Moldex3D

Simultaneous Estimation of In-Plane Permeability and Porosity in Fiber Reinforcement using Sensor Fusion

Wei Qi [1] , Tzu-Heng Chiu [2], Yi-Kai Kao [2], Yuan Yao [2], , Yu-Ho Chen [3], Hsun Yang [3], Chen-Chieh Wang [3], Chia-Hsiang Hsu [3] and Rong-Yeu Chang [3]

1 School of Information and Electrical Engineering, Zhejiang University City College, China;

2 Department of Chemical Engineering, National Tsing Hua University, Taiwan;

3 CoreTech System Co., Ltd. (Moldex3D), Taiwan

CoreTech System

Moldex3D
MOLDING INNOVATION

- Founded in 1995, a leading professional plastic injection molding simulation solution supplier for plastic injection molding industry
- World’s largest professional team (250+ employees, 80% technical professionals) dedicated to plastics injection molding simulation
- Based on CAE as Core-Technology, provides advanced technologies and solutions for industrial demands with worldwide marketed “Moldex3D” series
- Provide leading software solution and attentive technical support to work with global customers for optimizing the process from design through manufacturing

Outline

- Introduction
  - Why RTM?
  - Workflow of Moldex3D
  - What RTM Can Simulate?
- Modeling and experiment
  - Experimental setup
  - Modeling and methodologies
  - Material measurement
  - Validation of simulation
- Conclusion

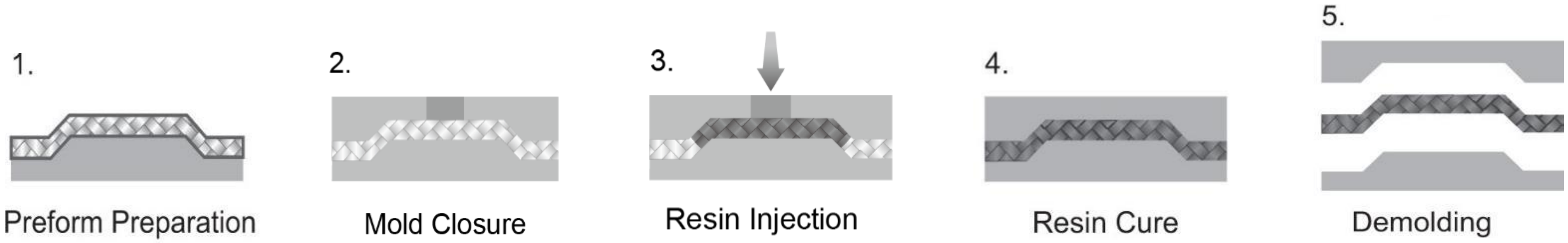
Introduction

- Why RTM?
- Workflow of Moldex3D
- What RTM Can Simulate?

Liquid Composite Molding (LCM) Processes

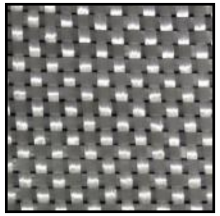
- For manufacturing of composite parts with a high content of oriented reinforcement
  - The impregnation of a dry preform with a liquid matrix by liquid composite molding processes
  - Very high potential for economical manufacturing of high performance composite components

- Types of processes covered
  - RTM, VARTM, RFI, CRTM

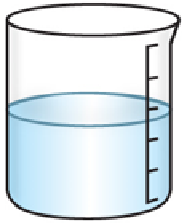


Fiber-reinforced plastic components

Reinforcement:
Glass fiber
Carbon fiber
Kevlar
Natural plant fibers



Resin:
Epoxy
Vinyl ester
Unsaturated Polyester



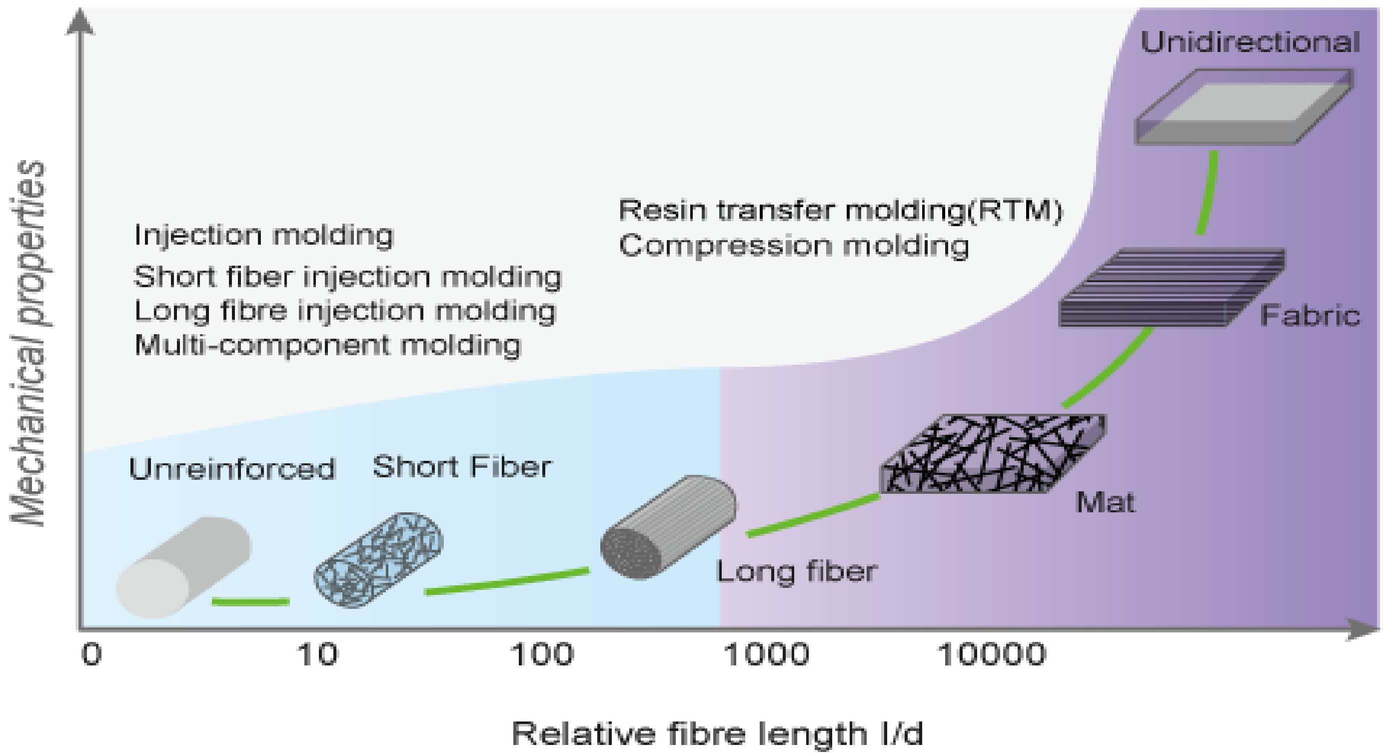
Manufacturing process

Wang, M.-L.; Chang, R.-Y.; Hsu, C.-H., Molding Simulation: Theory and Practice. Hanser Publications **2018**.

Composite Products

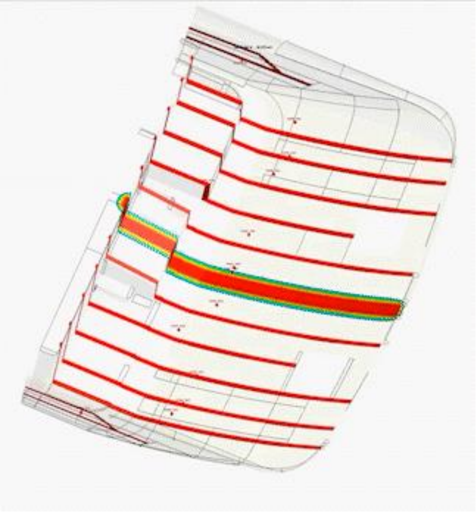
Goal:

› **Reduce vehicle weight, and improve mechanical strength of the product**

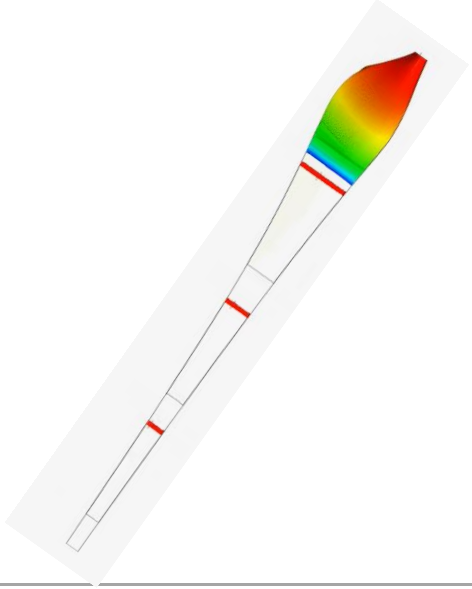


Success story in Resin Transfer Molding processes

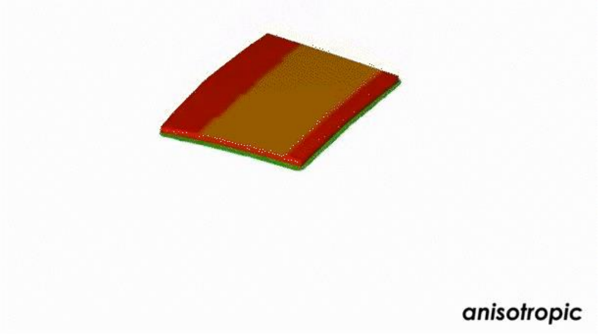
VARTM



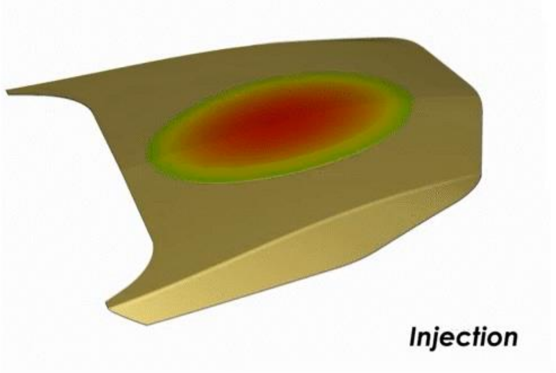
VARTM



Wet RTM



CRTM



Workflow of Integrated CAE Simulation for RTM

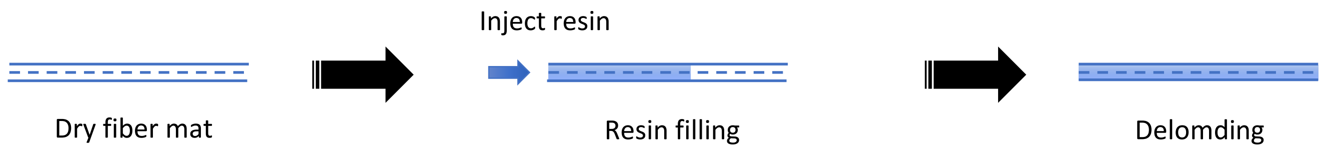
- **3-step simulation procedure**
  - **Step 1: Preform forming**
  - **Step 2: Resin injection filling**
  - **Step 3: Demolding**

RTM Wizard

Guide the user to build the RTM model: 3D mesh, fabric orientation, inlet location, etc.

RTM Analysis

Calculate the resin flow and product warpage

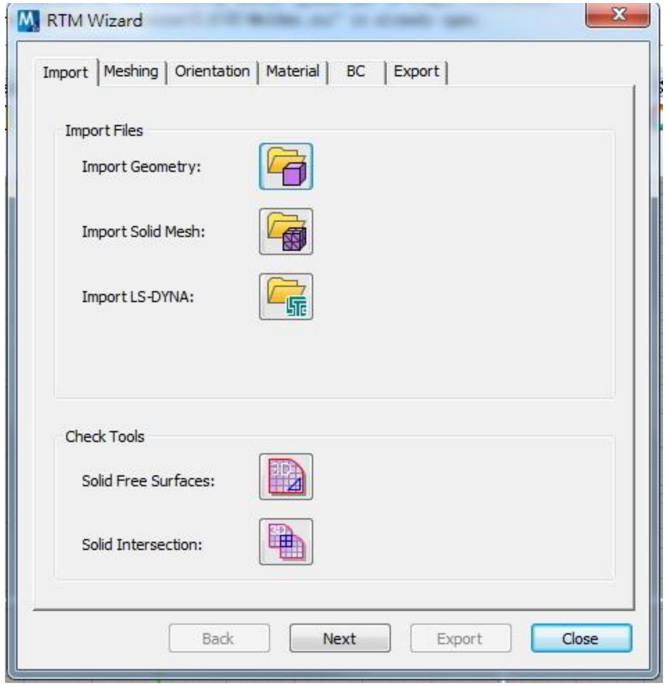


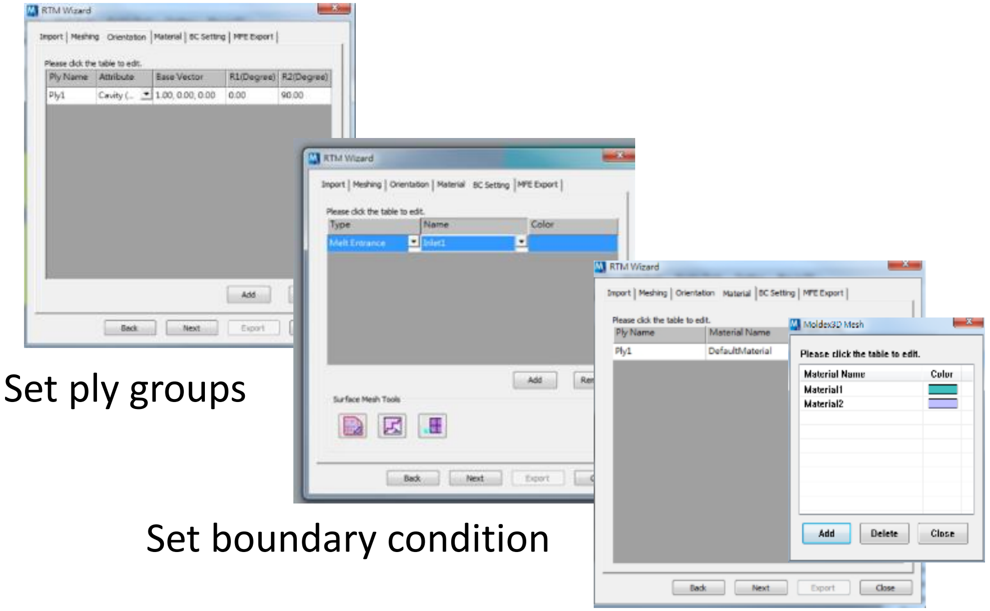
RTM Wizard

› **Moldex3D Mesh (RTM Wizard) helps users from building solid mesh to export input files**

› **Help users:**

  – **Set ply groups, boundary conditions, and ply material groups**





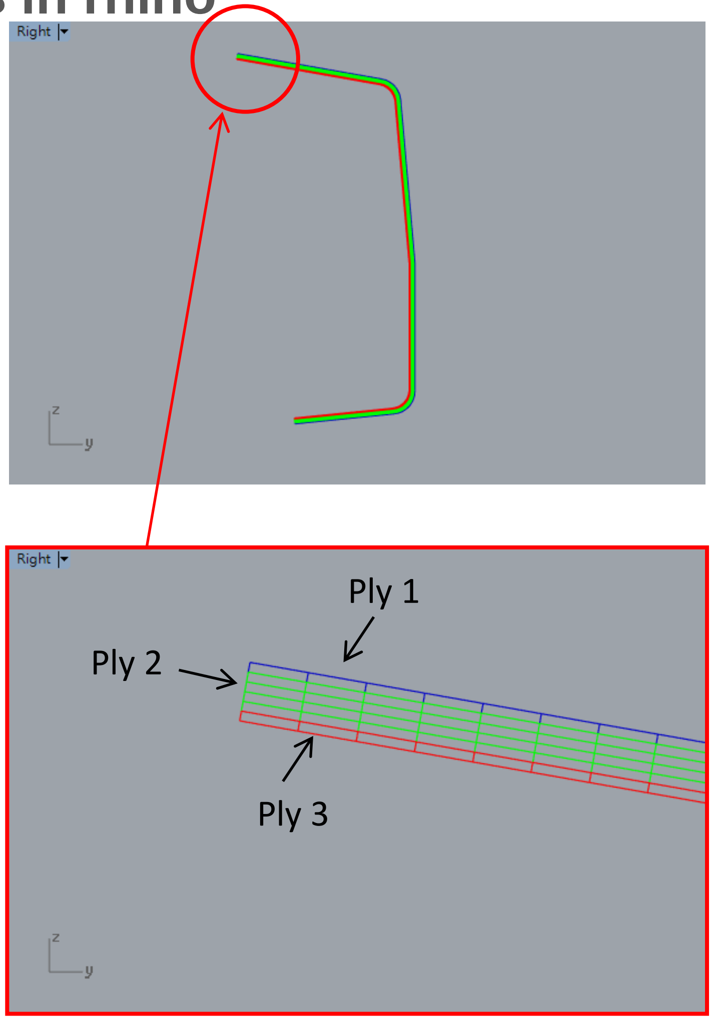
Set ply groups

Set boundary condition

Set ply material groups

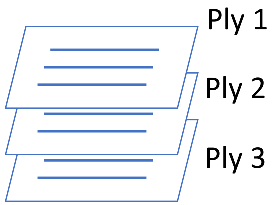
Settings of Ply Orientations in Moldex3D

› **Settings in rhino**



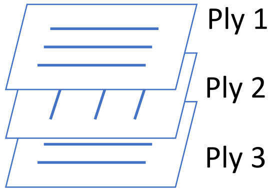
0°/0°/0°

Ply Name	Attribute	Base Vector	R1(Degree)	R2(Degree)
Ply1	Cavity (...	1.00, 0.00, 0.00	0.00	90.00
Ply2	Cavity (...	1.00, 0.00, 0.00	0.00	90.00
Ply3	Cavity (...	1.00, 0.00, 0.00	0.00	90.00



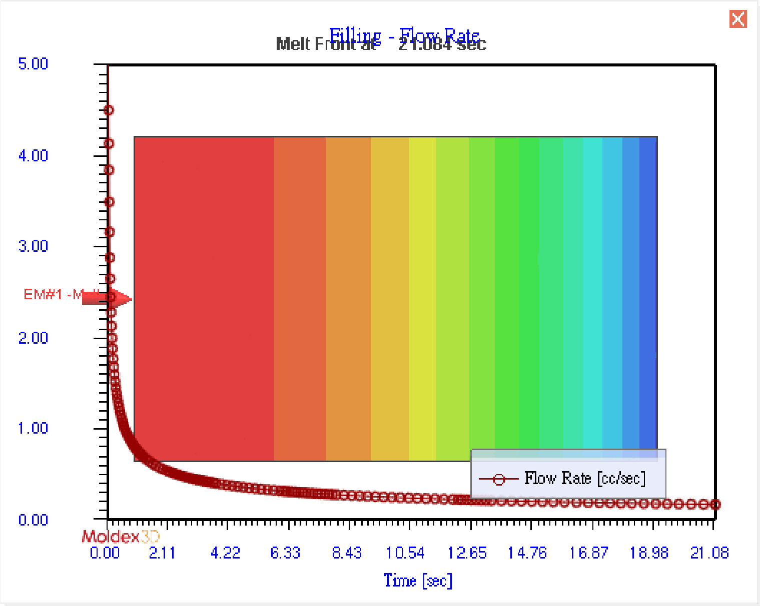
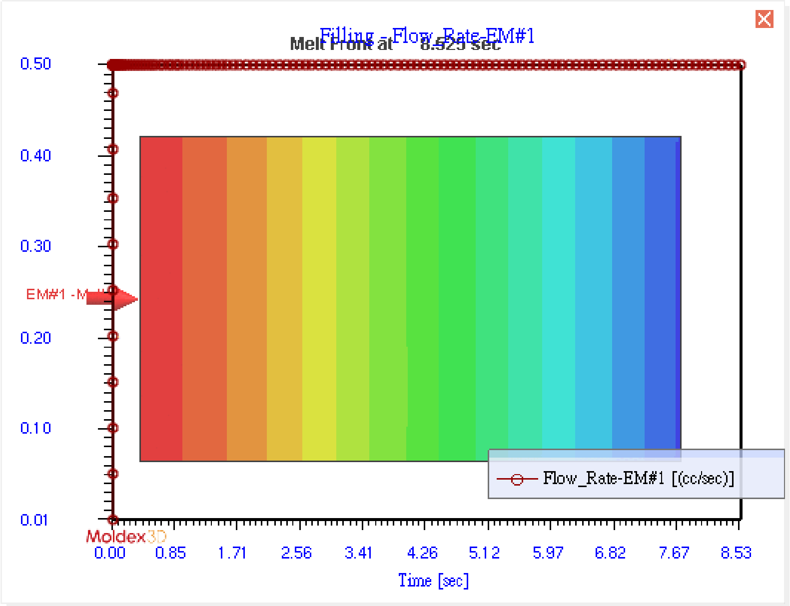
0°/90°/0°

Ply Name	Attribute	Base Vector	R1(Degree)	R2(Degree)
Ply1	Cavity (...	1.00, 0.00, 0.00	0.00	90.00
Ply2	Cavity (...	1.00, 0.00, 0.00	90.00	0.00
Ply3	Cavity (...	1.00, 0.00, 0.00	0.00	90.00



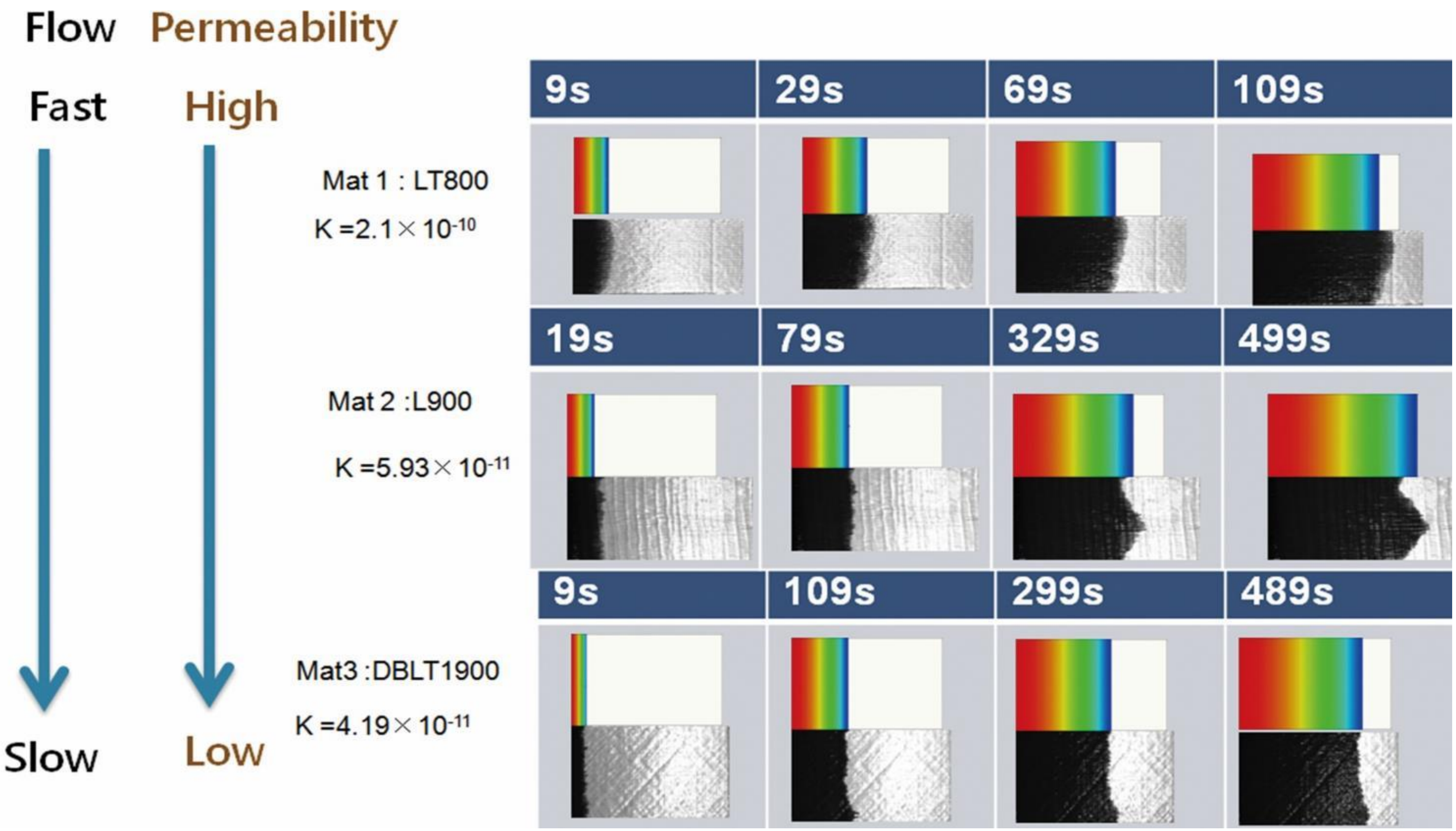
Pressure / Flow Rate Control

› **Resin infusion can be controlled by pressure or flow rate**

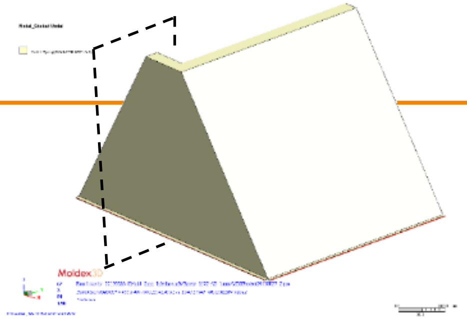
Pressure Control	Flow Rate Control
	

Flow rate comparison

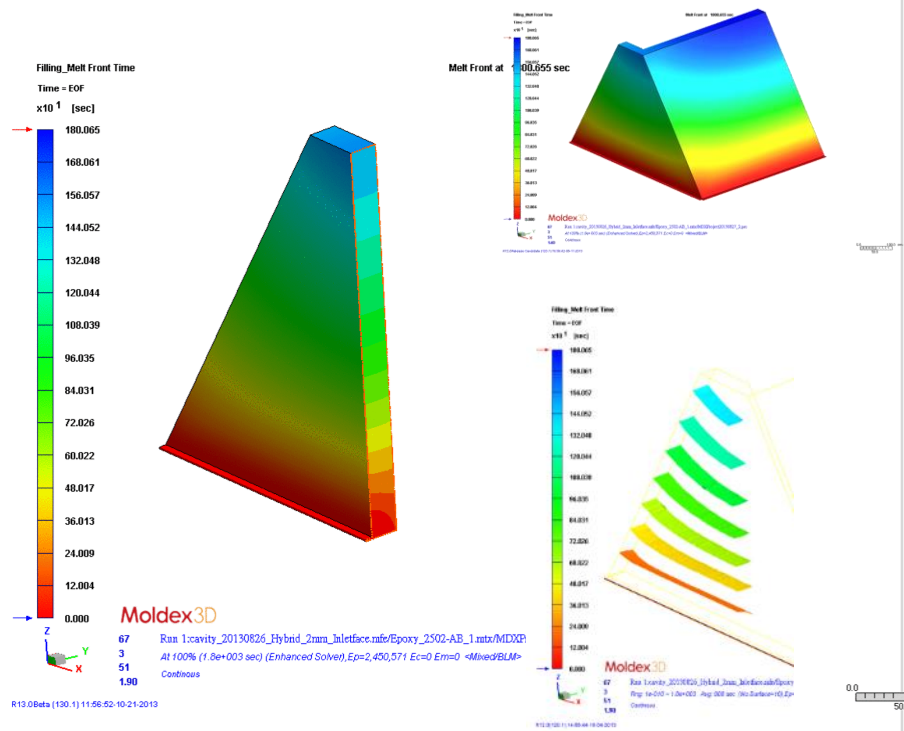
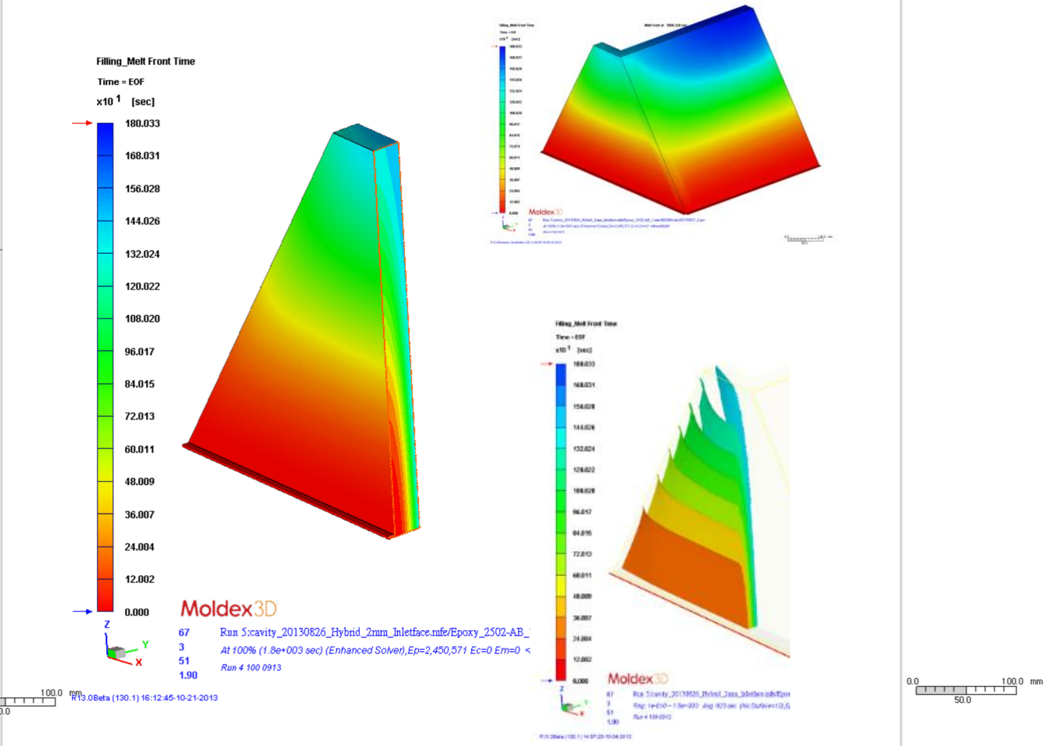
CAE Verification on Mat Effects



Anisotropic Permeability of Fiber Mat

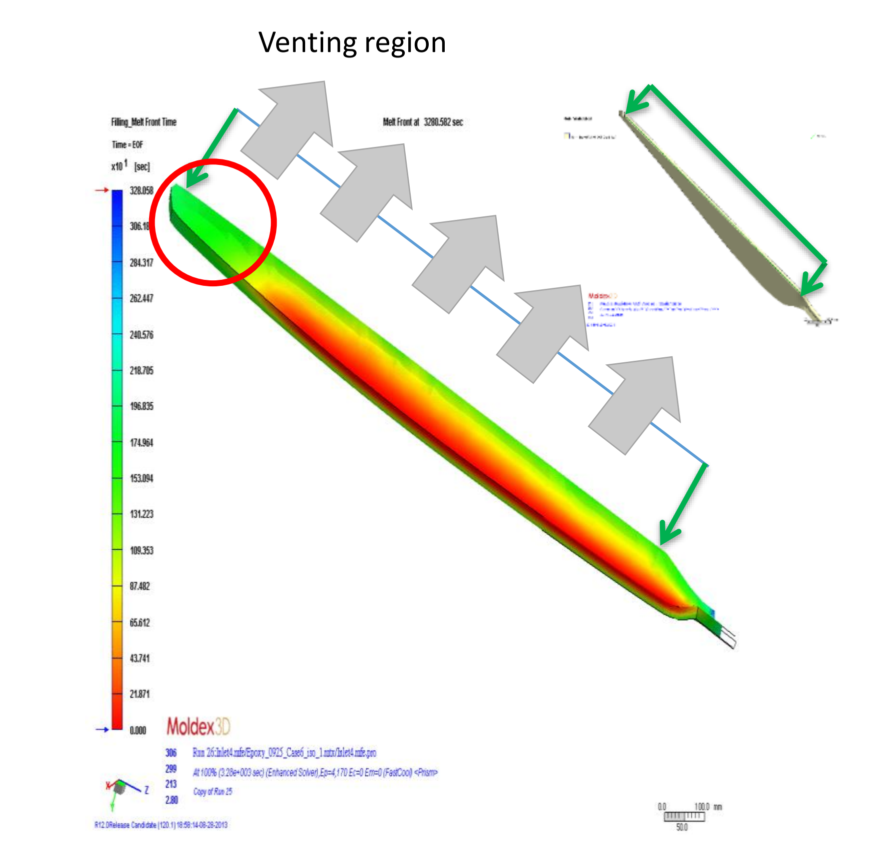
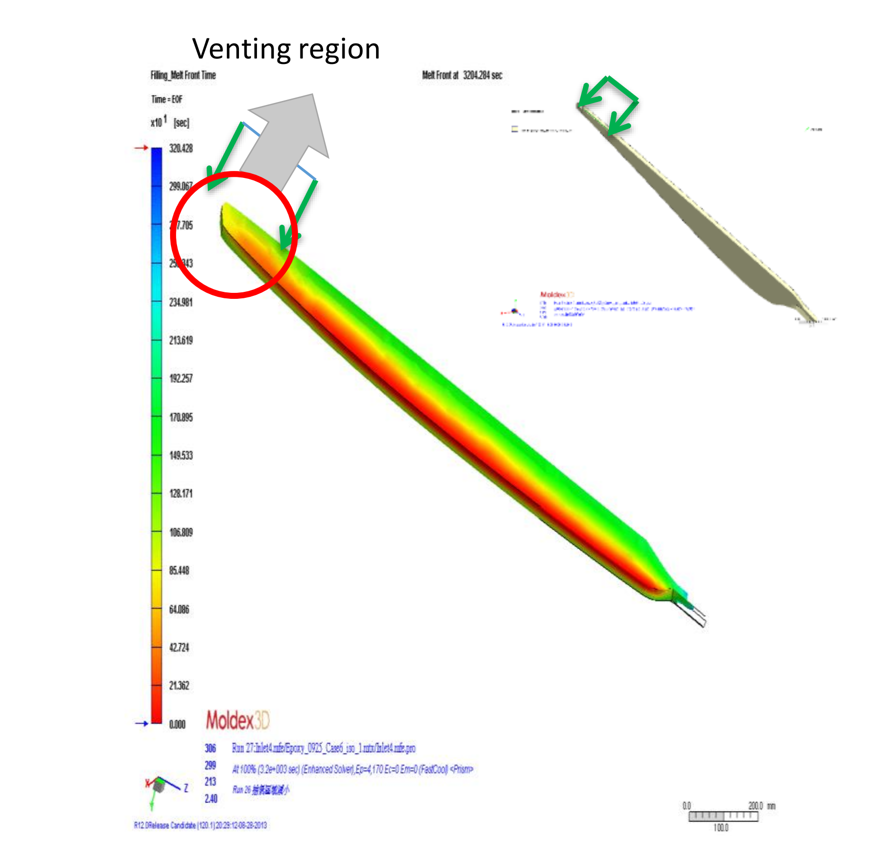


- Directional impact
  - Different filling behavior in thickness direction

Isotropic Permeability	Anisotropic Permeability
	

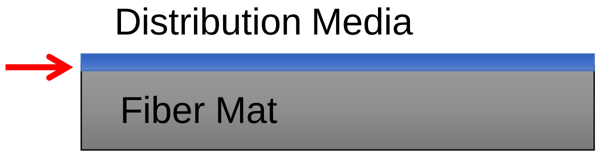
Venting Effect on the Filling Behavior

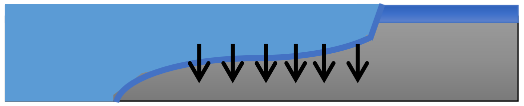
› **Filling pattern with different length of venting boundary**

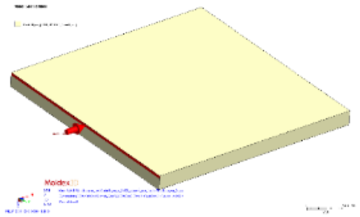
Long Venting Boundary	Short Venting Boundary
	

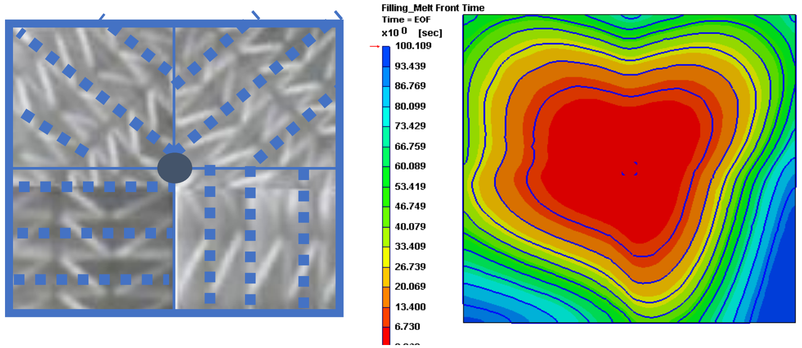
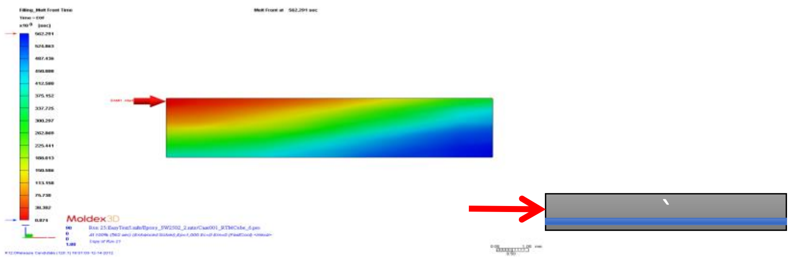
Multi-Layer Fabric Mats

› **Support to assign different permeability for different regions**







Without Distribution Media	Ply Orientation Affects the Filling Behavior
	
With Distribution Media	
	

Modeling and experiment

Experimental setup

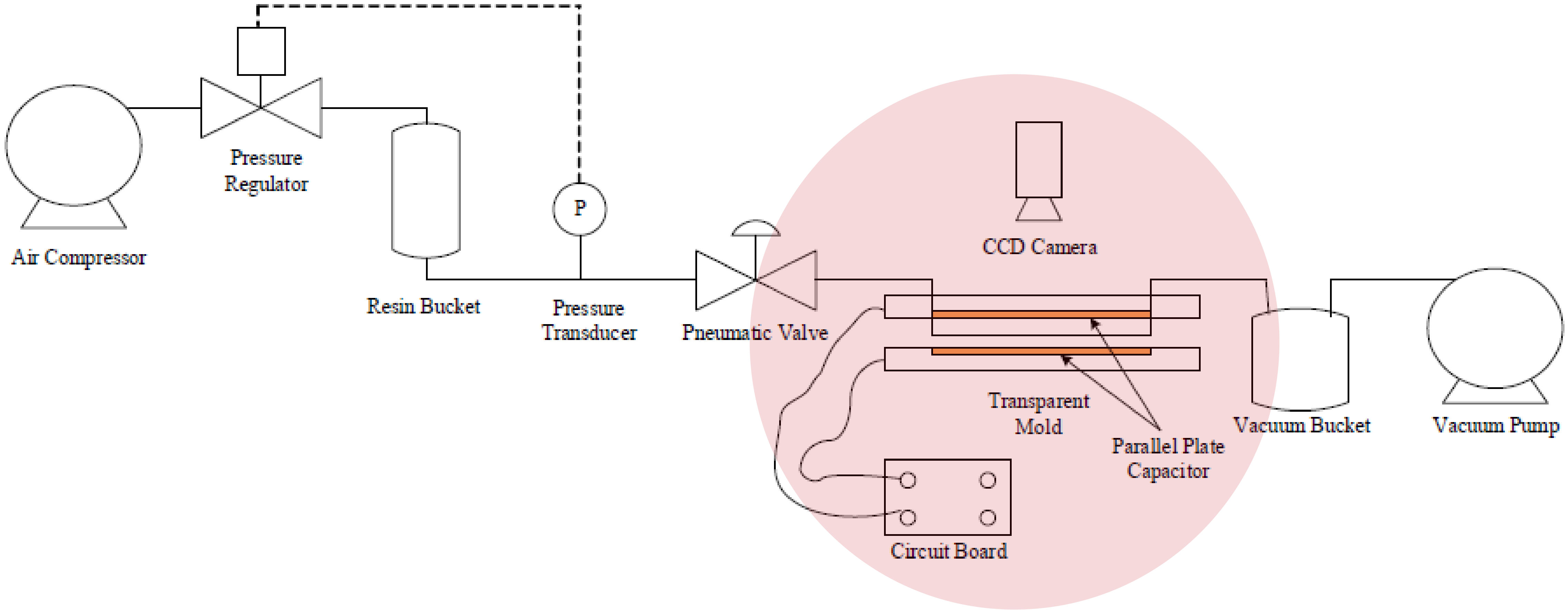
Modeling and methodologies

Material measurement

Validation of simulation

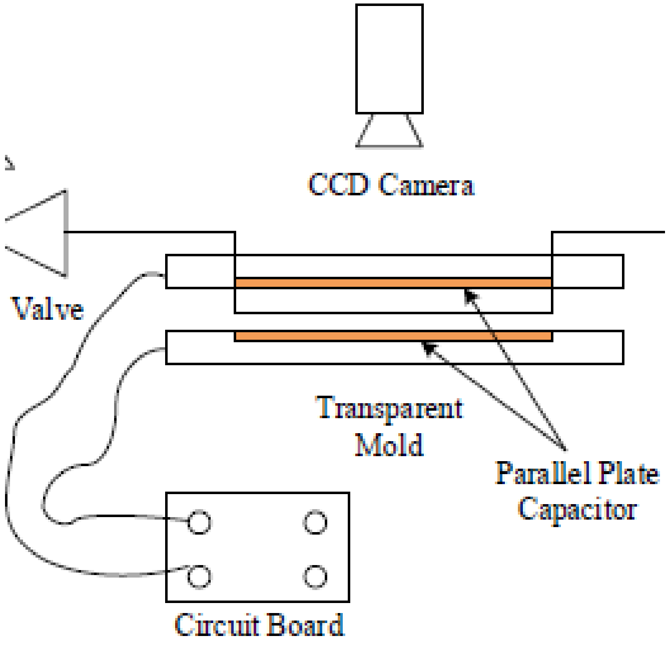
Experimental Setup

› **Process diagram:**



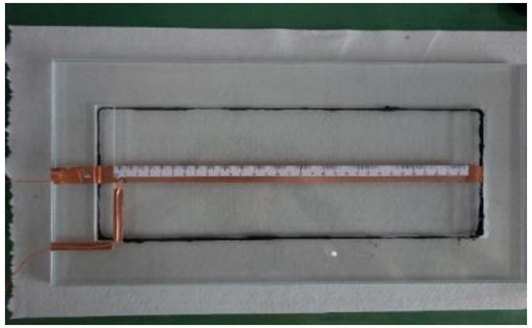
Experimental Setup

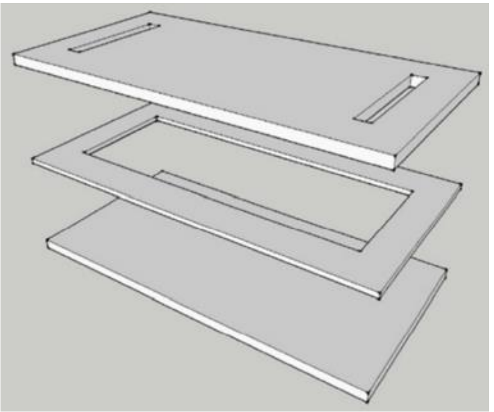
› **Process diagram:**



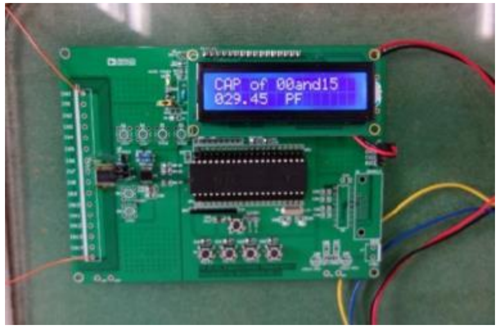
- **CCD Camera:**

- **Transparent mold with parallel-plate capacitor:**





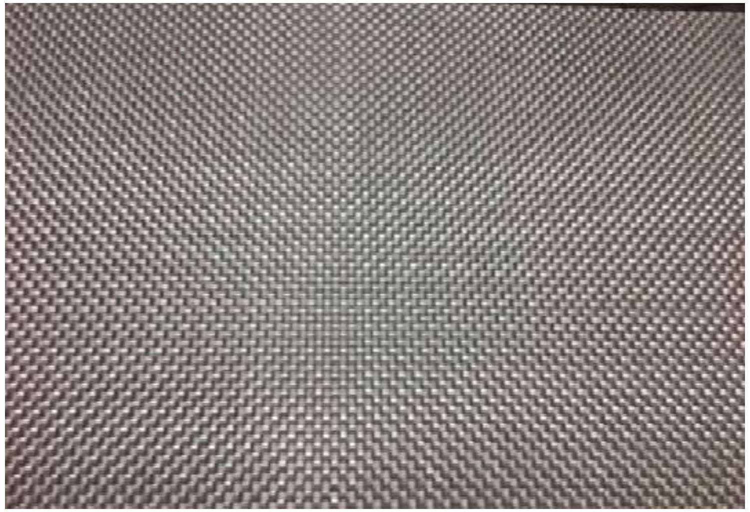
- **Circuit board for capacitance measurement and communication:**



Experimental Setup

› **Materials:**

- **Glass fiber sheet:**



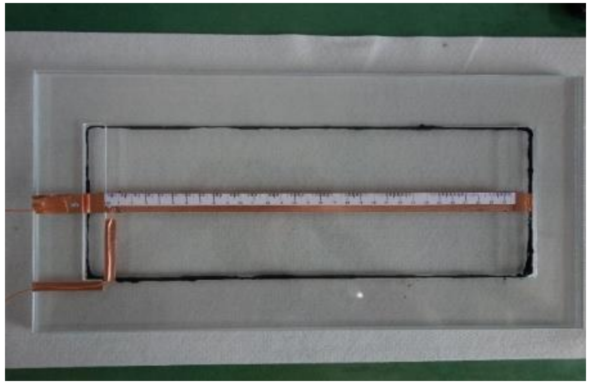
- **Epoxy resin:**

Produced by Swancor Ind. Co., Ltd.
The type is 2502-A.
The dielectric constant of the resin was measured as 4.25(pF/m).
The viscosity of the resin was 0.56(Pa.s).

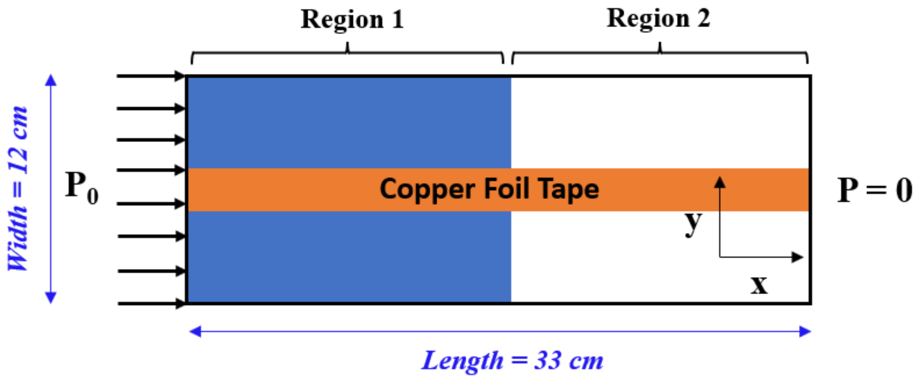
The one-dimensional flow mold

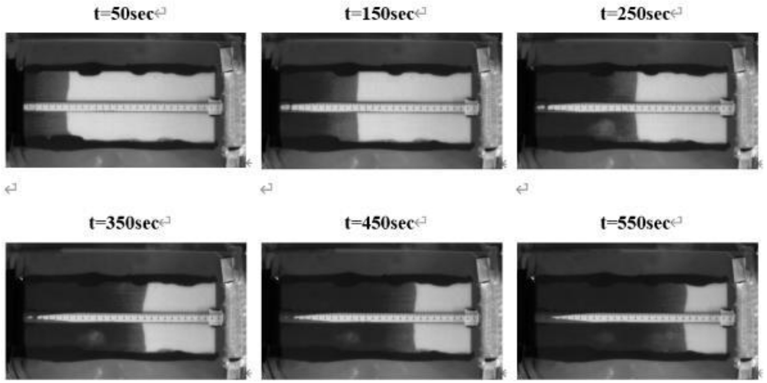
› **An integrated system to observe the flow front during filling process to get the permeability by Darcy's law**

Visualization system



Capacitance detector





Modeling

› **Darcy's law:**

$$u = -\frac{K}{\mu} \cdot \nabla P$$

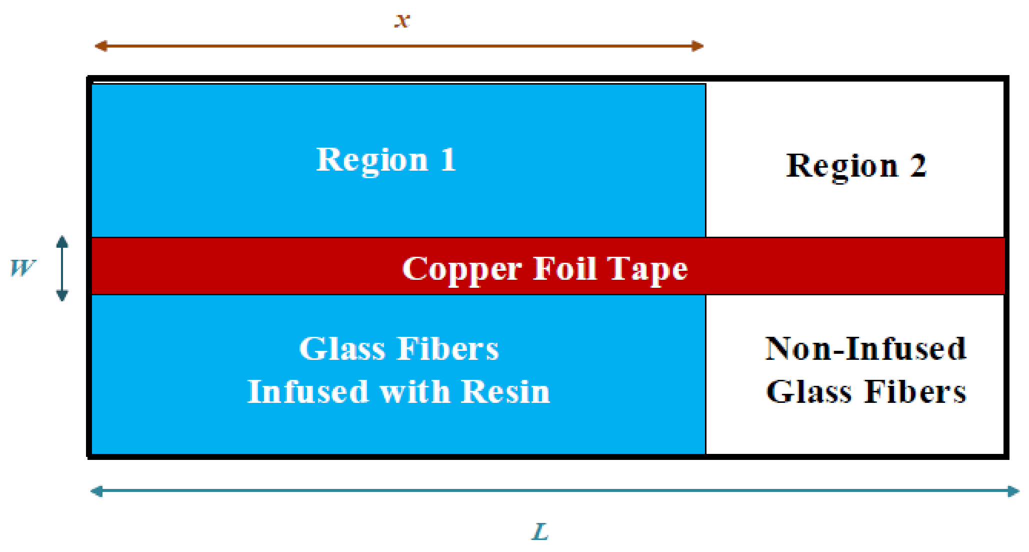
where ***K*** is the permeability tensor, **∇*P*** is the pressure gradient, ***μ*** is the fluid viscosity, and ***u*** is the vector of Darcy velocity.

› **Permeability tensor**

$$\mathbf{K} = \begin{bmatrix} K_{11} & 0 & 0 \\ 0 & K_{22} & 0 \\ 0 & 0 & K_{33} \end{bmatrix}$$

Methodologies

› **Capacitance Sensing for Porosity Measurement**



$$C = \varepsilon\,\varepsilon_0 \frac{A}{d}$$

$$\log(\varepsilon_{mix}) = V_1 \log(\varepsilon_1) + V_2 \log(\varepsilon_2)$$

$$\log(\varepsilon_{mix1}) = V_{f1} \log(\varepsilon_{f1}) + V_r \log(\varepsilon_r)$$

$$\varepsilon_{mix1} = \varepsilon_{f1}^{Vf1}\,\varepsilon_r^{Vr} = \varepsilon_f^{Vf}\,\varepsilon_r^{1\text{-}Vf}$$

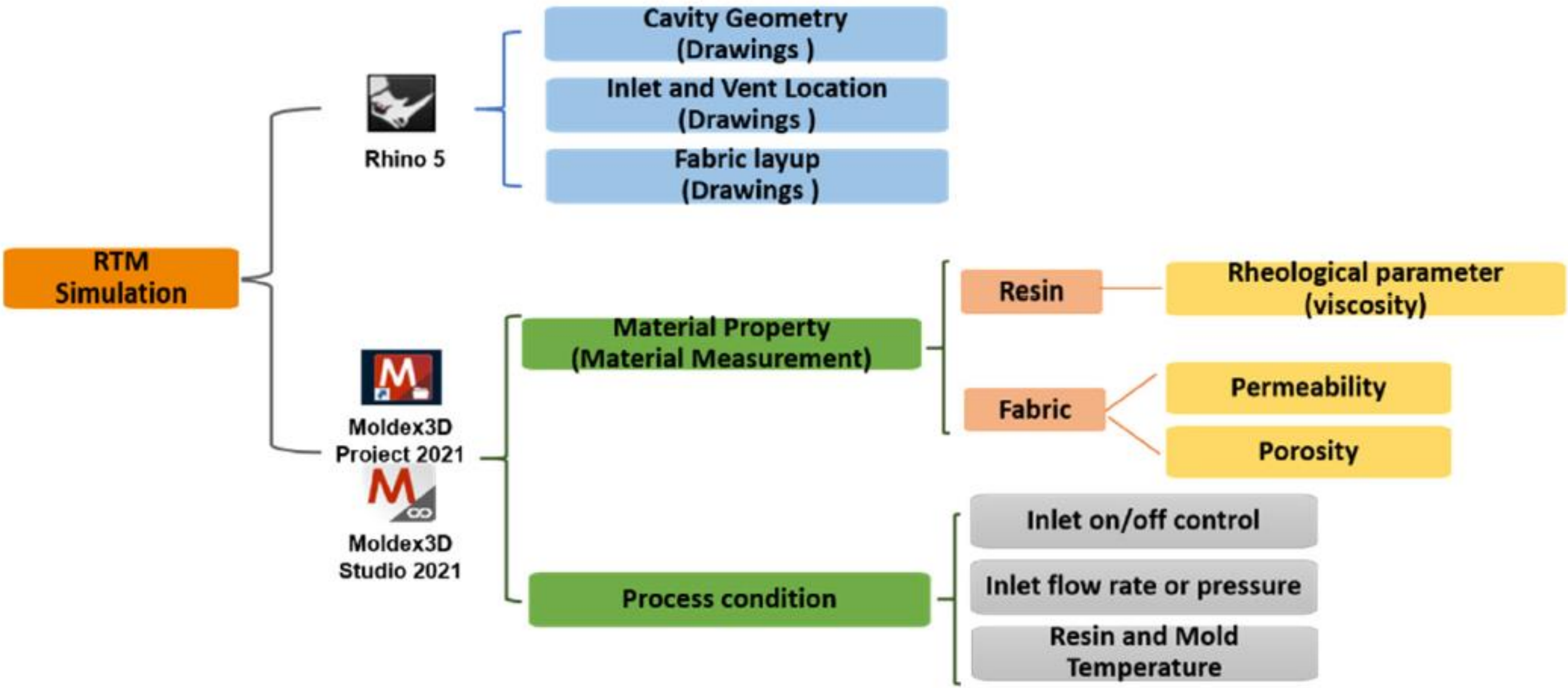
$$\varepsilon_{mix2} = \varepsilon_{f2}^{Vf2}\,\varepsilon_a^{Va} = \varepsilon_f^{Vf}$$

$$C = C_1 + C_2 = \frac{\varepsilon_{mix1}\,\varepsilon_0\,W x}{d} + \frac{\varepsilon_{mix2}\,\varepsilon_0\,W(L-x)}{d}$$

$$C = \frac{\varepsilon_0\,W\,\varepsilon_f^{Vf}(\varepsilon_r^{1-Vf}-1)}{d}\,x + \frac{\varepsilon_0\,W L\,\varepsilon_f^{Vf}}{d}$$

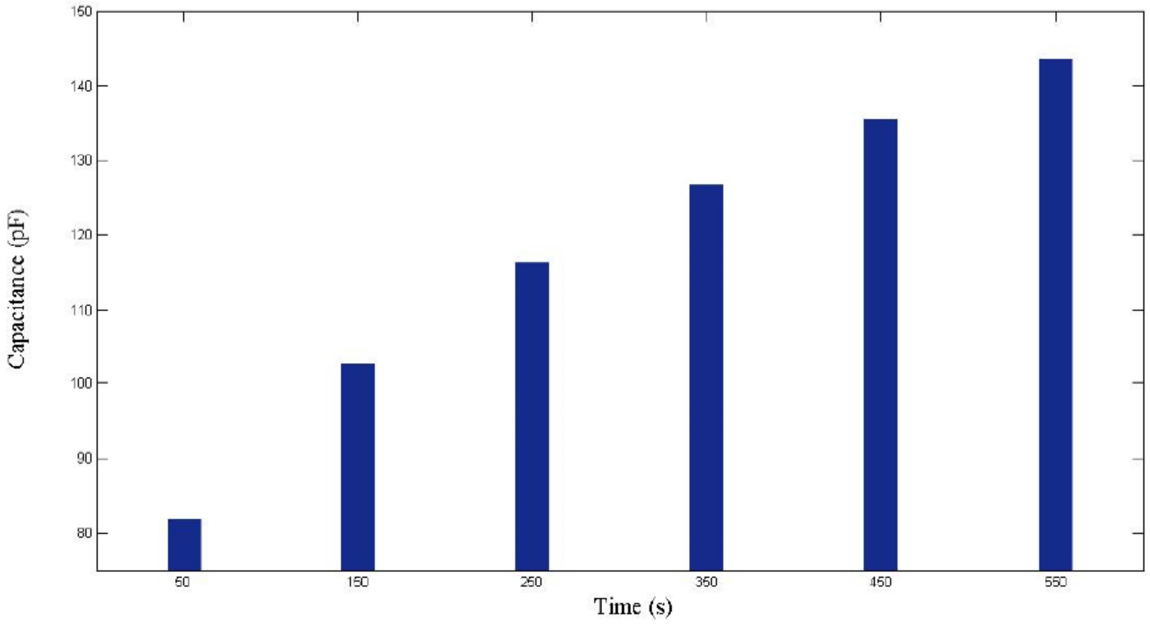
$W = 1.5$ cm, $d = 0.3$ cm, $L = 30$ cm, $\varepsilon_r = 4.25$, and $\varepsilon_0 = 0.08855$ pF/cm

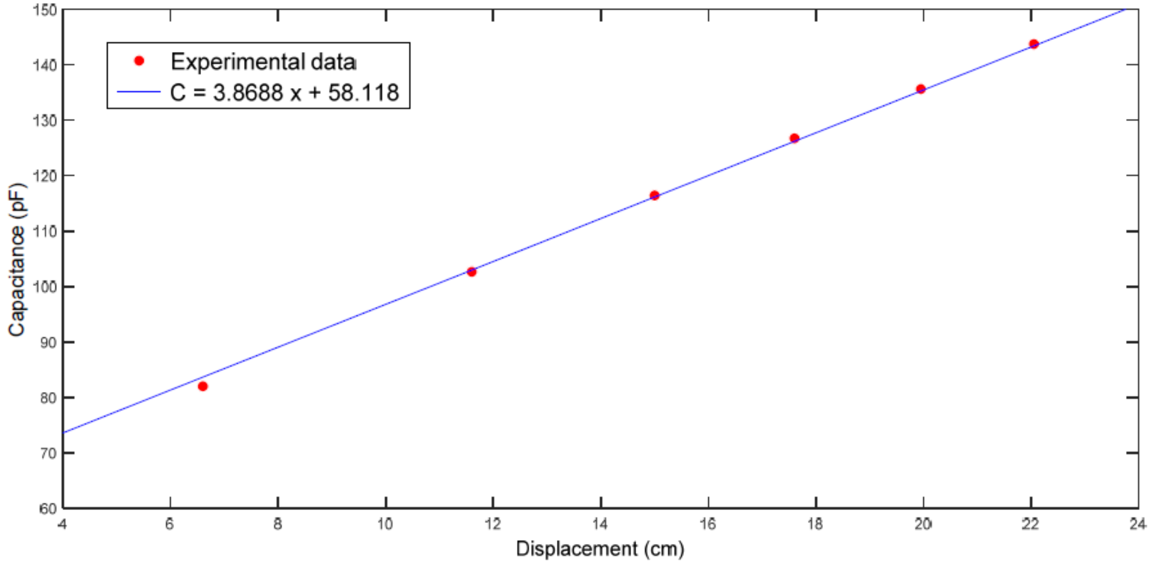
Parameters used in numerical simulations.



Case study 1: study of nine-layer fiber

› **Capacitance Sensing for Porosity Measurement: Experiment 1**





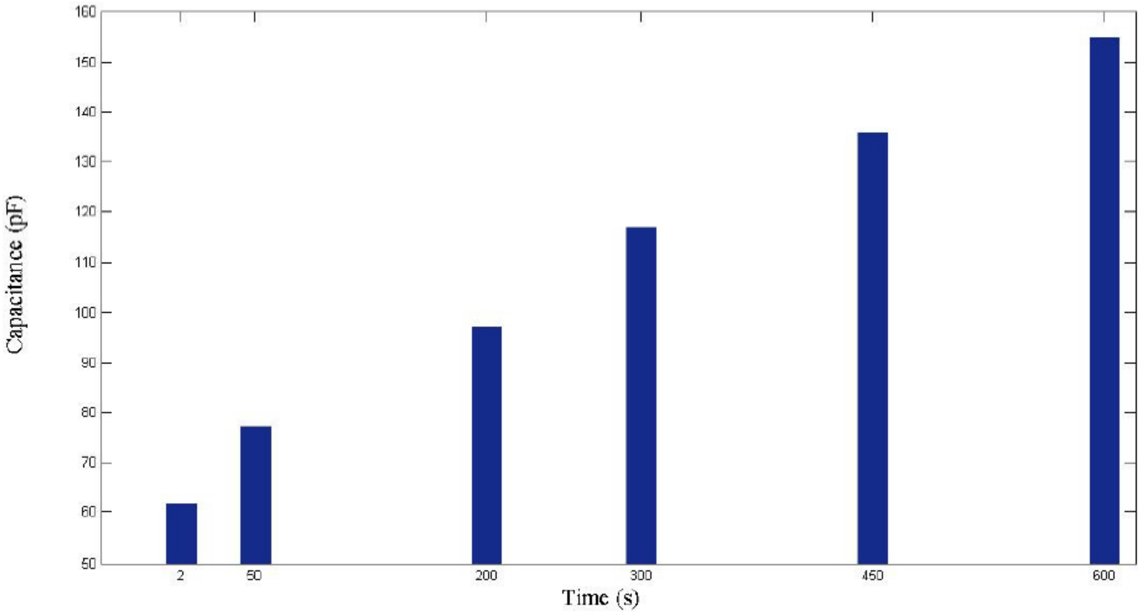
$$C=\frac{\varepsilon_0 W \varepsilon_f^{V_f}(\varepsilon_r^{1-V_f}-1)}{d}x+\frac{\varepsilon_0 W L \varepsilon_f^{V_f}}{d}$$

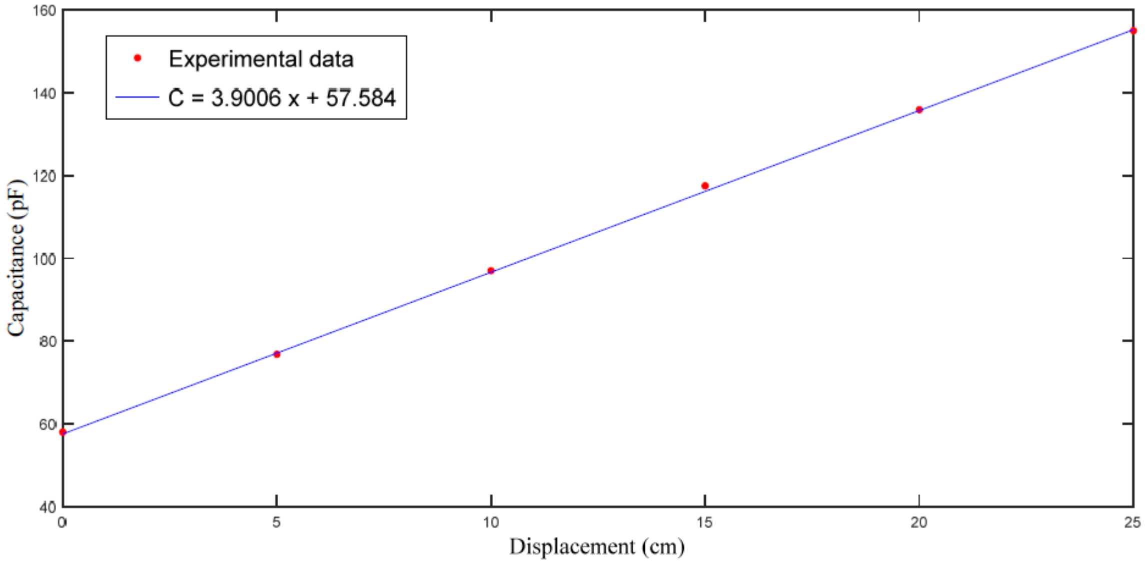
$$C=3.8688x+58.118$$

$$\Rightarrow \begin{cases} \dfrac{W \varepsilon_f^{V_f}(\varepsilon_r^{1-V_f}-1)}{d}=\dfrac{3.8688}{\varepsilon_0} \\ \dfrac{W L \varepsilon_f^{V_f}}{d}=\dfrac{58.118}{\varepsilon_0} \end{cases} \Rightarrow \begin{cases} V_f = 0.242 \\ K = 1.85\times10^{-10}\ (m^2) \end{cases}$$

Case study 1: study of nine-layer fiber

› **Capacitance Sensing for Porosity Measurement: Experiment 2**





$$C = \frac{\varepsilon_0 W \varepsilon_f^{V_f}(\varepsilon_r^{1-V_f} - 1)}{d} x + \frac{\varepsilon_0 W L \varepsilon_f^{V_f}}{d}$$

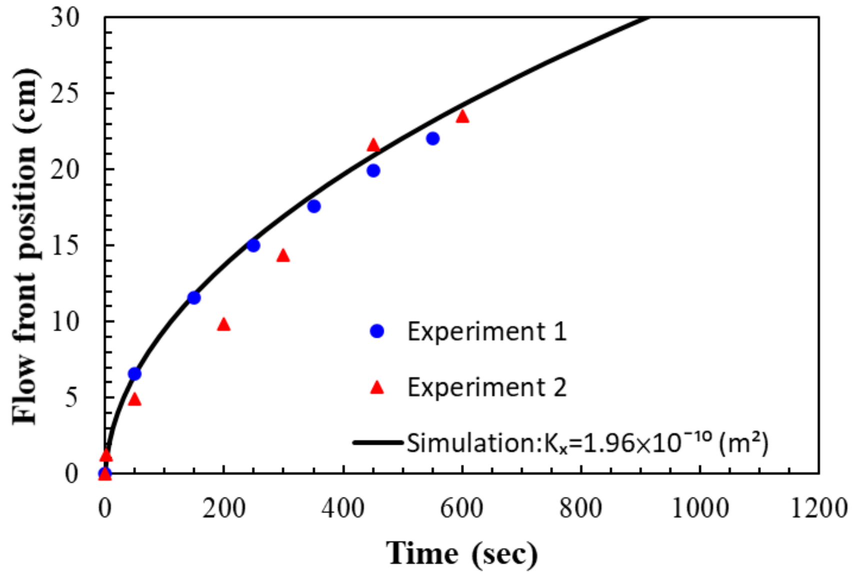
$$C = 3.9006x + 57.584$$

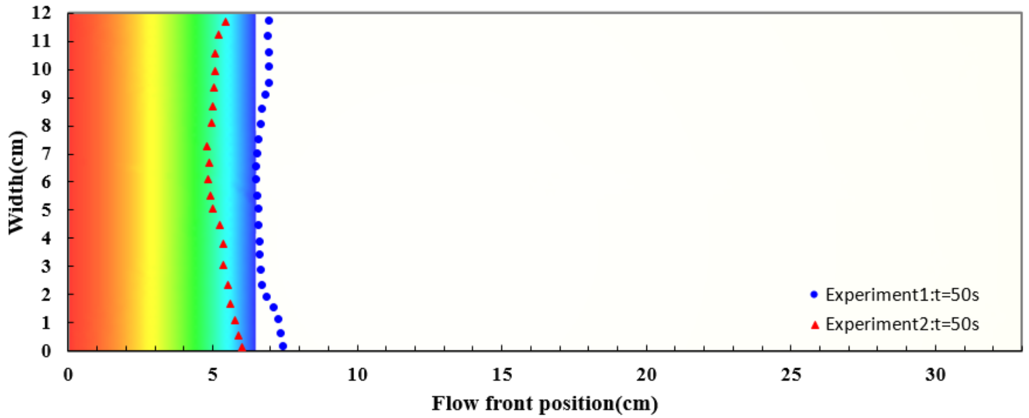
$$\Rightarrow \begin{cases} \dfrac{W \varepsilon_f^{V_f}(\varepsilon_r^{1-V_f} - 1)}{d} = \dfrac{3.9006}{\varepsilon_0} \\ \dfrac{W L \varepsilon_f^{V_f}}{d} = \dfrac{57.584}{\varepsilon_0} \end{cases} \Rightarrow \begin{cases} V_f = 0.233 \\ K = 2.07 \times 10^{-10}\ (\mathrm{m}^2) \end{cases}$$

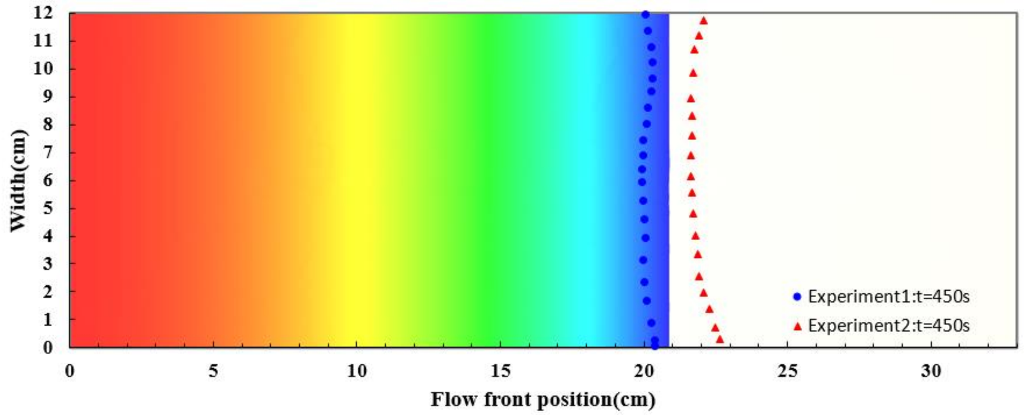
Case study 1:study of nine-layer fiber

› Experimental and simulation results of the one-dimensional flow.

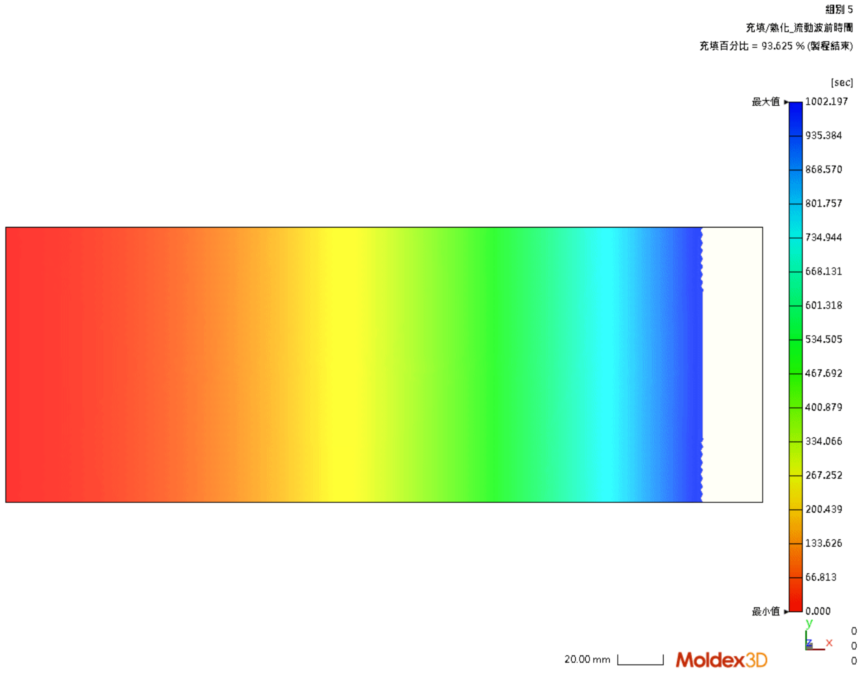
NO	Resin viscosity (Pa·s)	Porosity	Permeability (m^2)
Expt.1	0.56	0.758	1.85×10^{-10}
Expt.2	0.56	0.767	2.07×10^{-10}
Avg.	0.56	0.763	1.96×10^{-10}

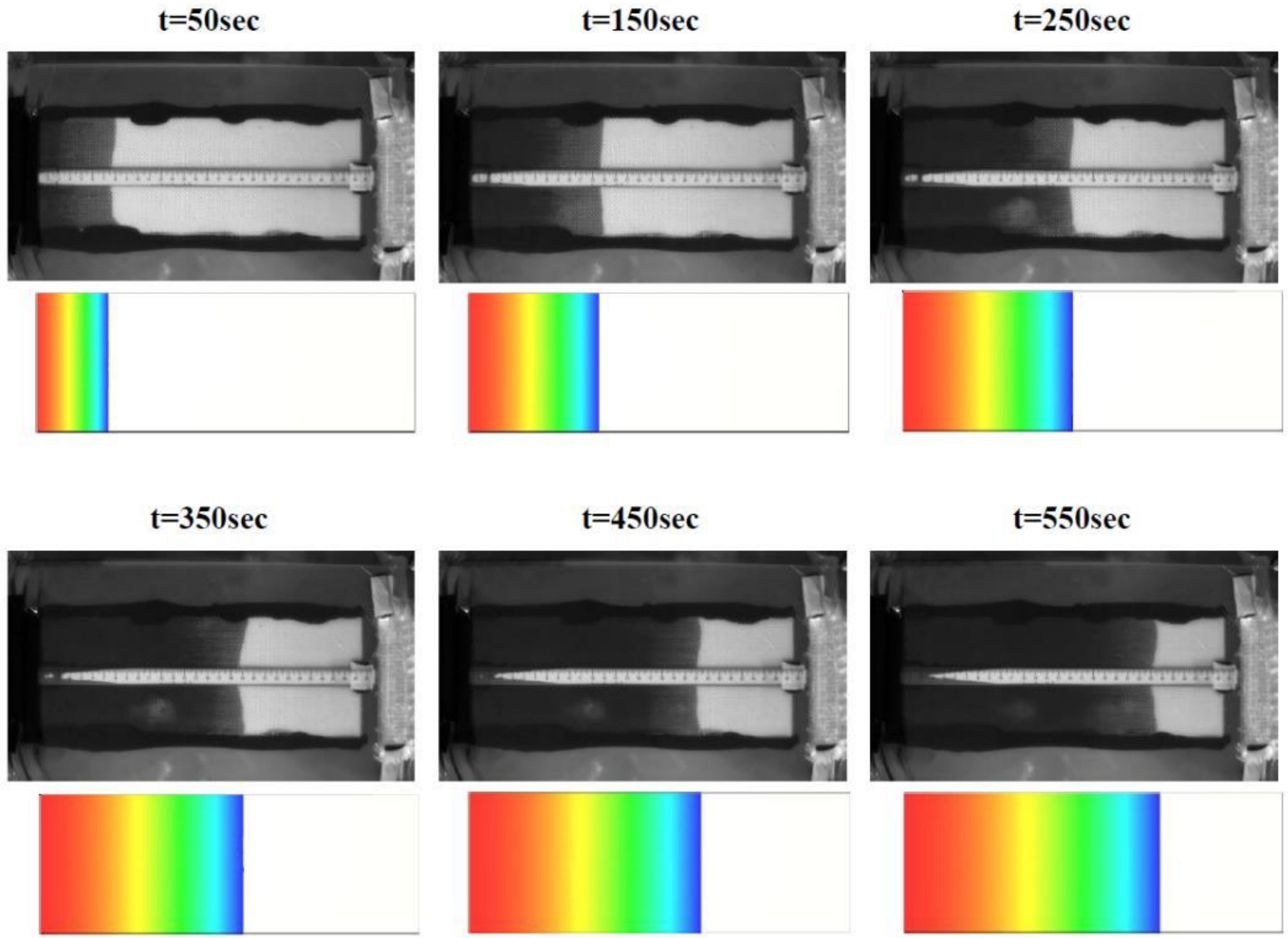






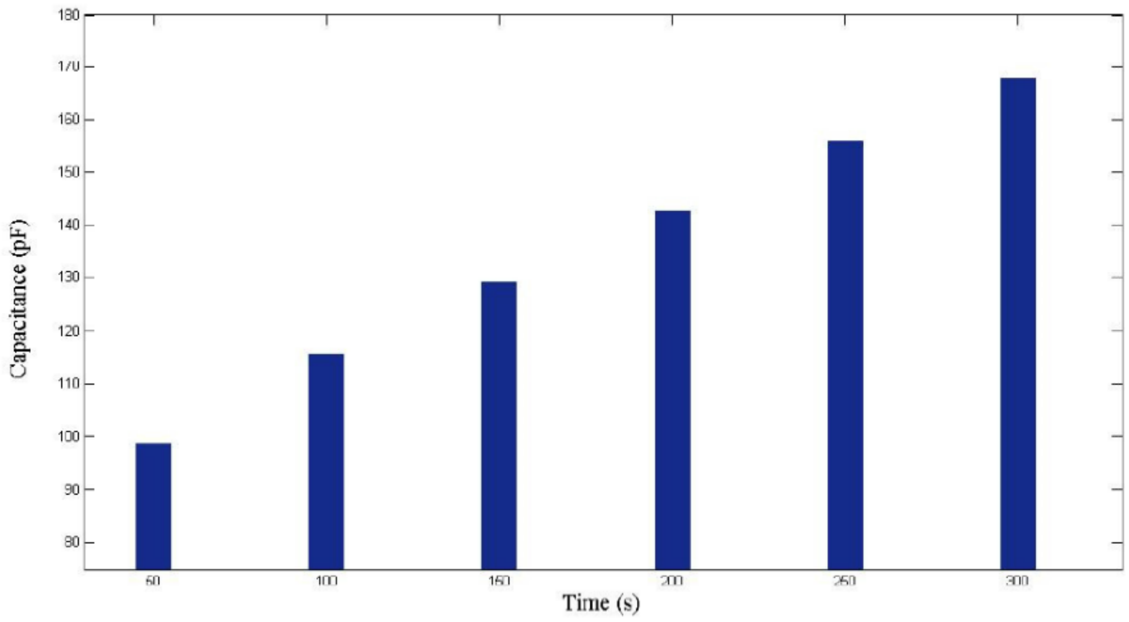
Case study 1: Filling analysis

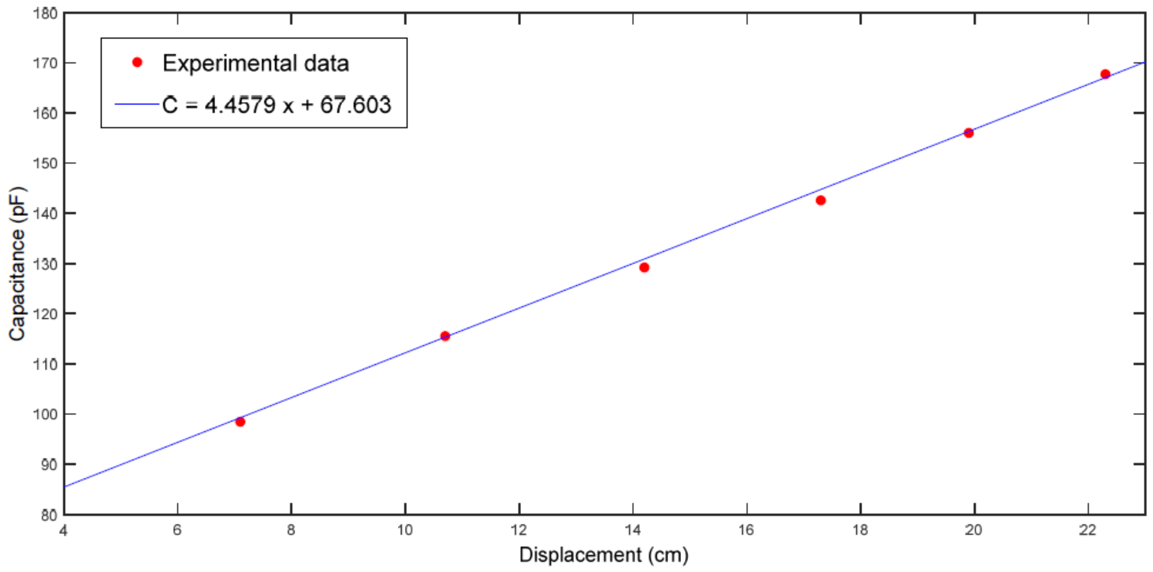




Case study 2: study of seven-layer fiber

› **Capacitance Sensing for Porosity Measurement: Experiment 3**





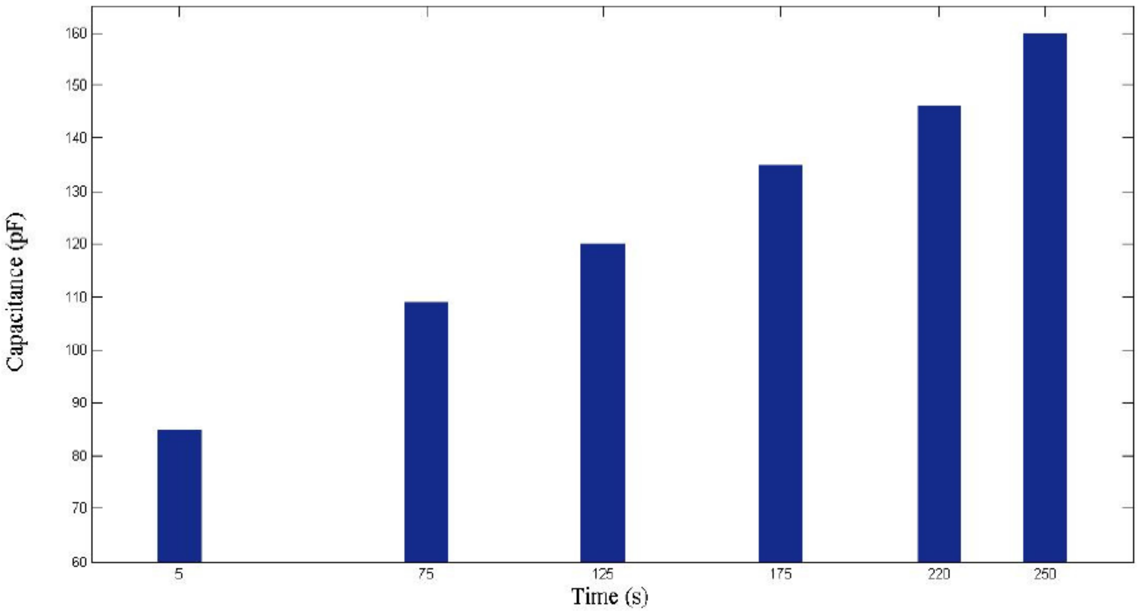
$$C=\frac{\varepsilon_0 W \varepsilon_f^{V_f}(\varepsilon_r^{1-V_f}-1)}{d}x+\frac{\varepsilon_0 W L \varepsilon_f^{V_f}}{d}$$

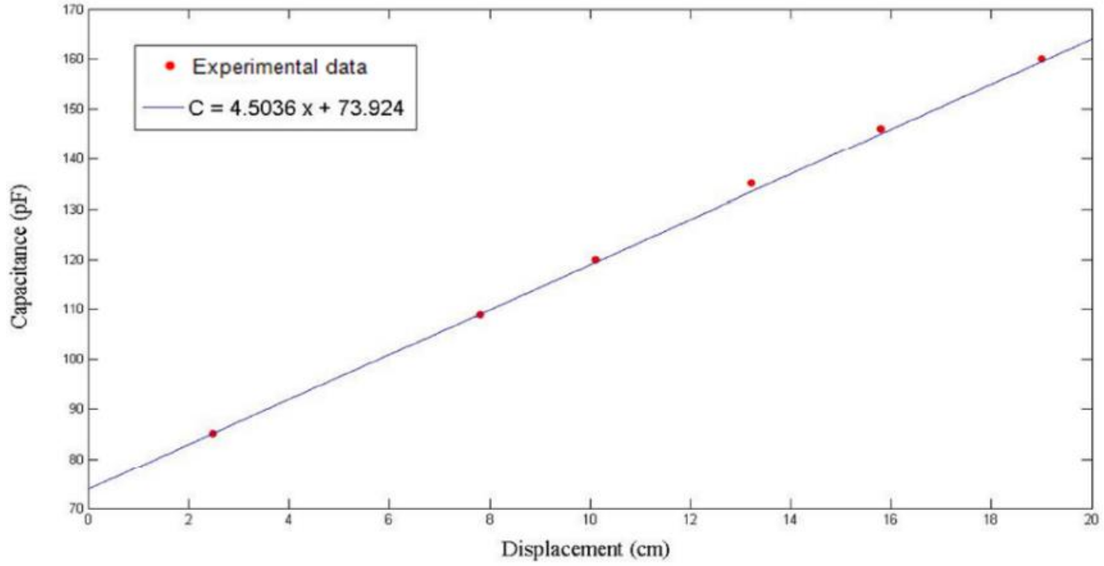
$$C=4.4579x+67.603$$

$$\Rightarrow \begin{cases} \dfrac{W \varepsilon_f^{V_f}(\varepsilon_r^{1-V_f}-1)}{d}=\dfrac{4.4579}{\varepsilon_0} \\ \dfrac{W L \varepsilon_f^{V_f}}{d}=\dfrac{67.603}{\varepsilon_0} \end{cases} \Rightarrow \begin{cases} V_f = 0.246 \\ K = 4.26\times10^{-10}\ (\mathrm{m}^2) \end{cases}$$

Case study 2: study of seven-layer fiber

› **Capacitance Sensing for Porosity Measurement: Experiment 4**





$$C = \frac{\varepsilon_0 W \varepsilon_f^{V_f}(\varepsilon_r^{1-V_f} - 1)}{d} x + \frac{\varepsilon_0 W L \varepsilon_f^{V_f}}{d}$$

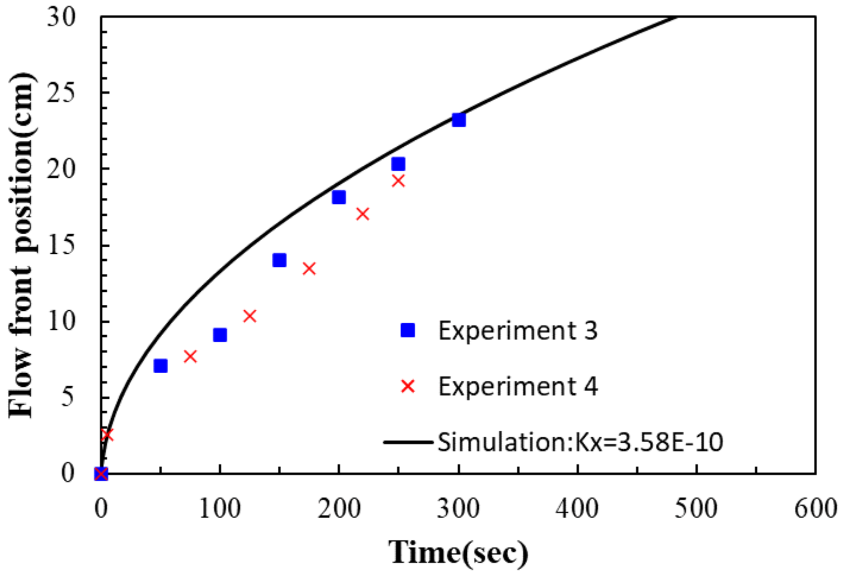
$$C = 4.5036x + 73.924$$

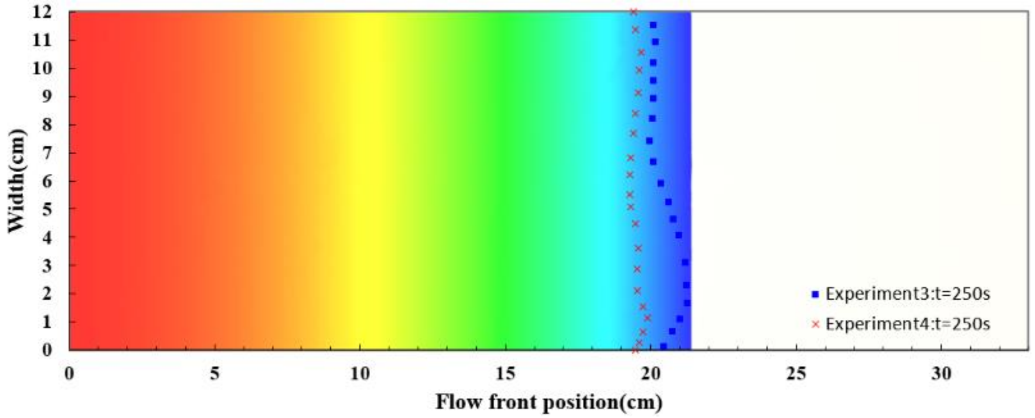
$$\begin{cases} \frac{W \varepsilon_f^{V_f}(\varepsilon_r^{1-V_f} - 1)}{d} = \frac{4.5036}{\varepsilon_0} \\ \frac{W L \varepsilon_f^{V_f}}{d} = \frac{73.924}{\varepsilon_0} \end{cases} \Rightarrow \begin{cases} V_f = 0.282 \\ K = 2.9 \times 10^{-10} (m^2) \end{cases}$$

Case study 2: study of seven-layer fiber

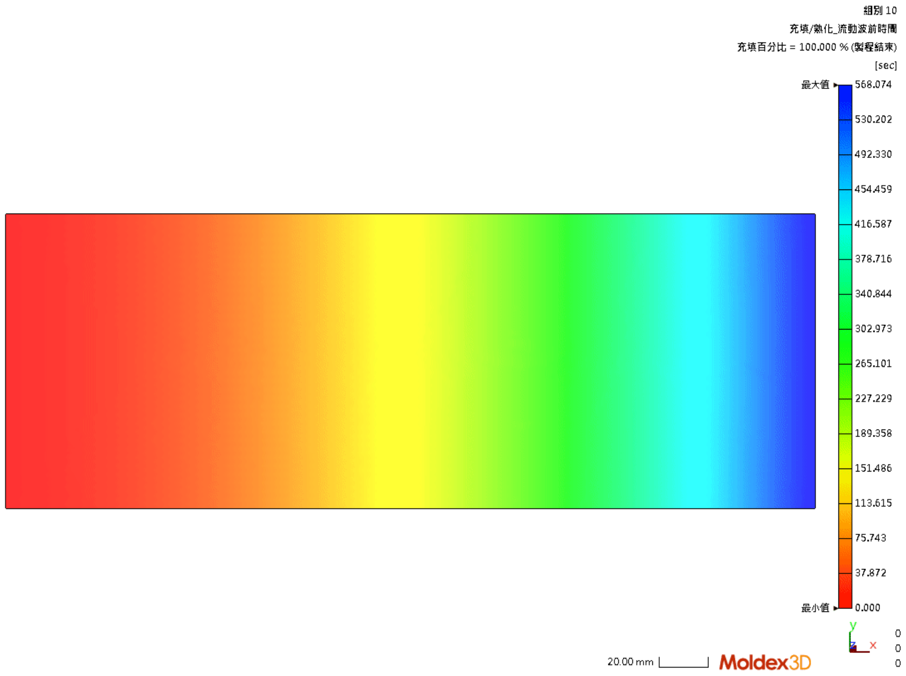
› **Experimental and simulation results of the one-dimensional flow.**

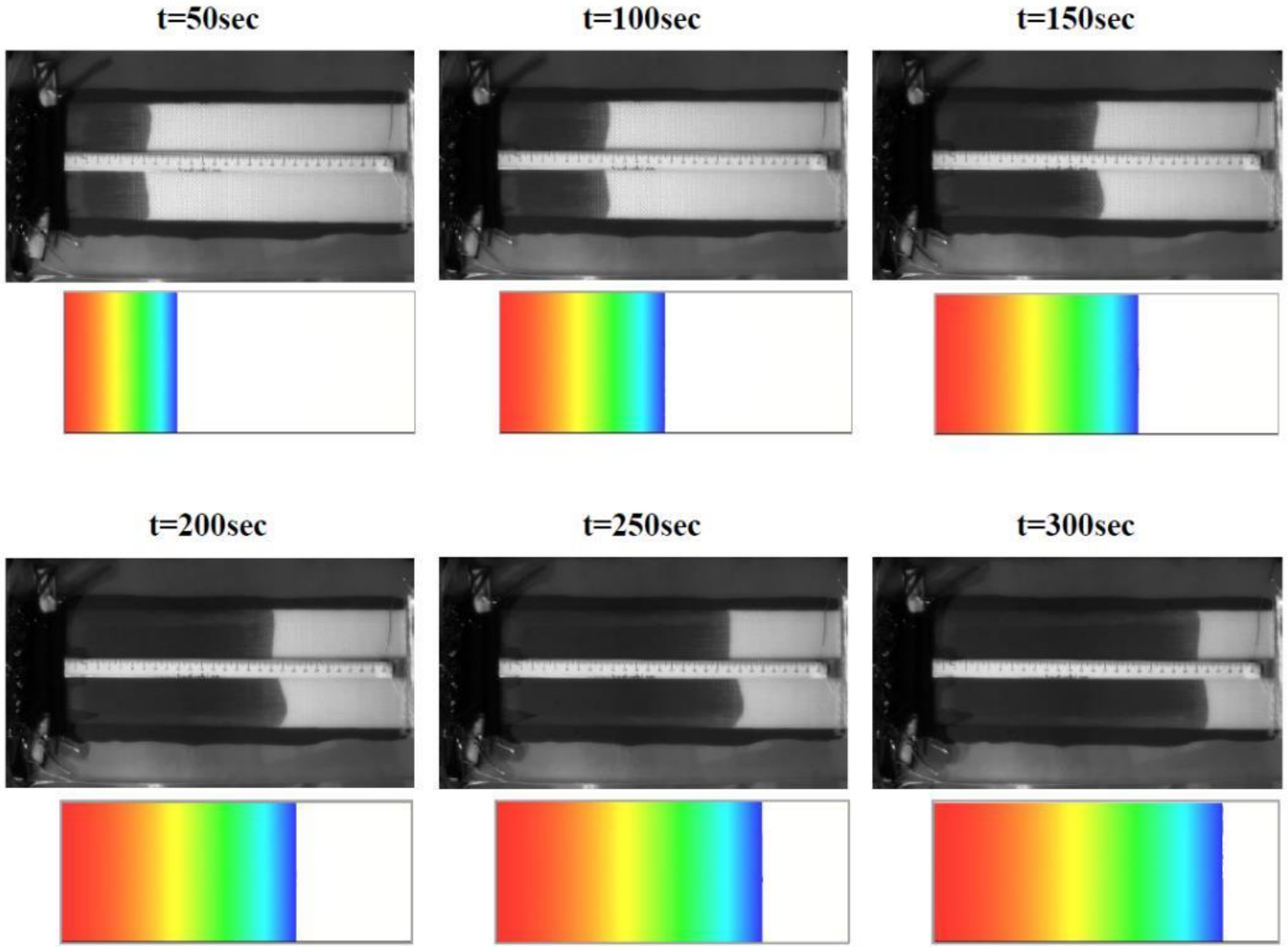
NO	Resin viscosity (Pa·s)	Porosity	Permeability (m^2)
Expt.3	0.56	0.754	4.26×10^{-10}
Expt.4	0.56	0.718	2.9×10^{-10}
Avg.	0.56	0.736	3.58×10^{-10}





Case study 2: Filling analysis





Conclusion

- **A good agreement is observed between the simulation and experiment.**
    - **- It is helpful to predict the flow front during filling process.**
    - **- Moldex3D simulation software can be used as a verification tool to compare the permeability.**

- **The workflow helps to effectively control processing condition parameters and to reduce expensive and time-consuming trial-and-error manufacturing process.**

Moldex3D *Thank you for your attention!*