Intelligent RTM and VARTM for Polymer Composites Manufacturing

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RTM and VARTM

The Resin Transfer Molding (RTM) and Vacuum Assisted Resin Transfer Molding (VARTM) belong to the Liquid Composite Molding (LCM) category. In RTM, the liquid resin is pumped into a closed mold to infuse the fiber preform placed inside the mold cavity. After the mold filling stage, the resin is allowed to cure and transform to solid thus bind the fiber together and form the solid composite part. The common steps of RTM is illustrated in Figure 1. VARTM is similar to the RTM but uses the vacuum to draw the resin into the mold cavity. In addition, the VARTM mold is usually an open mold and the fiber preform is sealed between the open mold and a vacuum bag as shown in Figure 2. Generally speaking, RTM is capable of producing small composites parts with mid-large volume and high quality in an automated way; on the other hand, VARTM is more labor intensive but can save great investment in mold tooling thus is suitable for low-mid volume production for large composite parts.

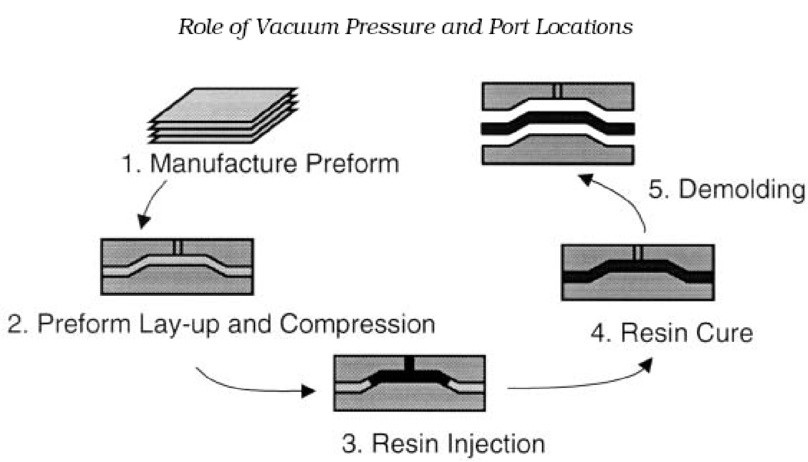


Figure 1. Typical steps in RTM process. [1]

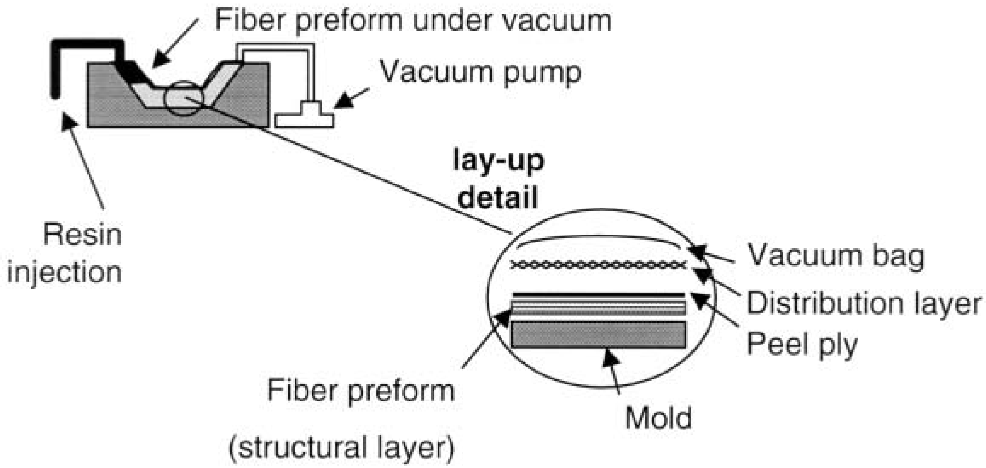
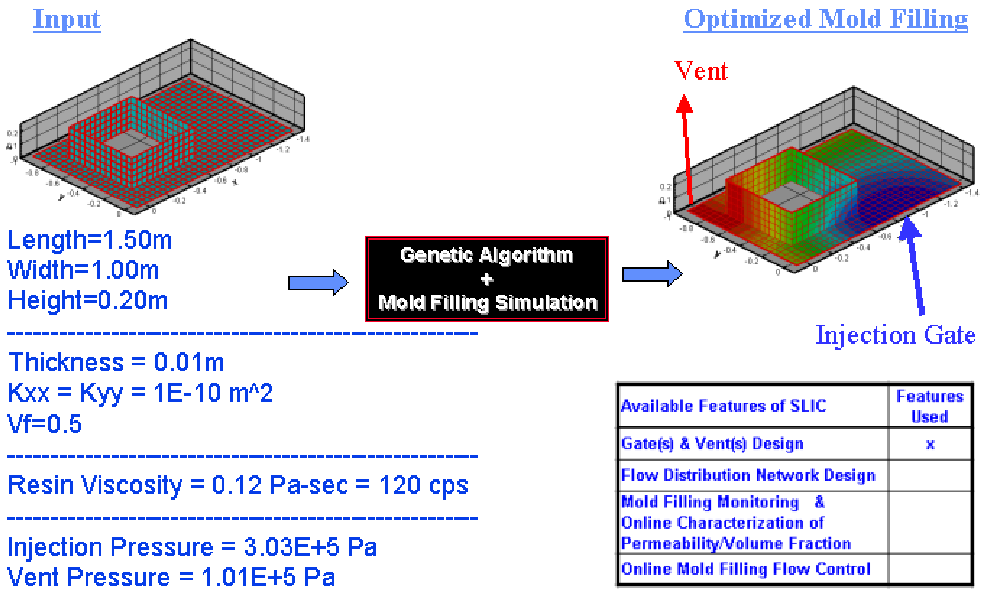


Figure 2. Typical VARTM setup. [1]

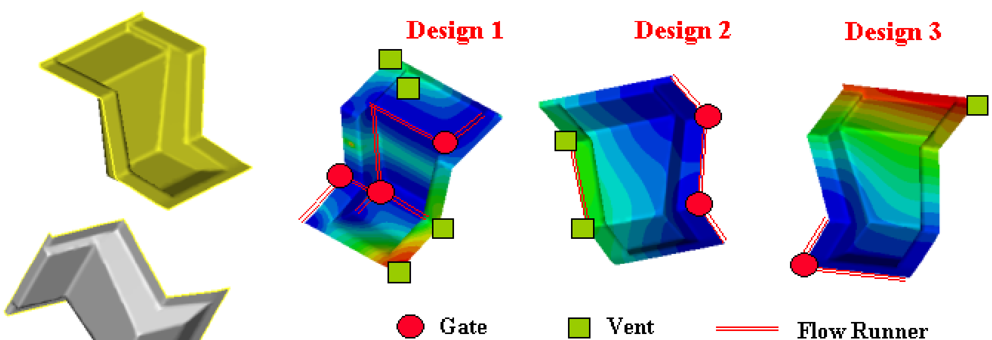
Intelligent RTM and VARTM Mold Filling

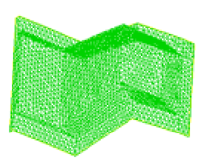
RTM and VARTM can be failed if some unexpected disturbances happen during the mold filling stage or curing stage. If resin flows from the injection gate to the vent before completely evacuate the air inside the mold cavity, the air will be trapped inside the fiber preform and form a dry spot. The dry spot does not possess any mechanical strength since there is no resin to bind the fibers together. Another possible scenario to yield the dry spot is that the resin in the mold cavity flows too slowly to fill the complete cavity before the resin curing starts. To find the gate and vent locations for a given part geometry is the first thing one has to design for the manufacturing process. Such tasks can be achieved by combining genetic algorithm with mold filling simulations [2,3,4] as shown in Figure 3 and Figure 4. In addition, such intelligent manufacturing approach can be used in VARTM process design (see Figure 5) as well as to correct the resin flow by open/close gates vents at correct timing based on mold embedded sensor signal and the process control computer’s decision (see Figure 7). The total intelligent design-manufacturing flow is schematically shown in Figure 8.



Available Features of SLIC	Features Used
Gate(s) & Vent(s) Design	x
Flow Distribution Network Design	
Mold Filling Monitoring & Online Characterization of Permeability/Volume Fraction	
Online Mold Filling Flow Control	

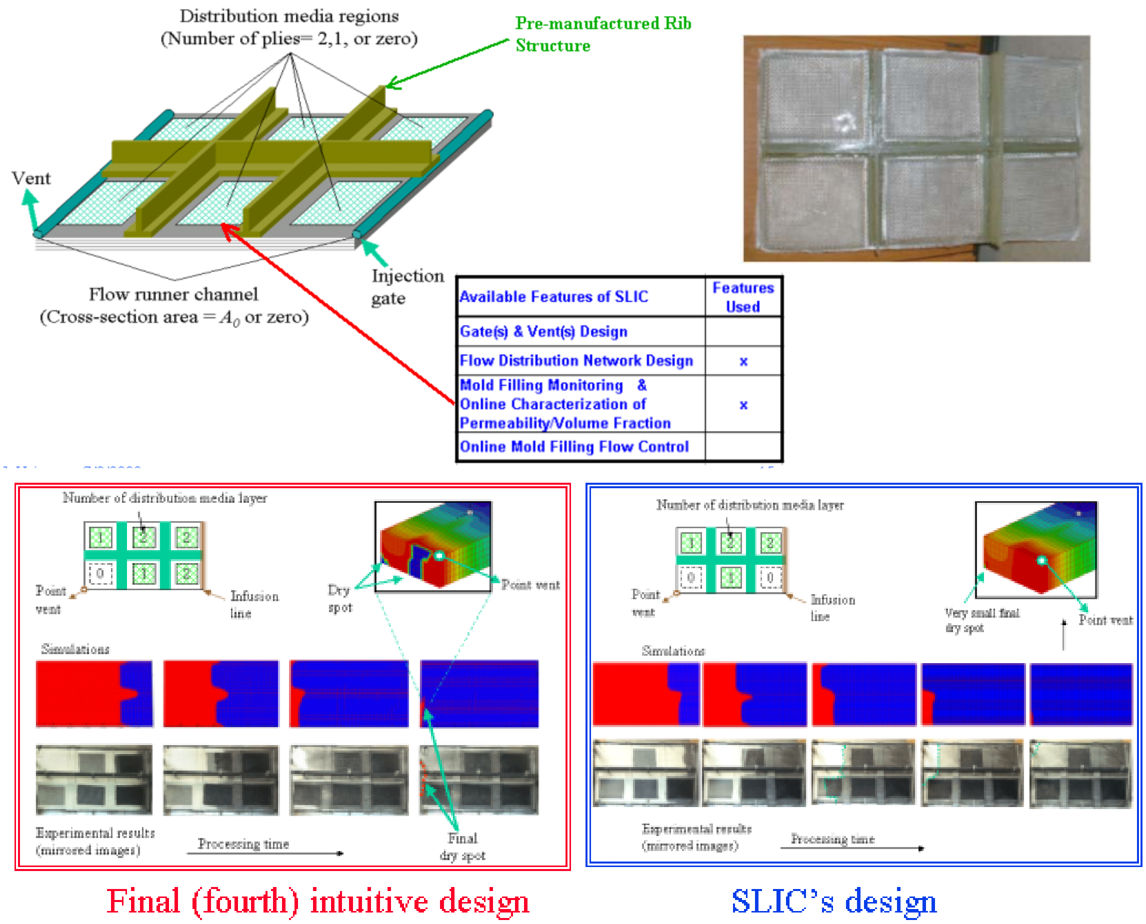
Figure 3. Single gate-vent pair optimization for a RTM part.





	Design 1	Design 2	Design 3
SLIC Gates & Vents Optimization	Yes	Yes	Yes
Number of Gates	3	2	1
Number of Vents	4	2	1
Fill Time Without Flow Runner	6min	15min	1hr
SLIC Flow Runner Optimization	Yes	Yes	Yes
Fill Time With Flow Runners	2min	14min	12min

Figure 4. Multiple gates and vents optimization with and without flow runners for a RTM part.



	Dry spot content	Fill time	Number of experiments
Trial-and-error intuitive design	0.851%	10.87 min	4
GA/simulation-based design (SLIC)	0.034%	13.05 min	1

Figure 5. VARTM optimization using genetic algorithm and mold filling simulations [4].

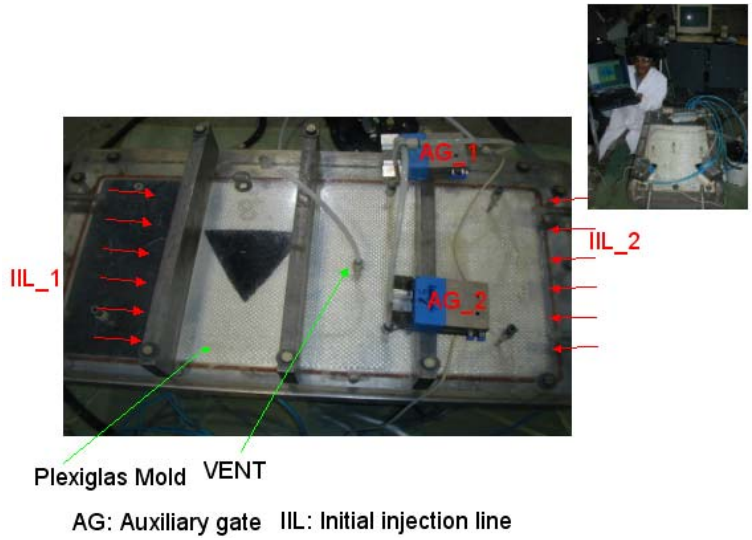


Figure 6. Experimental setup for intelligent RTM mold filling control [3]

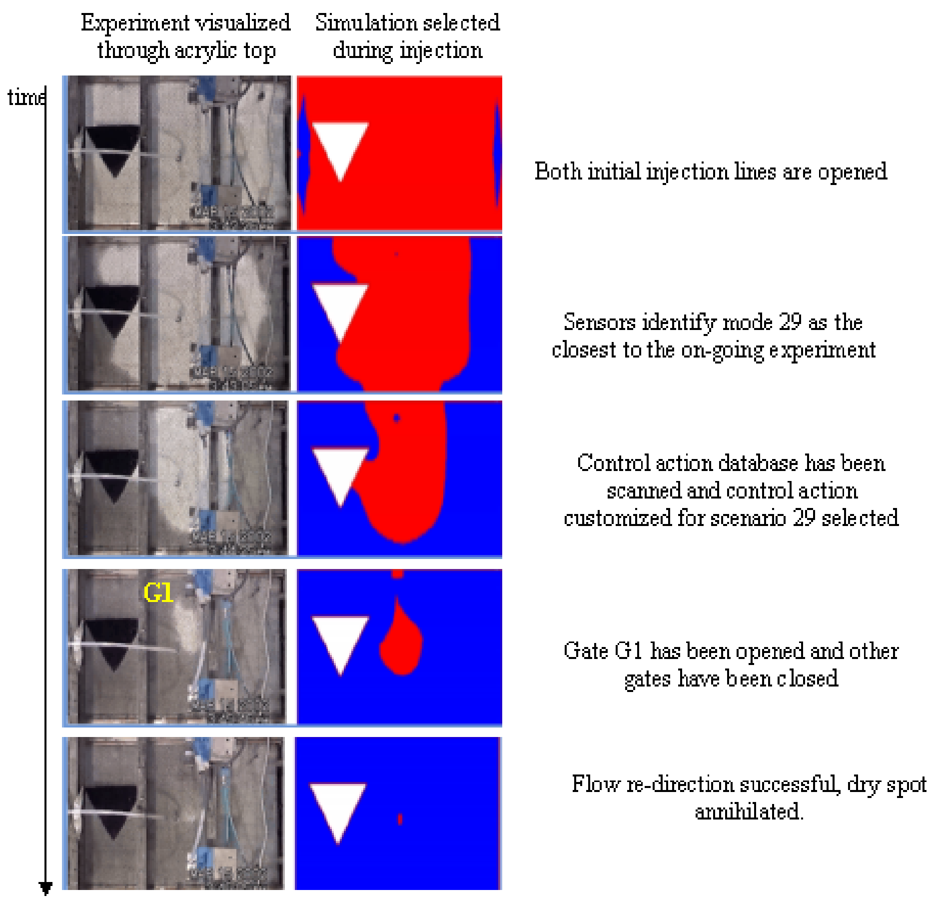


Figure 7. Genetic algorithm and molding filling simulation is integrated into a computer program to feedback control the RTM mold filling process to overcome any possible disturbance during the mold filling. The performance of such intelligent manufacturing control approach is validated with experiments [3].

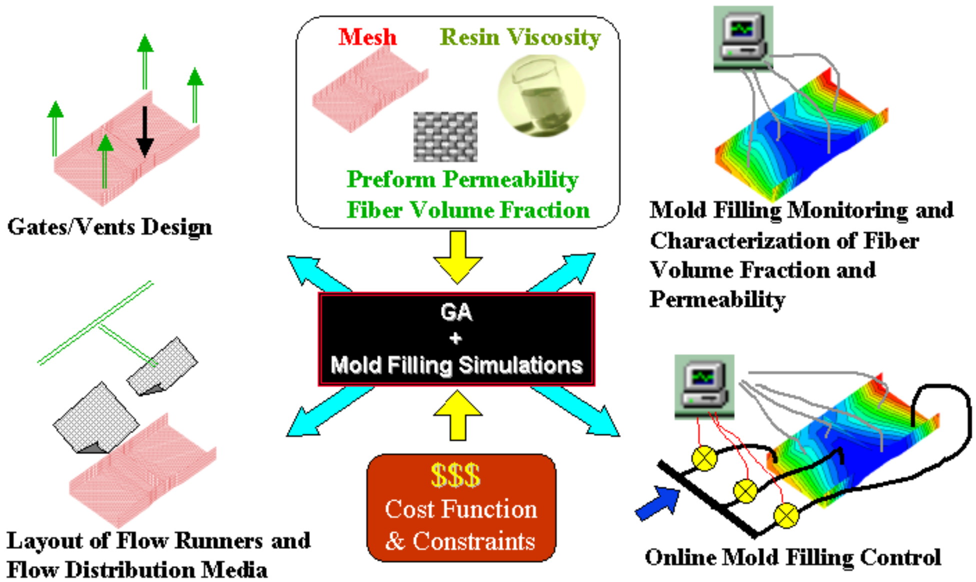


Figure 8. Flow of using genetic algorithm-simulations based manufacturing approach for RTM and RTM mold filling.

Another under developing RTM flow control approach is using adaptive control algorithms. Currently, this approach has been tried on simple geometry and with numerical results [5] (see Figure 9 and Figure 10). However, this approach has strong potential to be developed into a simulation-free control algorithm that can independently control the mold filling without rely on any mold filling simulations.

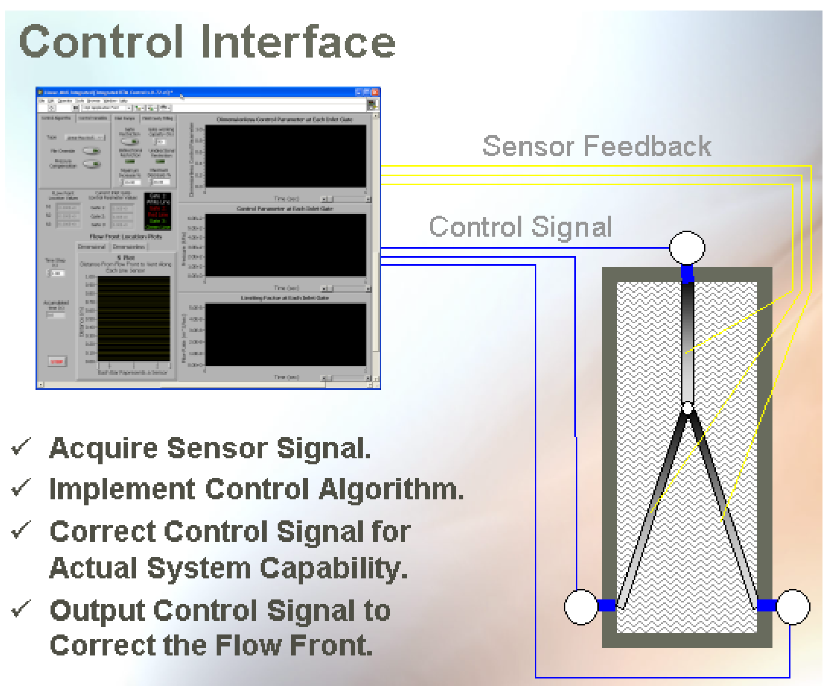


Figure 9. Adaptive control for RTM mold filling [5].

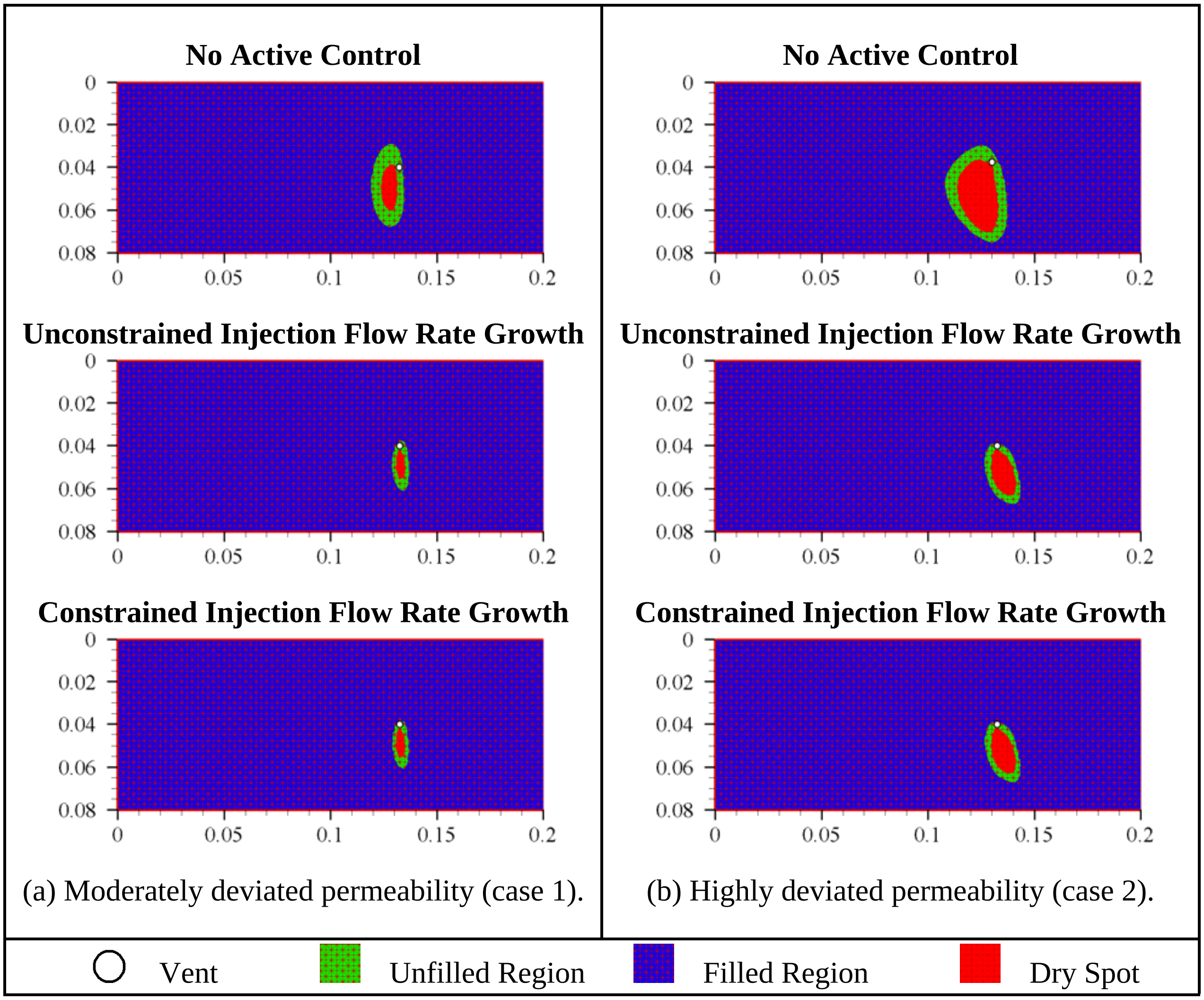


Figure 10. Numerical results of the adaptive RTM flow control [5]

Direct Cure Kinetics Characterization and Control

The cure kinetics of a thermosetting polymer system is varying with its shelf-life and can be significantly changed due to any small miscalculation in adding catalyst into the resin. Thus, a program use artificial intelligence to inversely solve the cure kinetics during composite curing was developed [6]. The concept is illustrated in Figure 11 and has been validated experimentally as shown in Figure 12 [7]. Consider a cure kinetics model as,

$$\frac{\partial c}{\partial t} = A \cdot \exp\left(-\frac{E}{RT}\right) \cdot c^m \cdot (1-c)^n$$

The computer program along with a few thermocouples can in-situly determine the values of the cure kinetics parameters: A, E, m, n, and also the total reaction heat H_r of the thermoset resin during a RTM or VARTM process. In addition to the cure kinetics parameters, the resin conversion evolution during the cure cycle can also be accurately calculated.

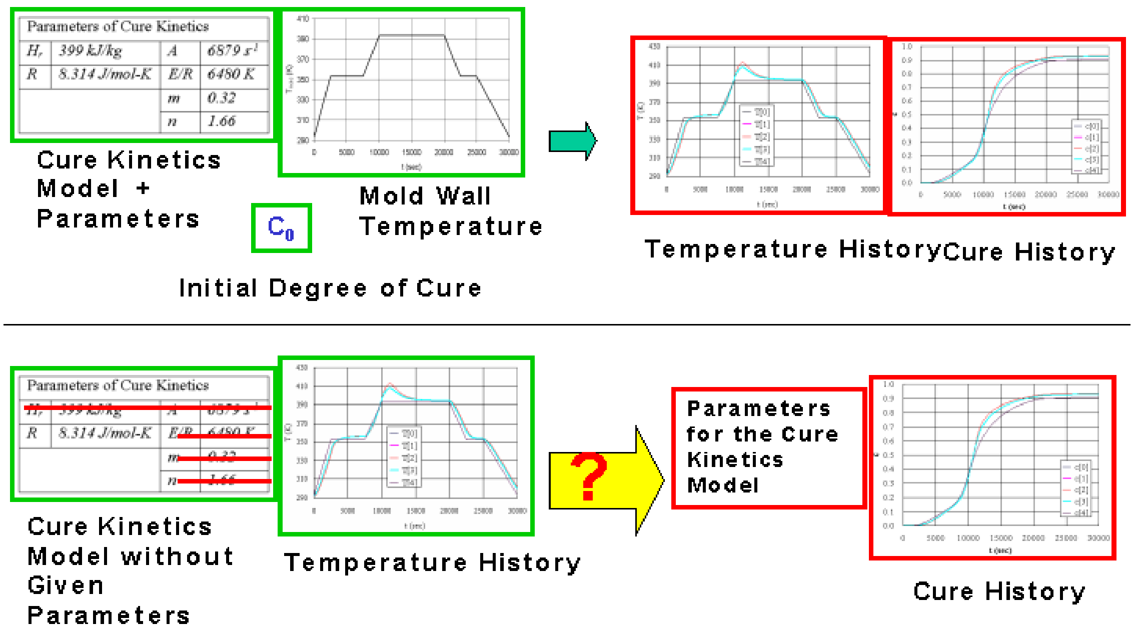


Figure 11. Concept of the direct cure kinetics characterization is actually an inverse solution problem [6].

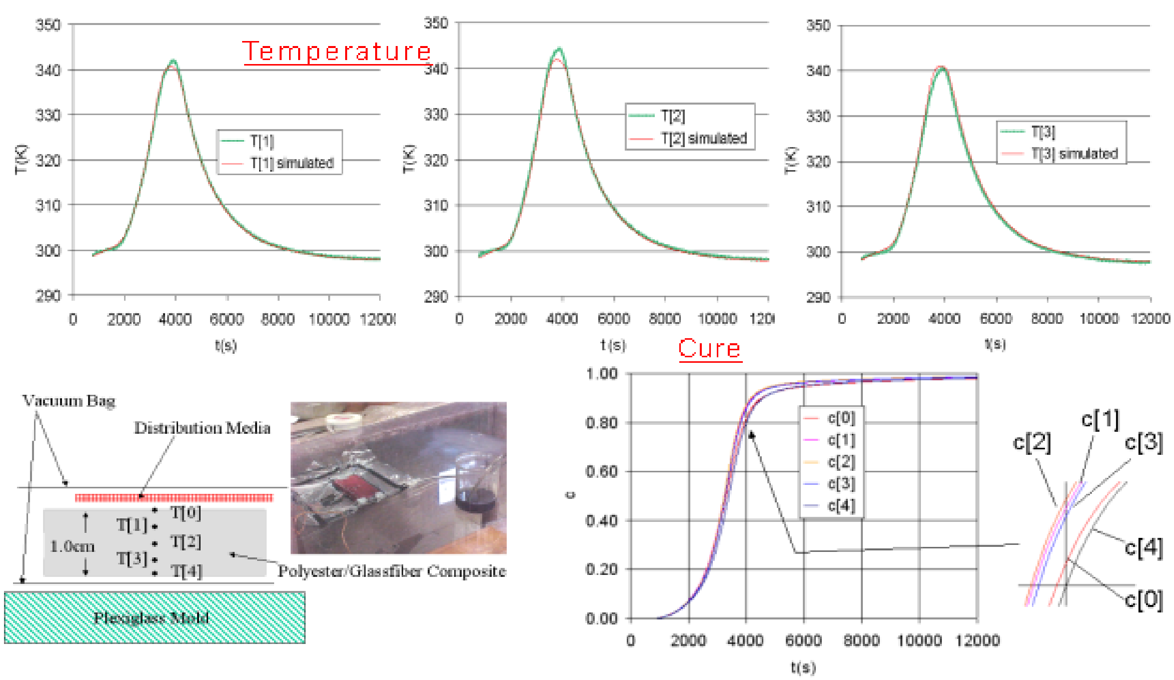
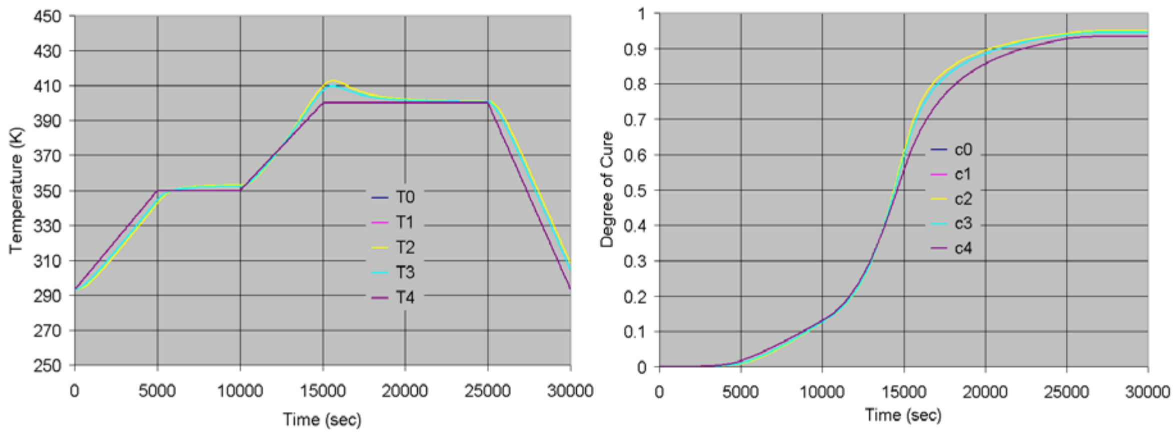
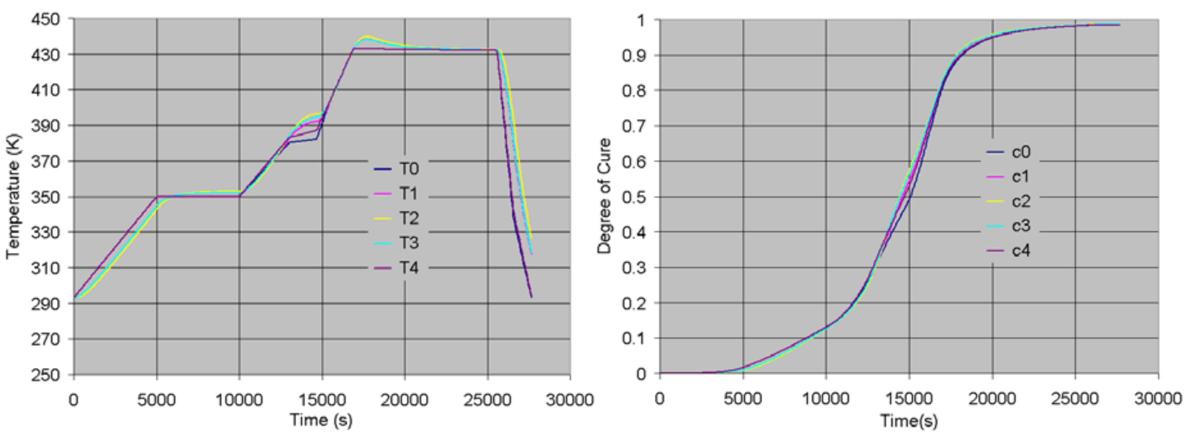


Figure 12. By using genetic algorithm to match the temperature simulation with experimentally measured temperature data (t_s=6000 seconds) for the VARTM part during curing process, the cure history and the cure kinetics parameters can be inversely calculated. [7]

The ultimate goal for this research is to have the system being further developed towards integrated online cure kinetics characterization and control [8]. An online cure control algorithm has been developed to realize this ideal and has been tested in numerical simulations to evaluate the feasibility and reliability. The simulated results in Figure 13 show that the temperature and resin conversion gradients during the critical stage for residual stress development (resin conversion >0.6) had been minimized in the computer-controlled mold heating cycle. Furthermore, the computer controlled curing process achieved higher final degree of cure and with short cycle time. As a result, this integrated online cure kinetic characterization and control method will be able to produce composite parts with better quality and in shorter cycle time.



(a) Original (non-controlled) temperature and resin conversion history



(b) The optimized temperature evolution and cure evolution.

Figure 13. Comparison of the original (non-controlled) and controlled RTM cure processes [8].

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