RTM AND VARTM DESIGN, OPTIMIZATION, AND CONTROL WITH SLIC

Kuang-Ting Hsiao

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Report Documentation Page

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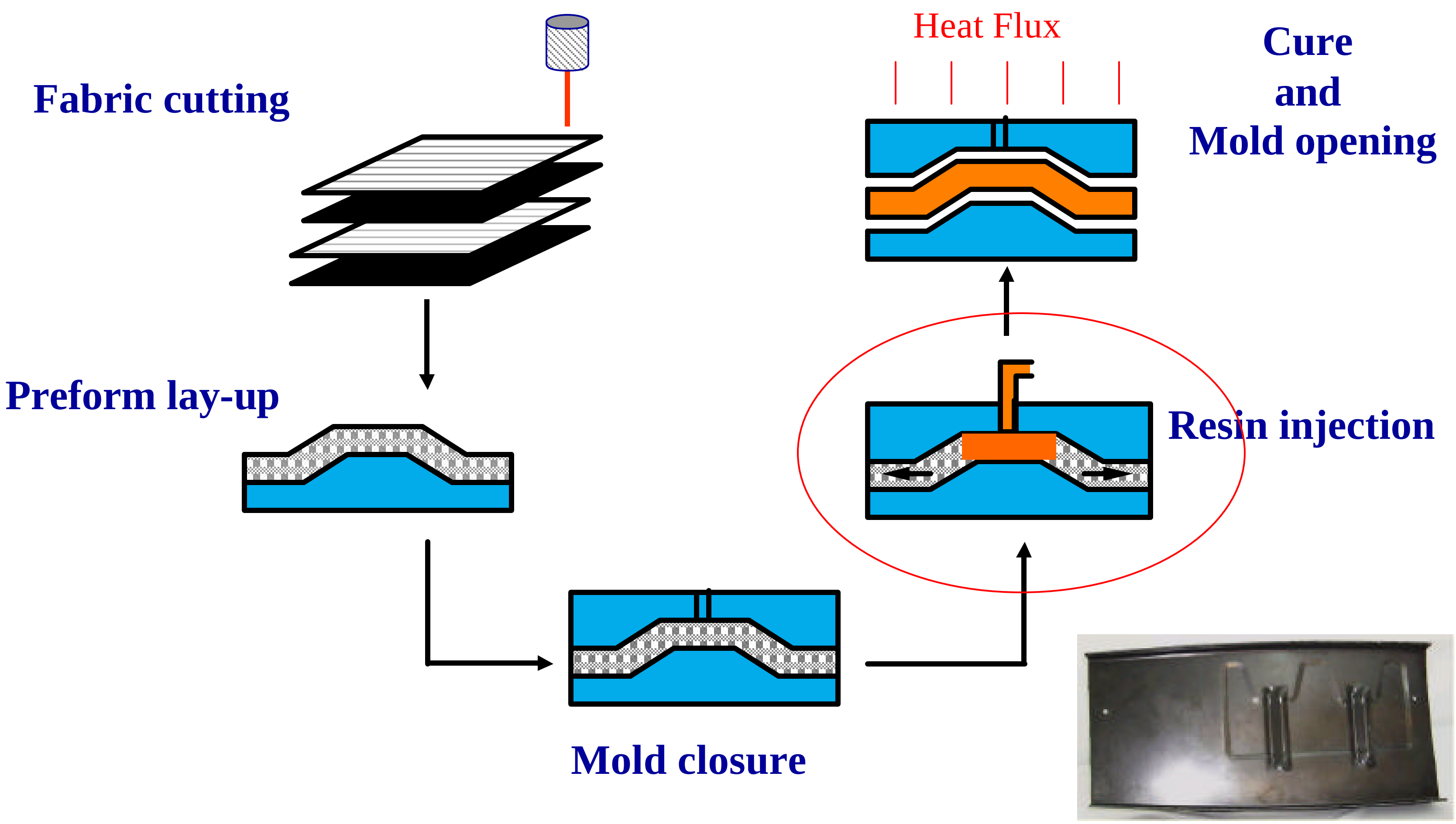
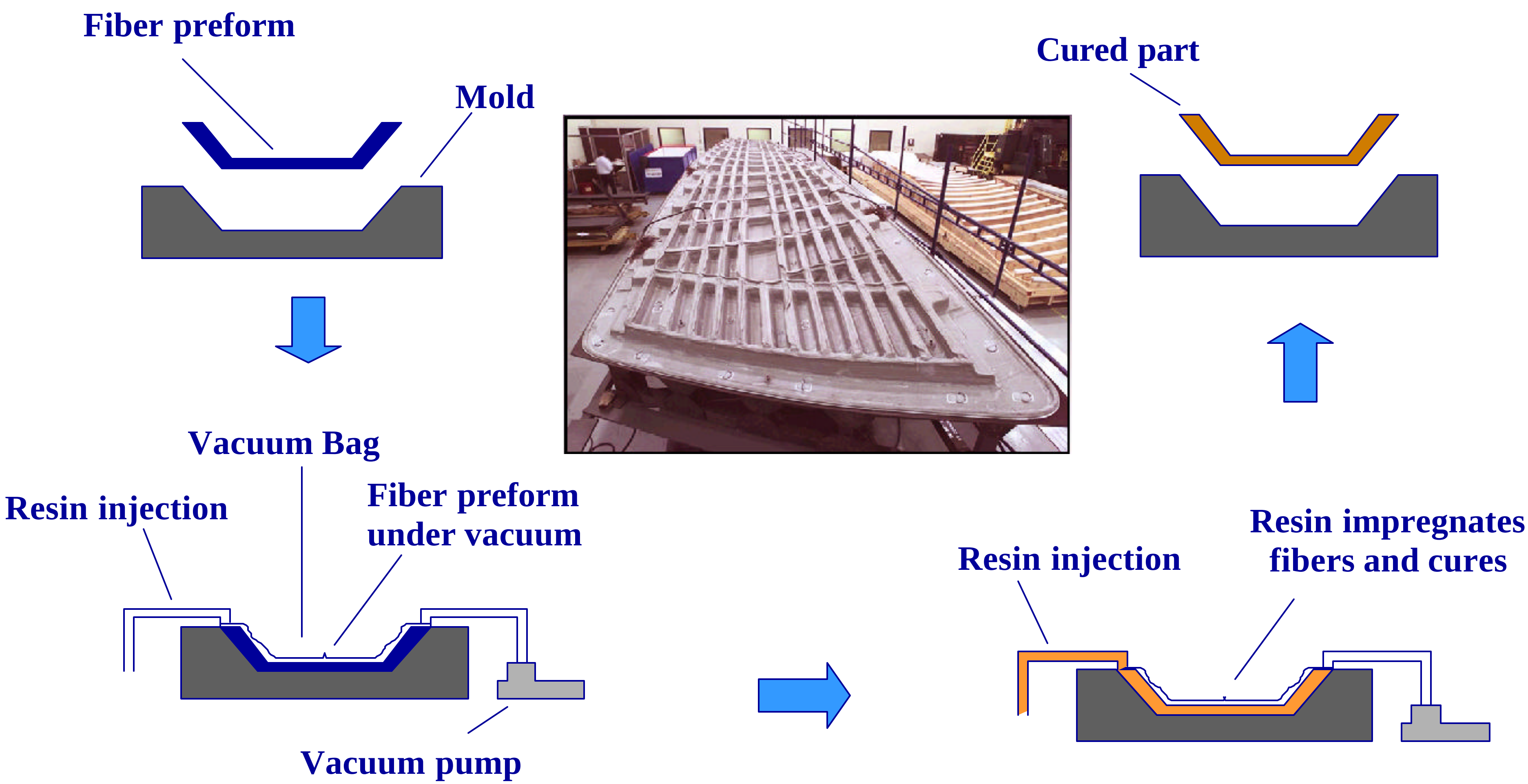
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The Resin Transfer Molding (RTM) Process



The Vacuum Assisted Resin Transfer Molding (VARTM) Process



Governing Equations for RTM Flow Simulations

Darcy's Law

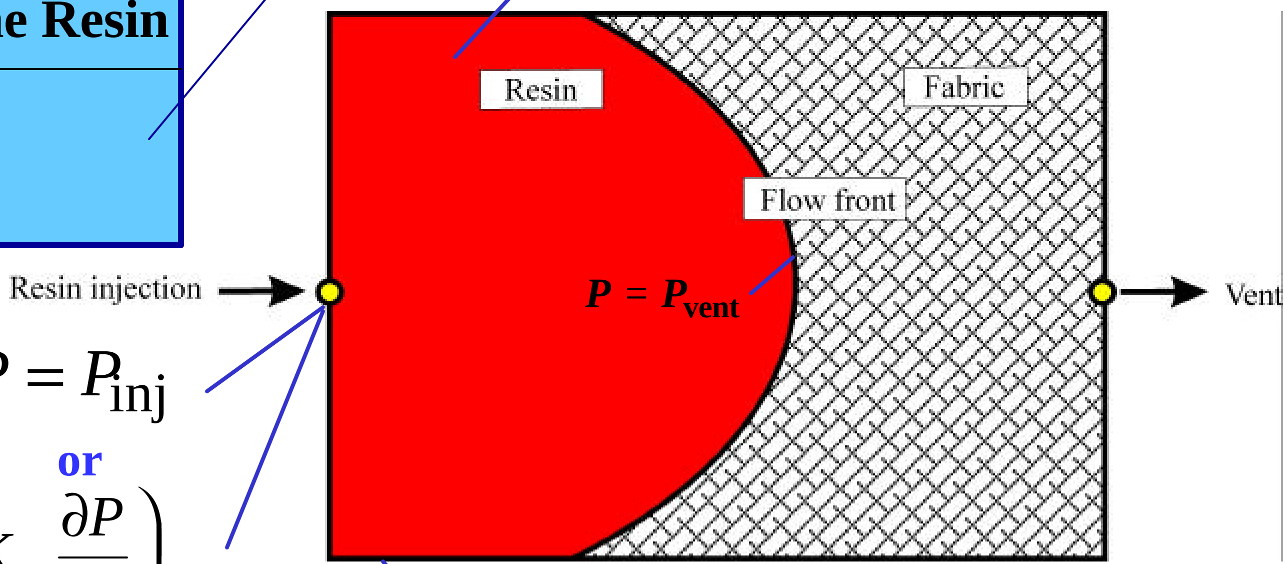
Volume averaged velocity-pressure relationship for flow in porous media:

$$u_i = -\frac{K_{ij}}{m}\frac{\partial P}{\partial x_j}$$

Continuity equation for the Resin

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial}{\partial x_i}\left(\frac{K_{ij}}{m}\frac{\partial P}{\partial x_j}\right) = 0$$



$$P = P_{inj}$$

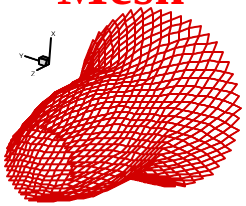
or

$$Q_{inj} = -\frac{A}{m}\left(K_{nn}\frac{\partial P}{\partial n} + K_{nt}\frac{\partial P}{\partial t}\right)$$

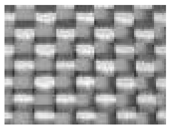
$$u_n = -\frac{1}{m}\left(K_{nn}\frac{\partial P}{\partial n} + K_{nt}\frac{\partial P}{\partial t}\right) = 0$$

Simulation-based Liquid Injection Control: Philosophy

Mesh



Resin Viscosity

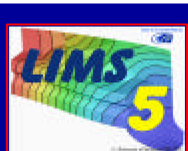


Preform Permeability
Fiber Volume Fraction

SLIC

Process Monitoring

Feedback Control



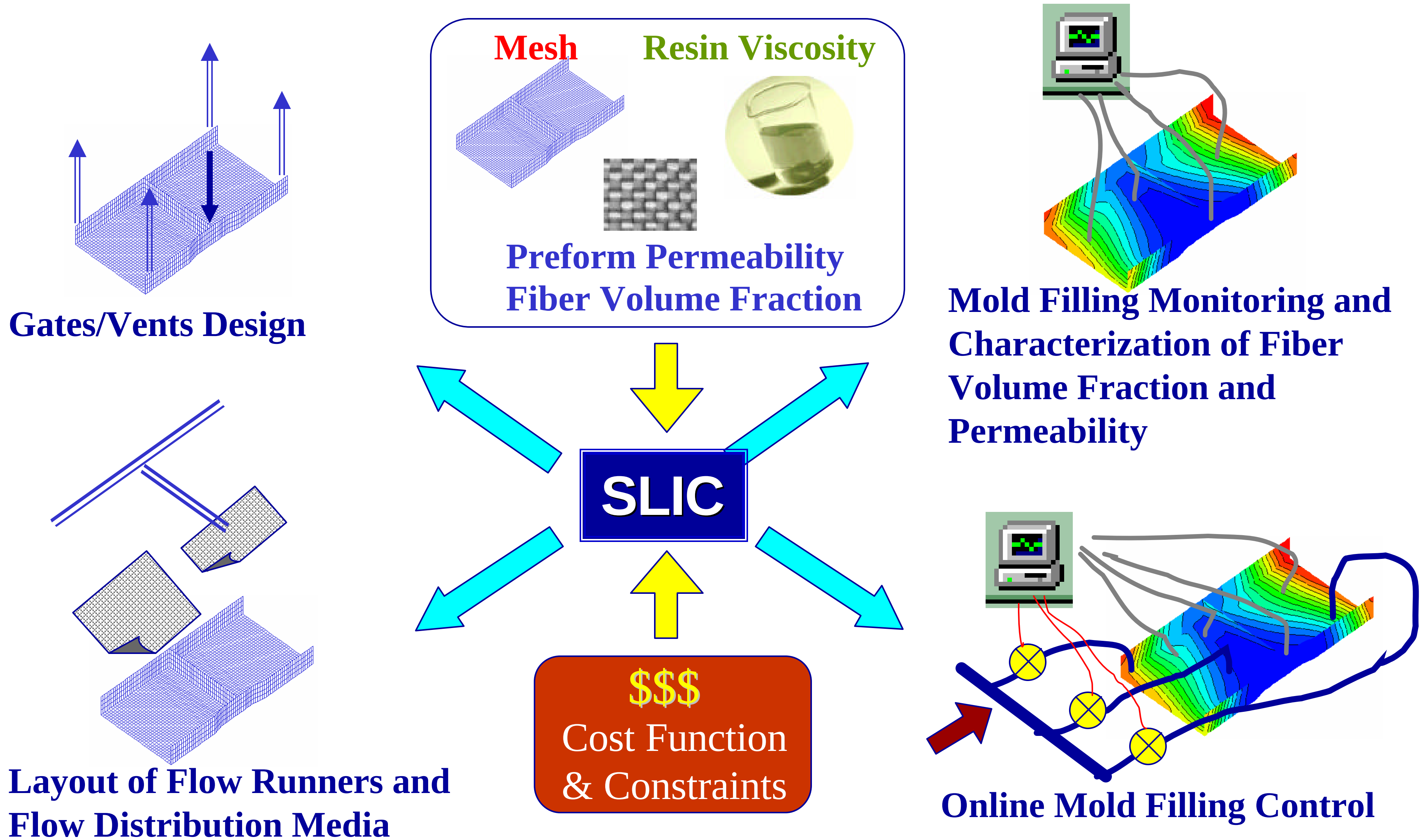
Artificial Intelligence

Sensors & Recognition Algorithms

Control Algorithms

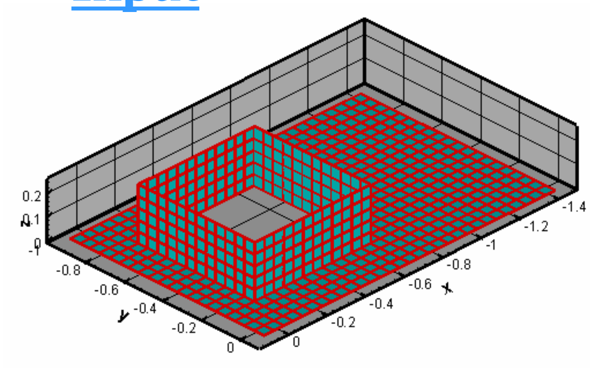
Optimized Design For RTM/VARTM

Features of SLIC



Case 1: Optimize Gate and Vent Locations

Input



Length=1.50m
Width=1.00m
Height=0.20m

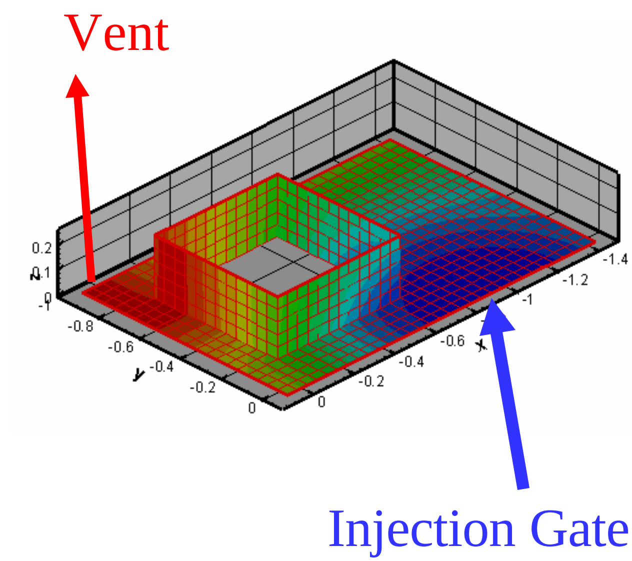
Thickness = 0.01m
Kxx = Kyy = 1E-10 m^2
Vf=0.5

Resin Viscosity = 0.12 Pa-sec = 120 cps

Injection Pressure = 3.03E+5 Pa
Vent Pressure = 1.01E+5 Pa

SLIC

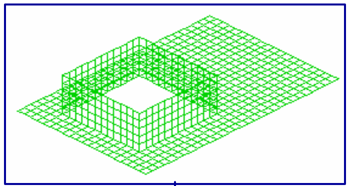
Optimized Mold Filling



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	

Flow of Optimizing Gate(s)/Vent(s) with SLIC (Case 1)

Mesh (part.dmp)



Gate/Vent Candidates

```
GATE_CANDIDATES
NODES
17
70 350 86 570
112 357 142 389
620 175 420 191
665 217 427 284
487
```

Constraints and Cost Function
f=f(Equip.Cost, Filling Time, Dry Spot)

```
NOTE: The following section defines the MAX_PROCESSING_TIME < Resin Gel Time.
MAX_PROCESSING_TIME: 1800.00

NOTE: The following section is to difinte the pressures.
INJECTION_PRESSURE: 5.05E+5
VENT_PRESSURE: 1.01E+5

NOTE: The following section is for Performoance evaluation definition.
WEIGHT_OF_TIME: 0.010000
WEIGHT_OF_VOID: 0.980000
WEIGHT_OF_COST_OF_LINES: 0.010000

NOTE: The following section is for Designing Initial Injection Gates & Initial Vent Gates.
NUMBER_OF_INITIAL_INJECTION_LINES: 1
NUMBER_OF_INITIAL_VENT_LINES_WITH_CONTROL_TRIGGER_SENSORS: 3

NOTE: The following section is for Flow Control Design.
NUMBER_OF_AUXILIARY_LINES: 2
NUMBER_OF_FLOW_DETECTION_SENSORS: 5
NUMBER_OF_ADDITIONAL_CONTROL_ACTION_TRIGGER_SENSORS: 4
```

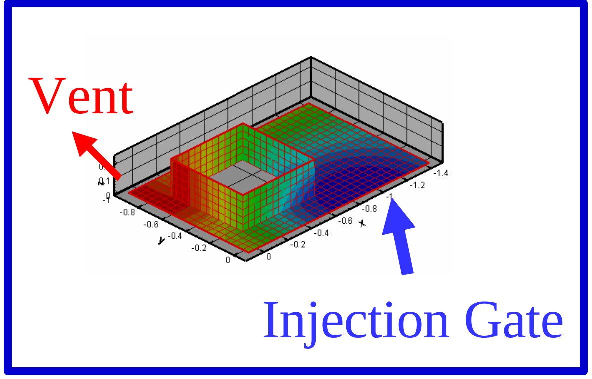
SLIC

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	

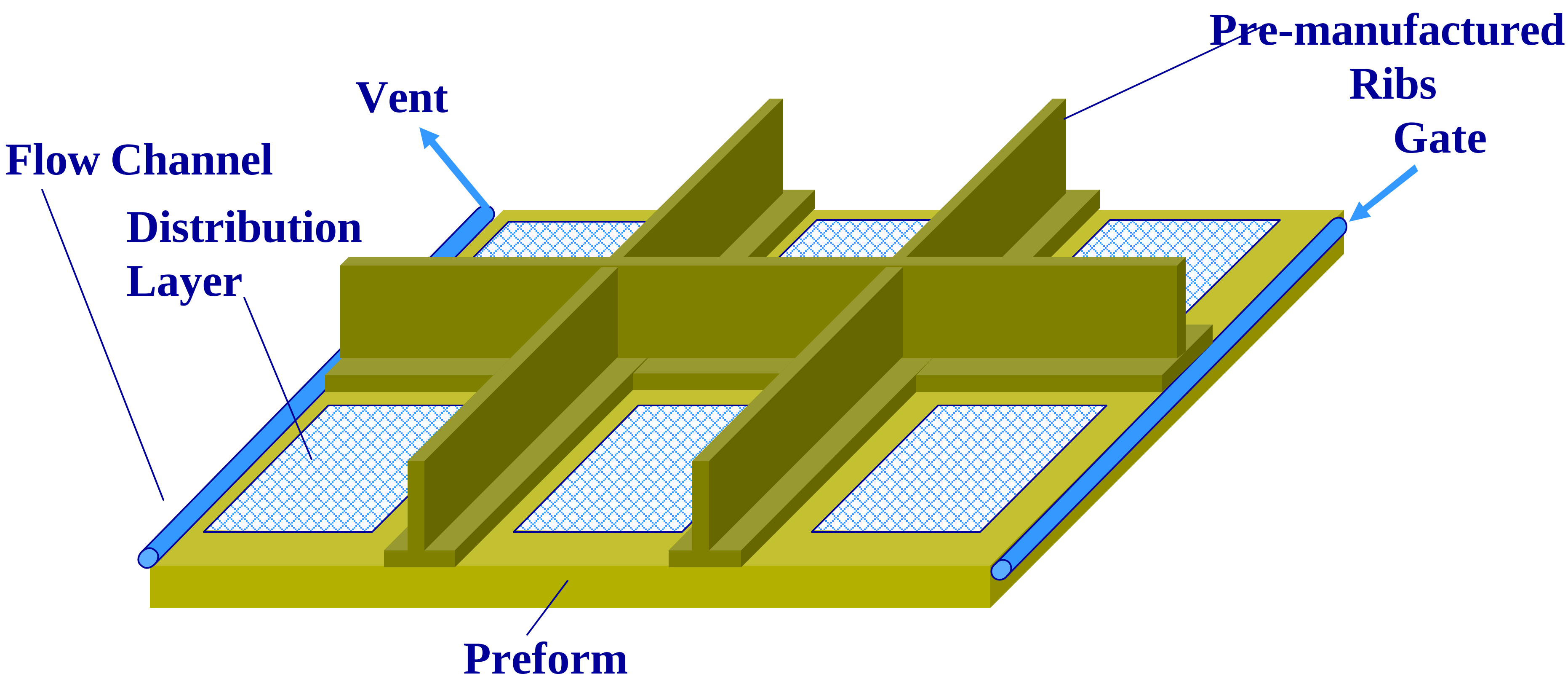
Select Desired Feature

```
10
10
0.01
0.2
100000
```

Use Corresponding Macro (Either SLIC Default or User Defined)

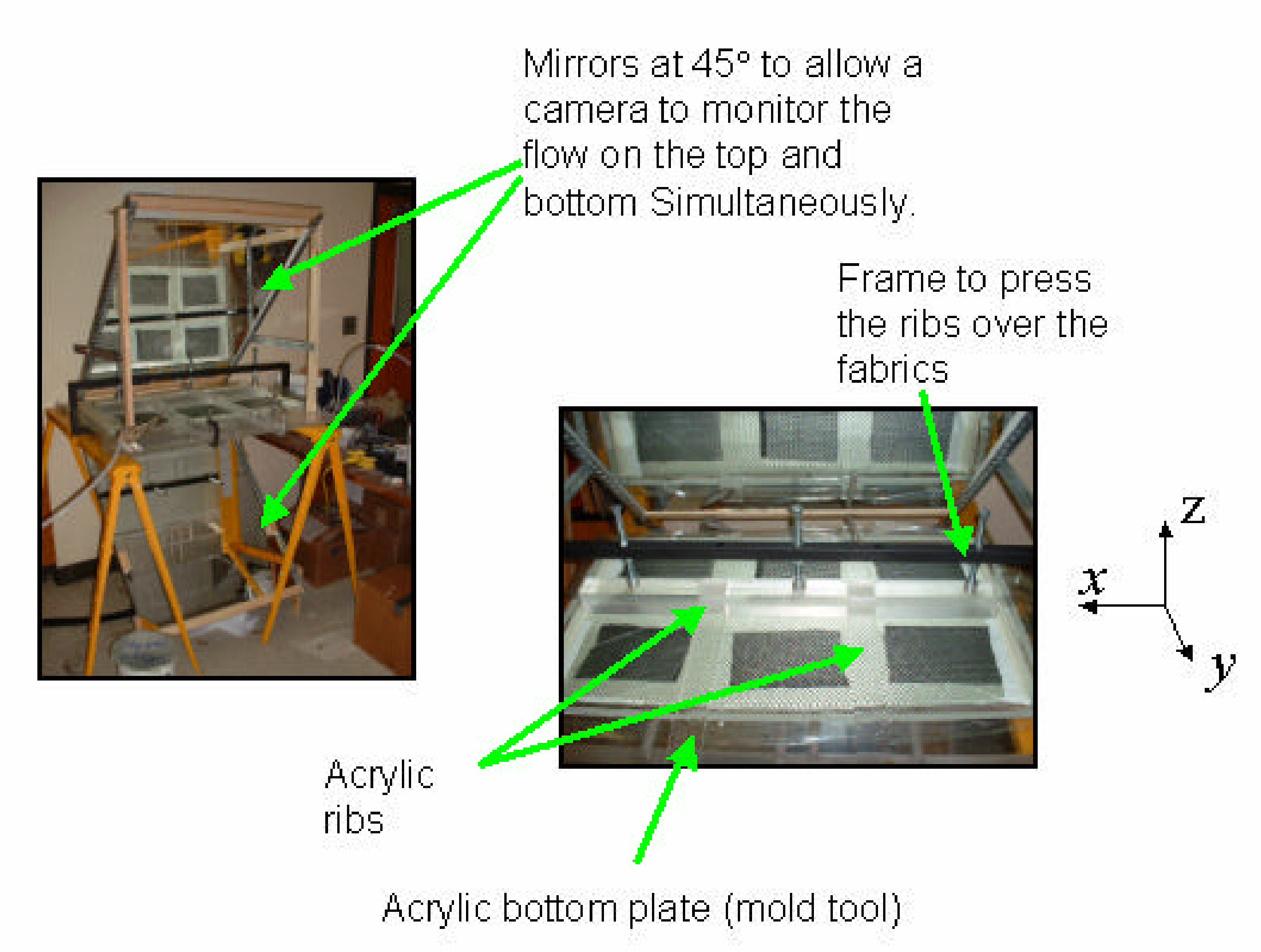


Case 2: A VARTM/Co-Cure Case Study

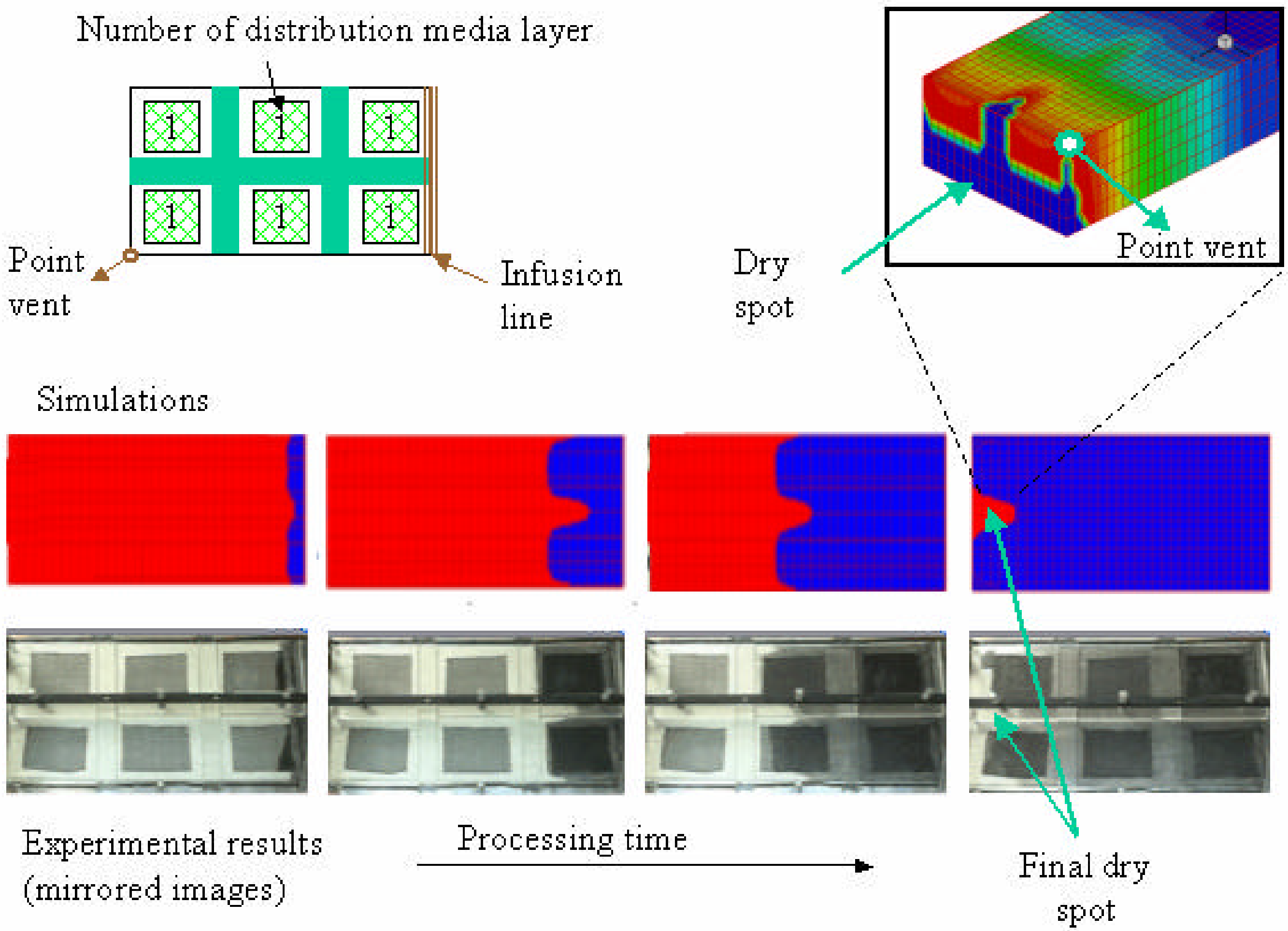


How to optimize the distribution network design?

Experimental Setup (for Case 2)

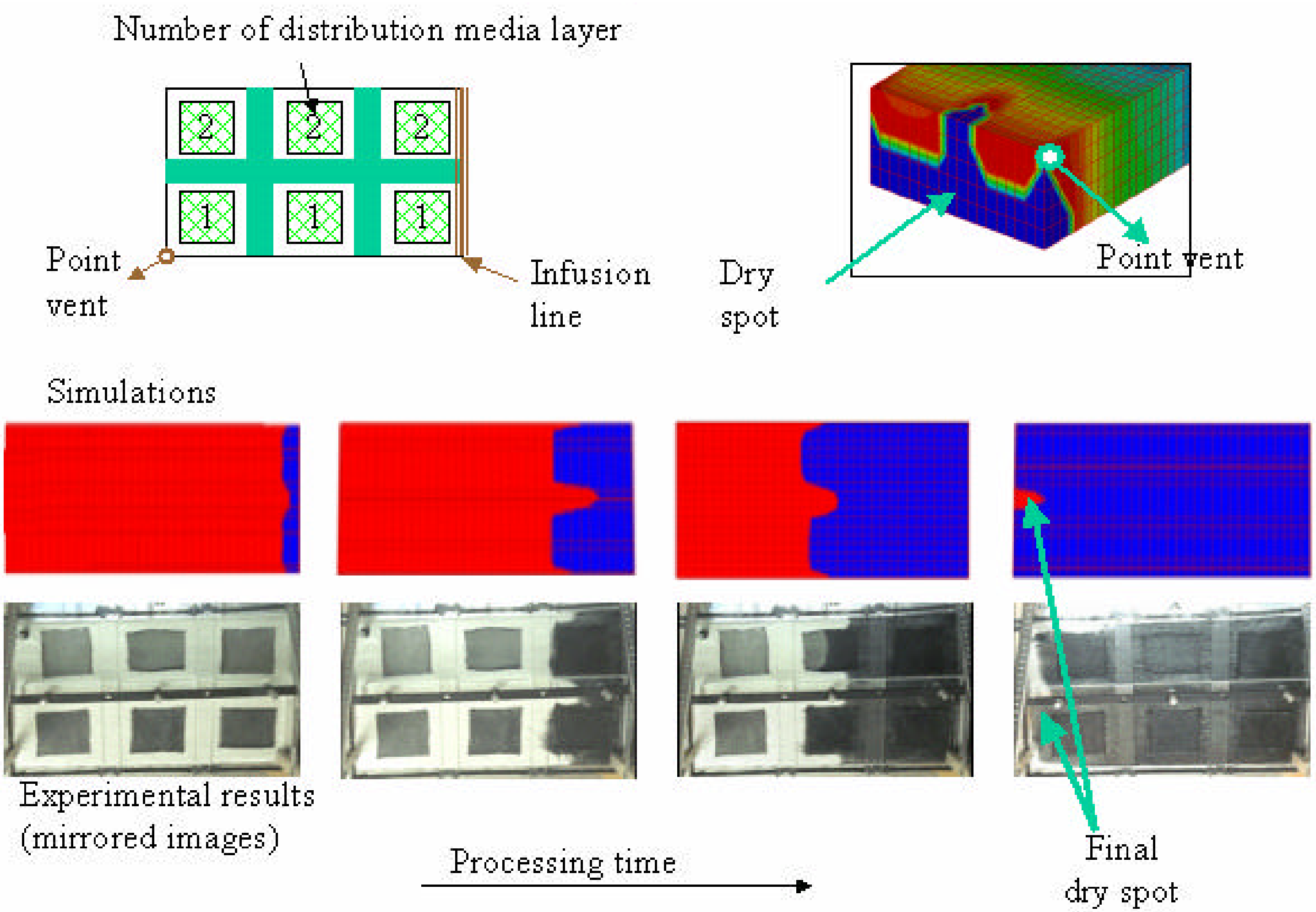


Trial and Error – 1 (for Case 2)



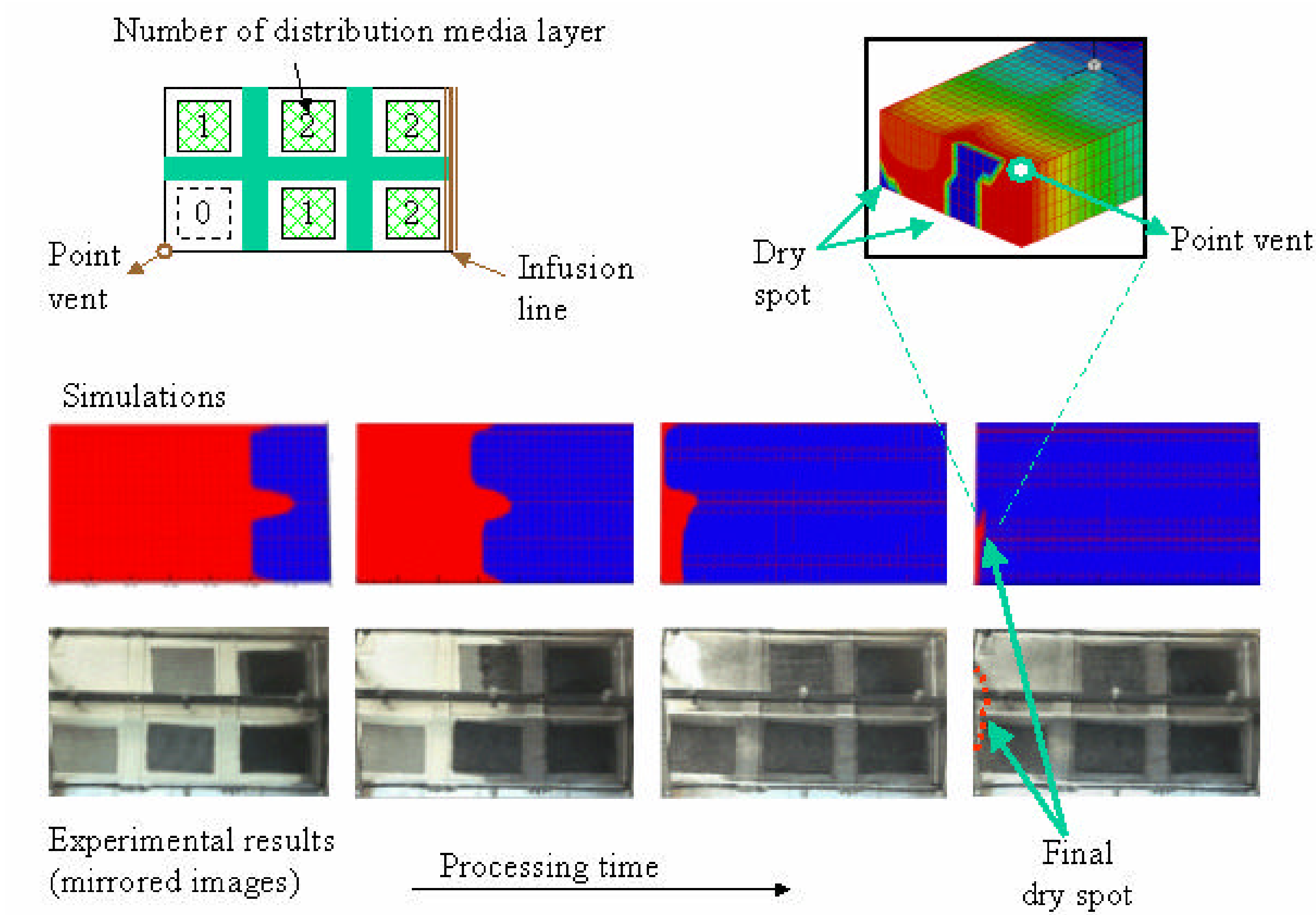
Fill Time ~ 19 min

Trial and Error – 2 (for Case 2)



Fill Time ~ 12 min

Trial and Error 4 - Expert Guess (for Case 2)



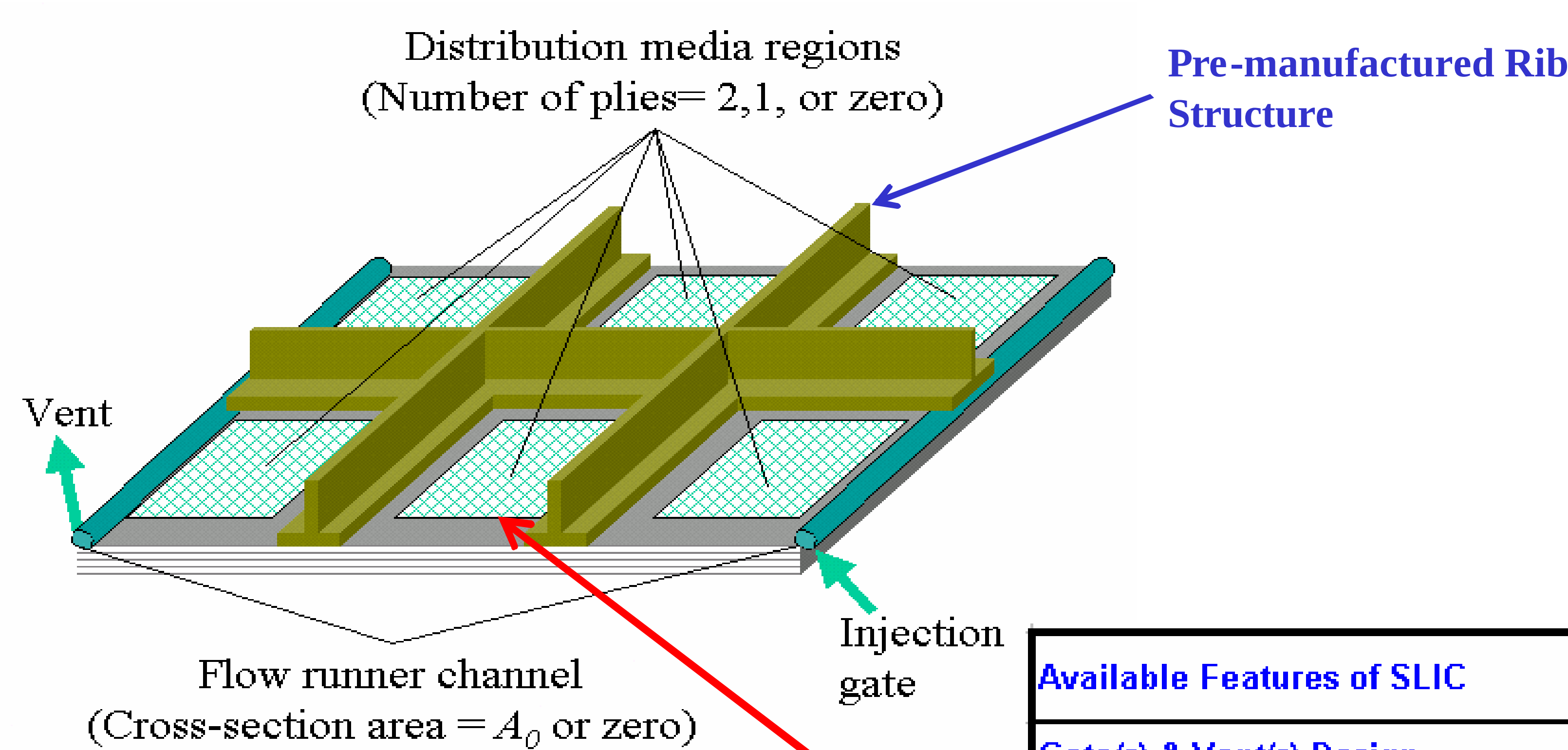
Fill Time ~ 11 min

Procedure – Optimizing Distribution Layers and Runner Channels with SLIC

1. Create Finite Element Mesh (Geometry) of the composite part.
2. Collect Permeability/Fiber Volume Fraction of the Preform.
3. Characterize the Permeability of the Distribution Media by using SLIC.
4. Calculate the Effective Permeability of the Flow Runner Channels.
5. Use SLIC to optimize the placement of Distribution Media and Flow Runner Channels.

Run an experiment to verify the design.

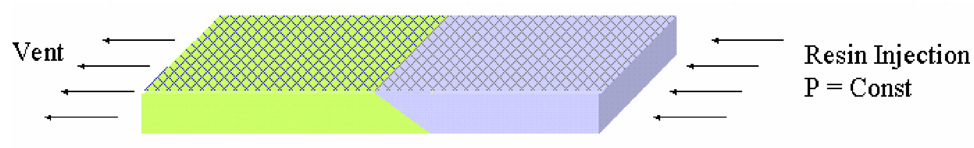
Case 2: A VARTM/Co-Cure Case Study



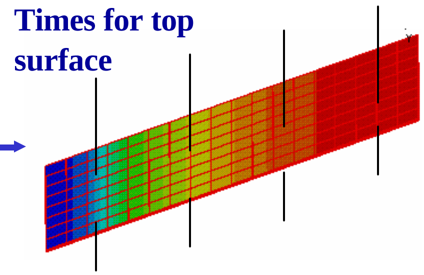
Available Features of SLIC	Features Used
Gate(s) & Vent(s) Design	
Flow Distribution Network Design	x
Mold Filling Monitoring & Online Characterization of Permeability/Volume Fraction	x
Online Mold Filling Flow Control	

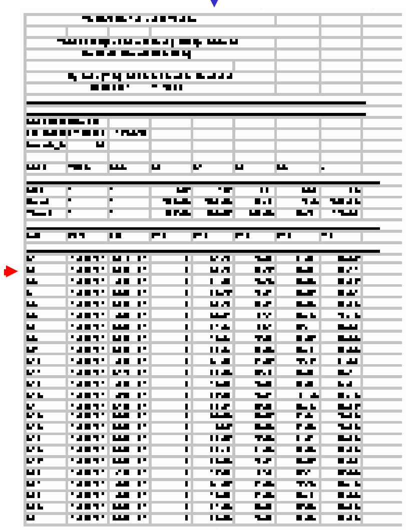
Distribution Layer Permeability Measurement with SLIC

Permeability ratio of the distribution layer and the preform is assumed as 5, 10, 15,…,150.

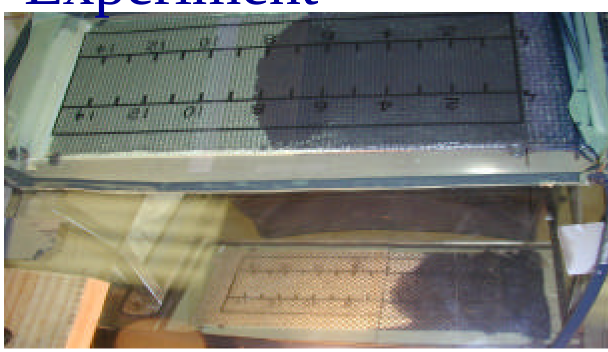


SLIC





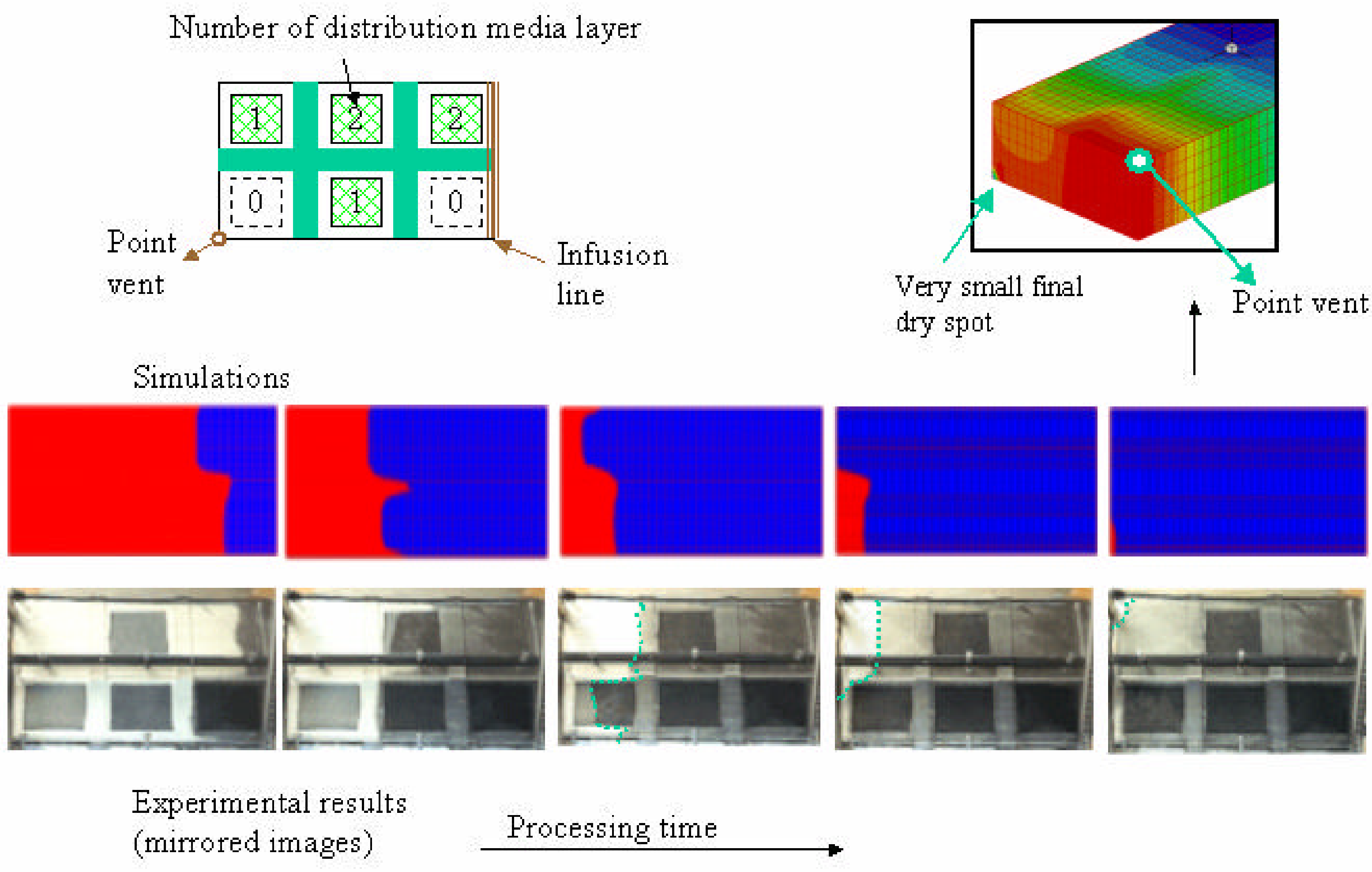
Experiment



Match

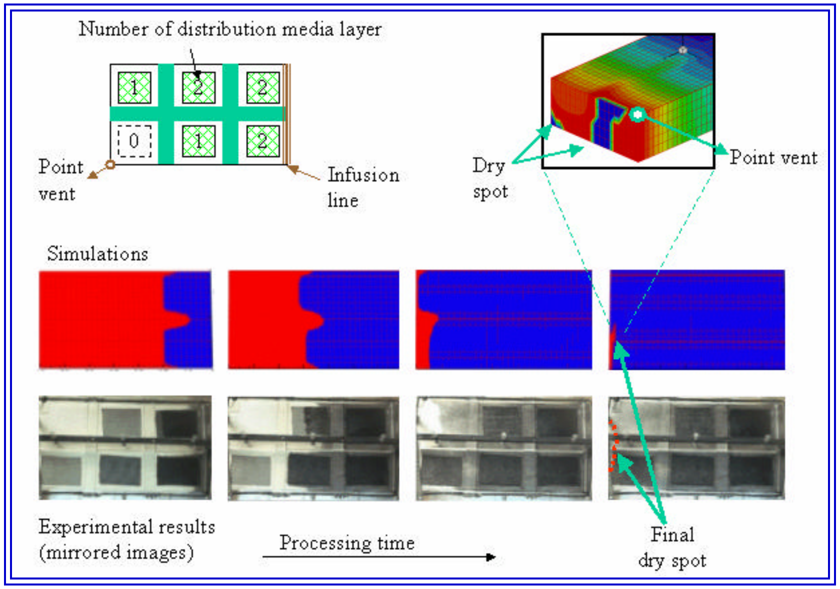
12 Experiments were conducted, the permeability ratio was obtained as 20-40.

Flow Distribution Network Design by SLIC

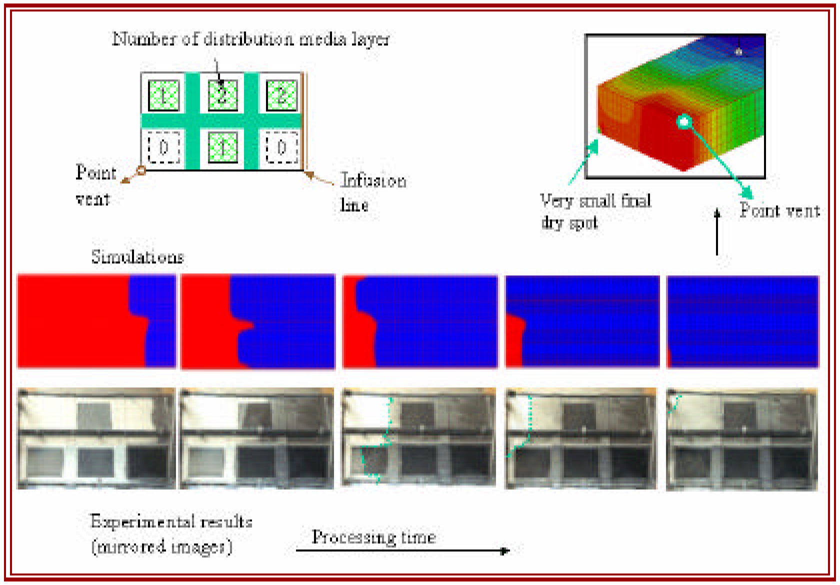


Fill Time ~ 13 min

Intuitive (Trial-and-Error) Design vs. SLIC's Design



Final (fourth) intuitive design



SLIC's design

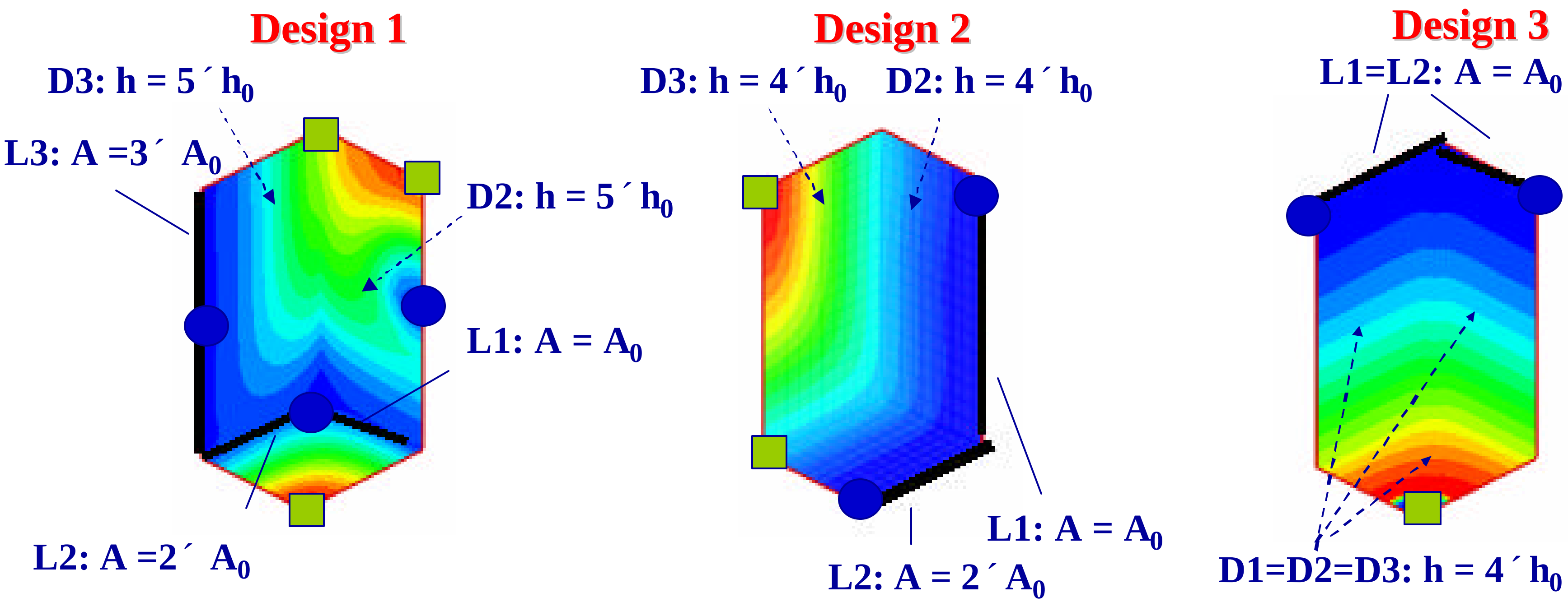
	Dry spot content	Fill time	Number of experiments
Trial-and-error intuitive design	0.851%	10.87 min	4
GA/simulation-based design (SLIC)	0.034%	13.05 min	1

Case 3: A VARTM Case Study

Gate
Vent

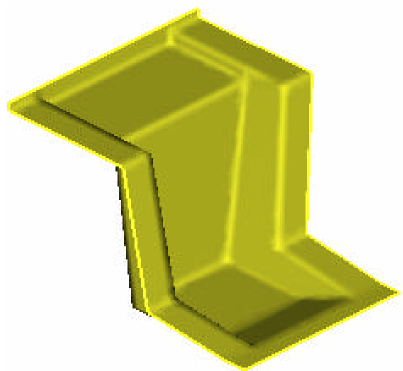
D: Distribution Media
L: Flow Runner

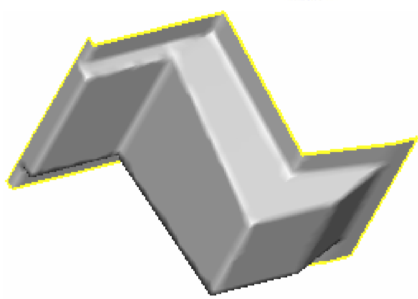
h_0: Thickness of 1-ply distribution media
A_0: Cross-section Area of reference Flow Runner

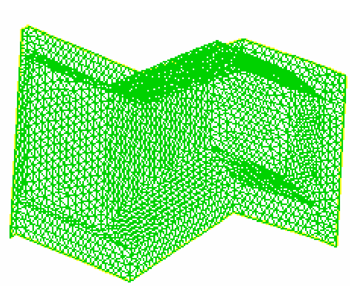


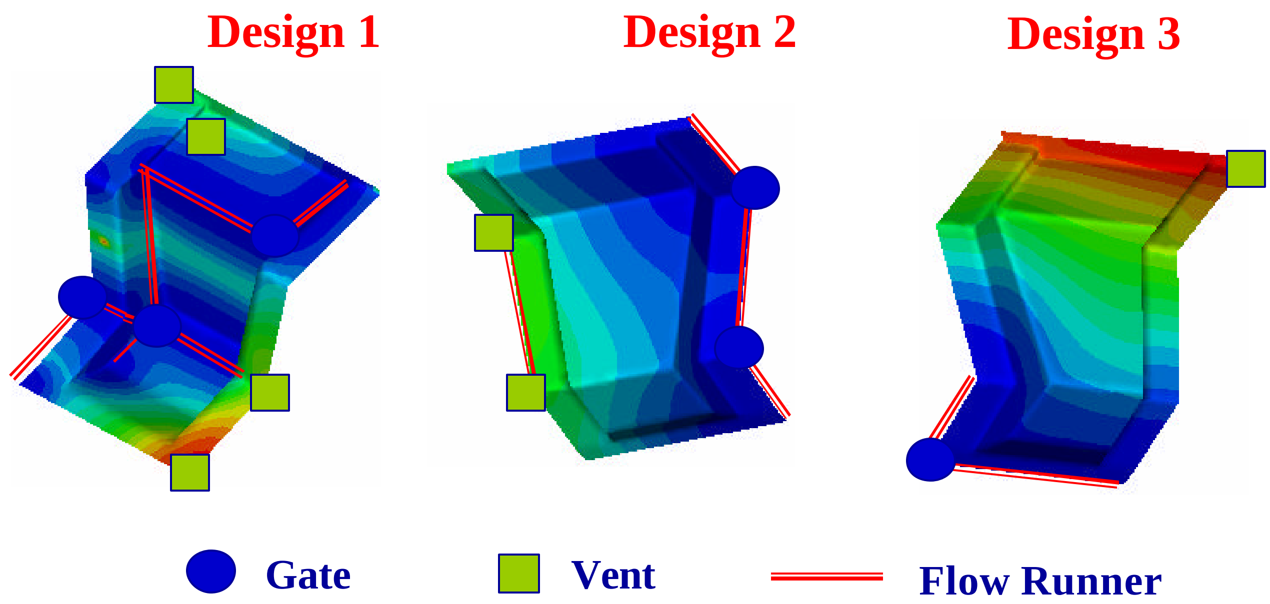
	Design 1	Design 2	Deign 3
SLIC Gates/Vents Optimization	Yes	No	No
SLIC Flow Distribution Network Optimization	Yes	Yes	No
Fill Time	28min	1hr 08min	1hr 38 min
Number of Empty Nodes/Number of Nodes	0/948	0/948	4/948

Case 4: Steps on a Boat Deck (VARTM with Flow Runners)









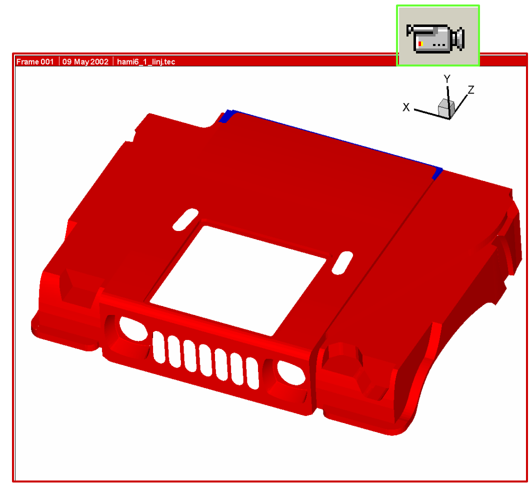
	Design 1	Design 2	Design 3
SLIC Gates & Vents Optimization	Yes	Yes	Yes
Number of Gates	3	2	1
Number of Vents	4	2	1
Fill Time Without Flow Runner	6min	15min	1hr
SLIC Flow Runner Optimization	Yes	Yes	Yes
Fill Time With Flow Runners	2min	14min	12min

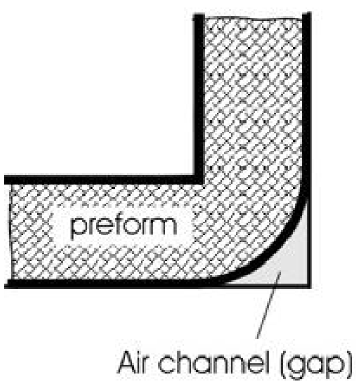
Permeability Variations

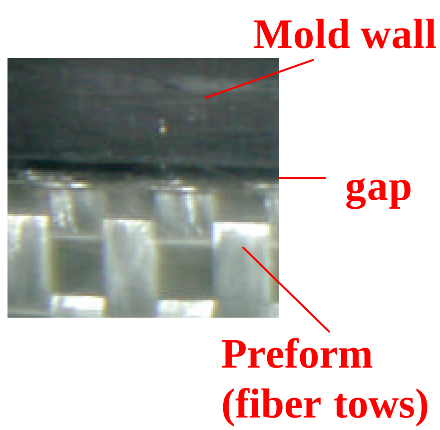
- ✓ •Injection Pressure/Port
- ✓ •Vent Pressure/Port
- ✓ •Resin Viscosity
- ? •Fiber Volume Fraction
- ? •Permeability of the the Preform

Characterization Challenges !

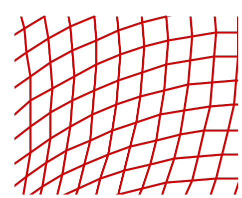
LIMS



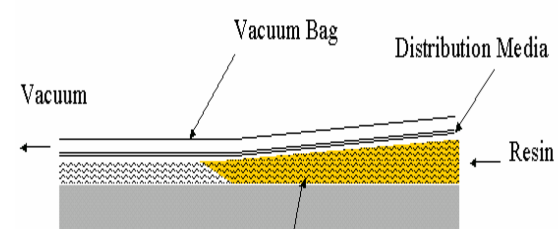




Deformed fabric Draping over a tool surface

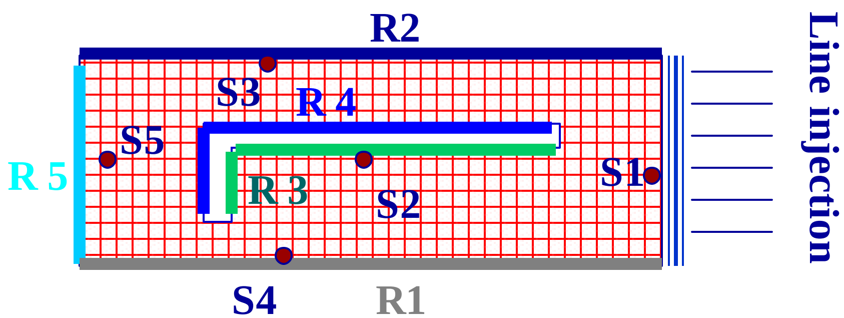


K and V_f change

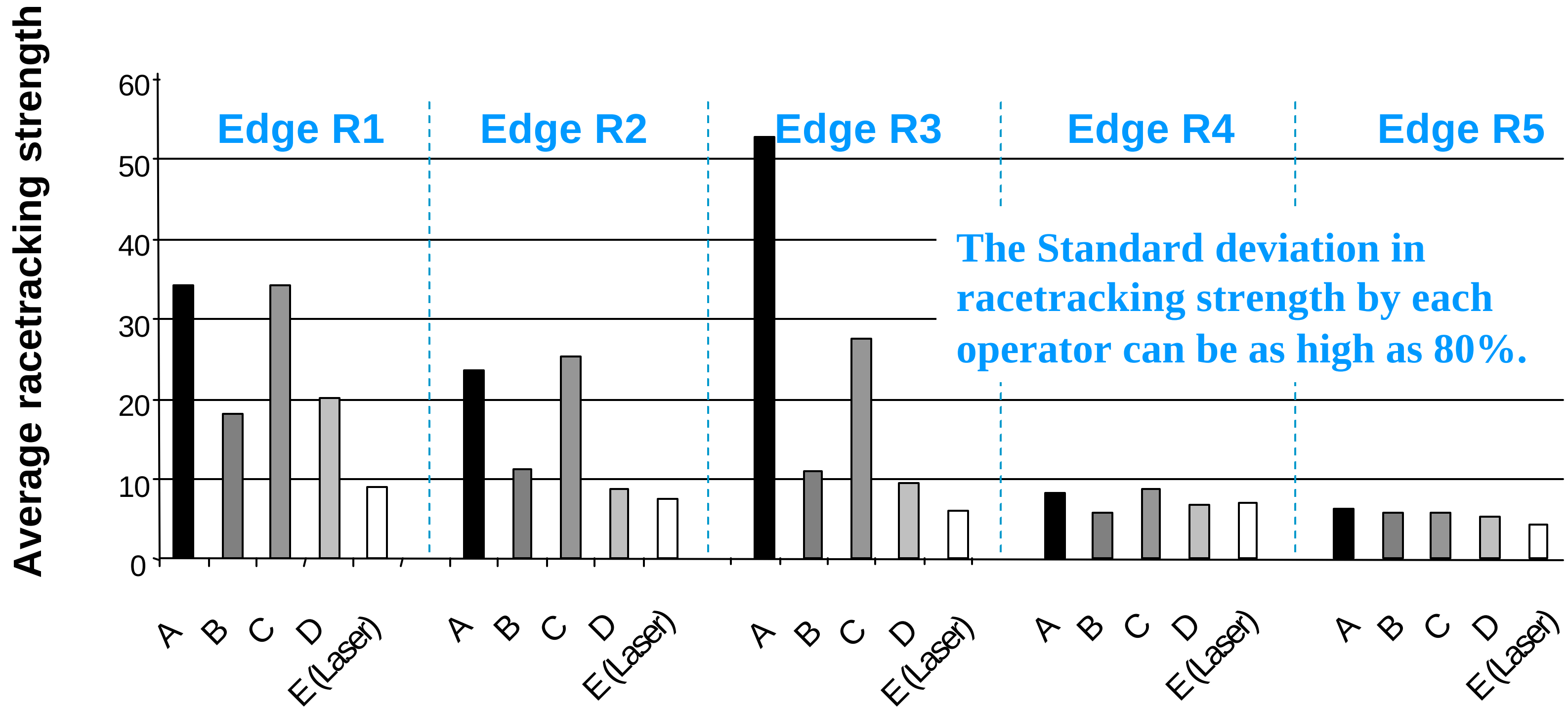


K and V_f Change due to the Compaction Variation in VARTM

Case 4: Using SLIC to Characterize the Racetracking



Five different operators A, B, C, D and E run 10 experiments each. A, B, C and D cut the fabrics by hands, E used a laser cutter.



Streamlined Flow Monitoring & Control - From Design To Automation

$$$
Cost Function
& Constraints

SLIC

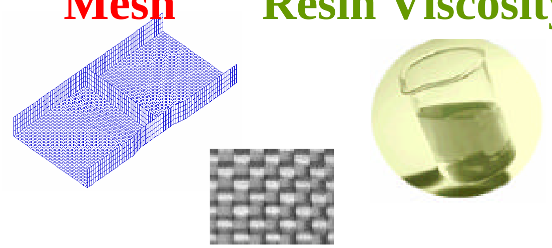
Equipment Installation Instructions

Flow Detection/Monitoring Database

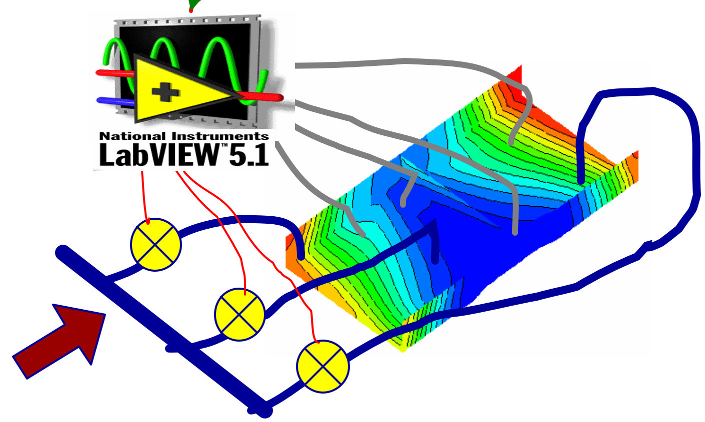
Flow Control Database

Mesh

Resin Viscosity



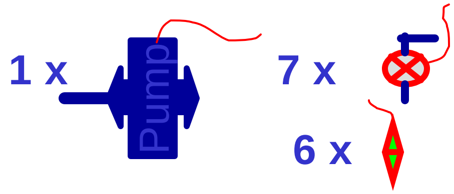
Preform Permeability
Fiber Volume Fraction



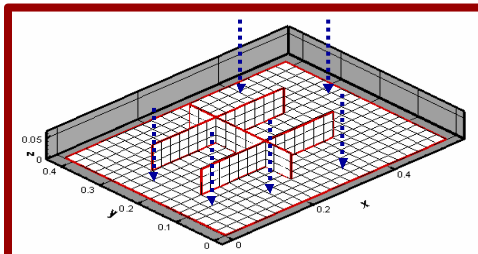
Desired Performance & Process Constraints

Automated Mold Filling Monitoring & Control

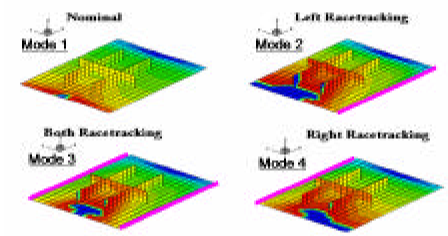
Developing Flow Sensing/Control System with SLIC



Number of Pumps, Lines, and Sensors to be used

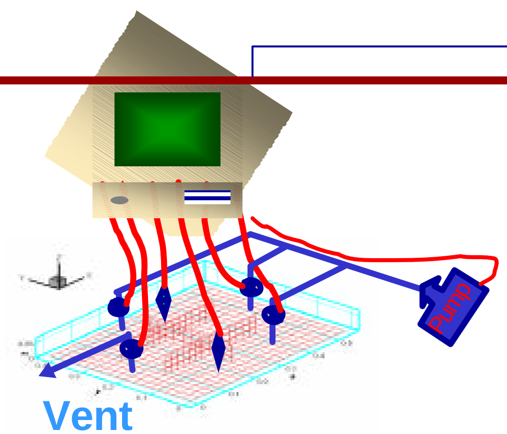


Potential Locations for Gates/Vents/Sensors

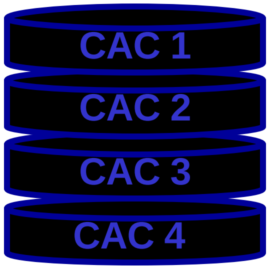


Mesh and Racetracking Information

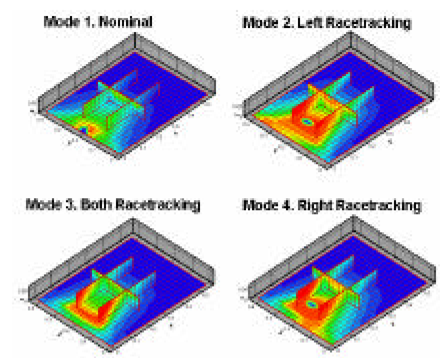
SLIC



Hardware Installation Code (HIC)



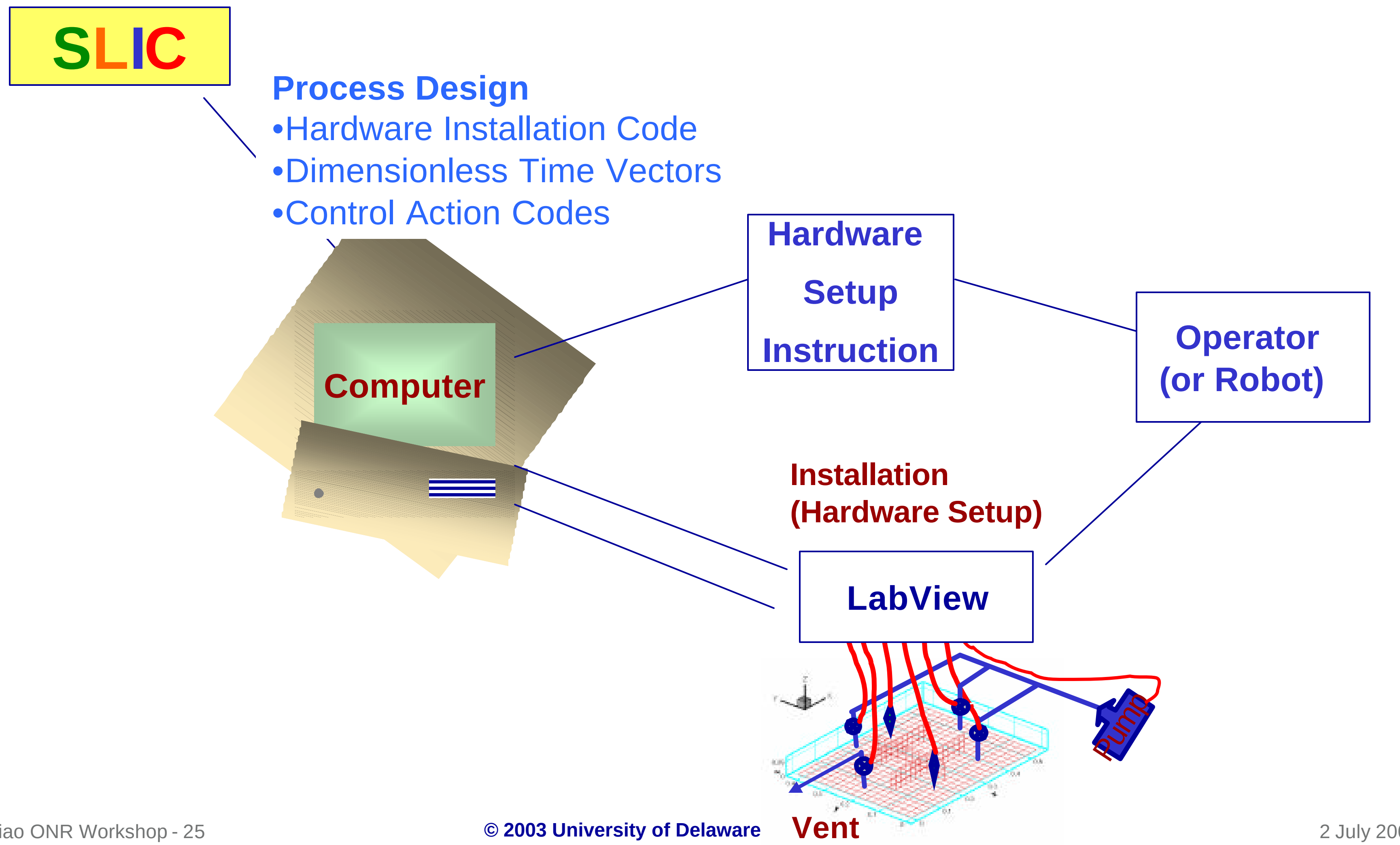
Control Action Code (CAC) for Each Disturbance Mode



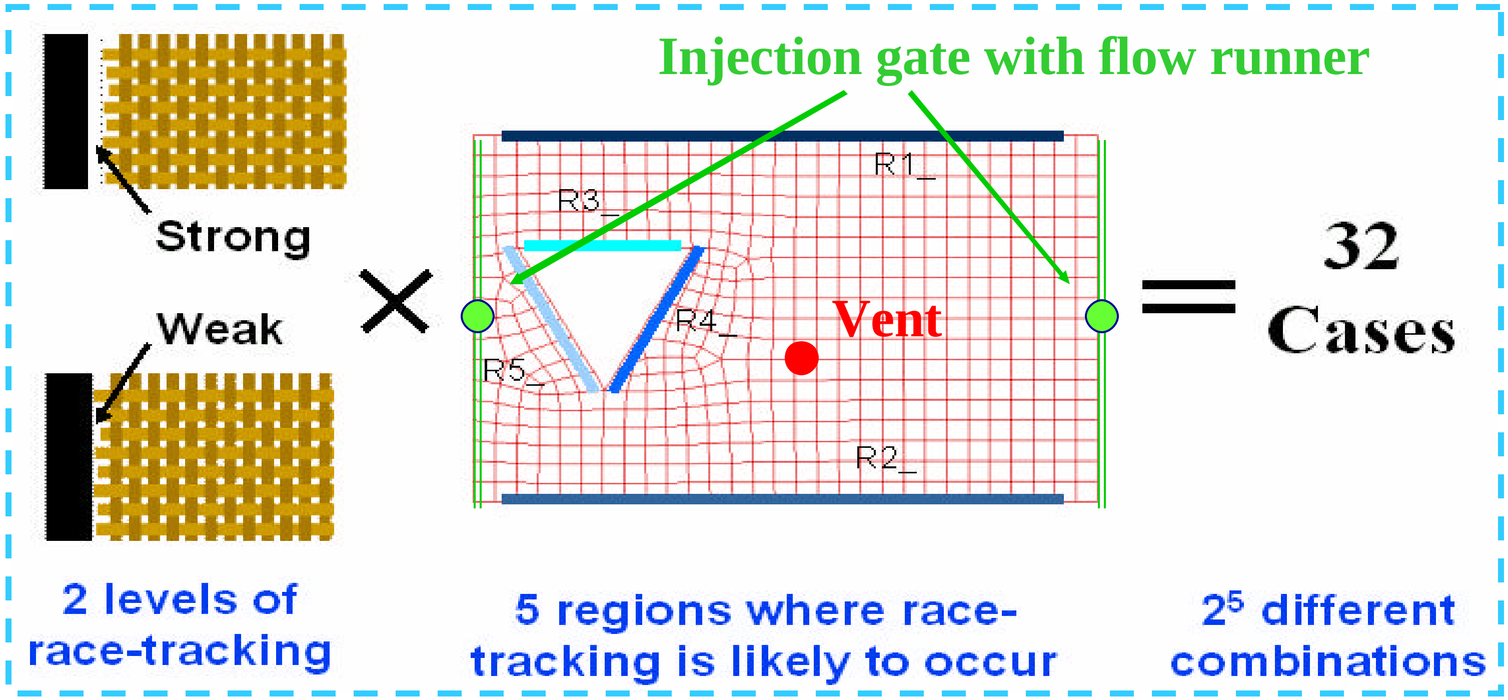
Controlled Results

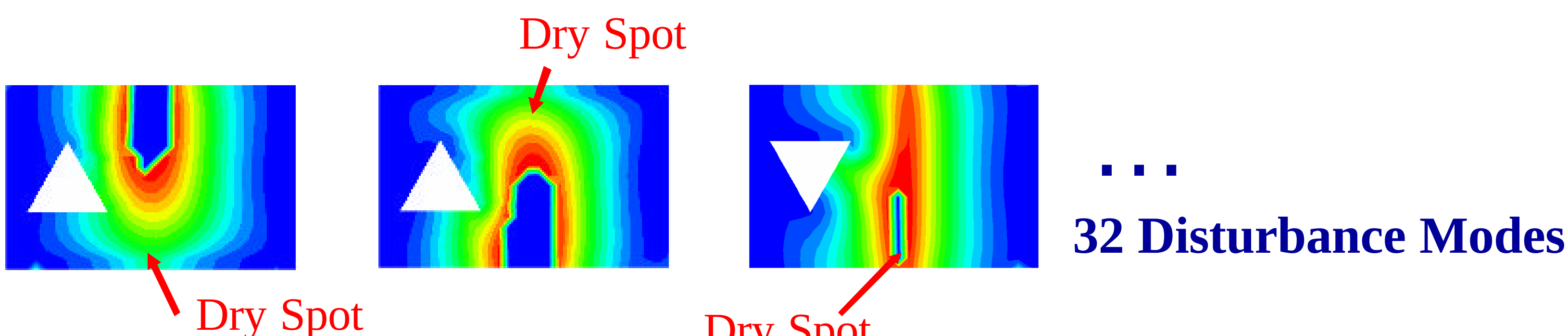
Flow of Automation

Simulation-based Liquid Injection Control (Intelligent Design Software)

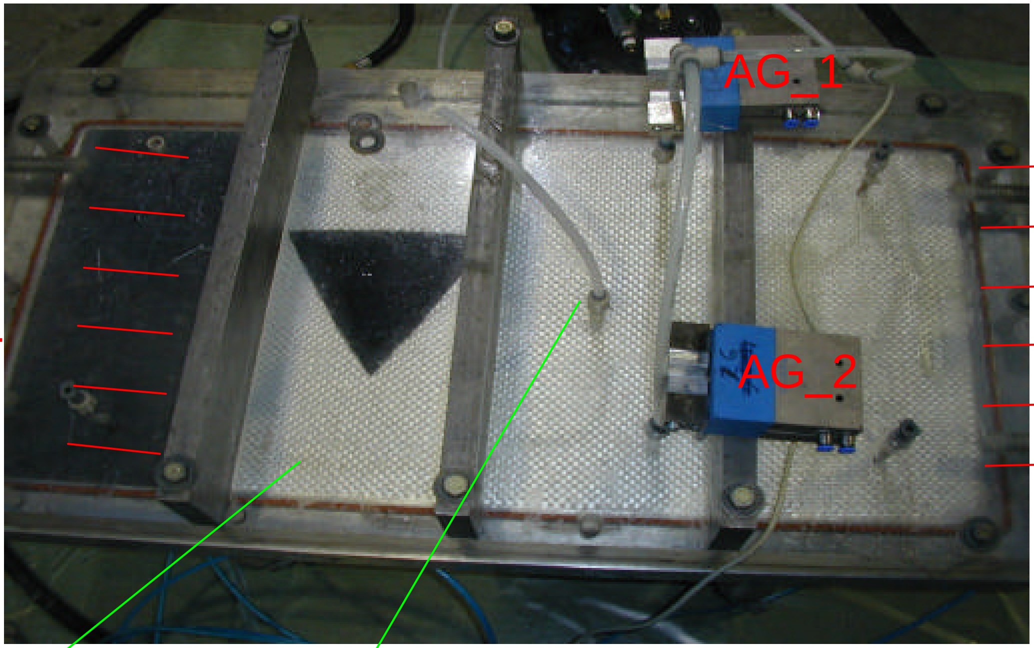


Case 5: Online Flow Sensing/Control with SLIC



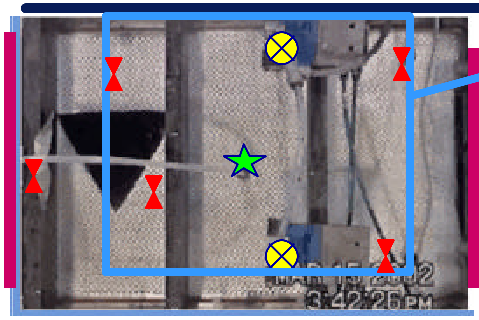


Experiment Preparation (for Case 5)



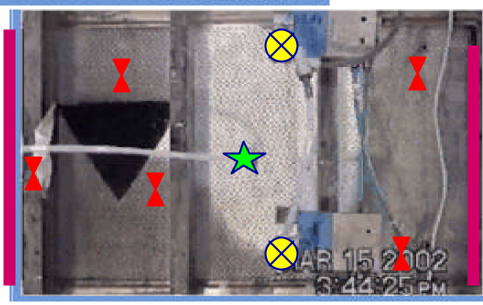
AG: Auxiliary gate IIL: Initial injection line

Case 6: Online Flow Monitoring & Control with SLIC



Tekscan™ Sensor Area (Pressure Grid Film)

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

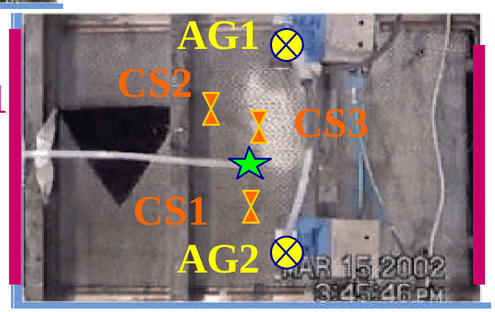


Experimental resin arrival times t_0, t_1, t_2, t_3, t_4 are all collected

Disturbance Mode 29 is selected from the Database

Implement the customized control action for Mode 29

IG1



IG2

Control action Mode 29 is taking place.

- CS1 >>> Close IG2
- CS2 >>> Open AG1
- CS3 >>> Close IG1
- Vent Sensor >>> Close All Gates.

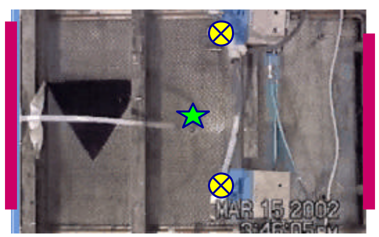
Initial injection gate (IG) with flow runner

Fixed vent

Auxiliary gate (AG)

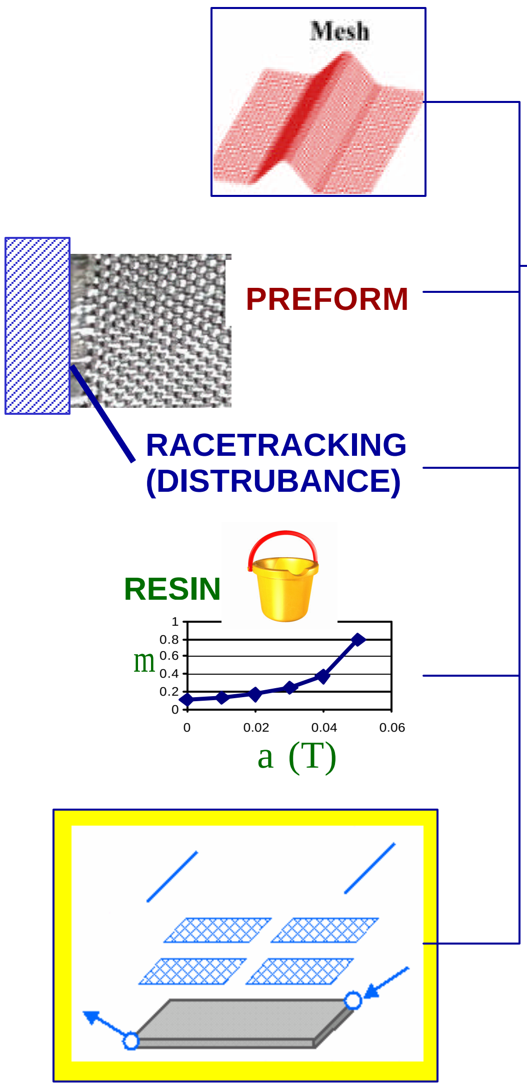
Disturbance detection sensor (DS)

Control action trigger sensor (CS)



Successful injection

Summary



SLIC

AUTOMATED DESIGN

- Selection of Initial Gate and Vent Locations
- Optimization of the Flow Distribution Network
- Online Flow Sensing/Permeability Characterization System Design
- Creation of Online Flow Control Solution

Advantages of developing RTM/VARTM with SLIC

- Rapid design for RTM/VARTM.
- Less cost for process development.
- Reliable and comprehensive mold filling solution.
- Advanced flow monitoring/control technology provides the opportunity to elevate the part quality and reduce the cycle time.

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