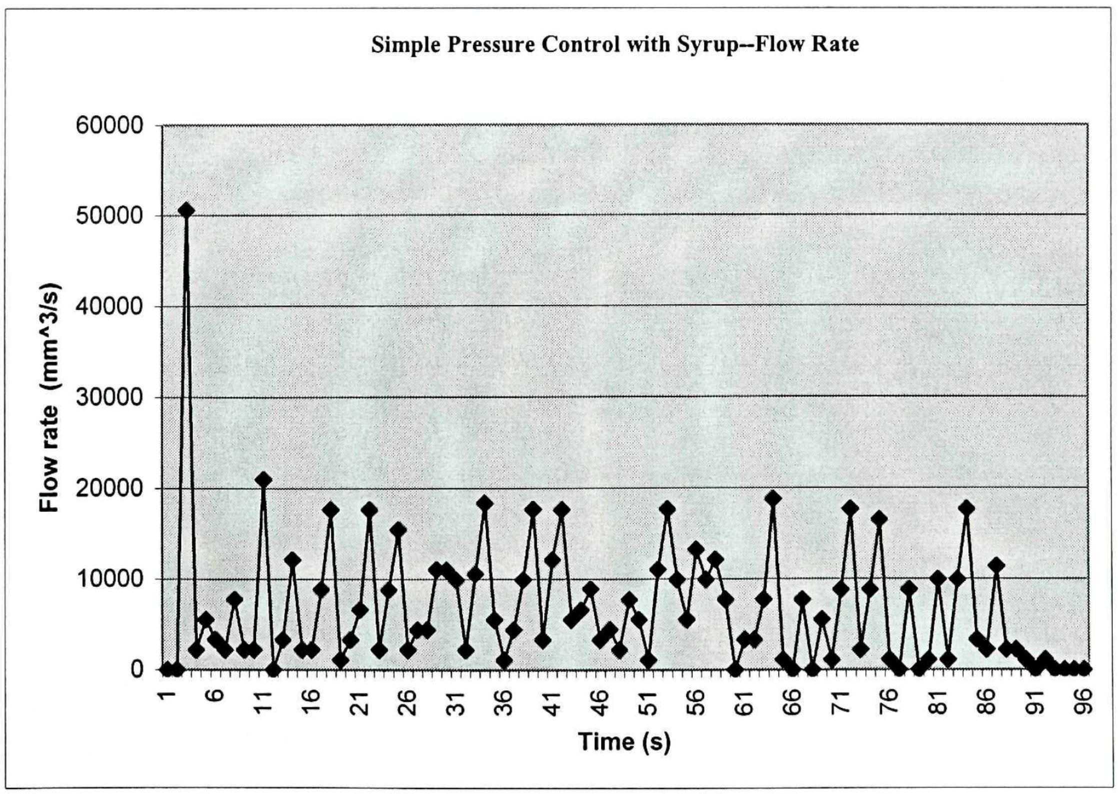
Resin: Corn syrup   Simple pressure control setting data

SimplePC with syrup	First stage	Second stage	Third stage
PC (0) or FC (1)	0	0	0
Time duration	0s	60s	60s
Initial value	0 psi	60 psi	10 psi
Final value	10 psi	60 psi	0 psi

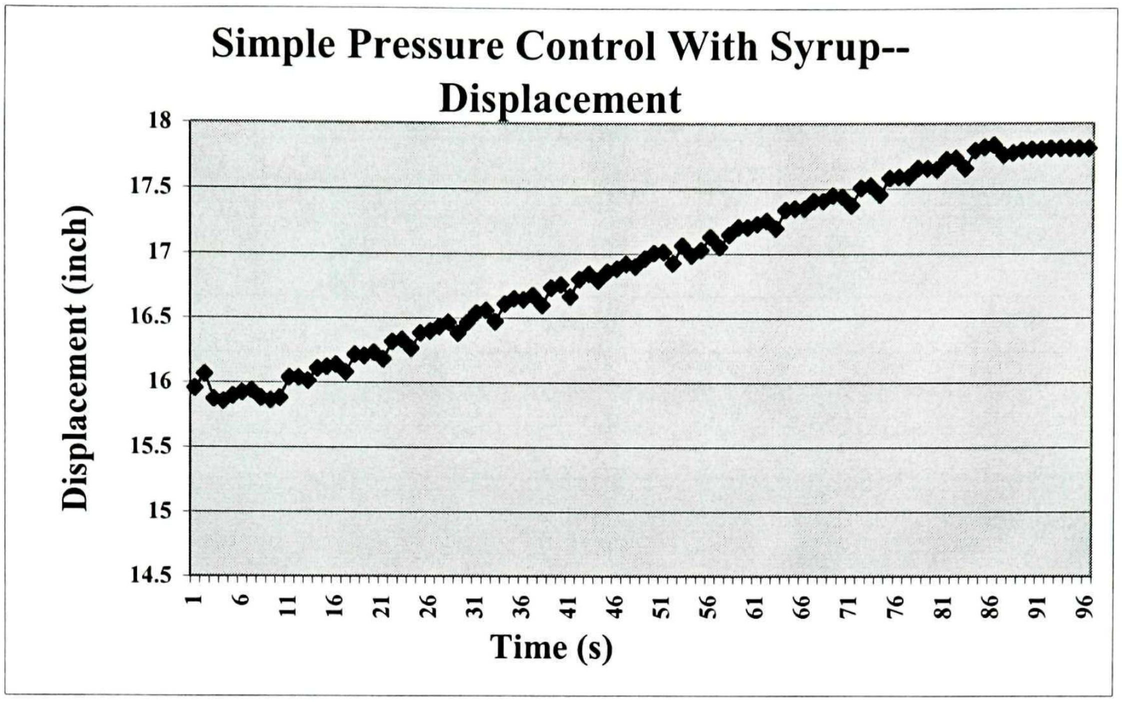
Table 1



Graph 1



Graph 2


Simple Pressure Control With Syrup--
Displacement
Displacement (inch)
18
17.5
17
16.5
16
15.5
15
14.5
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
76
81
86
91
96
Time (s)

Graph 3

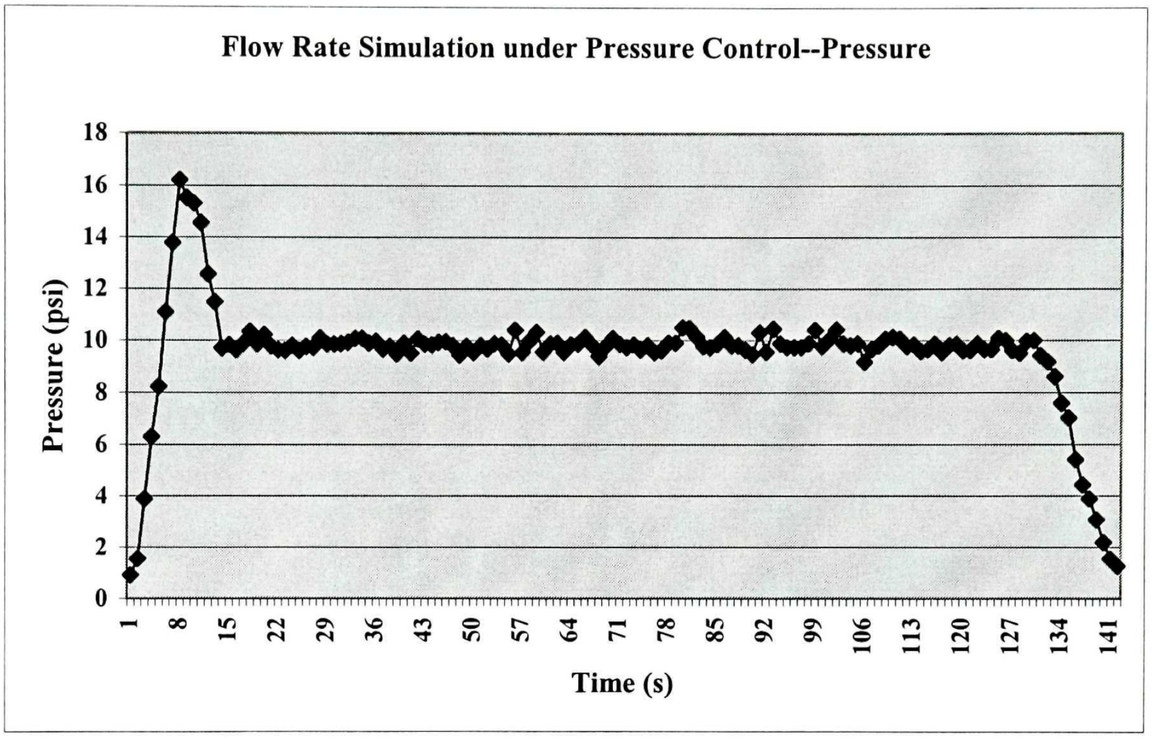
ppendix 3

Flow rate simulation under pressure control data summary

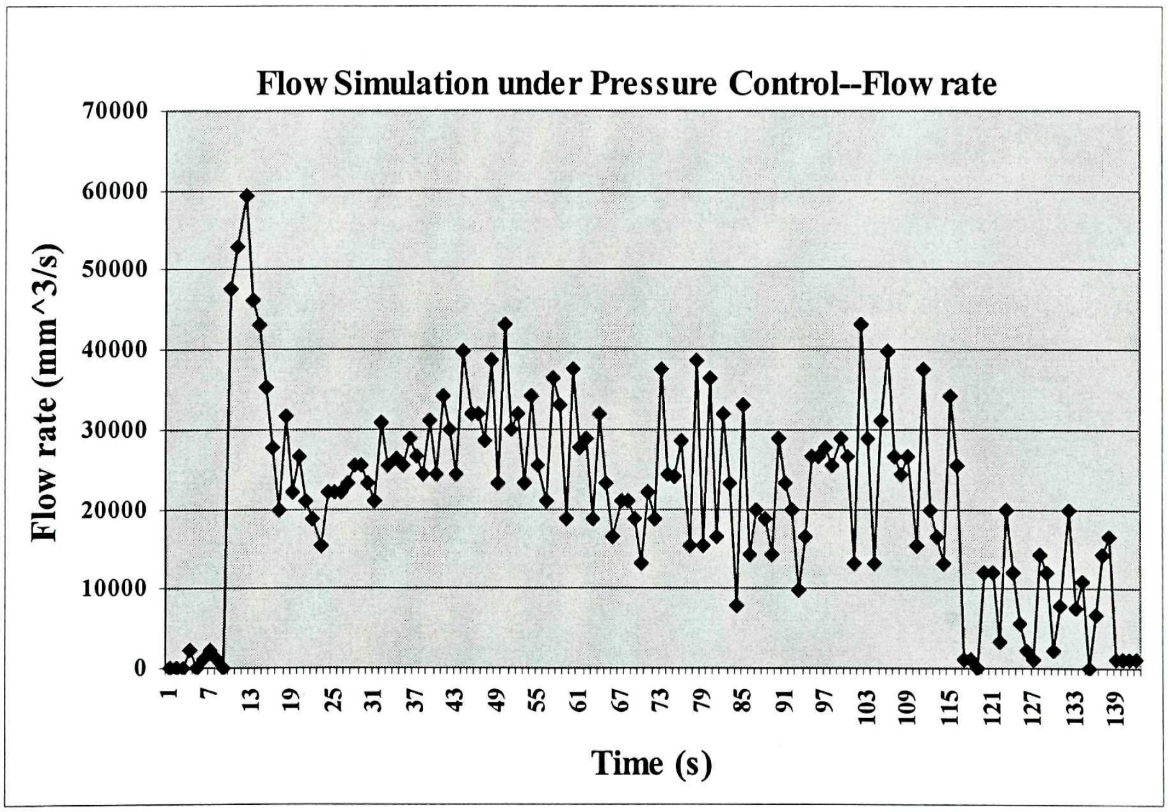
Resin: Water   Flow rate simulation under pressure control setting data

FRSPC	First stage	Second stage	Third stage	Fourth stage
FC(1)/PC(0)	0	0	0	0
Time duration	6s	4s	100s	10s
Initial value	0 psi	17 psi	10.5 psi	10.5 psi
Final value	17 psi	10.5 psi	10.5 psi	0 psi

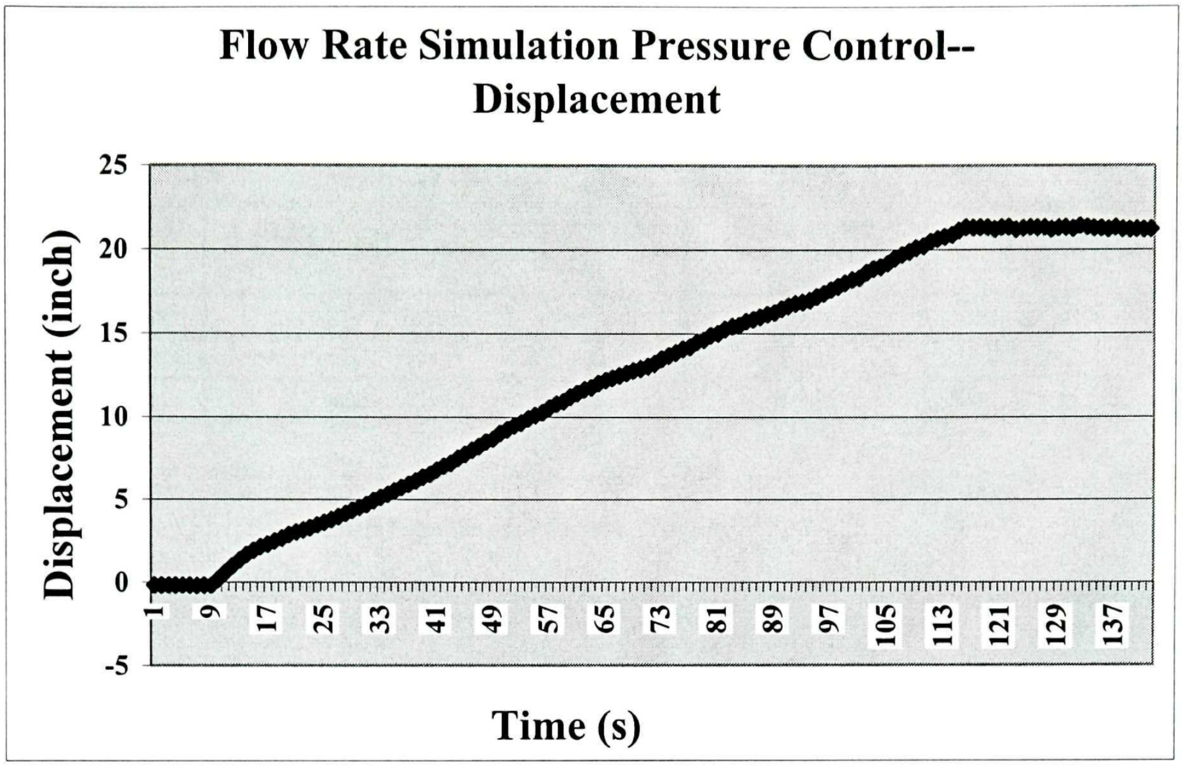
Table 1



Graph 1



Graph 2



Flow Rate Simulation Pressure Control--
Displacement
Displacement (inch)
25
20
15
10
5
0
-5
1
9
17
25
33
41
49
57
65
73
81
89
97
105
113
121
129
137
Time (s)

Graph 3

Appendix 4

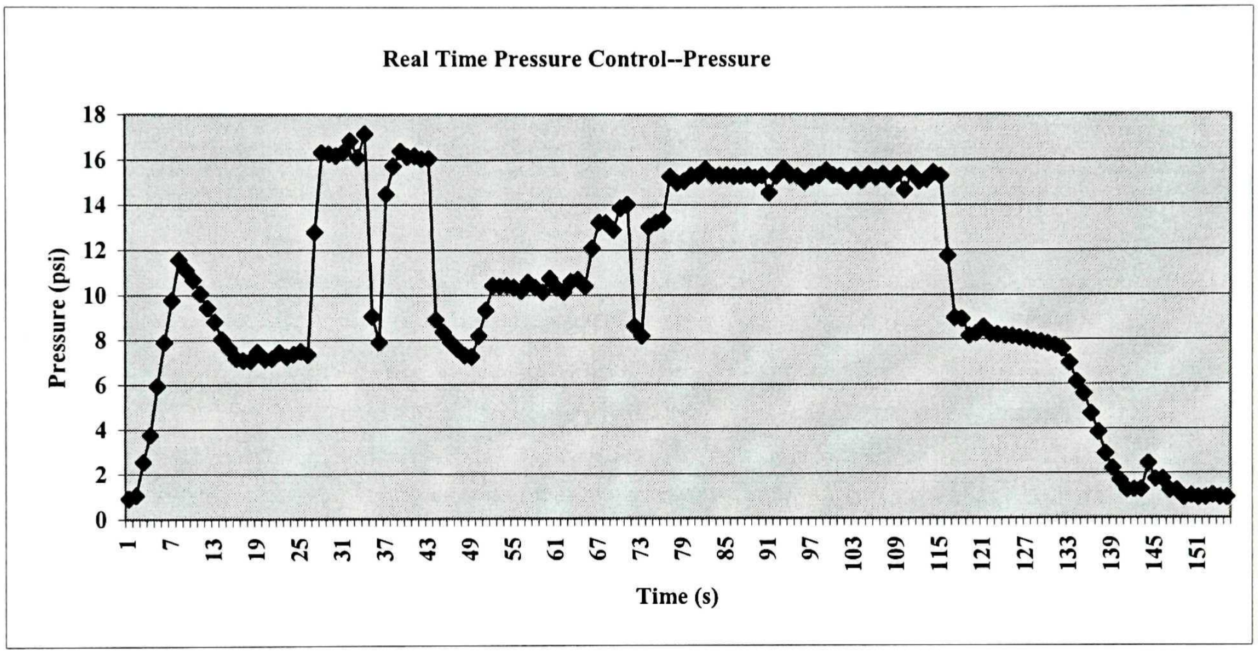
Real Time Pressure Control Date Summary

Resin: Water

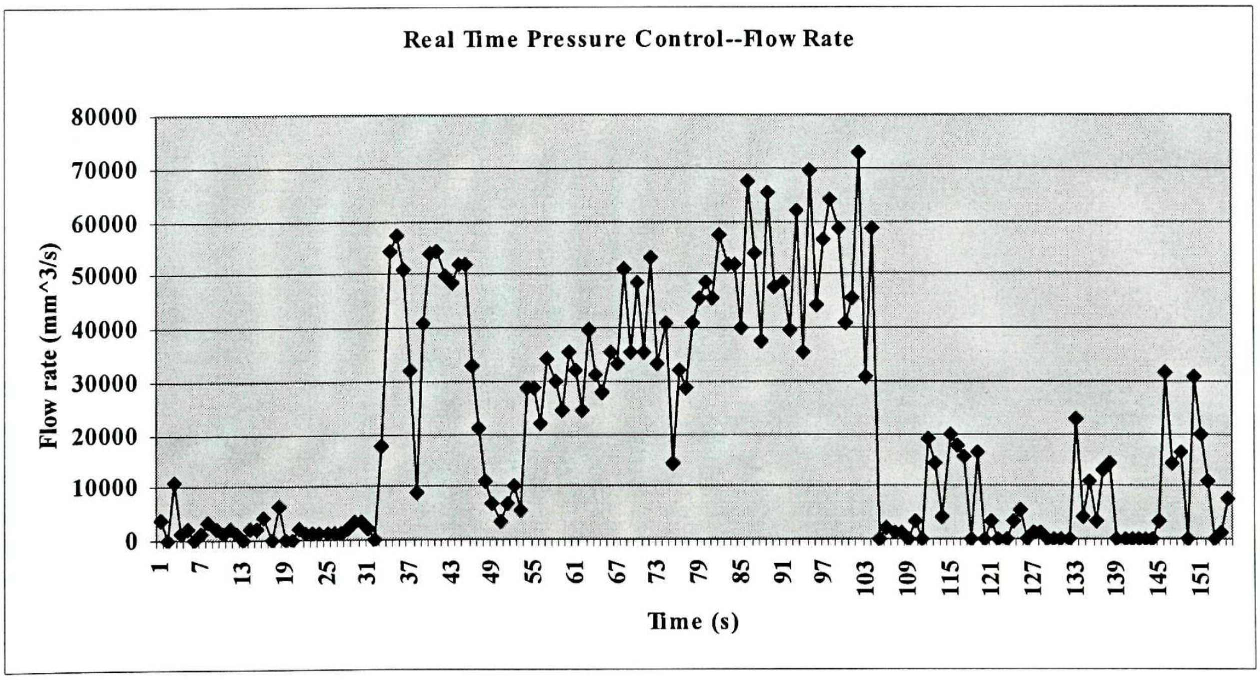
Real time pressure control setting data

RTPC	First stage	Second stage	Third stage	Fourth stage
PC(0)or FC(1)	0	0	0	0
Time duration	6s	4s	100s	10s
Initial value	0 psi	12 psi	8 psi	8 psi
Final value	12 psi	8 psi	8 psi	0 psi

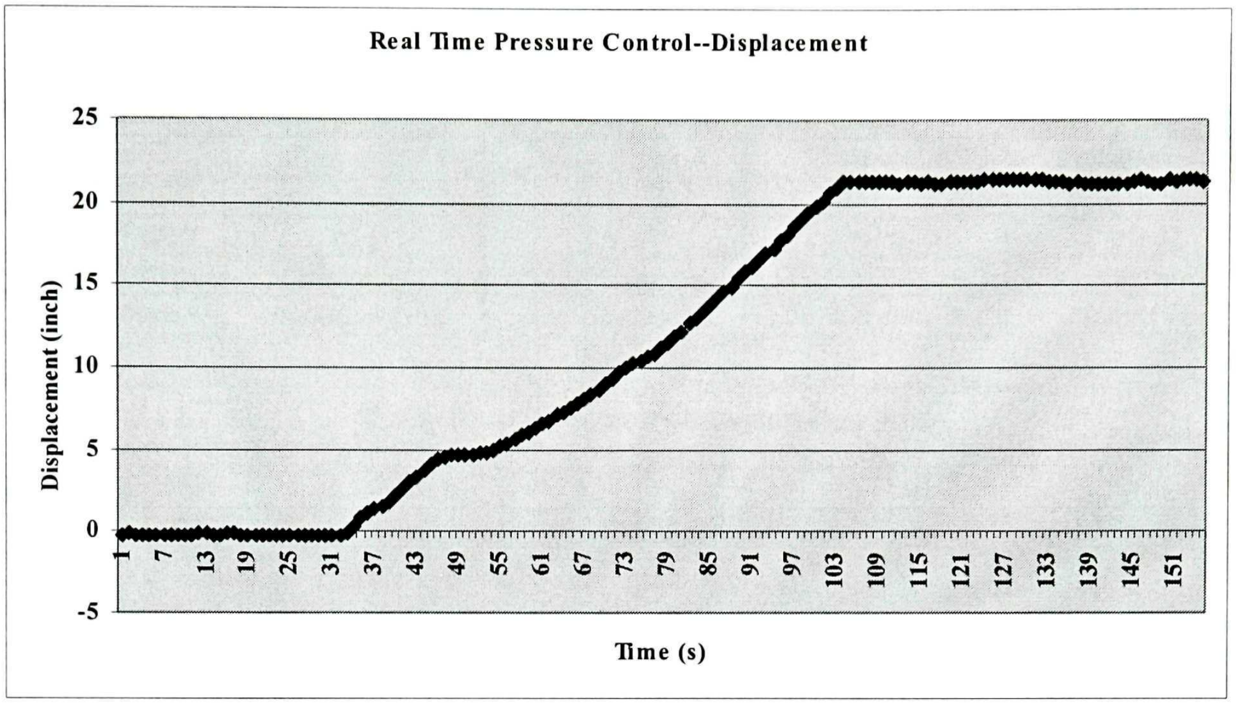
Table 1



Graph 1



Graph 2


Real Time Pressure Control--Displacement
Displacement (inch)
25
20
15
10
5
0
-5
1
7
13
19
25
31
37
43
49
55
61
67
73
79
85
91
97
103
109
115
121
127
133
139
145
151
Time (s)

Graph 3

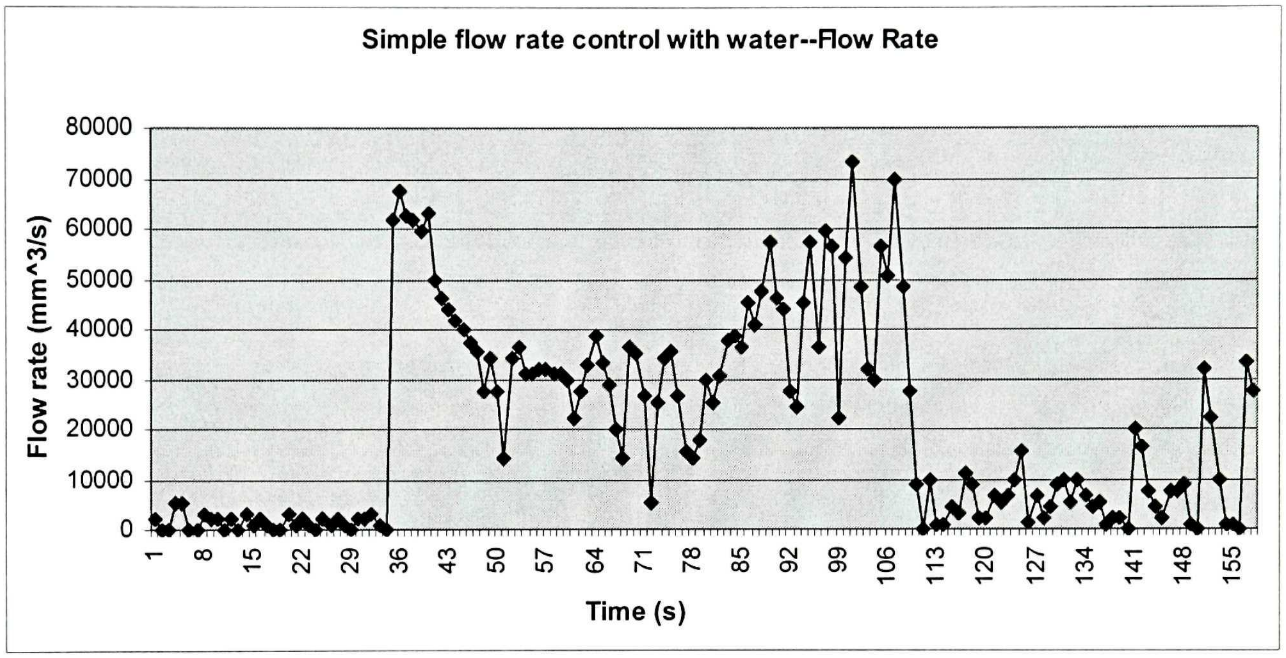
Appendix 5

Simple Flow Rate Control with Water Data Summary

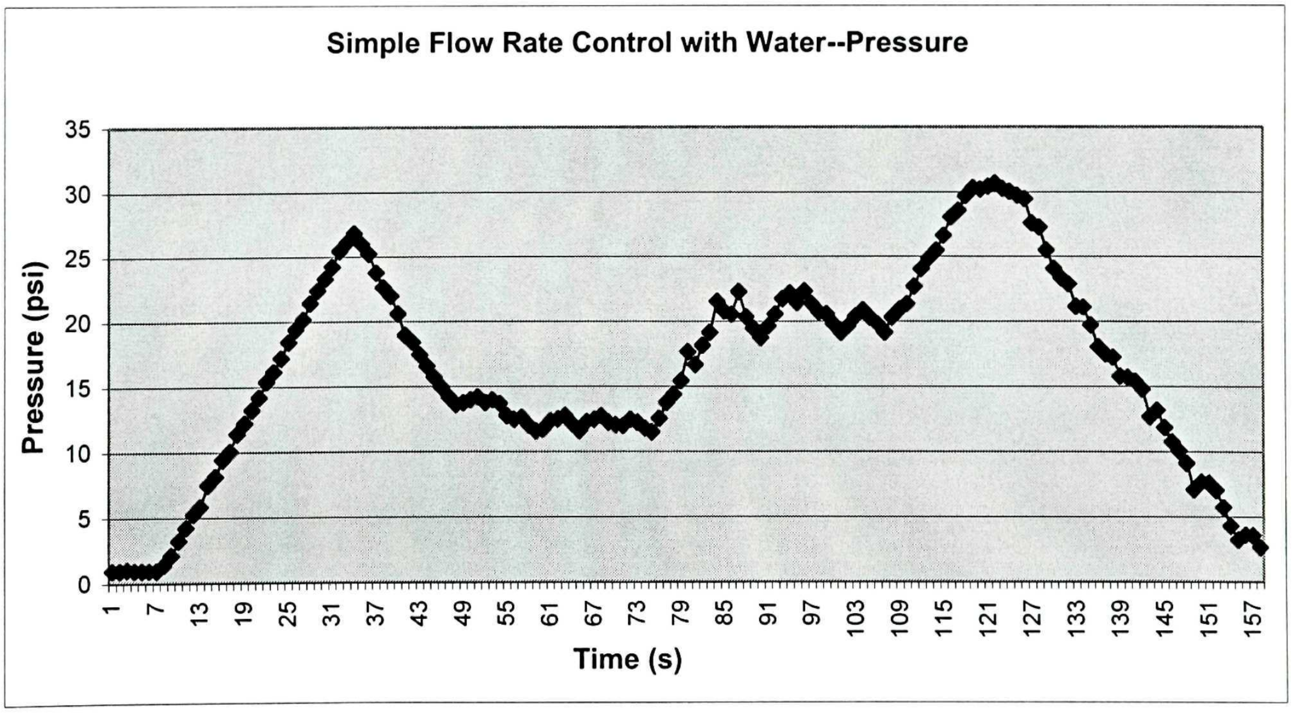
Resin: Water　　　　Simple flow rate control setting data

SimpleFC	First stage	Second stage	Third stage	Fourth stage
FC (1) /PC(0)	1	1	1	1
Time duration	20 s	25 s	40 s	30 s
Initial value	0 mm^3/s	30,000 mm^3/s	30,000 mm^3/s	50,000 mm^3/s
Final value	30,000 mm^3/s	30,000 mm^3/s	50,000 mm^3/s	0 mm^3/s

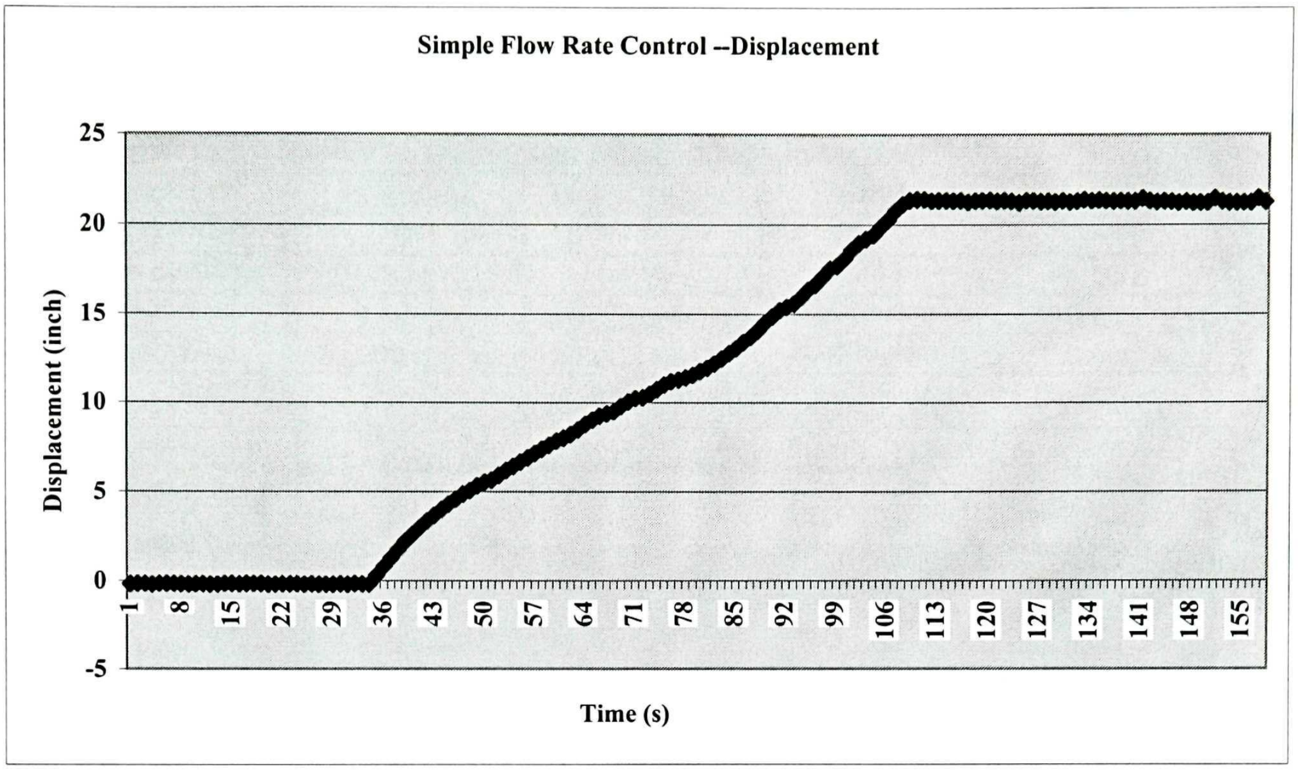
Table 1



Graph 1



Graph 2



Graph 3

Note:

1. The pressure increment is the pressure increase or reduction for every control interval according to the flow rate comparison results. During the first, third, fourth, and fifth stage, the pressure increment is +-1.5 psi/control interval; during the second stage, the pressure increment is +-0.3 psi/control interval. Please refer to session 2.4 for details for understanding how to set the pressure increment.

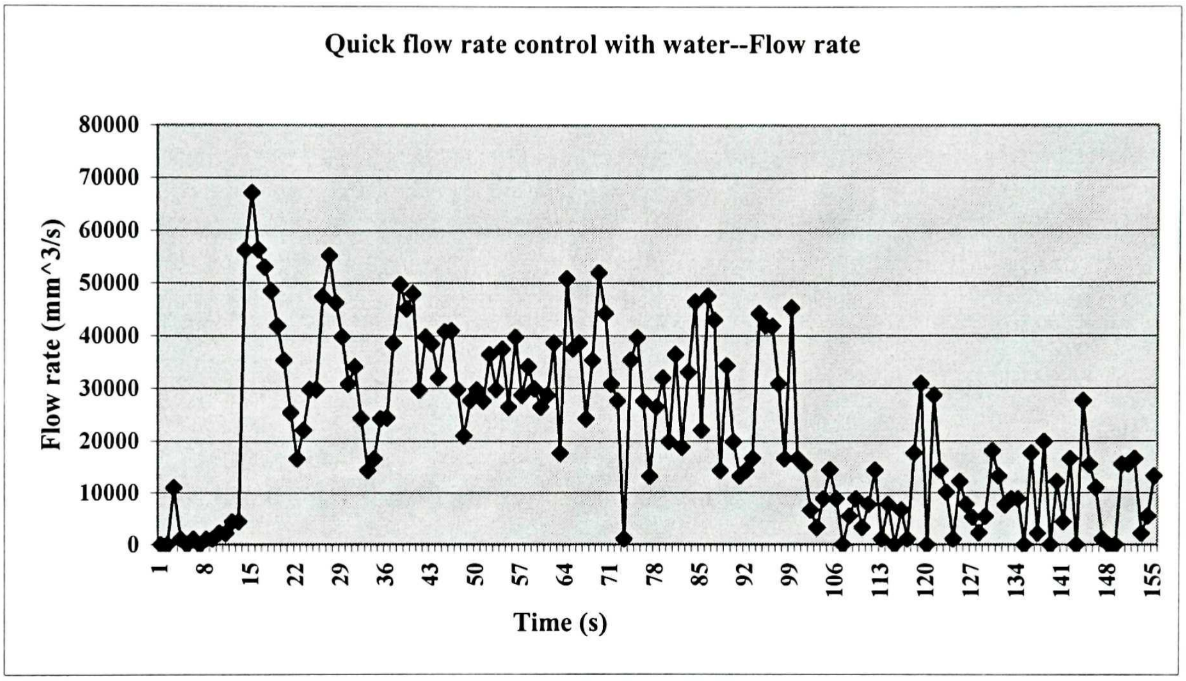
Appendix 6

Quick flow rate control with water data summary

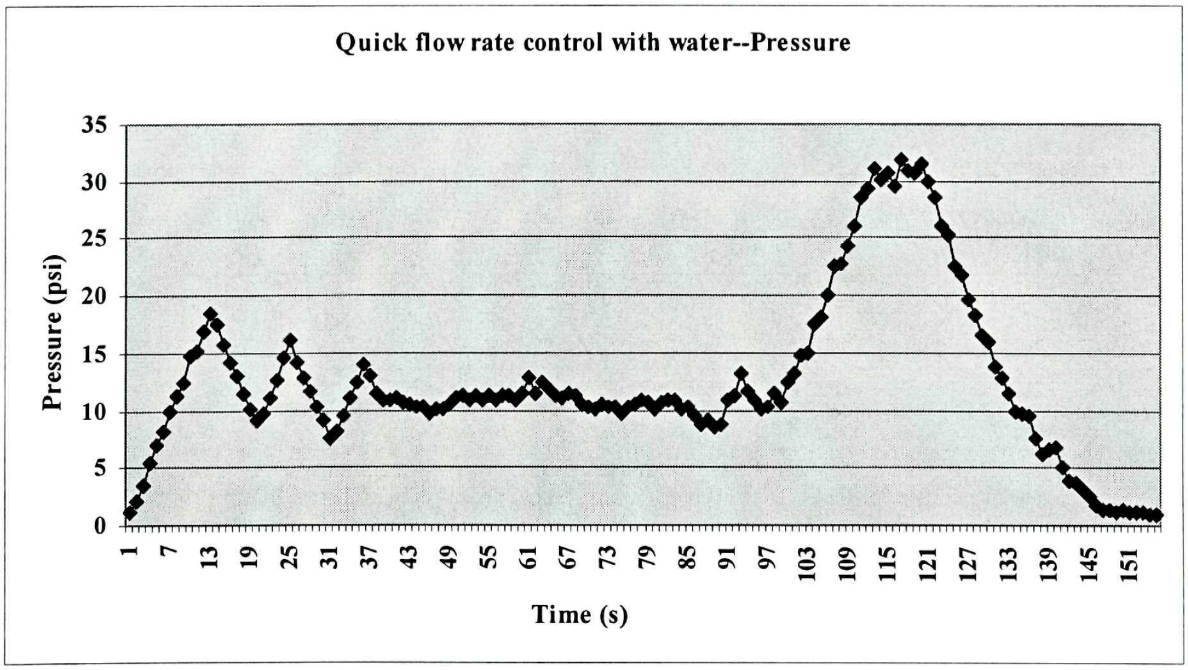
Resin: Water Quick flow rate control setting data

Quick FC	First stage	Second stage	Third stage	Fourth stage
FC (1) /PC(0)	1	1	1	1
Time duration	30 s	40 s	30 s	30 s
Initial value	0 mm^3/s	30,000 mm^3/s	30,000 mm^3/s	0 mm^3/s
Final value	30,000 mm^3/s	30,000 mm^3/s	50,000 mm^3/s	0 mm^3/s

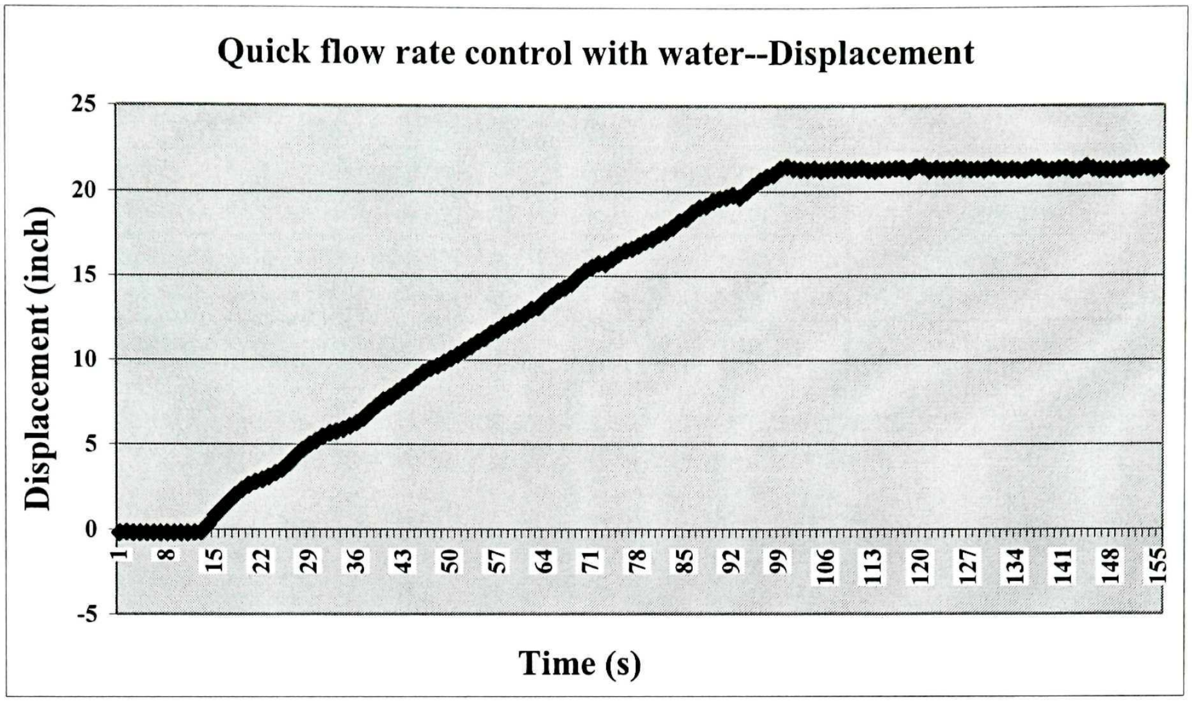
Table 1



Graph 1



Graph 2



Graph 3

Note:

1. During the first, third, and fourth stage, the pressure increment is +-1.5 psi/control interval; During the second stage, the pressure increment is +-0.3 psi/ control interval.

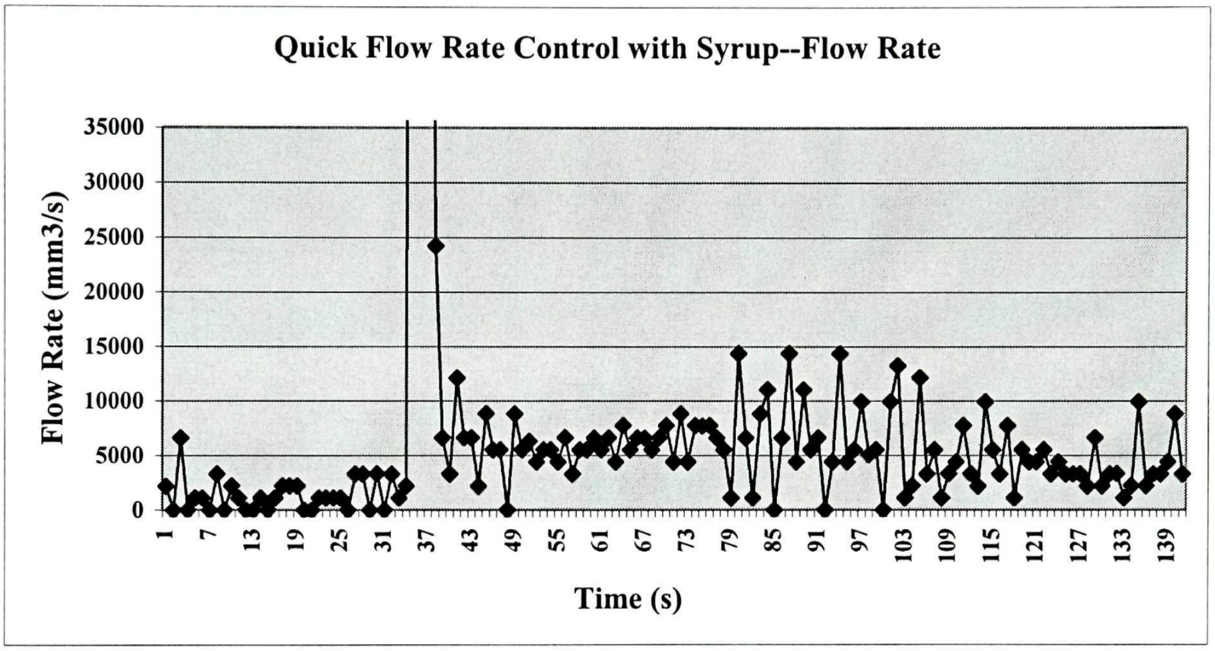
Appendix 7

Quick Flow Rate Control with Syrup 1 Data Summary

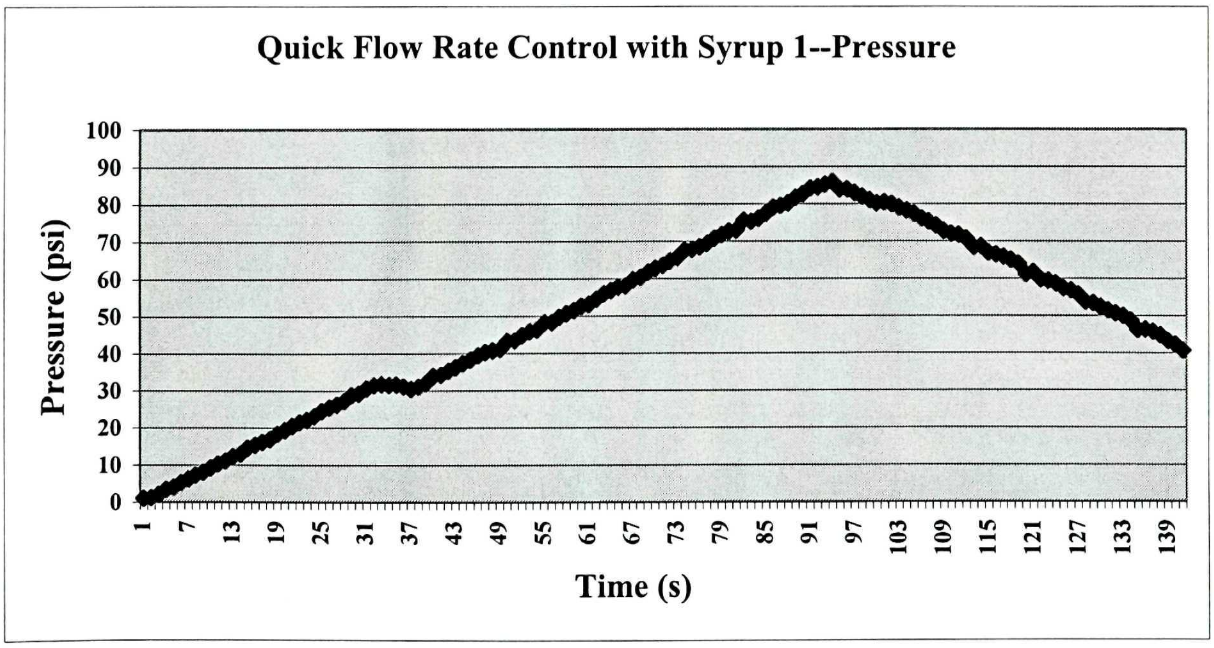
Resin: Corn Syrup   Quick flow rate control with syrup setting data

Quick FC	First stage	Second stage	Third stage
FC (1) /PC(0)	1	1	1
Time duration	40 s	40 s	40 s
Initial value	30,000 mm^3/s	30,000 mm^3/s	0 mm^3/s
Final value	30,000 mm^3/s	30,000 mm^3/s	0 mm^3/s

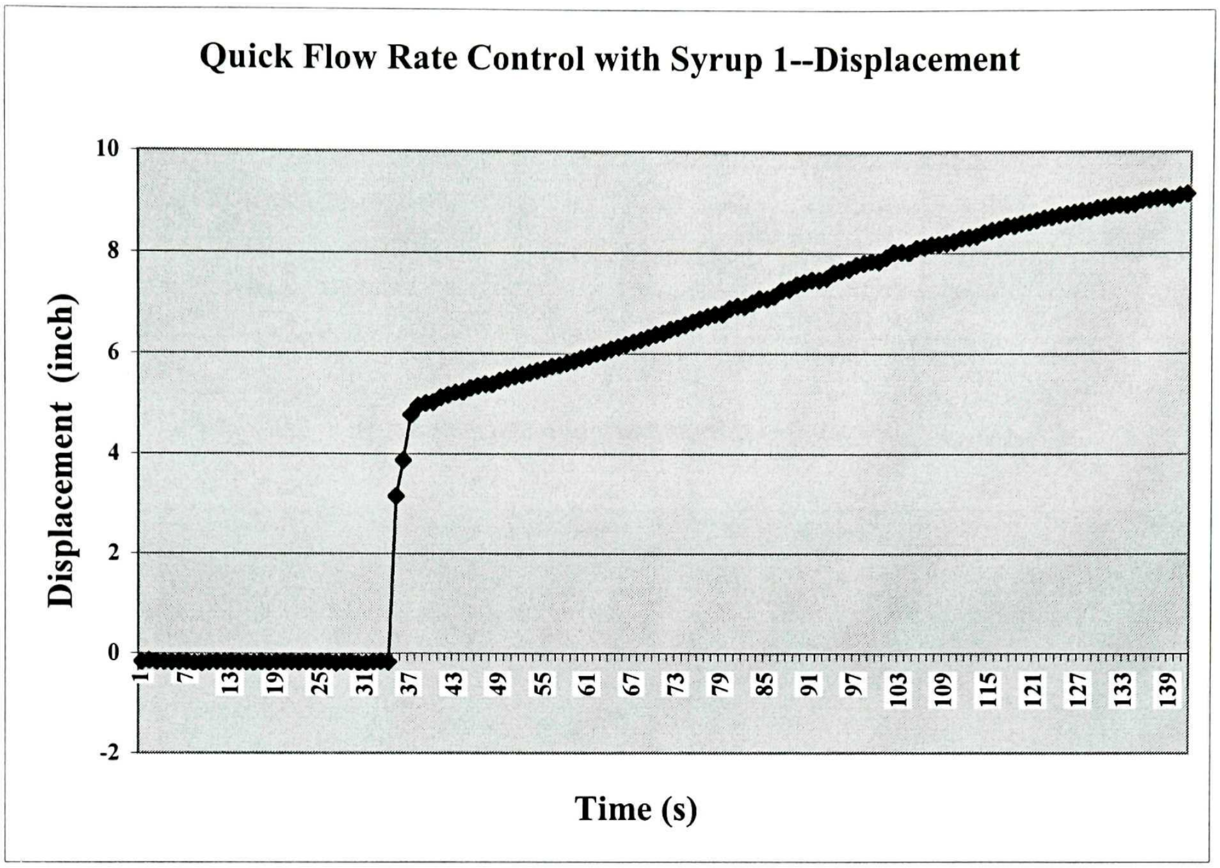
Table 1



Graph 1



Graph 2



Graph 3

Note:

1. The pressure increment is kept at +-0.3 psi/control interval in this experiment.

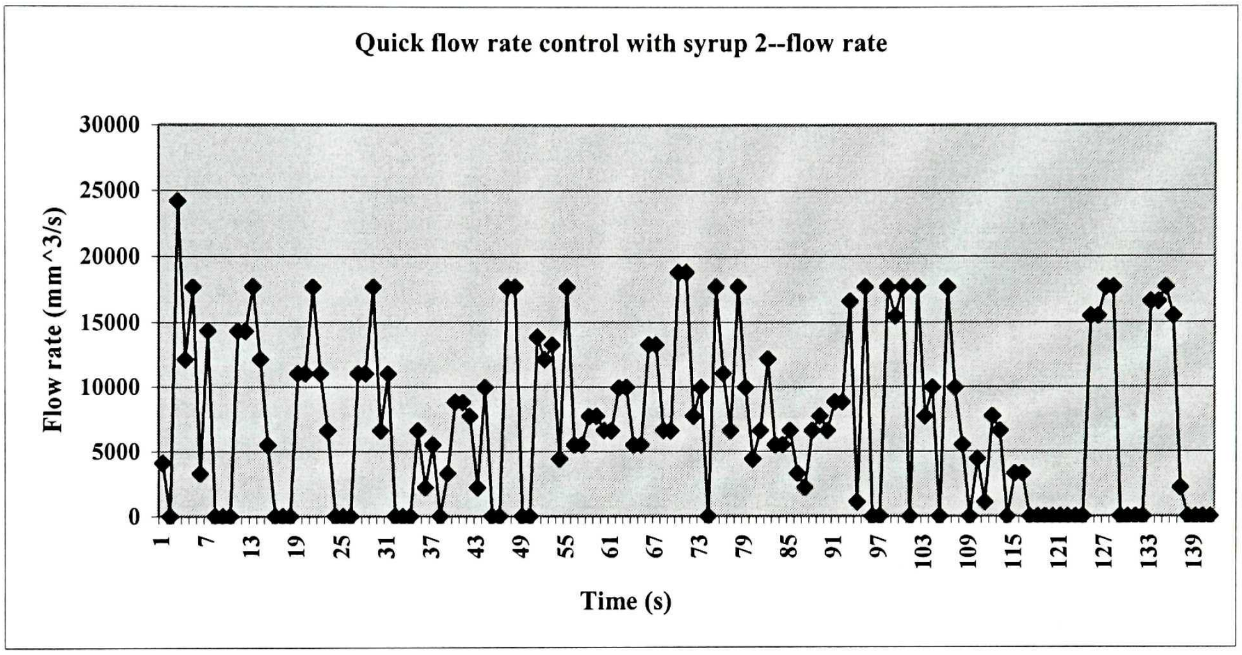
Appendix 8

Quick Flow Rate Control with Syrup 2 Data Summary

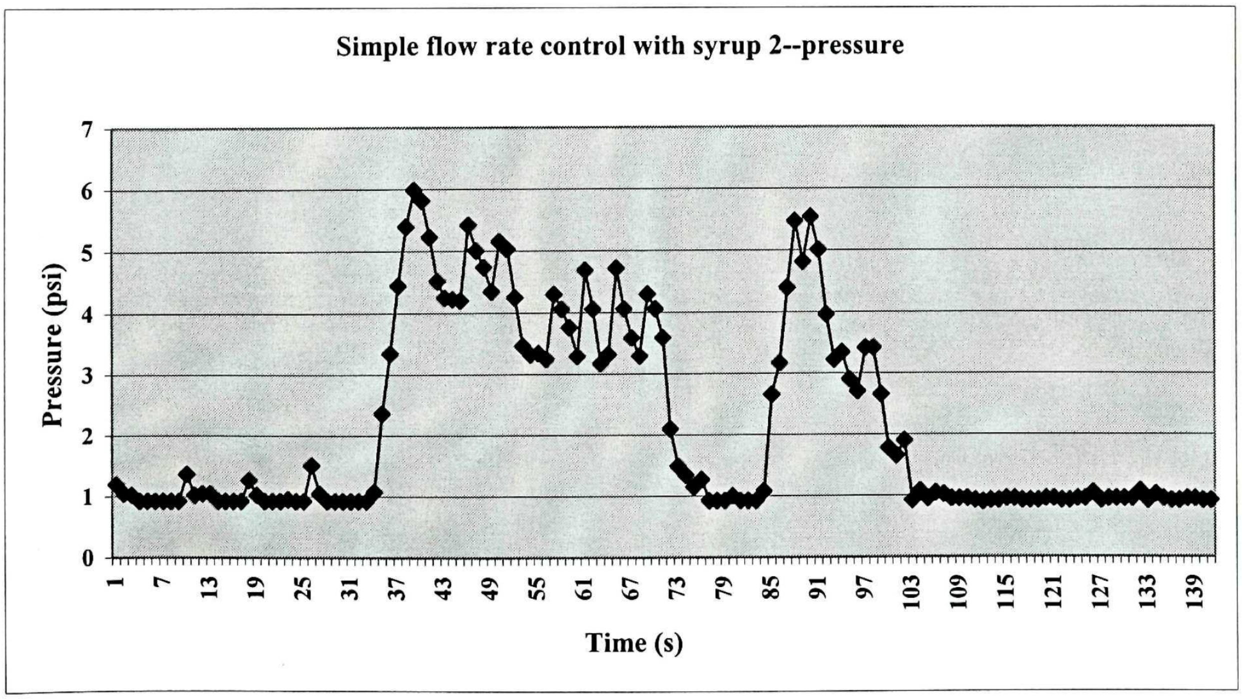
Resin: Corn Syrup Quick flow rate control setting data

Quick FC	First stage	Second stage	Third stage
FC (1) /PC(0)	1	1	1
Time duration	40 s	40 s	40 s
Initial value	7000 mm^3/s	7000 mm^3/s	0 mm^3/s
Final value	7000 mm^3/s	7000 mm^3/s	0 mm^3/s

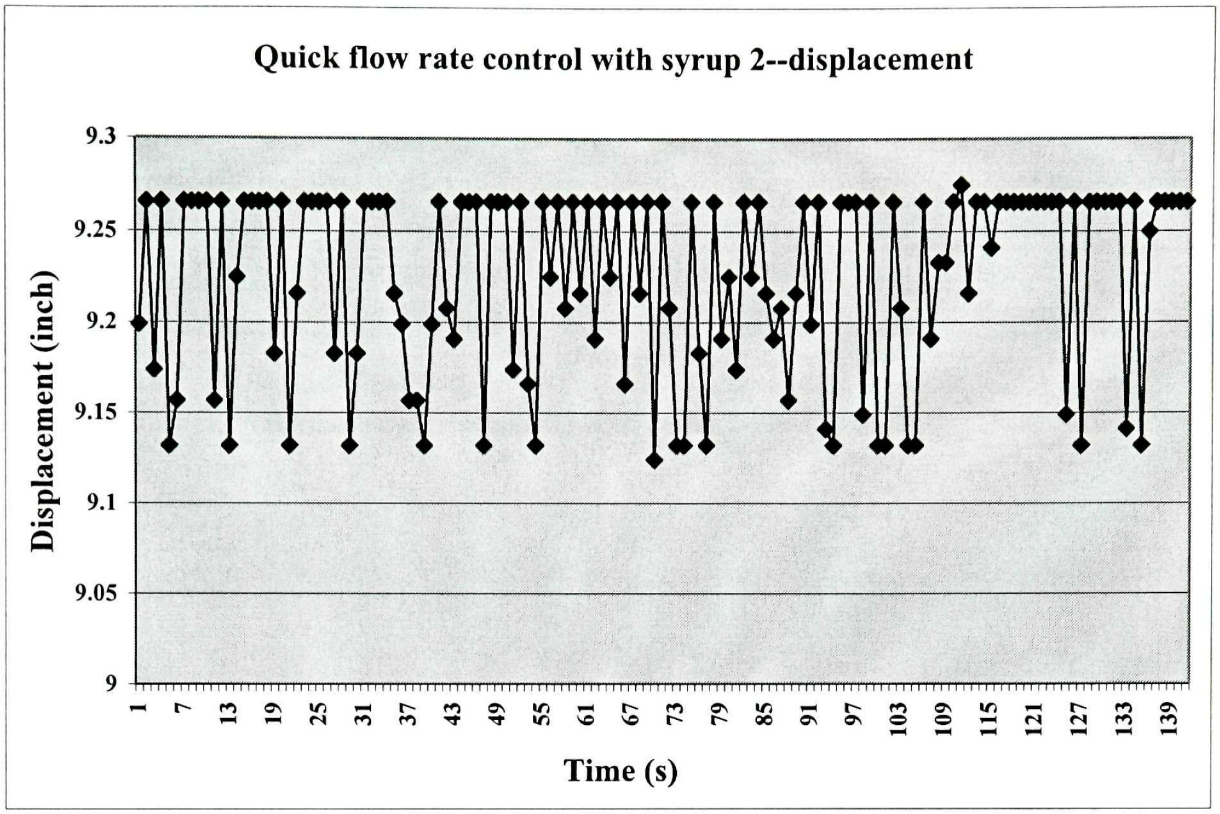
Table 1



Graph 1



Graph 2



Graph 3

Note:

1. During whole injection, the pressure increment is 1.0 psi/control interval.

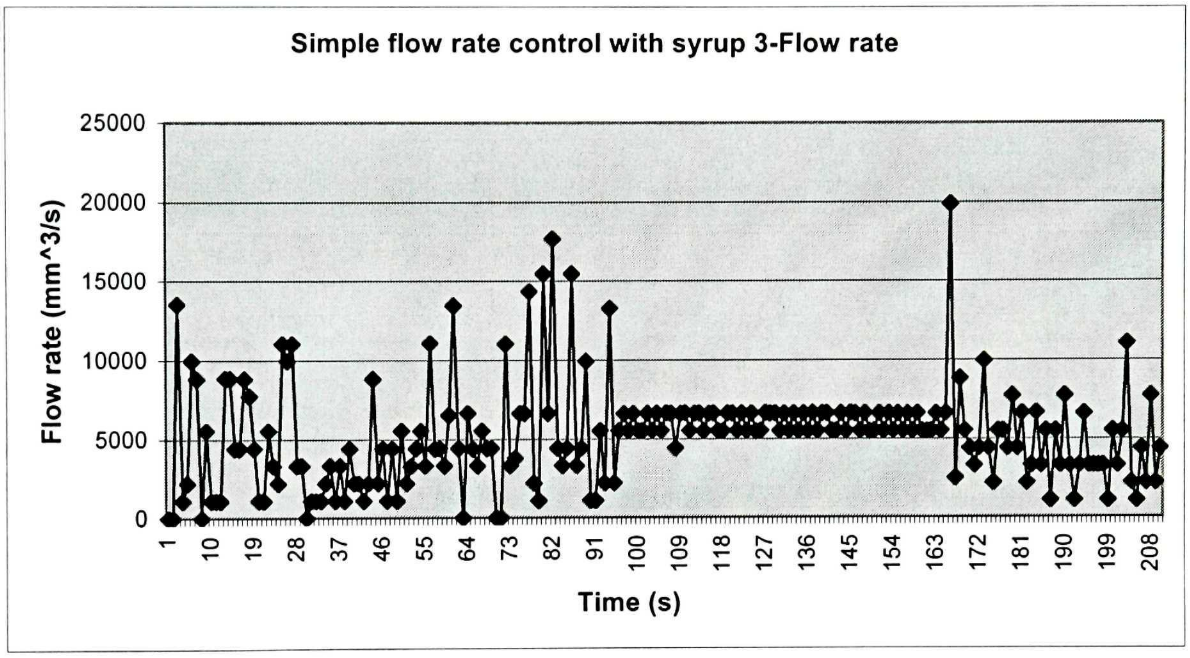
Appendix 9

Quick Flow Rate Control with Syrup 3 Data Summary

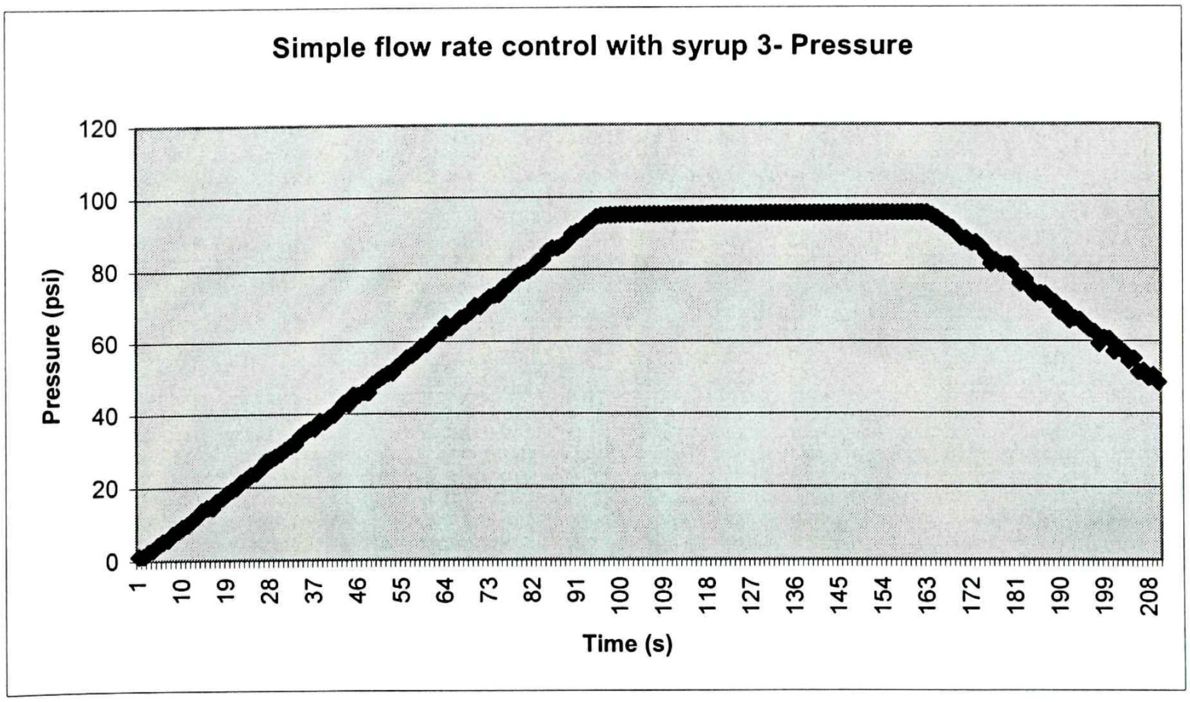
Resin: Corn Syrup Quick flow rate control setting data

Quick FC	First stage	Second stage	Third stage
FC (1) /PC(0)	1	1	1
Time duration	60 s	80 s	40 s
Initial value	30,000 mm^3/s	30,000 mm^3/s	0 mm^3/s
Final value	30,000 mm^3/s	30,000 mm^3/s	0 mm^3/s

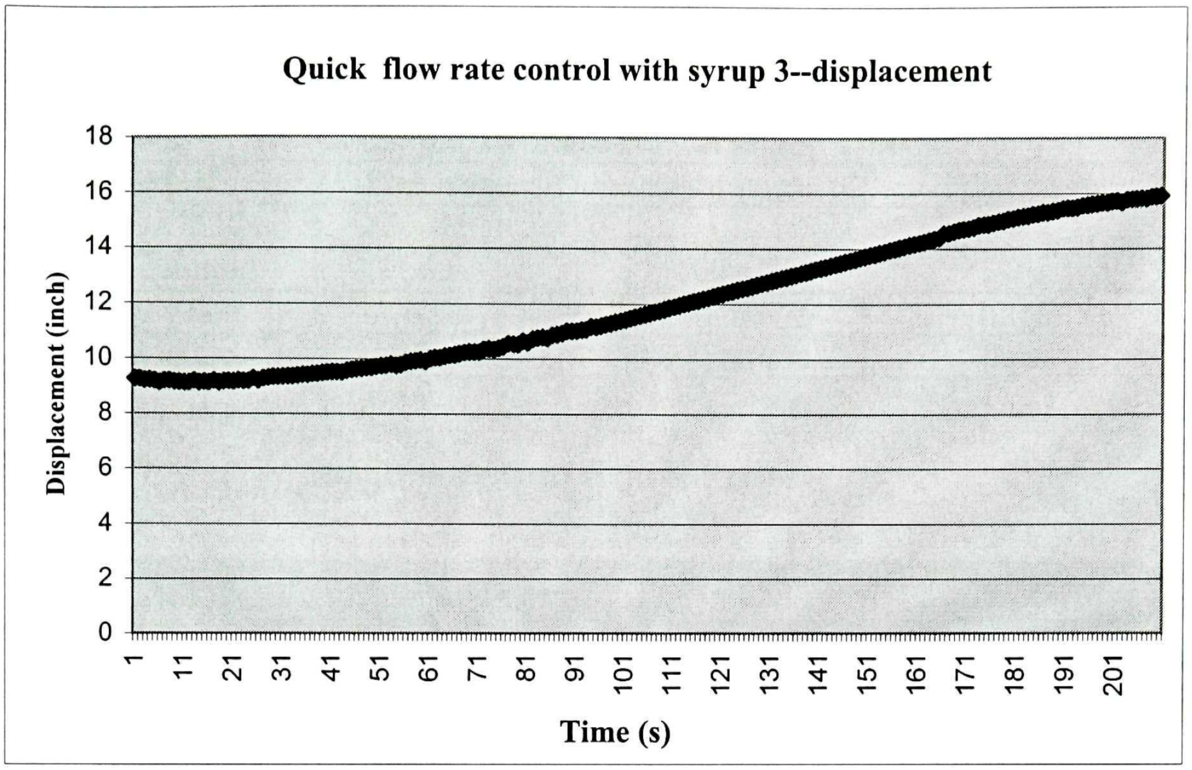
Table 1



Graph 1



Graph 2



Graph 3

Note:

1. During whole injection, the pressure increment is +-1.0 psi/control interval.

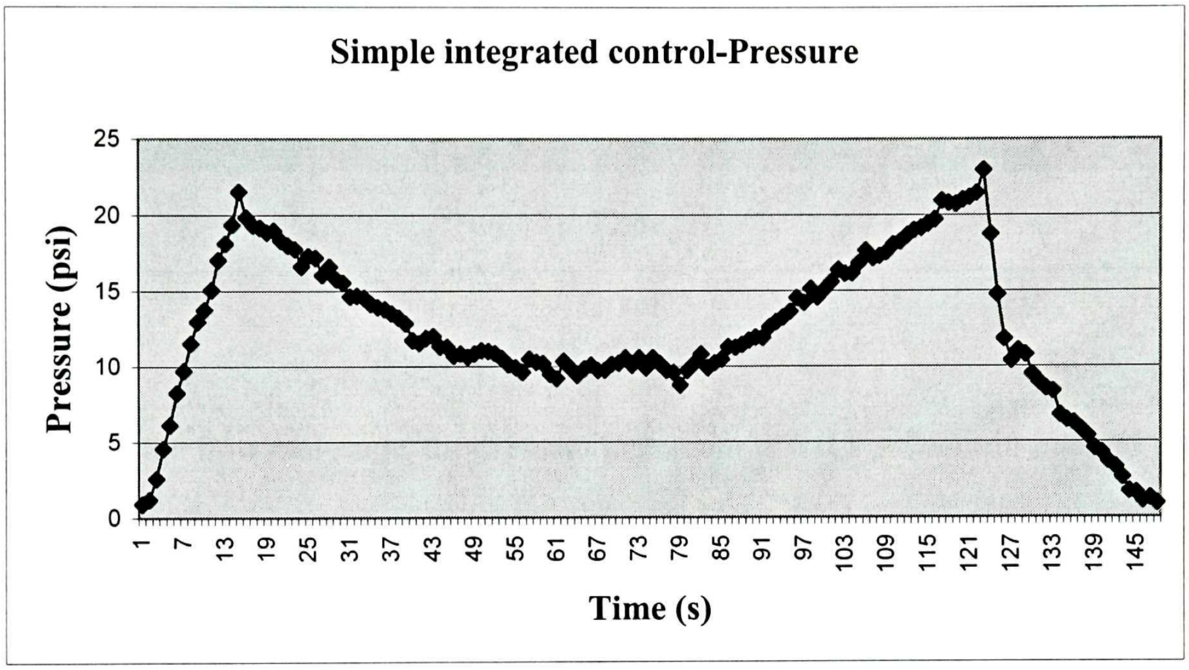
Appendix 10

Simple Integrated Control with Water Data Summary

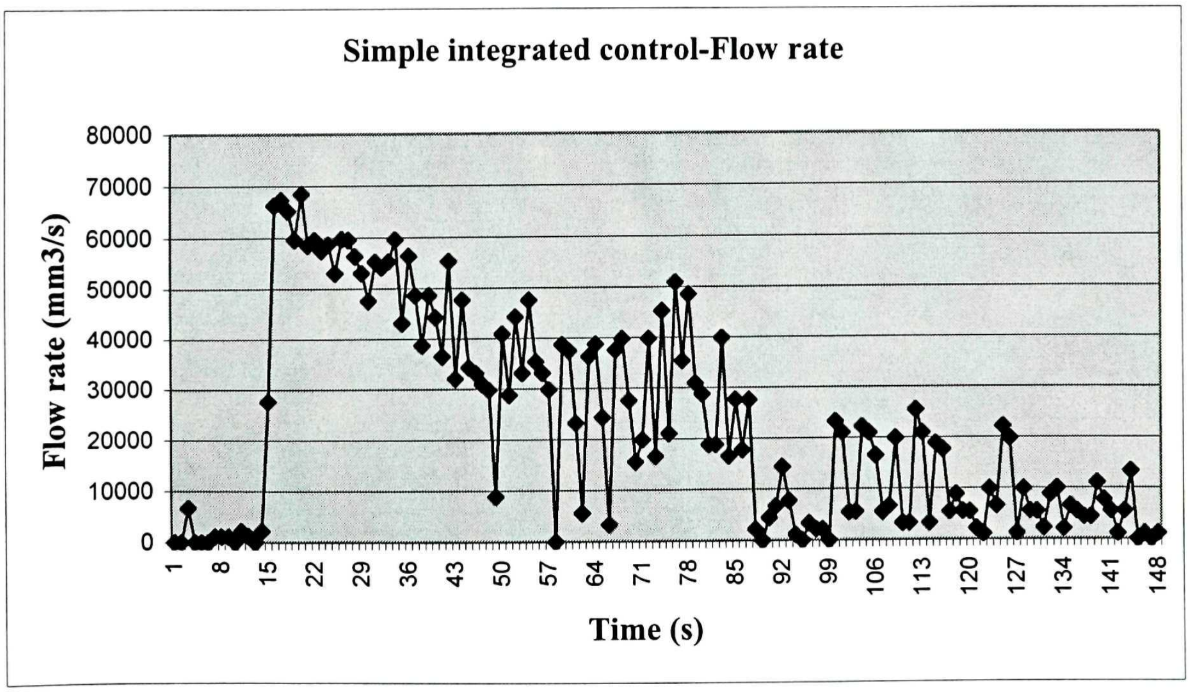
Resin: Water — Simple integrated control setting data

Simple IC	First stage	Second stage	Third stage
FC (1) /PC(0)	0	1	0
Time duration	6 s	100 s	20 s
Initial value	0 psi	30,000 mm^3/s	12 psi
Final value	12 psi	30,000 mm^3/s	0 psi

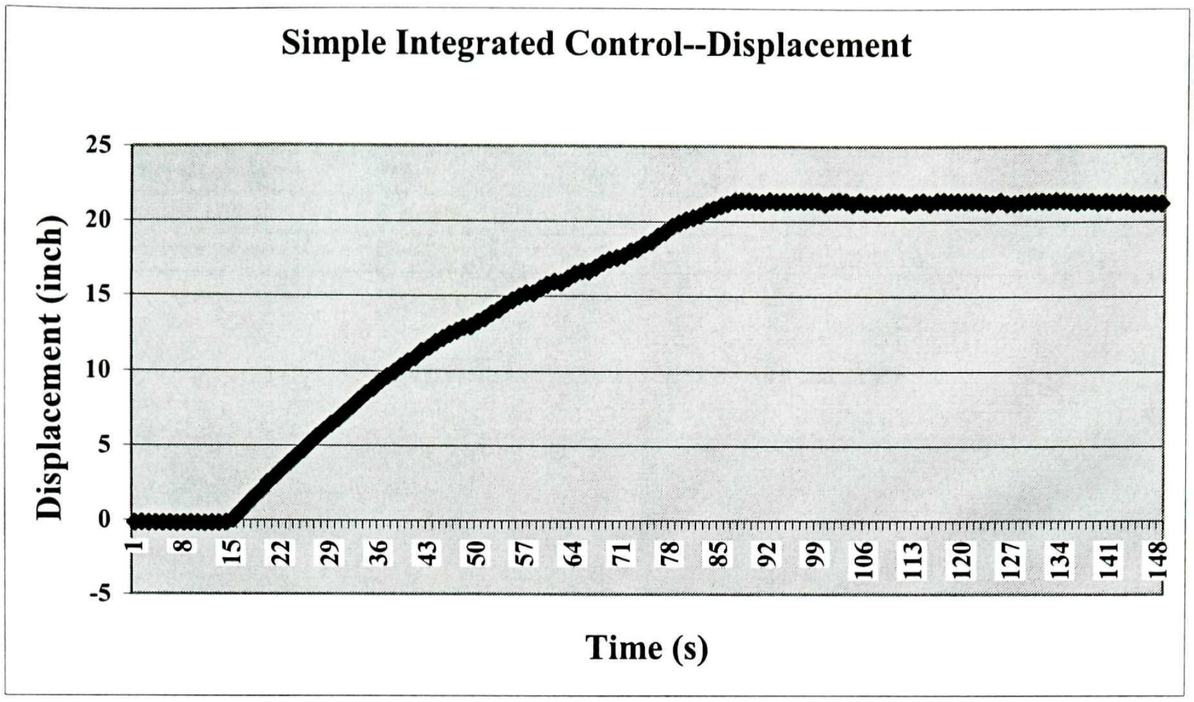
Table 1



Graph 1



Graph 2



Graph 3

Note:

1. During the flow rate stage, the pressure increment is +-0.3 psi/control interval.

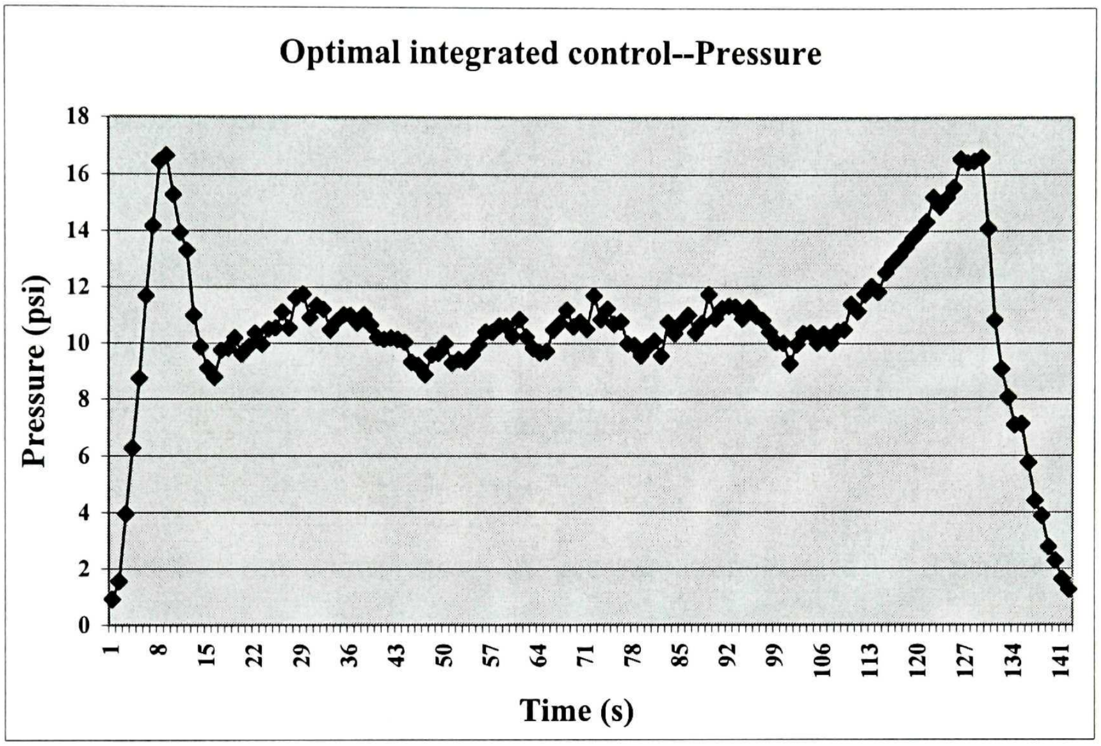
Appendix 11

Optimal Integrated control data summary

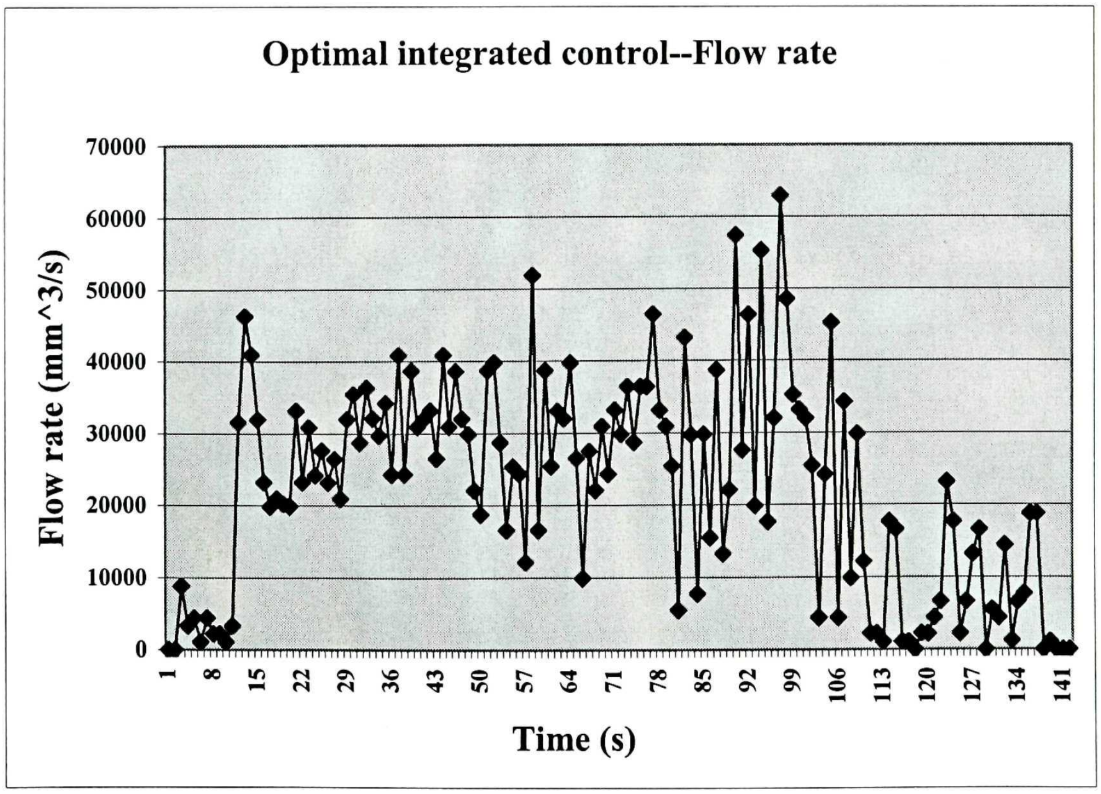
Resin: Water Optimal integrated control setting data

Optimal IC	First stage	Second stage	Third stage	Fourth stage
FC(1)/PC(0)	0	0	1	0
Time duration	6s	4s	100s	10s
Initial value	0 psi	17 psi	30,000 mm^3/s	10.5 psi
Final value	17 psi	10.5 psi	30,000 mm^3/s	0 psi

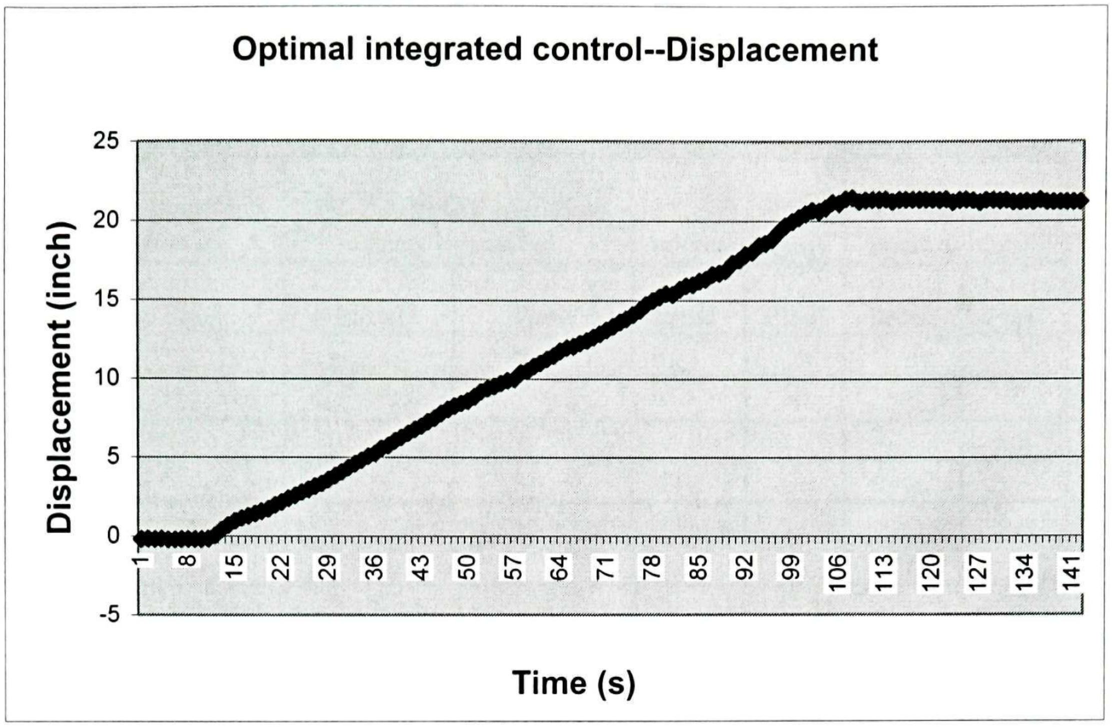
Table 1



Graph 1



Graph 2



Graph 3

Note:

1. During the flow rate control stage, the pressure increment is +-0.3 psi/control interval.

Appendix 12

Sample Injection Control Panel Worksheet
Pressure Control / Flow Rate Control

1.User input of pressure and flow rate

Resin	FC Set before operation ($inch^3$ or mm^3)		FC Set during operation ($inch^3$ or mm^3/s)		PC Set before operation (psi)		PC Set during operation (psi)		Time Duration(s)
Stages	Initial	Final	Initial	Final	Initial	Final	Initial	Final	
1									
2									
3									
4									
5									
6									

Note:

2. Processing parameters

	Set before operation	Set during operation	Note
Run No.			
Quick Increase Rate	Psi/control interval, Yes	Yes	The value does not work with pressure control
Quick Reduce Rate	Psi/control interval, Yes	Yes	
Processing Increase Rate	Psi/control interval, Yes	Yes	The value does not work with pressure control
Processing Reduce Rate	Psi/control interval, Yes	Yes	
File Names	Yes	Never	
Minimum Pressure	Yes	Yes	
Maximum Pressure	Yes	Yes	
Time Trial (MS):	Yes	Yes	

Note:

3.Switch

Items		Set Before Operation	Set During Operation
Mm/Inch	Mm (on)	Yes	No
	Inch (off)	Yes	No
Pressure Increase Rate Changing Switch	Processing (on)	Yes	Yes
	Quick change (off)	Yes	Yes
Injection Direction	Inject (on)	Yes	No
	Retract (off)	Yes	No

Note:

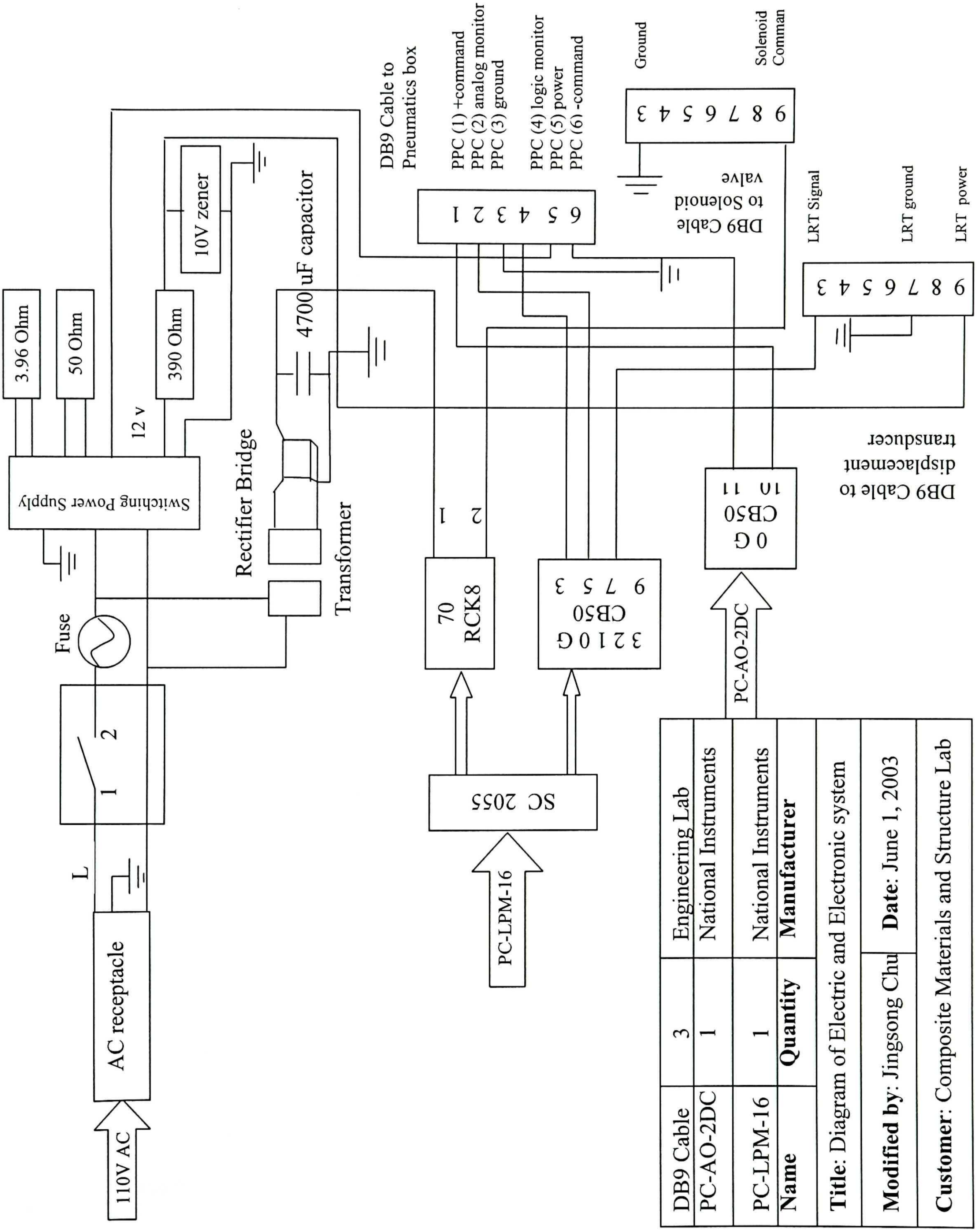
4.Parameters must be reset or recorded during operation:

Begin Calculate Resin		Inject beginning time	Resin moving pressure	Finish injecting time
On	Off			

Resin Used:__________mm^3 or __________$inch^3$

Note:

Appendix 13 [17]



DB9 Cable	3	Engineering Lab
PC-AO-2DC	1	National Instruments
PC-LPM-16	1	National Instruments
Name	**Quantity**	**Manufacturer**
Title: Diagram of Electric and Electronic system		
Modified by: Jingsong Chu		**Date**: June 1, 2003
Customer: Composite Materials and Structure Lab		

Appendix 14 [20]

Real part experiment procedure with intelligent injection system

Experiments have been done with Epoxy and Polyester under constant pressure control. Because of the presentation of noise inside the system, an accurate flow rate control was not tried with these two types of resin.

1. The mold set-up and fitting installation

The intelligent injection system is not involved in this stage.

- Apply one slight coat of 3M-spray glue to the outer walls of the upper part of the mold and to the inner and lower walls of the rubber seal, this will be useful to help the seal support the injection pressure.
- Apply the sealer Loctite (Frekote B-15) to all the surfaces that will be in contact either with the resin or the mold itself. Let it dry for 30 minutes, and repeat this operation, leaving it to rest for 24 hours.

  Note: This step will be done only once.
- Put a layer of Dexter (Frekote 770-NC) on the exactly the same parts and their surfaces as did in the previous step. Allow it to dry for 30 minutes, and repeat this operation 3 times, leaving it to dry for 30 minutes each time.

  Note: One layer of Dexter (Frekote 770-NC) will be applied every one or two injections, as required.
- Please refer [22] for the detail of fitting connections and hose connections.
- Situate a plastic bucket at the bottom of the vacuum tank large enough to prevent any spilling of the resin during injection.

- One hose will join the vacuum outlet of the mold and the vacuum tank. Situate one end of hose in the vacuum tank, passing through the inlet until the tip of the hose reaches the plastic bucket in the tank. The gummy tape should serve as a sealant between the hose and the remaining space on the cap of the tank.

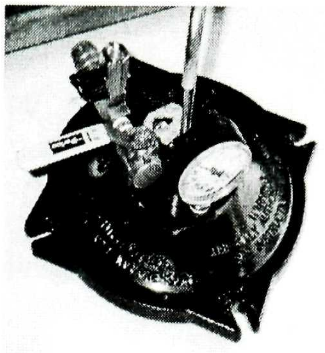


Figure 14A.1 Tank Cap

- Close the tank tightly and make sure all the connections in the tank are completely sealed and there is no leaking.
- The Vacuum tank will be bonded to the vacuum pump. However the pump will not be in operation until a certain time during the injection.

2. System connecting

Please refer to Figure 14A.2 for the cable position on the electronic box.

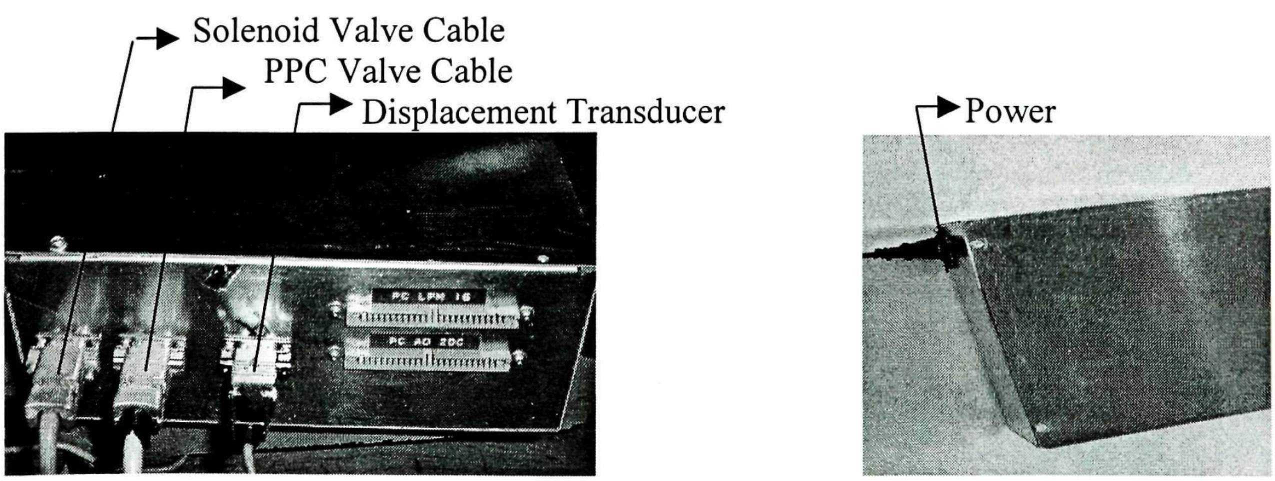


Figure14A.2 Pictures of Electronic box with connecting cables

- Connect the computer boards PC-LPM-16 and PC-AO-2DC with the Corresponding sockets on the electronic box by ribbon cables.
- Connect the displacement transducer with the electric box by the displacement signal cable of the injector.
- Connect the solenoid valve control cable with the corresponding socket on the electronic box.
- Connect the PPC valve control cable with the corresponding socket on the electronic box.
- Supply the power to the electronic box.
- Connect the shopping air with the air inlet on the Filter-lubricator-regulator (FLR) on the pneumatic box.
- Connect the regulated air pipeline from PPC valve with the inlet of manual valve controlling the injection direction.

After the connecting is finished, the system will look like the picture in Figure 14A.3.

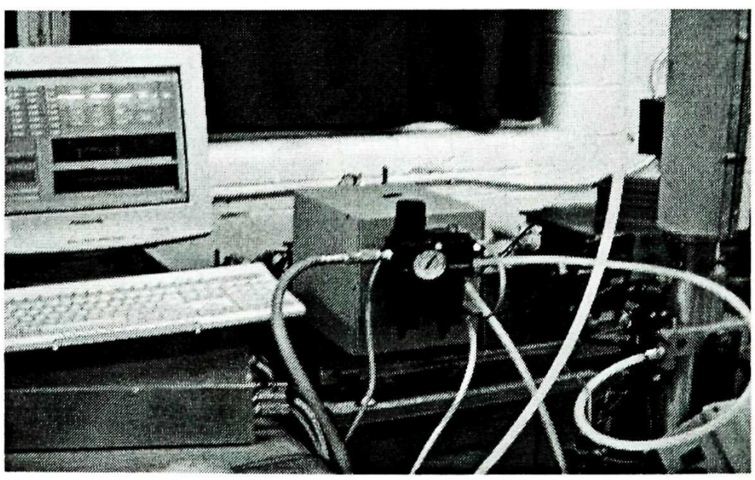


Figure 14A.3 Intelligent Injection system setup

3. Computer Set up

Please refer to Figure 2.4 for the Control Panel of this system on the desktop. Specific injection molding processing parameters should be designed and entered into the computer.

- Turn on the computer and double click on the label 'Final Injection Control Panel' on the desktop. The program should be in the default run state, if not the case, click the Run button on the left upper corner of the front panel.
- Set up the injection process parameters according to the worksheet you have made for a specific manufacture. Please refer to the Appendix 12 for the General Worksheet. The sheet will help the users set processing parameters step by step. Care must be taken in distinguishing the parameters that must be set before processing from those that must be set during the operation and the button must be turned on during the operation.
- Press green 'START' button will start the program.

4. Insertion of the fibers into the mold and mold fasten

The intelligent injection system is not involved in this stage.

- The fibers have to be cut to the exact same shape as the mold, but slightly smaller on 3 sides (left, right and back). This reduction on left and right is to allow the gummy tape to fill in the space between the inner walls of the mold and the fibers; the reduction in the back is to allow the rubber insert to be placed to make demolding easily.

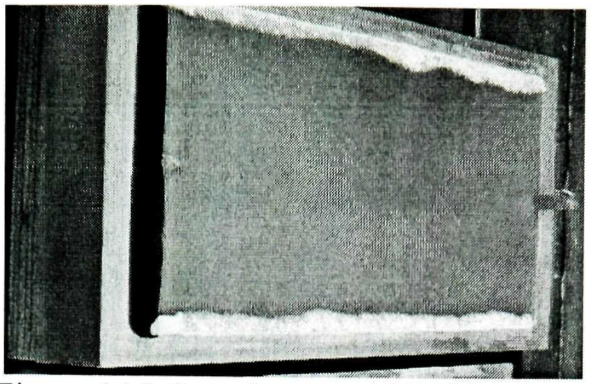


Figure 14.3 Sample part and Rubber insert

- The lower part of the mold is located on the securing table, then the upper plate and later, then 4 clamps will be employed.

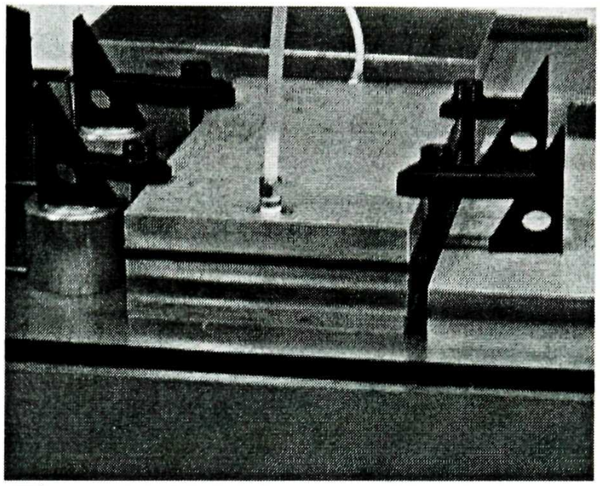


Figure 14.4 Mold Fastened by 4 clamps

5. Preparation of the resin-hardener mix

The intelligent injection system is not involved in this stage.

- Get all the essential materials ready at hand: resin, hardener, plastic recipient, latex gloves, plastic agitator, plastic sheet, and a scale (weighing machine). A plastic sheet will be put on the top of the scale to protect the scale.
- With the gloves, start by weighing the resin and the hardener. In the case of Epoxy the mix ratio is 100:25 resin to hardener; for Polyester it is 200:1.

- The resin and the hardener will be mixed in the plastic recipient and stirred with the plastic agitator. The stirring time also depends on the type of resin used. For Epoxy, the time is between 5 and7 minutes; for Polyester, the time is approximately 1 minute because the mixture cures quickly.
- To degas the mixture or not is up to the type of resin used. The degassing work is usually done with the epoxy, but not with the polyester due to the fast curing.
- Place a plastic bucket in the vacuum tank, and then situate the plastic recipient that contains the mix already stirred in this bucket.
- Close the tank tightly and make sure there is no leakage in trial vacuuming.
- Connect the vacuum pump to the tank and apply up to 30 inches of Mercury. Increase mercury from 0 to 30 around 5 inches per 30 seconds. When the 30 inches are reached, keep the vacuum applied for 6 minutes.
- Disconnect the Vacuum pump and decrease the vacuum pressure to 0 inch mercury at 5 inch every 30 seconds.
- Open the cover of the vacuum tank; the resin should have no bubbles at all. If there are still some bubbles on the surface of the mix, repeat this operation, and leave it at full vacuum for a longer time something like 9 minutes.

6. Injection

- Place the manual lever in the middle position.
- On the Injection Machine Control Panel, set a minimum pressure value and right time required for adjusting the piston position by reading its displacement display on the control panel. Operate the manual value level to move the piston to a height that is suitable for the amount of resin-hardener mix to be injected; This means not to leave

too much space that will be filled with air when the injection machine is closed. Keep the level in the middle position, and shed the mix into the injection cylinder very slowly starting at an angle of 45°; the cylinder itself must be at a 60° angle.

- Turn off the program by pressing the red 'Emergency Stop' button to restore the pressure to zero and then click on 'Start a New Program' button to reset the file name, minimum pressure and other processing parameters when needed. Care must be taken in setting a different file name, otherwise the processing parameters will be written to the wrong file.
- Locate the cap of the injection machine in the cylinder, close and secure the threaded nut cap that goes at the top of the machine.
- Turn on the vacuum pump and exert vacuum for roughly 4 minutes. Turn off the vacuum pump and the flow control valve to keep the achieved vacuum throughout all the injection.
- Have a clamp and a pair of pincers ready at hand, and place them on the side of your vacuum hose to facilitate their immediate use when requested. The pair of pincers can be used to clamp the hose so that the air flows faster than the resin during injection, and the clamp will stop the flow completely when the injection finishes. See Figure 14A.5.
- Place the level at up position.
- Press the green "START" button when everything is ready to start the process.
- Watching the displacement display indicator on the desktop, when the injection reaches 70%, start clamping the outer hose, the one that is connected to the vacuum tank; repeat this operation every 7 seconds, waiting for the injection to reach 90%;

keep it clamped for about 3 seconds each time and loosen it very slowly. When piston position is in the range of 20.32-20.82 inches (the total length is 21.32 inches, something there may be some tolerance due to calibration), stop the injection by clamping the outer hose.

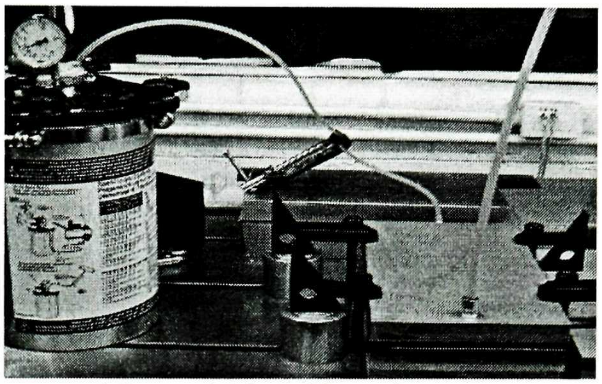


Figure 14A.5 Clamping

7. Curing Process

During this stage, the intelligent injection system is exerting a packing pressure that is critical to product quality. The program will automatically exert this pressure and stop under the control of processing parameters.

8. Demolding Process

The intelligent injection system is not involved in this processing stage. The part is taken out by hand from the mold.

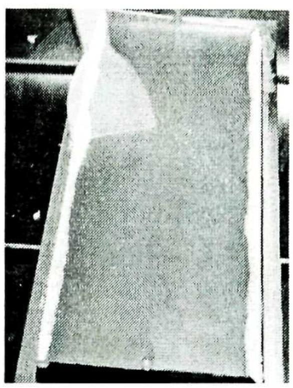


Figure 14A.6 Demolding