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# ACTIVE CONTROL OF THE VACUUM INFUSION PROCESS

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**ABSTRACT:** Heterogeneity in fibrous reinforcements can lead to unforeseen, unpredictable and at times, problematic flow patterns. This necessitates the injection of additional resin into the mould to ensure complete part infusion, creating higher resin wastage. In many cases, resin starts to cure before the infusion is complete, leading to higher part rejections. To address this issue, a new active injection control system is proposed. In addition, a camera-based system is also proposed for flow monitoring in the Vacuum Infusion process. The control system is capable of monitoring resin flow, identifying flow disturbances and taking an appropriate corrective action in real-time, through computer-controlled injection ports. The system has been fully implemented in a computer code and is validated through infusion experiments.

**KEYWORDS:** Polymer Composites, Vacuum Infusion, Active Control, Image Analysis.

## INTRODUCTION

Vacuum Infusion is a low cost process for manufacturing parts with large surface area to volume ratios. The process involves placement of cut reinforcement onto a solid mould bottom half, placement of vent and resin injection lines at pre-determined locations and sealing of the mould using a flexible mould top half. Many times, the reinforcement is also covered with materials to facilitate uniform vacuum pressure, resin flow and part extraction. The sealed mould is evacuated through vent lines which creates a driving potential for resin injection through the injection lines. The quality of manufactured parts, characterised by various mechanical properties, depends on the level of the reinforcement infiltration through resin flow [1]. Incomplete or partial infiltration of reinforcement can lead to dry spots, added salvage costs and many times, complete part rejection [2].

Many research efforts [3-6] have focused either on developing a fundamental understanding of the VI process or on applying current knowledge to design and develop modelling tools which replicate the process. The aim of such approaches is to reduce manufacturing costs, increase the part quality, and improve process reliability.

It is widely known that the reinforcement is heterogeneous in nature [2] and the level of heterogeneity varies with reinforcement architecture [7, 8]. In addition, the influence of heterogeneity depends on the reinforcement permeability. However, in general, the reinforcement is considered homogeneous for ease of modelling [2]. This generalisation, in addition to difficulties associated with reinforcement permeability characterisation, has led to limited success of these approaches.

Another alternative is to employ sensors to collect flow information and use this information for active control of the infusion process. This approach has been reported widely for the Resin Transfer Molding (RTM) process [9-11]. However, very few efforts [12, 13] have been reported for the VI process. Johnson and Pitchumani [12] proposed of producing localised changes in the infiltration rate through changes in resin viscosity. For this, an induction heat source was used. Based on the feedback from flow sensors, the location and the output of this heat source were controlled by a computer. The system was validated with numerical simulations. The system is limited to resin systems with long cure times.

Bender et al. [13] reported an injection system based upon active control of the injection flow rate. For this, the resin supply bucket was placed inside a pressure vessel. A fuzzy logic based controller altered the pressure inside the vessel. The system was validated using numerical simulations and experimental implementation.

The limited number of efforts aimed at controlling the VI process, is mainly due to large number of sensors required for flow monitoring. In addition to cost considerations, part intrusiveness is also a major factor. In this paper, we report the development of a low cost, non-intrusive flow sensing system. This system has been integrated with a flow simulation tool and other control hardware in an actual experimental set-up. Results from actual infusion experiments are also reported.

## CONTROL SYSTEM

### Design

The on-line control system developed in this work utilizes an image acquisition and analysis system to collect information about the flow progression inside a closed mould with at least one transparent side. This information is used to define the nodal fill-factors (initial conditions) for mould filling simulations. With a pre-defined set of port configurations (injection schemes or boundary conditions) and the initial conditions, mould-filling simulations are performed to predict flow advancement over the next time period. Then, the optimisation algorithm uses a pre-defined cost function to select an optimum injection scheme i.e. from the simulation results, a value of a cost function for each port configuration is calculated and the configuration with the lowest value of the cost function is relayed to the computer controlled injection valves to correct the flow deviations. The strategy is repeated during the entire infusion phase in a series of control steps. Figure 1 shows a flow chart of the system.

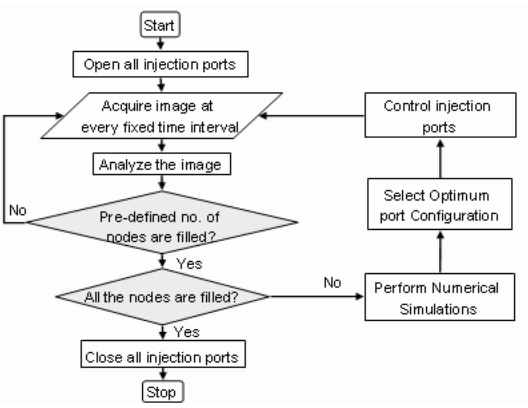
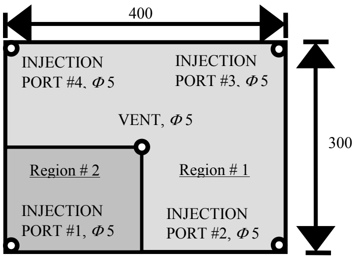


Figure 1 Flow chart of the control system.

Next, the development and implementation of each individual control step is reported for a model case study. The mould (Figure 2), in this case study, had four injection ports located in four corners, while the vent was located in the centre. It was packed with three rectangular layers (Figure 2 Region # 2), of one quarter the mould size, of bi-axial reinforcement (FGE 106, Table 1) sandwiched between two layers (Figure 2 Region # 1) of Continuous Fibre Random Mat (CFRM, Unifilo U750/450, Table 1).



All dimensions are in mm.

Figure 2 Schematic of the mould used in the case study to demonstrate the development and implementation of the control system.

*Image Acquisition and Analysis*

Top side images, of the mould during the infusion phase, were captured using a web-camera (Fire-i™, Unibrain S.A.). The 640x480 pixels resolution images were captured at a fixed time interval of one second. Analysis of the captured images was performed in MATLAB™ using the native image analysis toolbox. The captured images were processed to select a region of interest. In addition, the images were processed to remove a perspective. Then, they were passed through an averaging and a high-pass filter to convert them into binary images. Note that the relative position of the camera with respect to the mould can vary between experiments. Hence, the entire image acquisition and analysis system was calibrated before the start of any experiment. Then, the stored calibration values were used during the actual infusion experiment.

*Numerical Simulations*

The flow advancement simulations in this work were carried out using LIMS. LIMS is a finite element/control volume (FE/CV) method based flow simulation tool, developed at the University of Delaware, the details of which can be found elsewhere [14].

Before starting the infusion, a set of sixteen simulation models, corresponding to the 16 individual permutations of the possible port configurations for four injection ports (Table 3 A), was generated. Each port can be in either an open or a closed configuration. In addition, the entire mould filling phase was divided into a number of equal control-steps such that in each step, a pre-defined number of nodes are required to be filled (a filled node lies in the infused region, while an unfilled node is outside the infused region). It is important to distinguish between a time-step and a control-step, which is a set of time-steps.

At the start of any control-step, the current flow front status in the experiment was used to describe the initial conditions (or nodal fill-factors) in all the numerical models. This was done by assigning the fill-factor of each node the same value as that of the corresponding pixel in the matrix of the binary image (Figure 3). Numerical simulations were performed to advance the flow in all models individually until the end of current control-step.

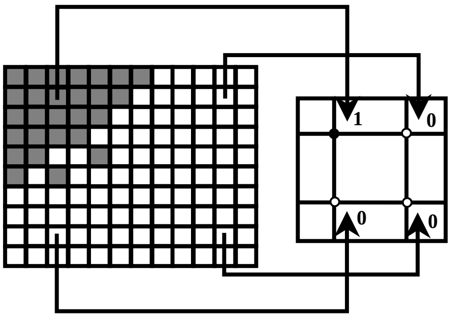


Figure 3 Definition of nodal fill-factors in the numerical model from the captured image.

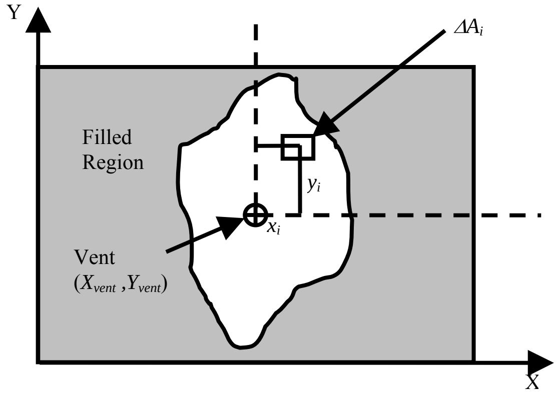
*Control Algorithm Design*

To select an appropriate corrective action from the available choices, design of a port configuration selection strategy is necessary. This strategy involves defining a cost function as well as its preferred optimum value (maximum or minimum). Various cost functions such as fill-time, weight ratio of resin wasted via bleeding to the porous volume of the mould, distance between the centroid of an unfilled region and the vent (henceforth, denoted as the centroid scheme) etc. were considered. The centroid scheme, with minimum as the optimum value, was chosen as it indirectly reflects the other cost functions.

Figure 4 shows a schematic of the centroid scheme. Using the simulation results, the centroid of an unfilled region, and hence the value of the cost function (the distance between the centroid and the vent), was calculated for all port configurations. The configuration with the lowest value of the cost function was selected as an optimum injection strategy for the next step.

*Hardware Interfacing*

The optimum port configuration as selected by the control algorithm is relayed to solenoid valves, which control the resin injection and hence the infusion process. In this work, each injection port was connected to a solenoid valve (Type 6213, Burkert Contromatic) having a response time of 700 milliseconds. These solenoid valves were controlled by a computer through a digital input/output board (DAQCard DIO- 24) and control modules (SSR series) from National Instruments.



$$\overline{X} = \frac{\Sigma\, x_i \Delta A_i}{\Sigma\, \Delta A_i}; \quad \overline{Y} = \frac{\Sigma\, y_i \Delta A_i}{\Sigma\, \Delta A_i};$$

$$D = \left[ \left( \overline{X} - X_{vent} \right)^2 + \left( \overline{Y} - Y_{vent} \right)^2 \right]^{1/2}$$

Figure 4 Calculation of distance between the centroid of an unfilled region and the vent. The port configuration with the minimum value of this distance is selected for the next control step.

## Experimental Implementation

The experimental programme included four uncontrolled and controlled experiments. In the uncontrolled experiments, all the injection ports were simultaneously opened at the beginning of the infusion and closed at the end of the infusion. For the controlled experiments, the injection ports were computer controlled and the infusion was completed in eleven control steps, resulting in ten control actions. In all experiments, the mould was evacuated to 90 KPa vacuum pressure and the reinforcement layers were infused with hydraulic oil with a viscosity of 0.25 Pa s (at 23 $^{o}$C temperature). The numerical model of the mould had 1271 nodes and 1200 quadrilateral elements. Elements in different regions of the mould were assigned different properties (Figure 2, Table 1).

Table 1 Material properties used in the numerical model for active control experiments.

| Material | Permeability ($m^2$) | Fibre Volume Fraction | Thickness (m) |
|---|---|---|---|
| CFRM Unifilo U750/450 (Region 1) | 1.00E-08 | 0.18 | 0.0015 |
| CFRM Unifilo U750/450 +<br>(-/+) 45 , FGE 106 (Region 2) | 2.74E-09 | 0.412 | 0.0055 |

To compare the flow progression in various experiments, all the experiments were recorded with a camera. For quantitative comparison, three parameters were identified and monitored for each experiment. They were: (1) the distance between the vent and the centroid of an unfilled region when resin reached the vent, (2) the unfilled area (as fraction of the mould area) when resin reached the vent, and (3) the amount of resin bled through the vent, as fraction of the mould porous volume (calculated from the amount of resin injected inside the mould and the amount of resin bled through the vent), for complete infusion of the mould.

## RESULTS

Results from the uncontrolled experiments show a delayed flow front in the thick region of the preform, which contains three layers of bi-axial reinforcement sandwiched between two layers of CFRM. The unfilled area, when resin reaches the vent, is considerably larger leading to larger resin wastage due to bleeding (Figure 5, Table 2). One can argue that readjustment of the vent position could lead to a reduction in resin wastage. However, as shown in Figure 5, the last point to be filled varies between experiments and it is difficult to predict a suitable vent position. In addition, a number of design factors can influence the selection of suitable vent locations [10]. Relocating vents may also be difficult for variety of reasons such as reworking costs for the mould. In such cases, it is still desirable to fill the mould with the current set-up without a major increase in the production costs or part rejection rates.

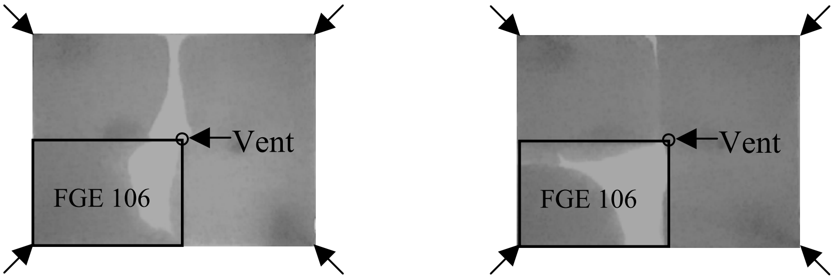


Figure 5 Flow front positions and unfilled region, when resin reaches the vent, in uncontrolled infusion experiments. The injection is from the four corner injection ports.

Table 2 Parameters characterising the efficiency of infusion experiments. Actively controlled experiments show significant improvements in the infusion efficiency as compared to uncontrolled experiments.

| | Uncontrolled Experiments | | | | Controlled Experiments | | |
|---|---|---|---|---|---|---|---|
| | **Distance (m)** | **Area (%)** | **Resin Waste (%)** | | **Distance (m)** | **Area (%)** | **Resin Waste (%)** |
| 1 | 0.070 | 9.044 | 13.3 | 1 | 0.007 | 4.076 | 4.4 |
| 2 | 0.069 | 14.231 | 13.5 | 2 | 0.028 | 5.037 | 6.6 |
| 3 | 0.053 | 13.915 | 11.7 | 3 | 0.029 | 1.853 | 5.3 |
| 4 | 0.081 | 16.171 | 20.5 | 4 | 0.036 | 3.406 | 6.7 |

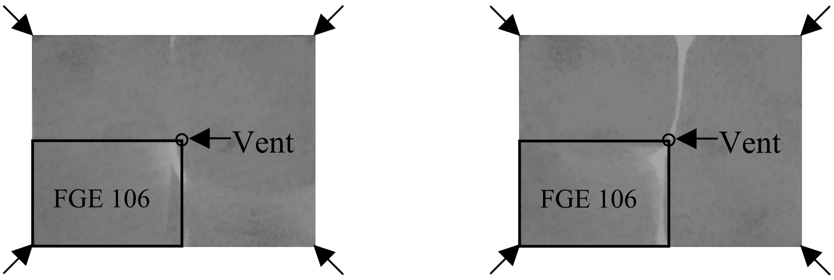


Figure 6 Flow front positions and unfilled region, in the controlled infusion experiments. The control system successfully identifies the flow deviations and implements appropriate corrective action, leading to reduced resin wastage and improved infusion efficiency.

Controlled experiments show considerable improvement in the flow front progression, and a smaller unfilled area when resin reaches the vent, reducing the requirement for resin bleeding as well as reducing resin wastage (Figure 6, Table 2). In addition, the control actions implemented by the system are different from experiment to experiment, which highlights the process variability (Table 3 A, B).

Table 3 (A) Possible port configurations for the mould used in the case study. (B) Port configurations selected by the control system to optimise the infusion process in actively controlled experiments.

(A)

| | **Injection Gate #** | | | |
|---|---|---|---|---|
| | **1** | **2** | **3** | **4** |
| **Port Configuration #** | | | | |
| **1** | Open | Open | Open | Open |
| **2** | Open | Open | Open | Close |
| **3** | Open | Open | Close | Open |
| **4** | Open | Open | Close | Close |
| **5** | Open | Close | Open | Open |
| **6** | Open | Close | Open | Close |
| **7** | Open | Close | Close | Open |
| **8** | Open | Close | Close | Close |
| **9** | Close | Open | Open | Open |
| **10** | Close | Open | Open | Close |
| **11** | Close | Open | Close | Open |
| **12** | Close | Open | Close | Close |
| **13** | Close | Close | Open | Open |
| **14** | Close | Close | Open | Close |
| **15** | Close | Close | Close | Open |
| **16** | Close | Close | Close | Close |

(B)

| | **Experiment #** | | | |
|---|---|---|---|---|
| | **1** | **2** | **3** | **4** |
| **Control Step #** | | | | |
| **2** | 8 | 8 | 8 | 8 |
| **3** | 8 | 8 | 8 | 8 |
| **4** | 4 | 4 | 8 | 8 |
| **5** | 3 | 11 | 4 | 4 |
| **6** | 11 | 2 | 2 | 10 |
| **7** | 2 | 2 | 3 | 9 |
| **8** | 10 | 1 | 7 | 5 |
| **9** | 9 | 11 | 3 | 11 |
| **10** | 1 | 2 | 3 | 11 |
| **11** | 3 | 2 | 1 | 1 |

## CONCLUSIONS

Heterogeneity in fibrous reinforcements can lead to unforeseen, unpredictable and at times, problematic flow patterns. Hence, for full part infusion, it is necessary to continue resin injection, even after it has reached the vent. This results in resin wastage and longer fill-times. In some cases, resin may start to cure before the infusion is complete, leading to higher part rejections.

To address this issue, a new control system, complete with a flow monitoring and analysis system as well as computer controlled injection ports, was developed. Low cost web-cameras were used to capture images of the flow progression, which were then analyzed to identify flow disturbances. Using an infusion process simulation tool, the flow advancement was simulated to identify the optimum corrective action, which was implemented through computer controlled injection ports. All the steps of this control system were performed and implemented in real-time and were repeated a number of times during the infusion stage. Experimental results show that the control system is able to identify flow deviations and take corrective actions, resulting in reduced resin waste, and improved infusion efficiency.

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