Definition of a Process Performance Index Based on Gate-Distance and Incubation Time for Liquid Composite Molding Processes Design

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SUMMARY: The success of filling and curing stages in a liquid composite molding (LCM) depends on many variables such as locations of gates and vents, temperature distribution, flow rate, injection pressure, etc. A great challenge to obtain high quality finished parts is to accurately predict flow pattern, and temperature and conversion profiles using simulation for process design optimization. With the predicted process performance measures, the LCM process can be optimized through locating the gates and vents properly. In this study, a process performance index based on gate-distance and incubation time for liquid composite molding processes is defined. This index allows the consideration of both resin flow and curing issues in process design optimization. Another advantage of using this index in process optimization is that the computation involved is very efficient as only two-dimensional calculation is required. This makes the index very useful in LCM process design optimization where lengthy iterative stochastic search algorithms such as genetic algorithms are used. In this study, the new index is used to optimize the resin transfer molding (RTM) process design, considering both resin flow and curing. The effectiveness of the approach is illustrated through a number of examples which involve race tracking, varying permeability areas, different filling conditions, etc.

KEYWORDS: Fixed Mesh Resolution, RTM, Liquid Composite Molding, Incubation time, Optimization.

INTRODUCTION

Mold conforming processes of materials made from liquid resins and, in particular, Resin Transfer Molding (RTM), are increasingly used in the fabrication of polymeric matrix composites reinforced with fibers. These processes are based on the reinforcement impregnation with a low viscosity resin, from which composites parts are conformed after the curing reaction.

The polymerization starts when the resin components are mixed just before the injection (see Fig. 1). The elapsed time since the reactive components are mixed, also known as incubation time [3, 7] is directly related with the resin curing conversion. The incubation time depends on the traveled path of each fluid particle throughout the mold, and therefore is not always easily to predict it.

The resin gelling time can be delayed and controlled by using different inhibitor concentrations in the polymerization resin agents as the fluid flows, see for instance [1, 2]. In [2] Comas-Carmona, Advani et al. used the correlation of the gelling time and the concentration of the inhibitor as follows:

$$\ln(t_{gel}) = a + bC_{hardener} + cC_{accelerator} + dC_{inhibitor} \qquad (1)$$

Where *a, b, c, d,* are constants to be determined for each resin, and *C* refers to the concentration of the chemical agents. Since the time to gel and the incubation time are directly related, the LCM process can be optimized through locating the gates and vents properly in order to reduce cycle time, avoid dry spots and obtain spatially homogenized curing.

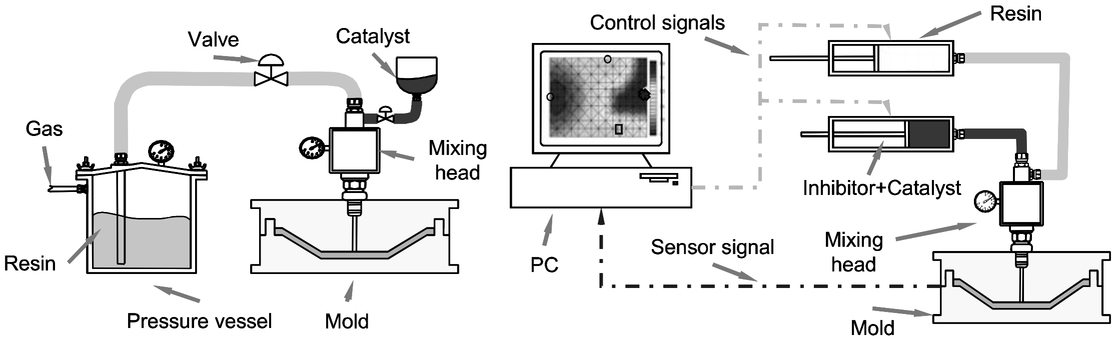

Fig. 1. Schematic resin injection system without control (left) and with PC-based control providing automatic mixing of resin components at injection gate (right)

PROCESS OPTIMIZATION AND RESIN FLOW INDEX.

The success of filling and curing stages in liquid composite molding (LCM) depends on many variables such as locations of gates and vents, temperature distribution, flow rate, injection pressure, etc. Traditionally the selection of gate and vent locations in mold design is based on the experience and trial and error attempts. Many research studies have been conducted to reduce cycle time by using computer simulation and optimization. Zhang, Wang et al, employed in [4] and [5] a process performance index based on gate-distance of the resin located on the flow front at different time steps. A good process should have short filling time and a desired resin flow pattern (small standard deviation) as shown in Fig. 2.

A process performance index was proposed as follows:

$$Q = \frac{T\times\sum_{k=1}^{m}\sqrt{\frac{\sum_{i_k=1}^{n_k}(d_{ik}-\bar{d}_k)^2}{n-1}}}{m} = \frac{T\times\sum_{k=1}^{m} q_k}{m} \tag{2}$$

where:

Q: overall process performance index (the lower the better)

q_k: intermediate flow front index for flow front k

m: number of flow fronts taken from the simulation model

n_k: number of nodes on flow front k

d_{ik}: distance from node i on flow front k to the outlet.

$\bar{d}_k$: average distance from nodes on flow front k to the outlet.

T: Total mold filling time.

This index has been redefined in this work in order to include the incubation time as a variable related with a optimal curing performance. The new index is completed as follows:

$$QD = \frac{T\times D\times\sum_{k=1}^{m} q_k}{m}$$

$$D = \frac{\sum_{i=1}^{n_f} D_i}{n_f} \quad ; \quad D_i = \max_{j=1}^{nn_i}(E_j) - \min_{j=1}^{nn_i}(E_j) \tag{3}$$

where:

QD: overall process performance index (the lower the better).

D: resin incubation time dispersion index defined for all filled nodes.

D_i: filled node i dispersion index (see Fig. 3).

E_j: incubation time for node j.

nn_i: number of nodes connected with node i.

n_f: number of filled nodes.

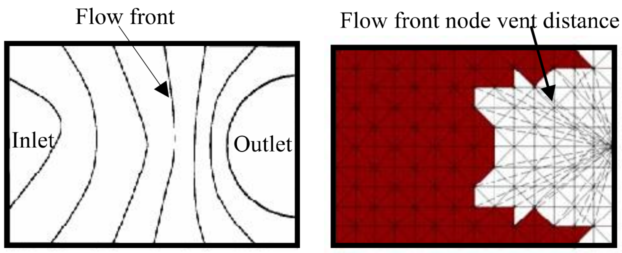

Fig. 2. Desired Flow front shape (left) and distances between flow front nodes and vent (right).

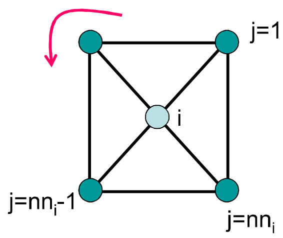

Fig. 3. Dispersión index D_i definition

NUMERICAL SIMULATIONS

In order to validate the resin flow index, a series of simulation experiments have been conducted to check how the index represents the RTM process behavior. In all cases a mold of 100 mm x 140 mm, a thickness of 6.4 mm, a permeability of 2.714 e-10 m^2 with 50 % fiber volume, a viscosity of 0.1 Pa·s, and a constant flow rate injection of 0.5 cm^3/s, has been used. Three cases with different permeability conditions (10, 50, 0.1 and 0.02 times the uniform permeability) as shows Fig. 4 have been studied. In case 1a, the resin is injected with constant inhibitor concentration during filling, and in case 1b three sensors separately located in the mold allow to control the inhibitor concentration in order to obtain spatially homogenized curing. The gate incubation time is set to be the time in that the fluid presence sensor detects resin. A similar sensor-based control technique was implemented with satisfactory results by Comas-Carmona, Advani et al. in [2]. It can be observed in Fig. 5 that the index *QD* defined in equation (2) is better in the second case and, as was expected, *Q* does not show this behavior. The coloring map of the dispersion index predicts this proper homogenized curing. In Fig. 6 is shown the variation of the resin incubation time dispersion index *D* for both cases at each time step. The three peaks of the controlled case correspond to the sensor signals. Case2 and Case3 are also shown in Fig. 5.
It can be noticed that without changes in the inhibitor concentration, both index *Q* and *QD* agree that Case2a represent the best filling conditions and Case3b the worst ones.

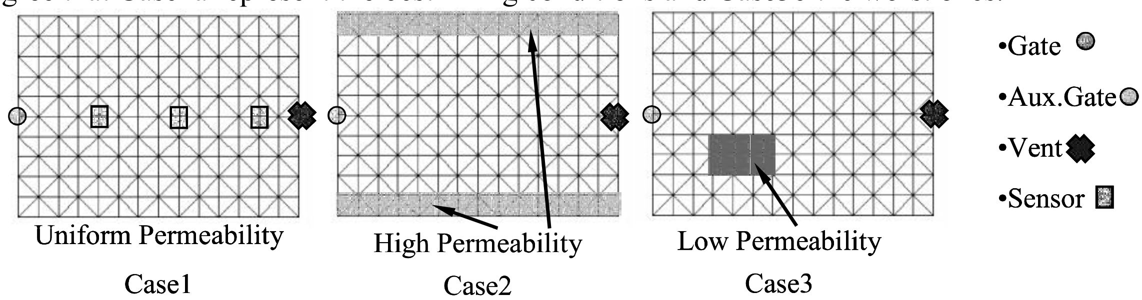

Fig. 4. Simulated conditions for the RTM part

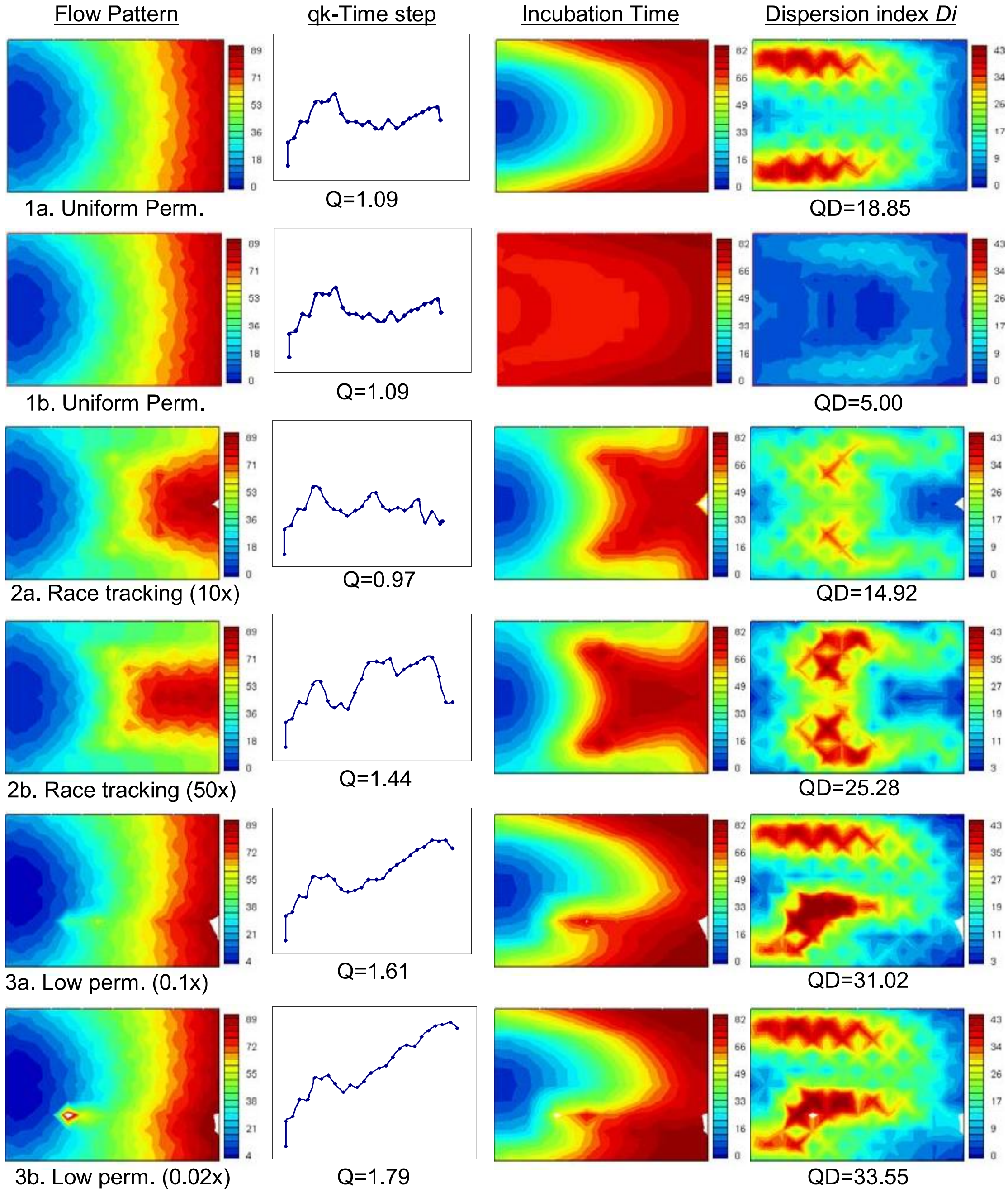

Fig. 5. Illustrations for different simulation cases.

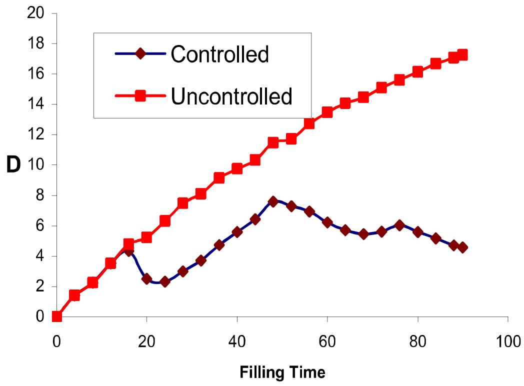

Fig. 6. Time evolution of the resin incubation time dispersion index D for case 1

CONCLUSIONS AND FURTHER WORK

This index allows the consideration of both resin flow and curing issues in process design optimization. Another advantage of using this index in process optimization is that the computation involved is very efficient as only two-dimensional calculation is required. This makes the index very useful in LCM process design optimization where lengthy iterative stochastic search algorithms such as genetic algorithms are used. It may be necessary to redefine the cost weight of considering more than one injection gate or the control of the inhibitor concentration for optimization purposes.

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