Moldex3D
MOLDING INNOVATION

RTM製程問題仿真預測及解析

CONFIDENTIAL

CoreTech System Co., Ltd.
www.moldex3d.com

Outline

> Introduction

> Implementation details

> Case study for Resin Transfer Molding

> Conclusions

> Acknowledge

Introduction

Introduction

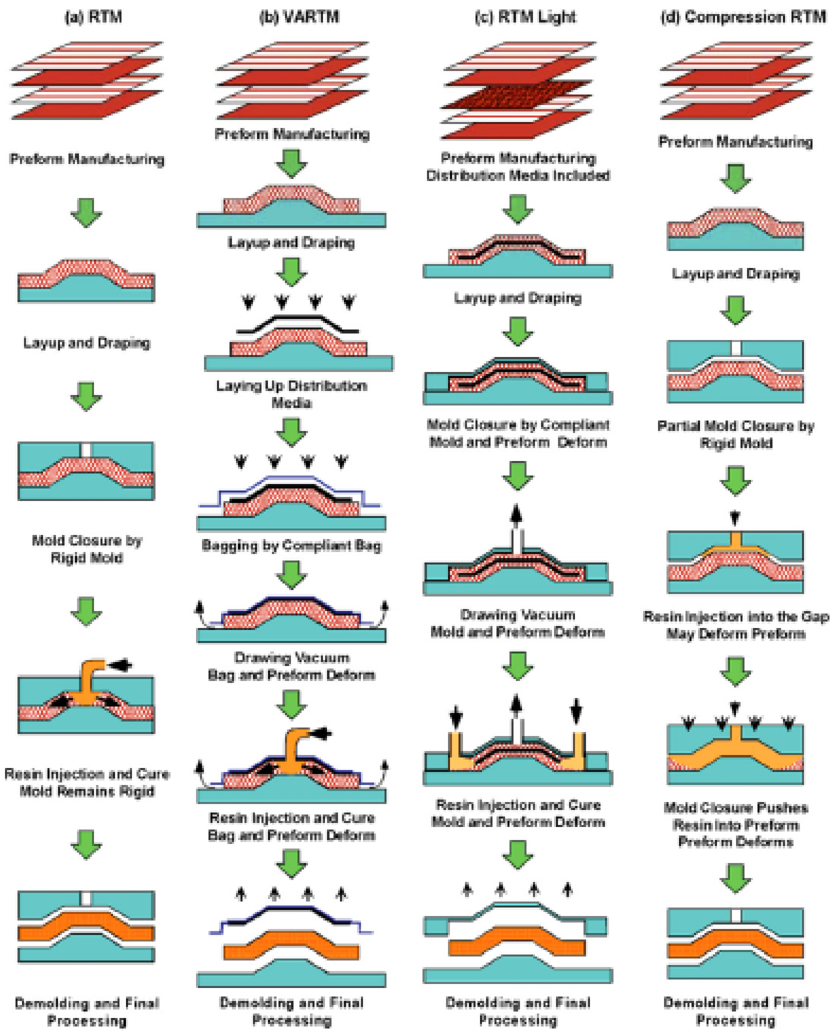
> **Resin transfer molding(RTM)**
  - **A branch of a broader class of fiber reinforced composite process known as Liquid Composite Molding (LCM)**
  - **Different to SRIM (Structural Reaction Injection Molding) for its longer filling time under lower pressures**

http://www.swancor.com.tw
http://www.moneydj.com/KMDJ/News/

Introduction

> **Schematic of comparison of different RTM processes.**
  - **RTM**
  - **VARTM**
  - **RTM light**
  - **Compression RTM**

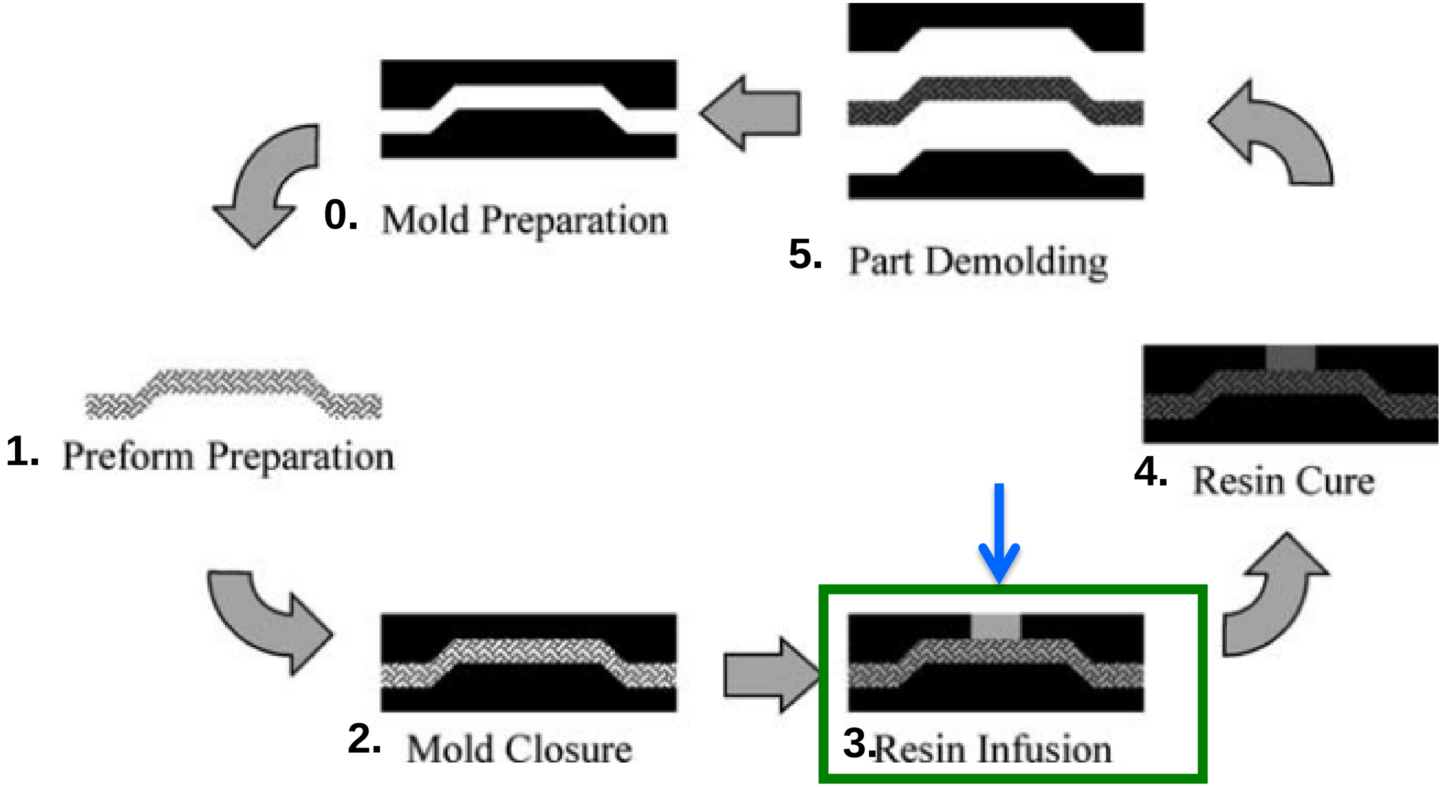
Pavel Simacek, SureshG. Advani, "Modeling resin flow and fiber tow saturation induced by distribution media collapse in VARTM", Composites Science and Technology, Volume 67, Issue 13, October 2007, Pages 2757–2769



Benefits and Disadvantages

Benefits	Disadvantages
● Faster Production	● Mold design is complex
● Tight Dimensional Tolerance	● Higher Tool Cost
● Labor Savings	● Requires leak-proof molds
● Repeatability	
● High surface finish	
● High mechanical performance	

Introduction RTM process steps



Source : A. Shojaei, S. R. Ghaffarian, S. M. H. Karimian, "Modeling and simulation approaches in the resin transfer molding process: A review", Polymer CompositesVolume 24, Issue 4, pages 525–544, August 2003

Issues and Objectives

- Issues
  - The traditional simulation tools for RTM process use 2.5D model to analyze the filling behavior.
  - These tools is not really suitable for simulating complex geometry and complex mat layers condition.

- Objectives
  - To Simulate the resin Filling behavior through the novel 3D simulation technique.

  - Compare the experiment and simulation result of actual manufacturing process

Implementation details

Governing Equation

> **Continuity Equation**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

> **The Equation of Energy**

$$\frac{\partial}{\partial t}(\rho C_p T) + \nabla \cdot (\rho \mathbf{u} C_p T) = k \nabla^2 T + \eta \dot{\gamma}^2 + \phi \frac{d\alpha}{dt} \Delta H$$

> **Darcy's Law**

$$\mathbf{u} = -\frac{\mathbf{K}}{\eta} \nabla p$$

> **Permeability Tensor**

$$\mathbf{K} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}$$

ρ : fluid density

$\mathbf{u}$: velocity vector

$\mathbf{K}$: Permeability Tensor

T : temperature

t : time

p : pressure

η : viscosity

k : thermal conductivity

$\dot{\gamma}$: shear rate

C_P : specific heat

α : conversion

ΔH : Heat generation of reaction

Viscosity and Kinetic Model

- Curing kinetic model:
  - Combined model

$$\frac{d\alpha}{dt} + \mathbf{u} \cdot \nabla \alpha = \left(Ka + Kb \bullet \alpha^{m}\right) \bullet (1-\alpha)^{n}$$

- Viscosity model:
  - Cross Castro-Macosko model

$$\eta = \frac{\eta_0 \left(\frac{\alpha_g}{\alpha_g - \alpha}\right)^{c1+c2\alpha}}{1 + \left(\frac{\eta_0 \bullet \dot{\gamma}}{\tau^*}\right)^{1-n}}$$

$$\eta_0 = A\exp\left(\frac{Tb}{T}\right)$$

η : viscosity

η_0 : zero shear rate viscosity

α : conversion

n : the power law index

$\dot{\gamma}$: shear rate

α_g : conversion the gel point,

T : temperature

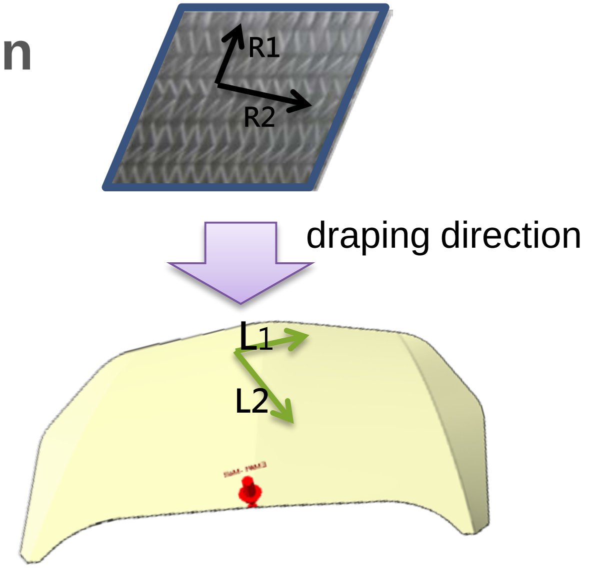
u : velocity vector

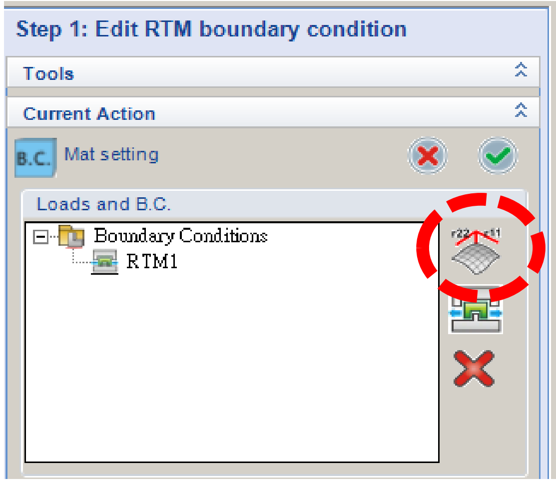
Ka, Kb : material constants

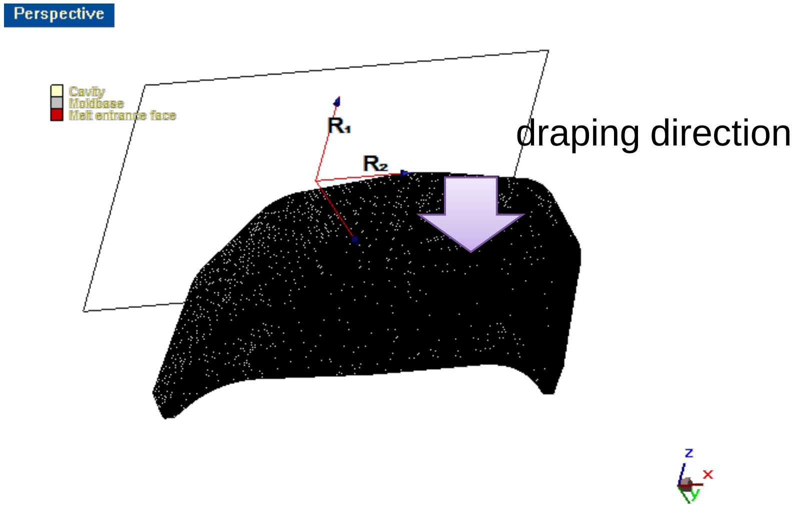
t : time

Mat Orientation of Fiber Preform

> **Permeability tensor axis direction**
- **Fiber mat orientation**
  - **Before draping** $\vec{R}_1, \vec{R}_2$
  - **After draping** $\vec{L}_1, \vec{L}_2$

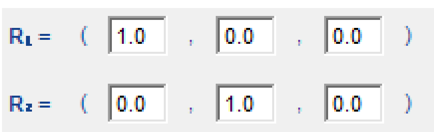


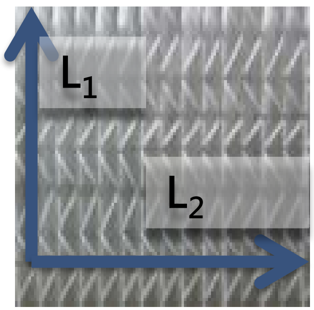




Set Permeability tensor

> **Permeability tensor axis direction**

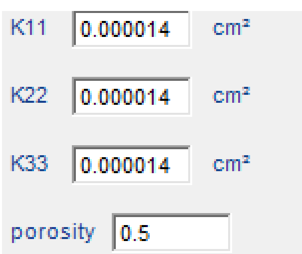




$$\mathbf{L_1} = (l_{11}, l_{12}, l_{13})$$
$$\mathbf{L_2} = (l_{21}, l_{22}, l_{23})$$
$$\mathbf{L_3} = (l_{31}, l_{32}, l_{33})$$

Fiber mat orientation Before draping

$$\mathbf{K} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} = \begin{bmatrix} l_{11} & l_{12} & l_{13} \\ l_{21} & l_{22} & l_{23} \\ l_{31} & l_{32} & l_{33} \end{bmatrix} \begin{bmatrix} K_{11} & 0 & 0 \\ 0 & K_{22} & 0 \\ 0 & 0 & K_{33} \end{bmatrix} \begin{bmatrix} l_{11} & l_{21} & l_{31} \\ l_{12} & l_{22} & l_{32} \\ l_{13} & l_{23} & l_{33} \end{bmatrix}$$



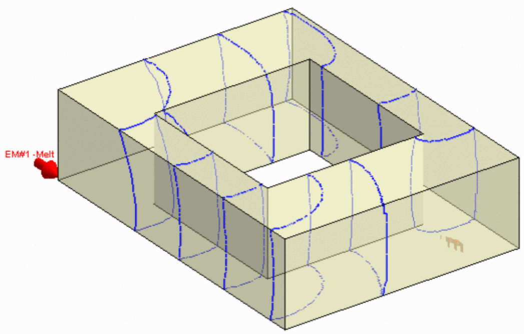
Set Permeability tensor principal value

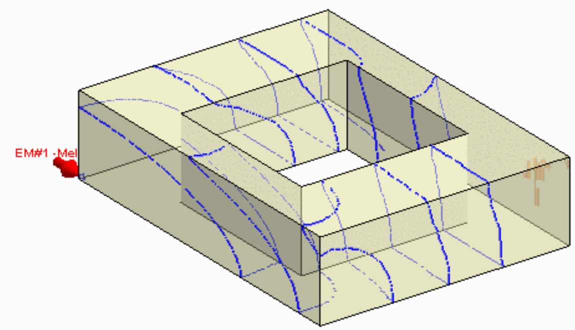
Anisotropic Permeability Tensor (principal value)

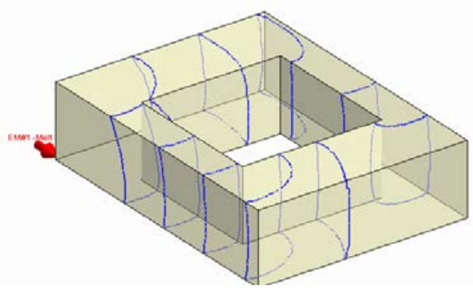
> **Compare with result between Isotropic and Anisotropic permeability**

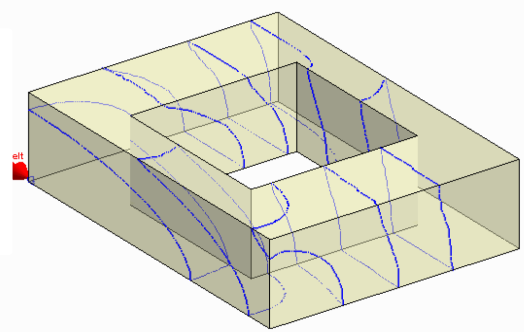
$$\mathbf{K}=\begin{bmatrix}K_{xx} & K_{xy} & K_{xz}\\ K_{yx} & K_{yy} & K_{yz}\\ K_{zx} & K_{zy} & K_{zz}\end{bmatrix}=\begin{bmatrix}K_{11} & 0 & 0\\ 0 & K_{22} & 0\\ 0 & 0 & K_{33}\end{bmatrix}=\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix}$$

$$\mathbf{K}=\begin{bmatrix}K_{xx} & K_{xy} & K_{xz}\\ K_{yx} & K_{yy} & K_{yz}\\ K_{zx} & K_{zy} & K_{zz}\end{bmatrix}=\begin{bmatrix}K_{11} & 0 & 0\\ 0 & K_{22} & 0\\ 0 & 0 & K_{33}\end{bmatrix}=\begin{bmatrix}10 & 0 & 0\\ 0 & 2.5 & 0\\ 0 & 0 & 1\end{bmatrix}$$







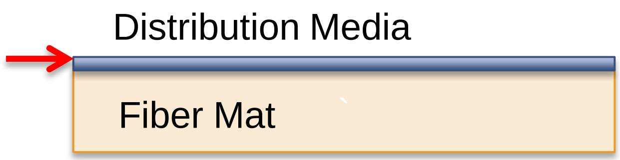


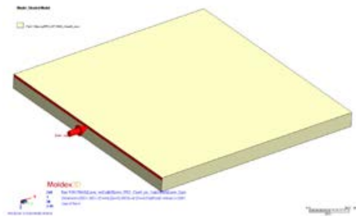
Isotropic permeability
$K_{11} : K_{22} : K_{33} = 1:1:1$

Anisotropic permeability
$K_{11} : K_{22} : K_{33} = 10:2.5:1$

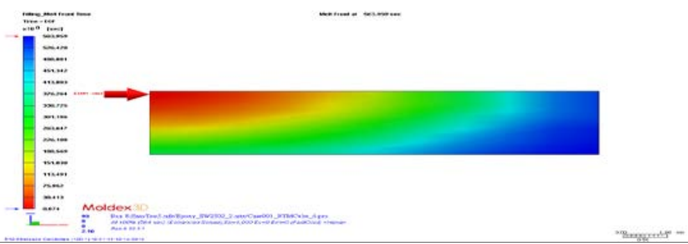
Multi-layer fabric preforms

> Support to assign different Permeability for different regions

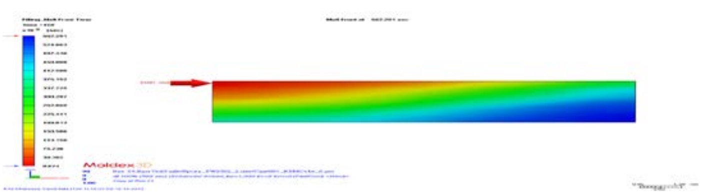




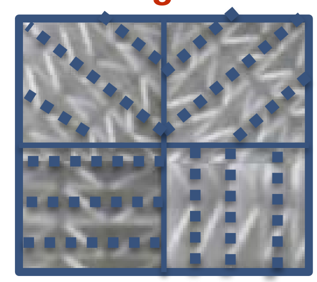
Without Distribution Media

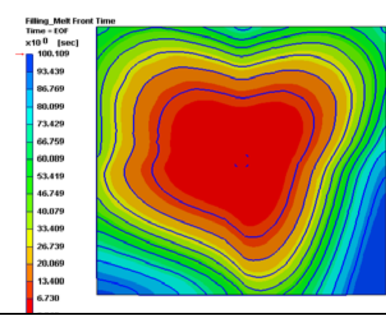


With Distribution Media



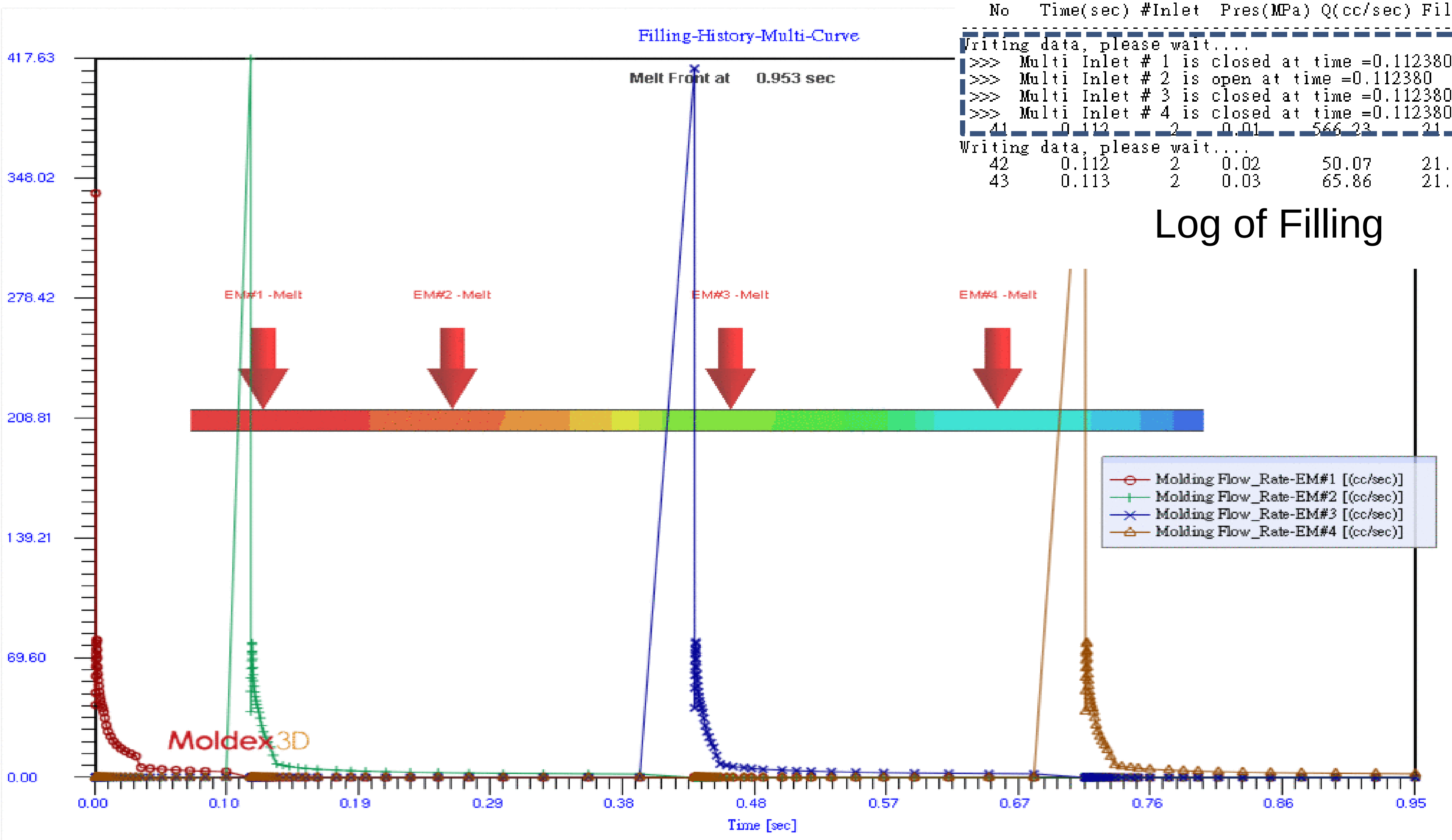
Orientation of fiber preforms affect filling behavior





Multi-Inlet Control

> Multi-inlet Open/Close period control by sensor nodes

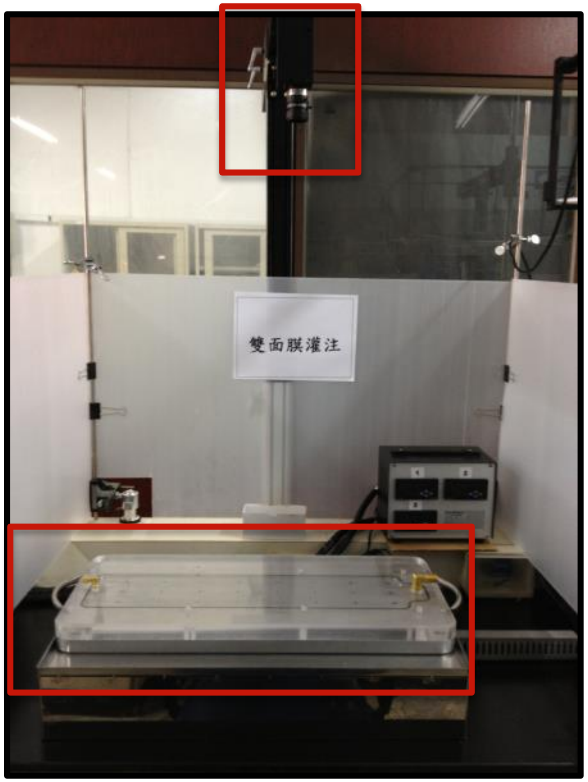


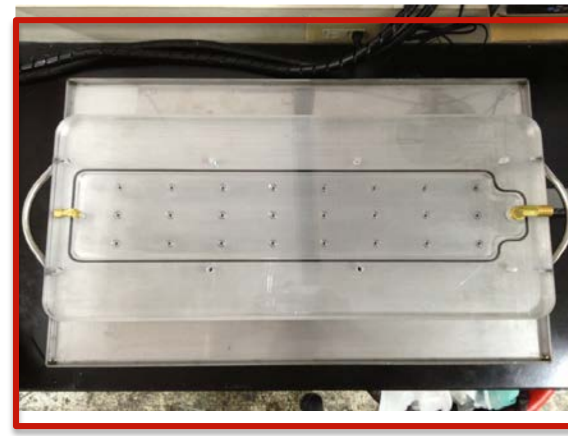

```
------------------------------------------------------------------
  No   Time(sec) #Inlet  Pres(MPa) Q(cc/sec) Fill(%)
------------------------------------------------------------------
Writing data, please wait....
>>>  Multi Inlet # 1 is closed at time =0.112380
>>>  Multi Inlet # 2 is open at time =0.112380
>>>  Multi Inlet # 3 is closed at time =0.112380
>>>  Multi Inlet # 4 is closed at time =0.112380
   41     0.112      2     0.01      566.23     21.197
Writing data, please wait....
   42     0.112      2     0.02       50.07     21.706
   43     0.113      2     0.03       65.86     21.781
```

Log of Filling

Permeability Measurement

Visualization system





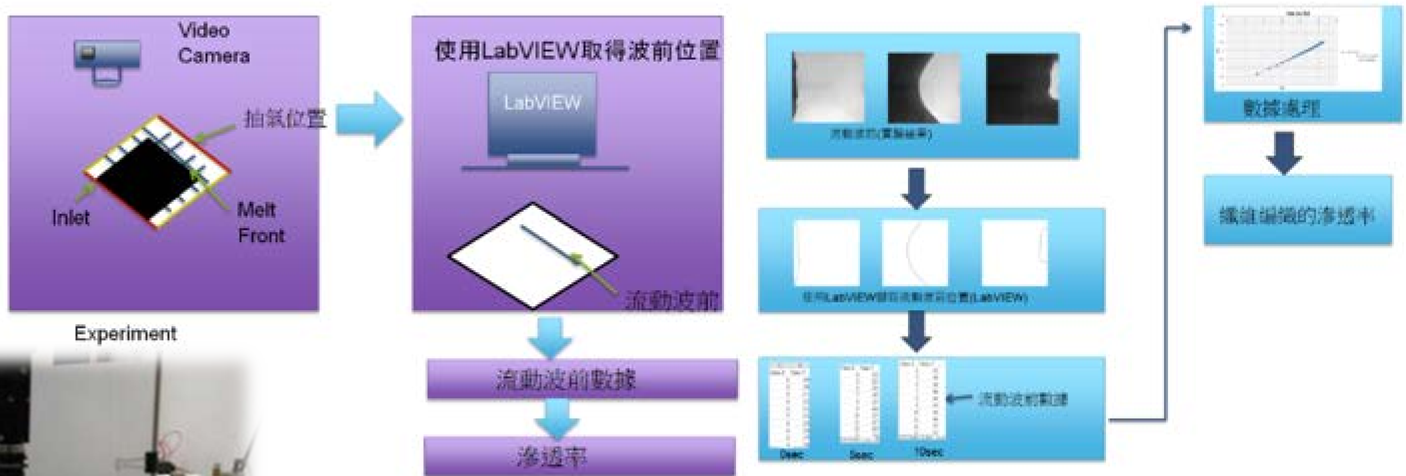
Camera

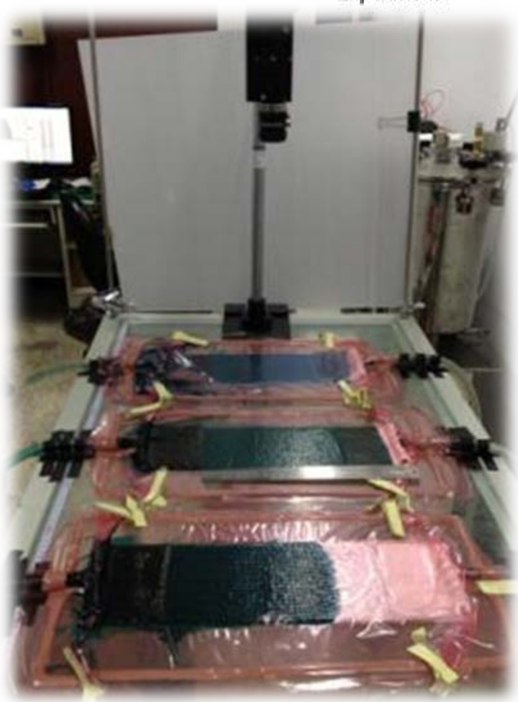
Mold

Visualization system

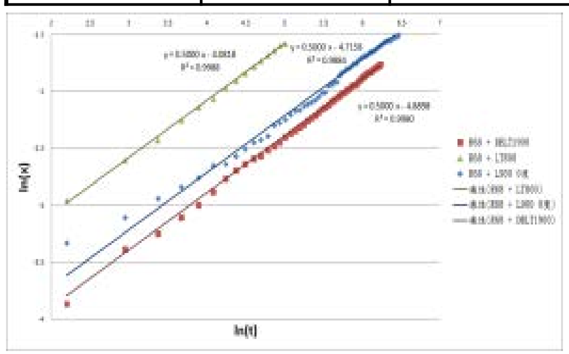
Integrated system for permeability measurement

> **A integrated system to transfer the melt front during filling process to get the permeability by Darcy's law**





	L900	LT800	DBLT1900
滲透率 (m^2)	5.9328E-11	2.1085E-10	4.1895E-11



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Permeability Measurement Result

> Compare with different fiber mats

LT800

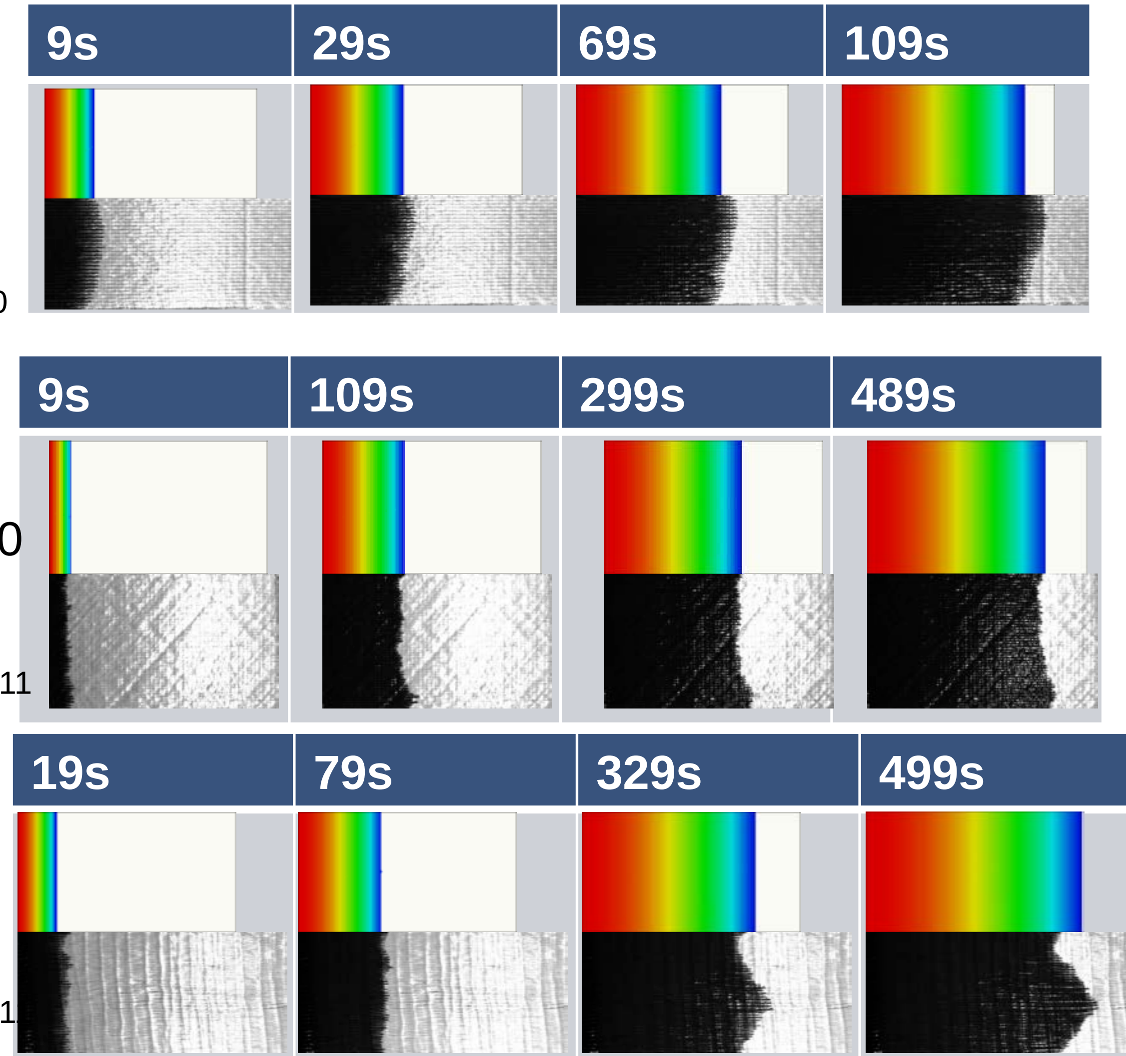
$K = 2.1 \times 10^{-10}$

DBLT1900

$K = 4.19 \times 10^{-11}$

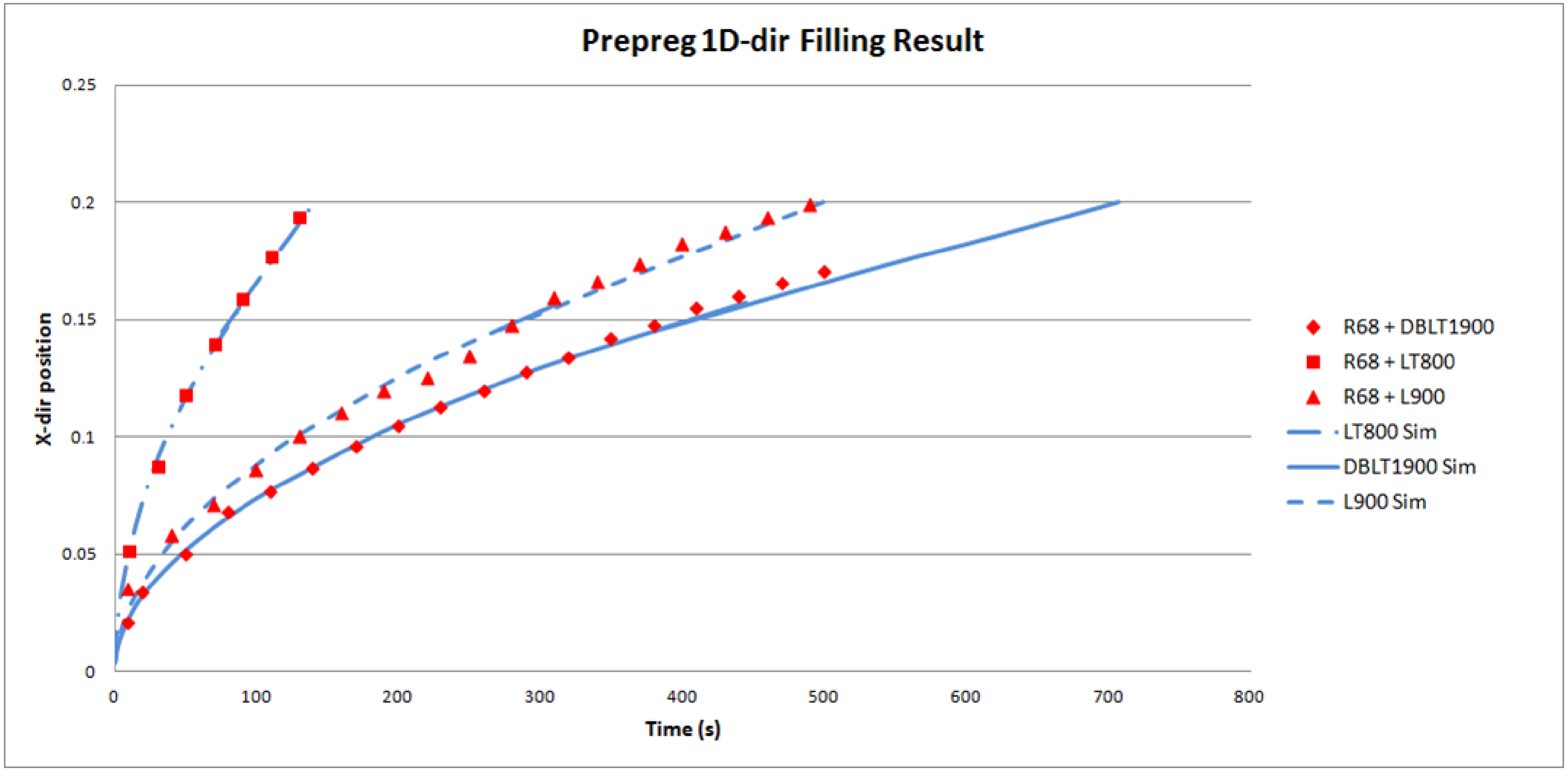
L900

$K = 5.93 \times 10^{-1}$



Result

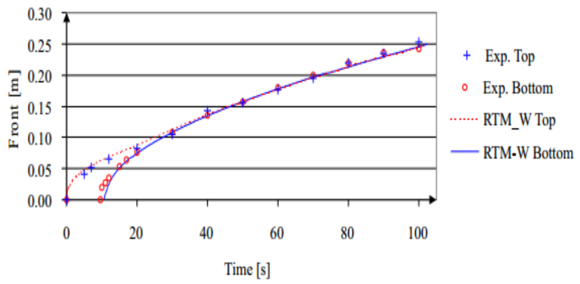
> **Experiment compare with the RTM Simulation**



2-D Simulation

Case 1 Single material preforms CFM 450

Case 1 : Single material preforms
Reference Study



- > **Fabric preform:**
  - – **CFM 450**
- > **Single component of fabric preform**
  - – **Viscosity = 0.239 Pa s**
- > **Operating Condition**
  - – **Inlet Pressure = 0.9 atm = 0.09 MPa**

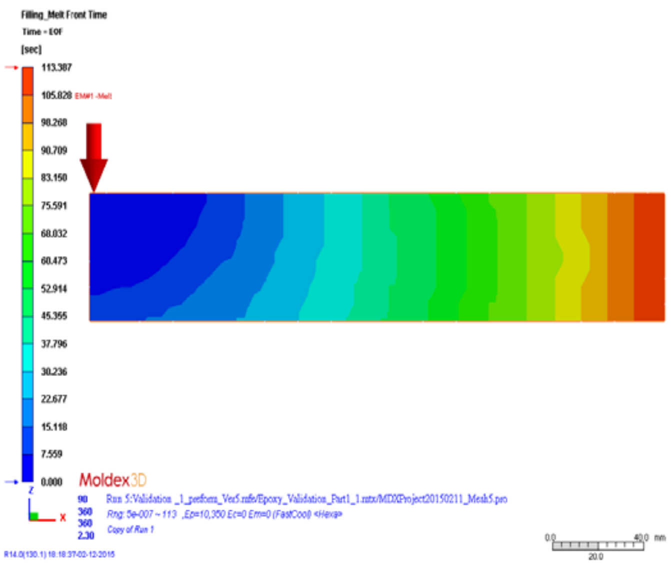
K and ϕ	K_{11} (m^2)	K_{22} (m^2)	K_{33} (m^2)	ϕ (-)
CFM 450	1.04E-9	1.04E-9	5.16E-10	0.8

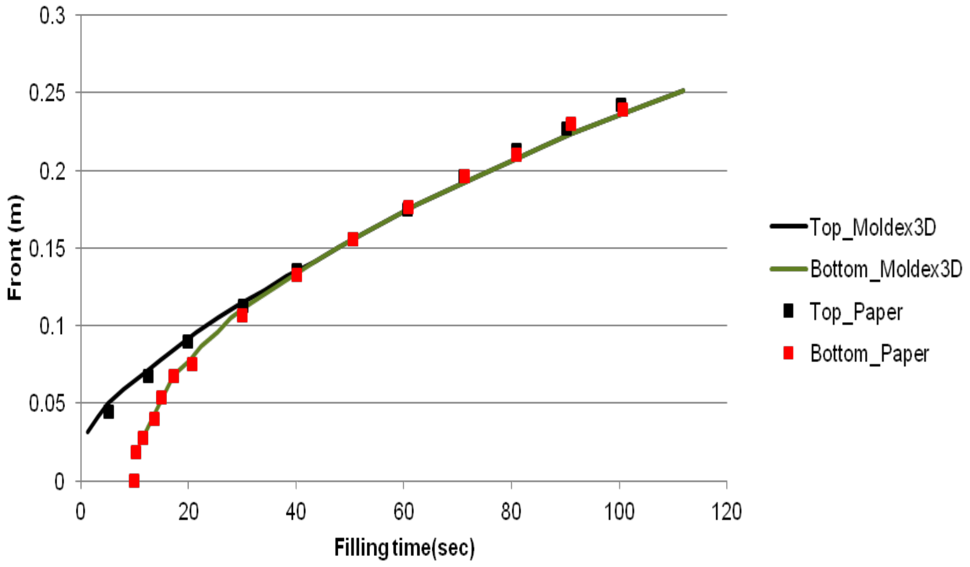
Figure 7.8: *CFM450 50 layers lay-up.*

Reference : Koefoed, M. "Modeling and simulation of the VARTM Process for Wind Turbine Blades." *Industrial Ph. D. Dissertation* (2003).

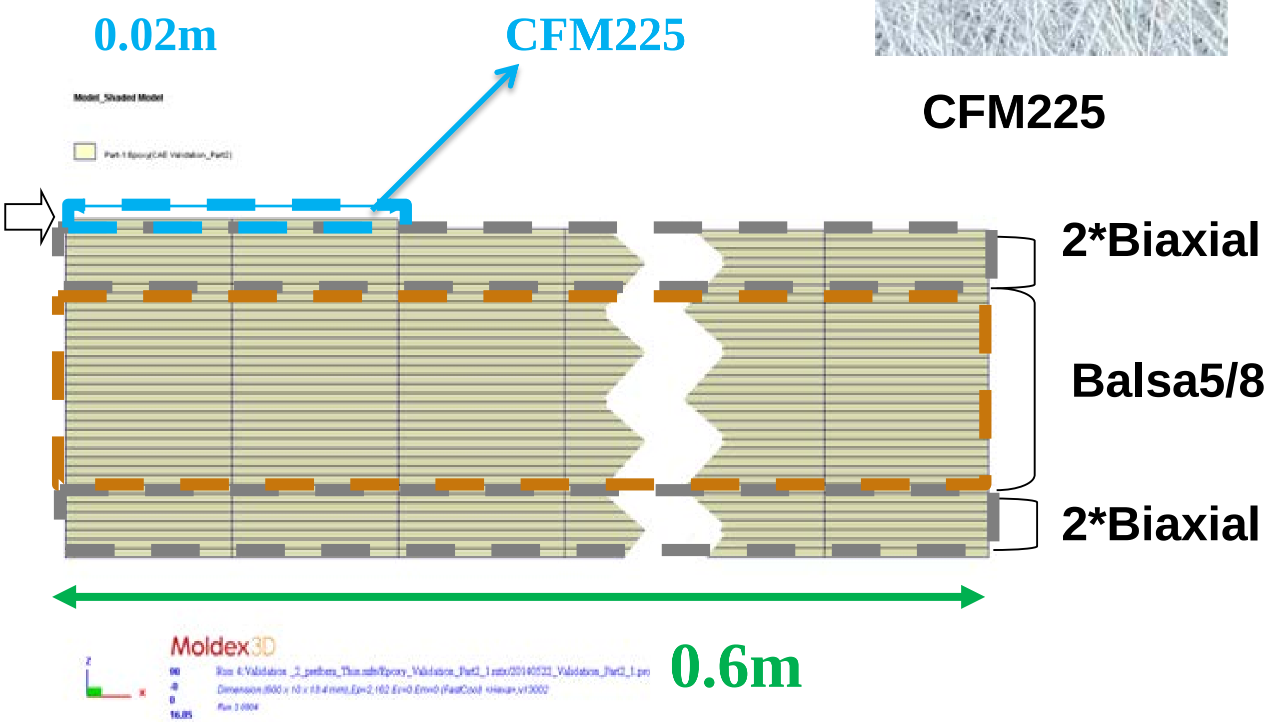
Moldex3D RTM Simulation Result

- Flow front time result at end of filling stage and flow front location vs. filling time.

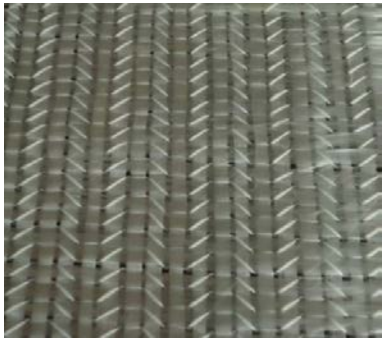




Case 2 : Sandwich Structure Geometry and Fabric Preforms



CFM225



Biaxial Fib

Balsa5/8

Picture Reference

1. http://nuplex.com/Composites/products/browse-products/corematerials/gurit%E2%84%A2-balsaflex
2. http://www.ec21.com/product-details/Fiberglass-Biaxial-0-90-Degree--7506537.html
3. http://www.alibaba.com/product-detail/Glass-Fiber-Continuous-Filament-Strand-Mat_327073845.html

Material Property and Operating condition

> **Material Property**

– **Viscosity = 0.239 Pa s**

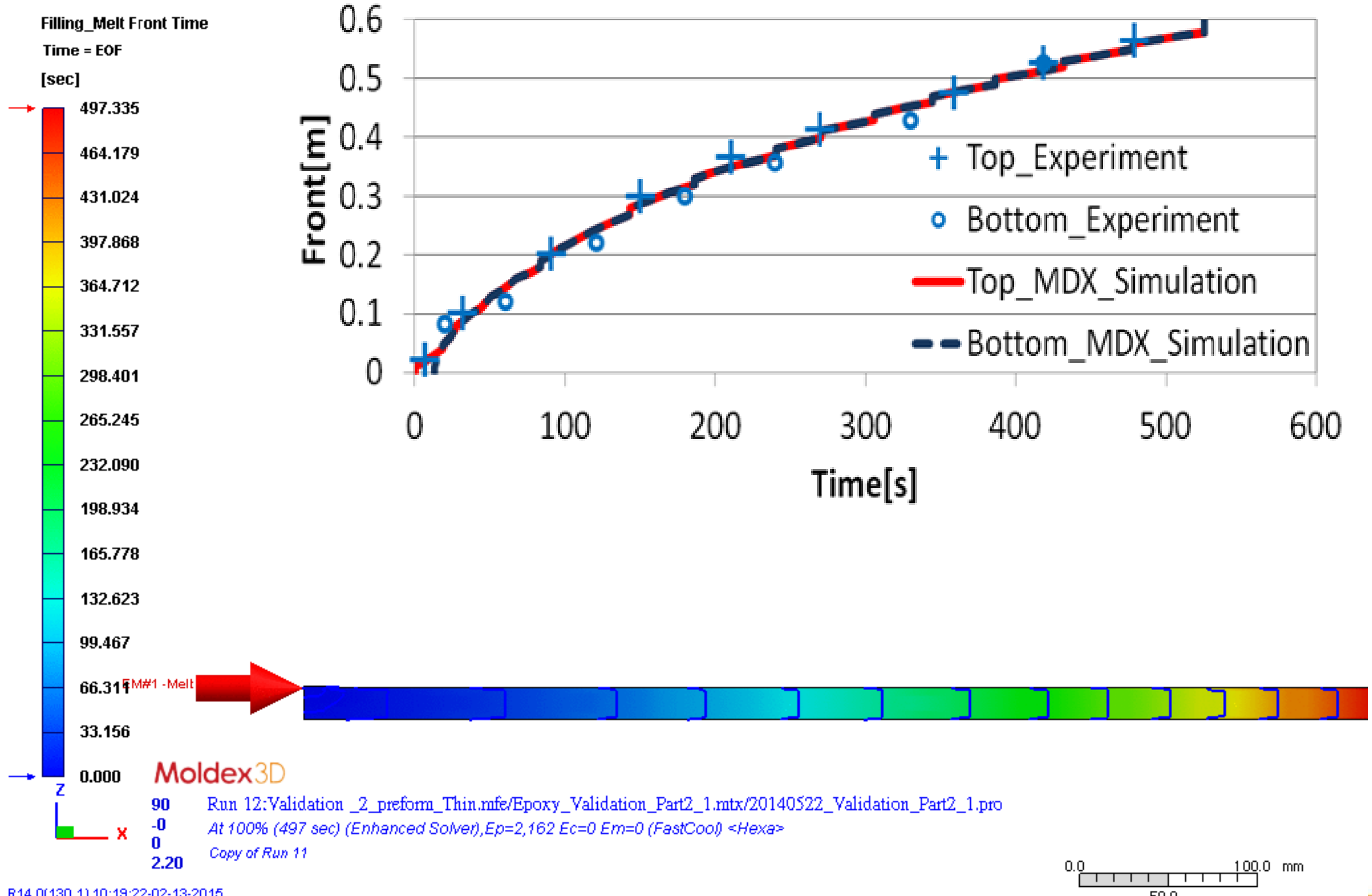
K and ϕ	K_{11} (m^2)	K_{22} (m^2)	K_{33} (m^2)	ϕ (-)
CFM225	1.16E-9	1.16E-9	5.44E-10	0.81
Biaxial	1.8E-13	1.8E-13	1.11E-12	0.44
Balsa 5/8	4.4E-11	1.47E-10	1.47E-10	0.11

> **Operating Condition**

– **Inlet Pressure = 0.9 atm = 0.09 MPa**

Moldex3D RTM Simulation Result

> Flow front animation and front location vs. filling time.



3-D Simulation

3D flow behavior prediction in RTM

Background (1)

> **Industrial challenge**
  - **How to make the smooth filling for huge part?**
  - **What is the filling behavior**

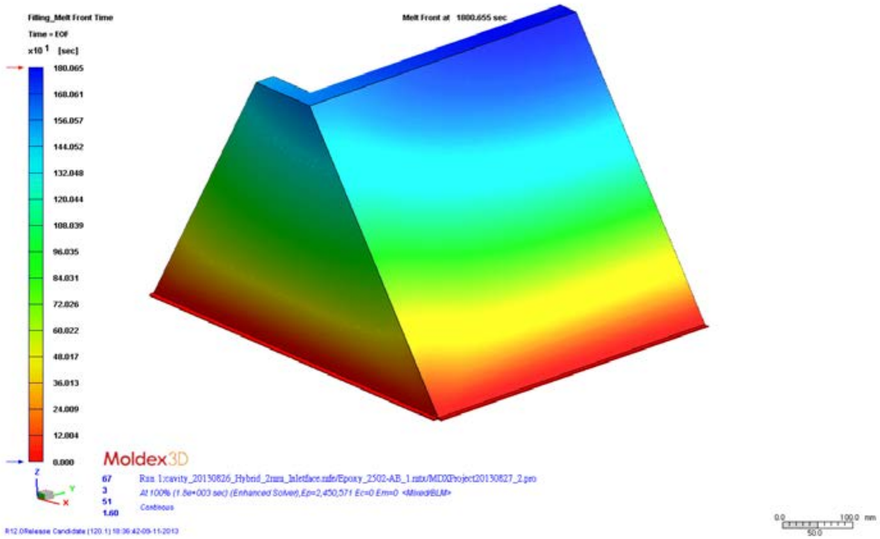


圖 4-2 模型焊道突出示意圖

Background (2)

> **Reference**
  - **Study on the application of VARTM technique and mold flow analysis to the lamination of sandwich plates**

> **Professor**
  - **Ya-Lung Lee**

> **Author**
  - **Kai-Lin Chen**

> **Polymer**
  - **Eternal Chemical 1629**
  - **Environment temperature 24.4^{o}C**
  - **D+P+(MR)*1+M+DC+(MR)*1+M**

D: distribution media
P: peel ply
M: fiber mat
DC: double cut core

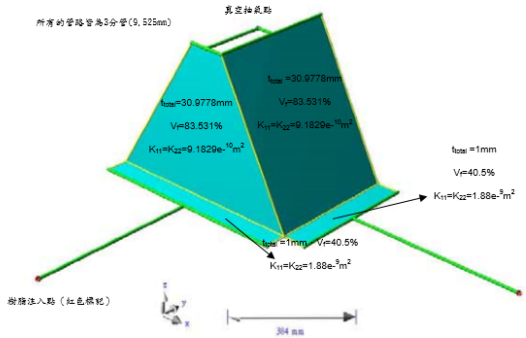


圖 4-5 模擬樹脂流動時，滲透率及相關參數的設定

紅色圈圈者為突出
的焊道

圖 4-2 模型焊道突出示意圖

Geometrical System

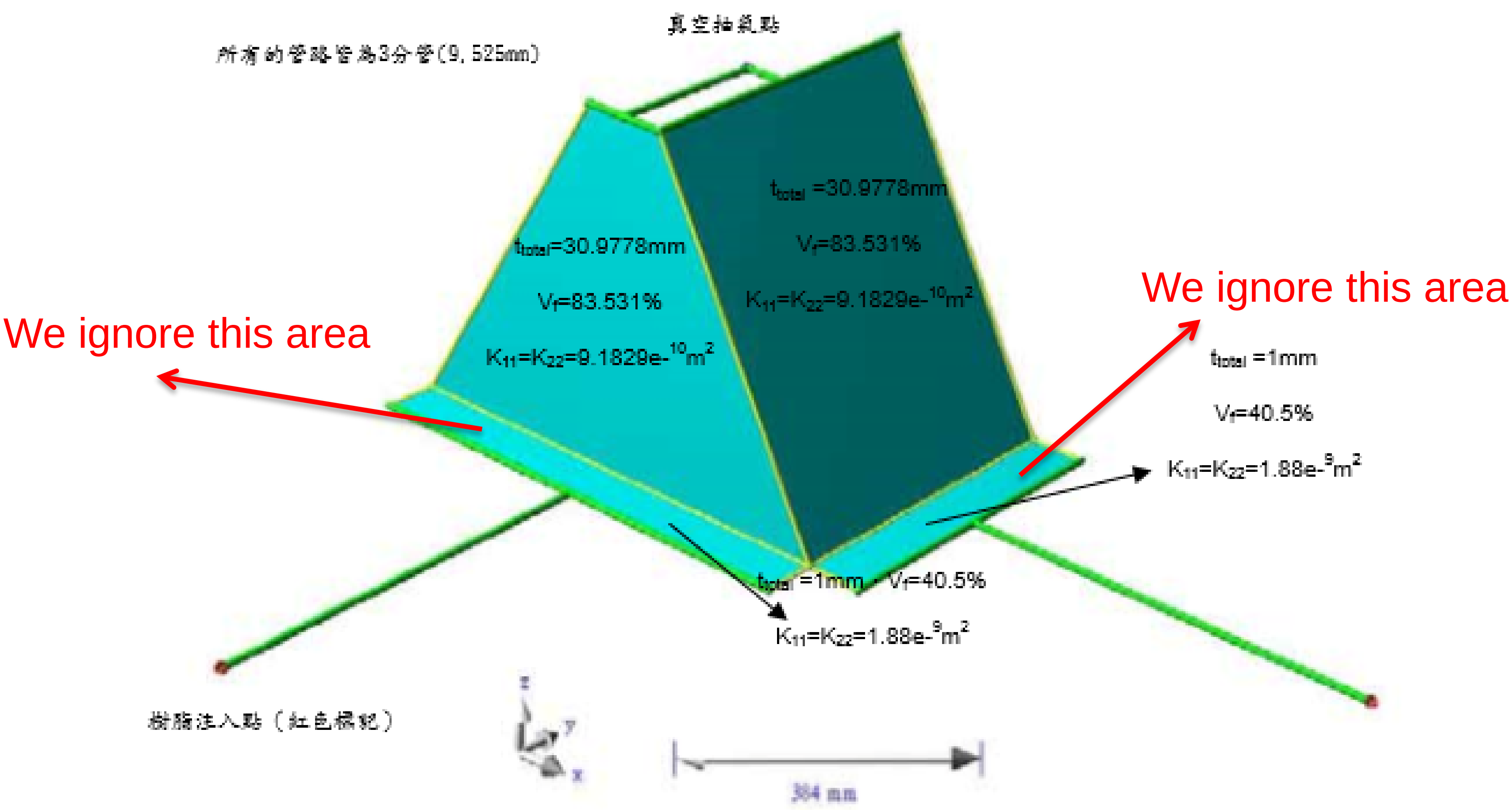
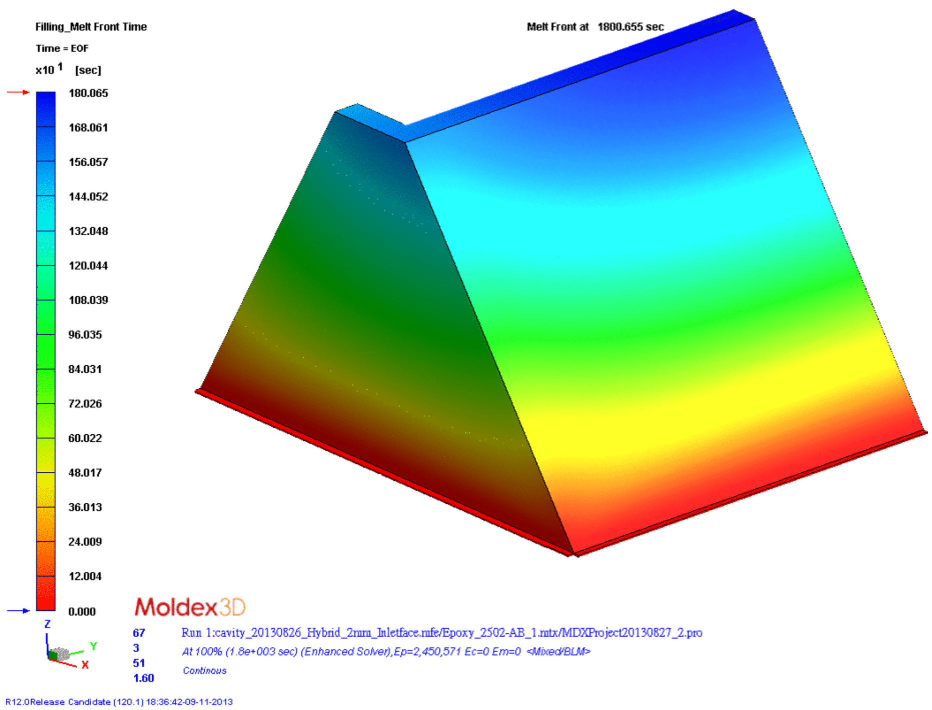


圖 4-5 模擬樹脂流動時，滲透率及相關參數的設定

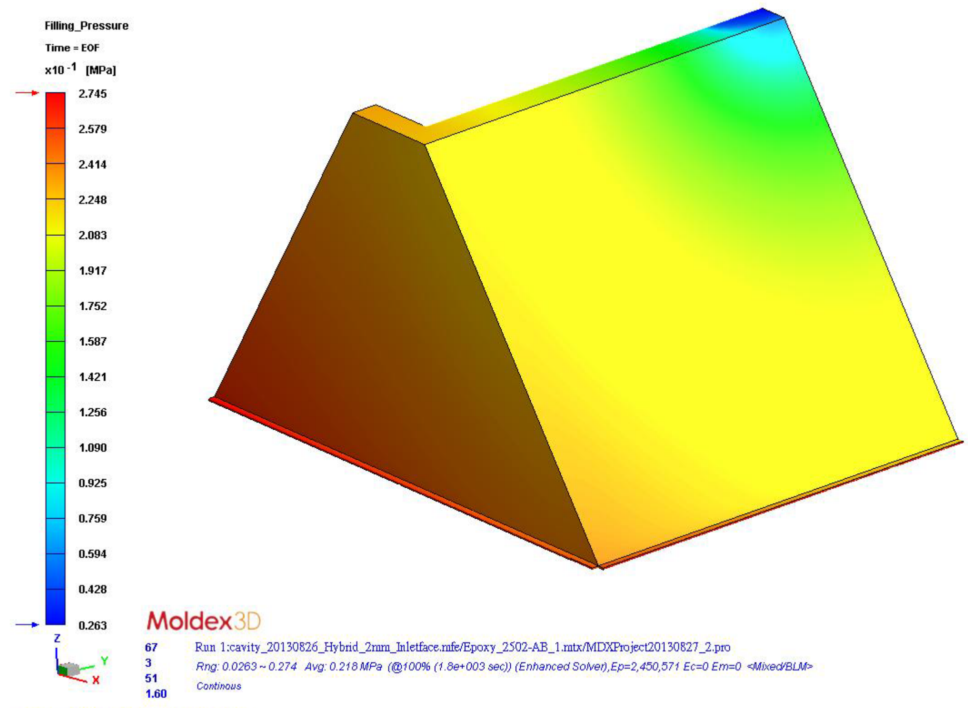
Reference :Study on the application of VARTM technique and mold flow analysis to the lamination of sandwich plates

Filling Results: $Q=6.35\times10^{-6}m^3$

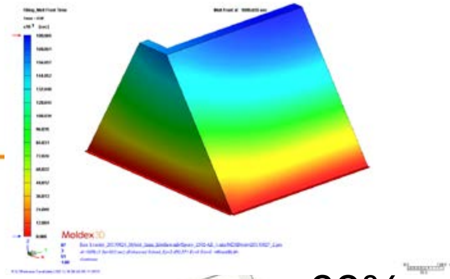
Melt Front Time



Pressure Distribution



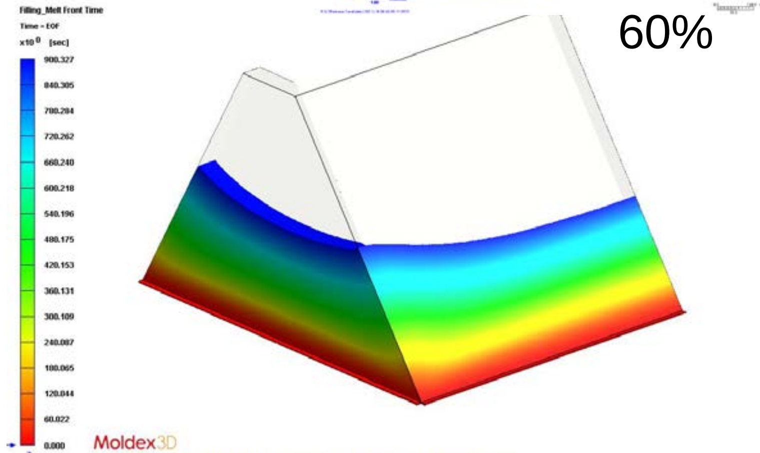
Comparison with Research (1/2)



60%

圖 4-6 樹脂灌注實驗與模擬流動圖形比較圖(矩形面)

60%



81%

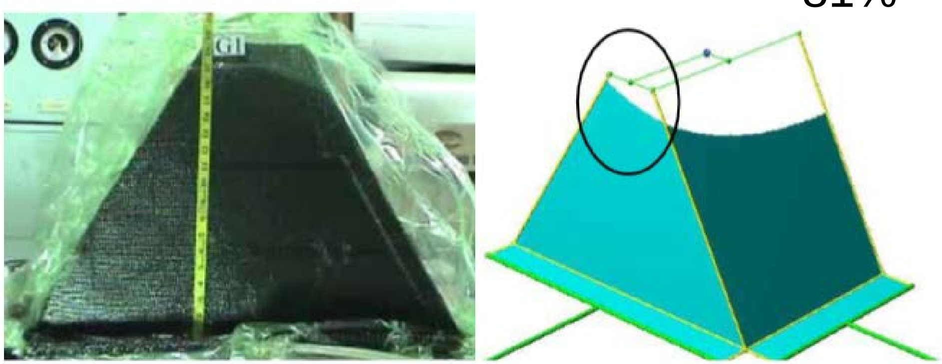
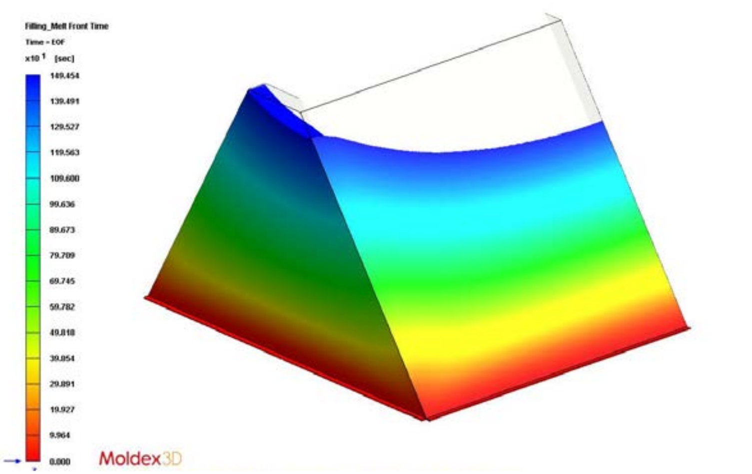


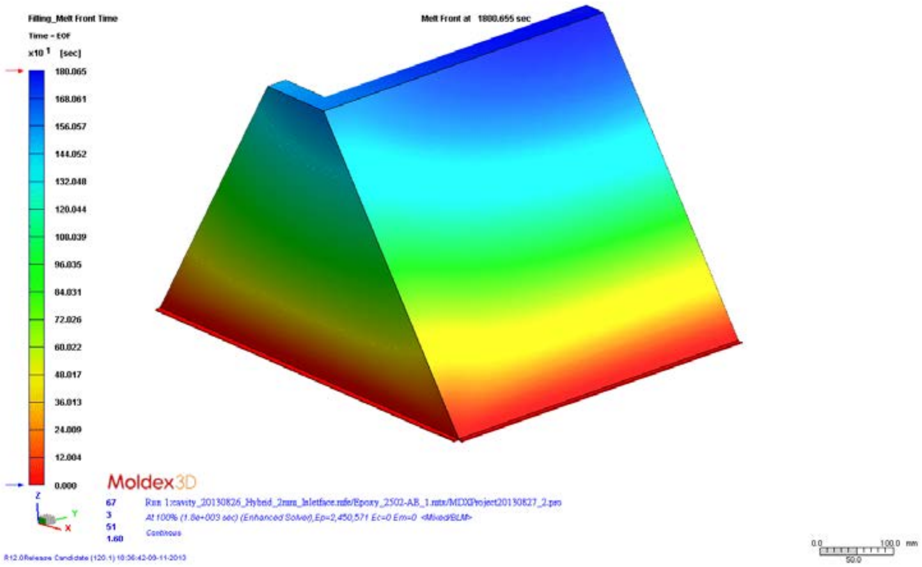
圖 4-7 樹脂灌注實驗與模擬流動圖形比較圖(梯形面)

81%

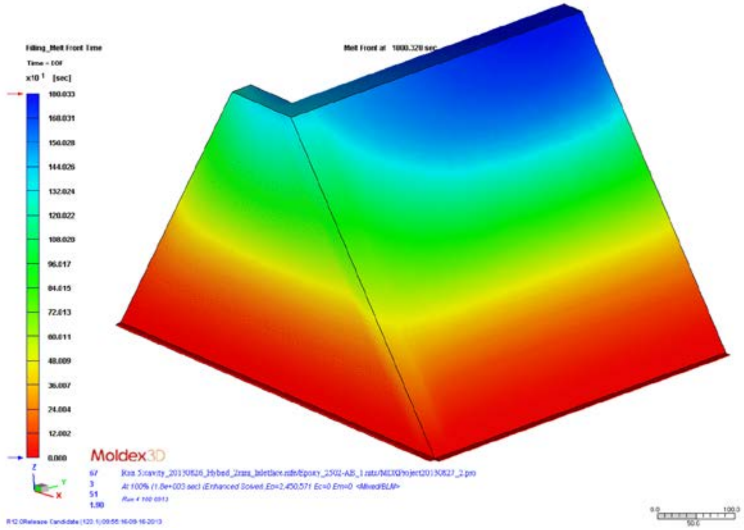


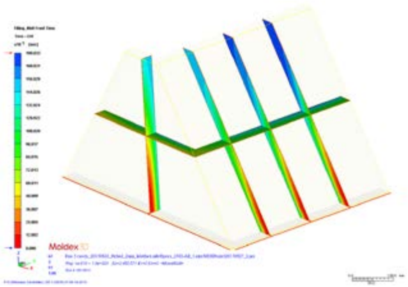
Reference :Study on the application of VARTM technique and mold flow analysis to the lamination of sandwich plates

Adding the Thickness Effect



K11 : K22 : K33 = 1 : 1 : 1
Thickness not considered
2D Behavior

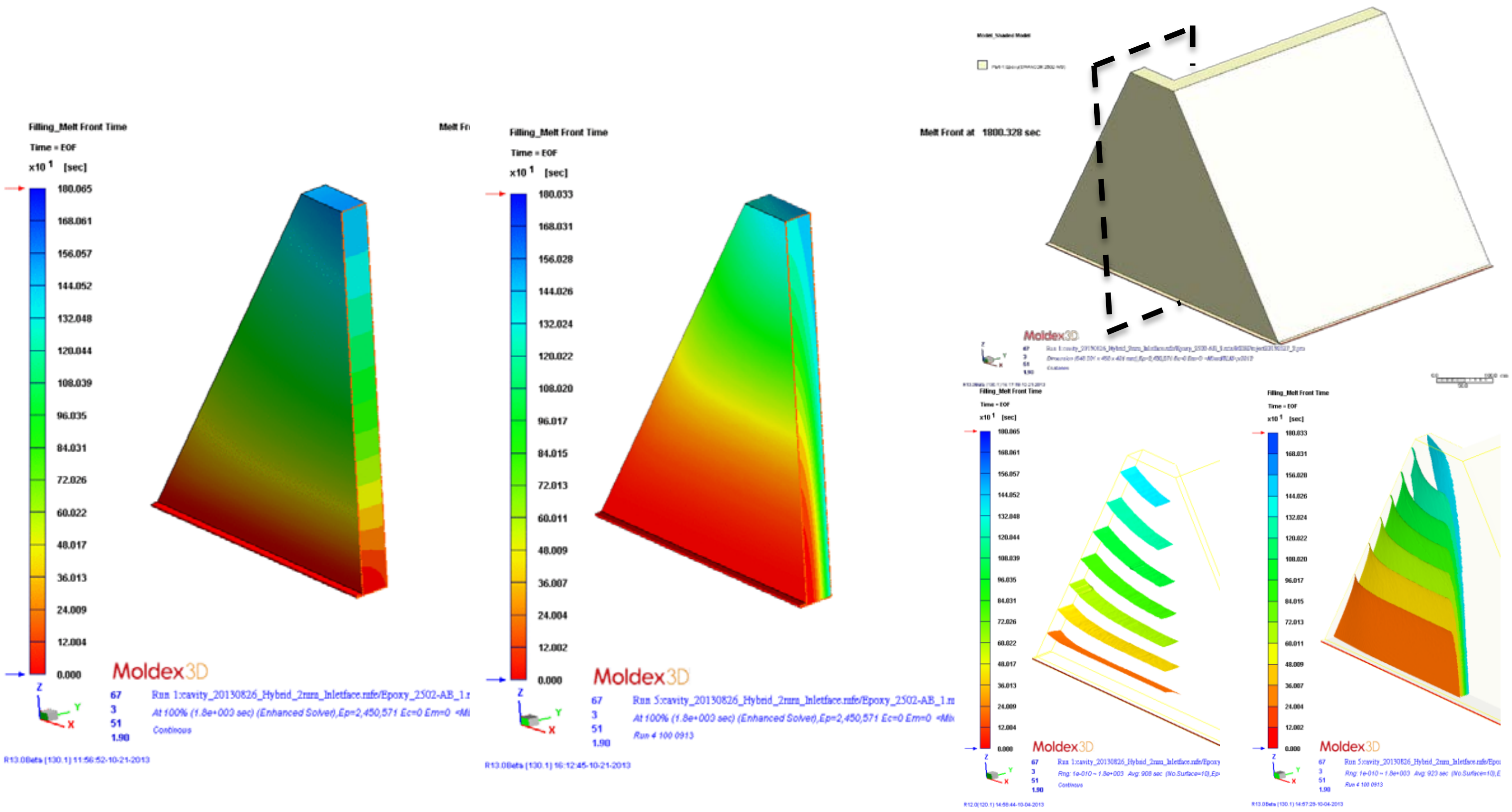




K11 : K22 : K33 = 100:10:1
Thickness considered
3D Behavior

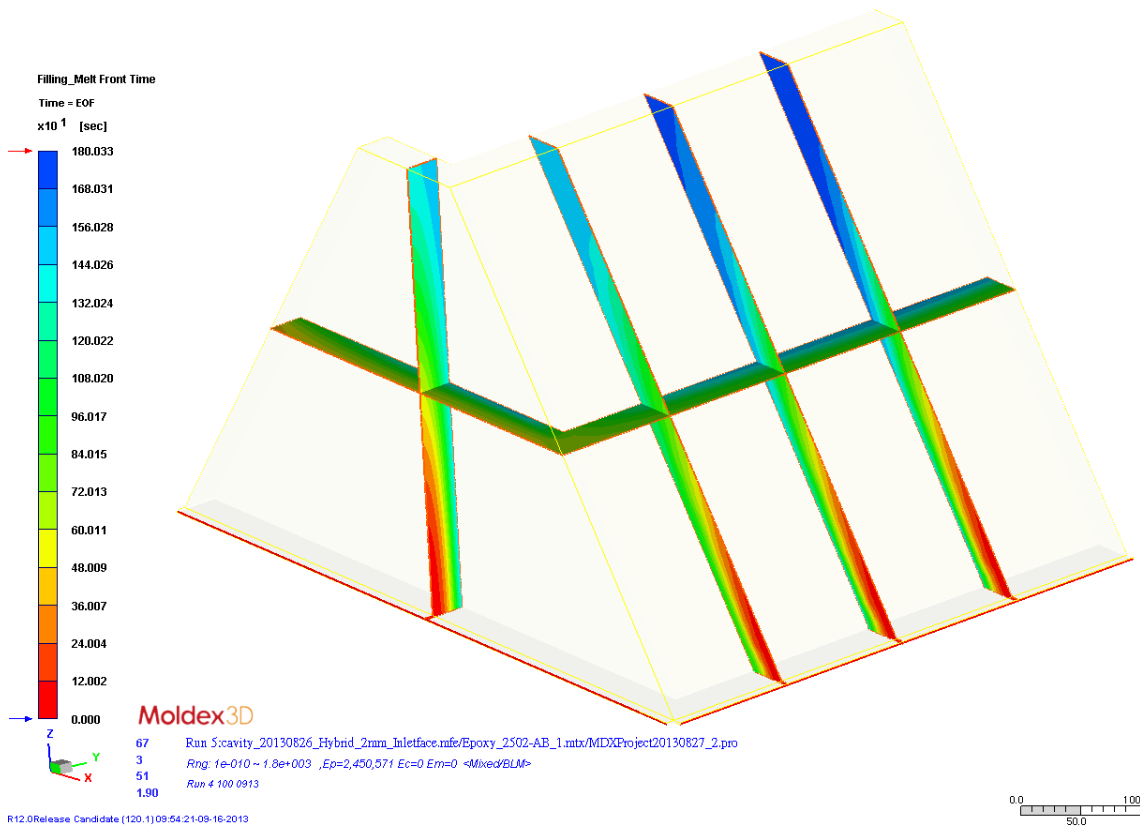
Melt Front Difference Across the Thickness

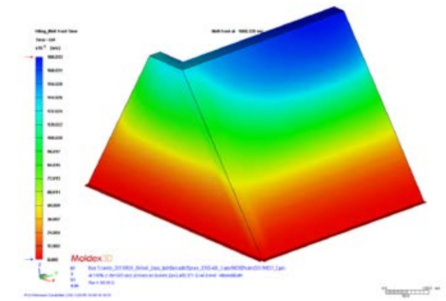
Capturing the thickness difference with a true 3D simulation

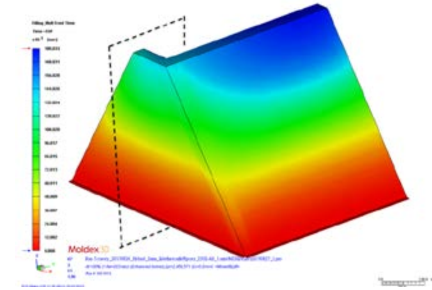


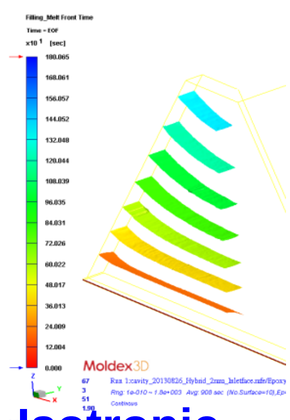
Isotropic Anisotropic Isotropic Anisotropic

Melt Front Difference Across the Thickness

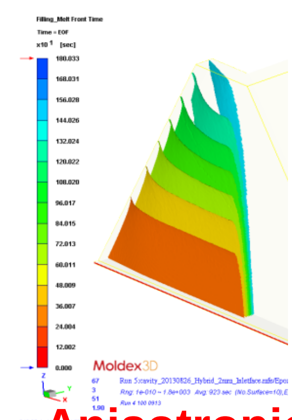








Isotropic



Anisotropic

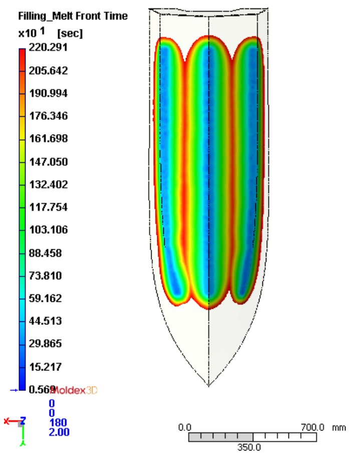
3-D Simulation

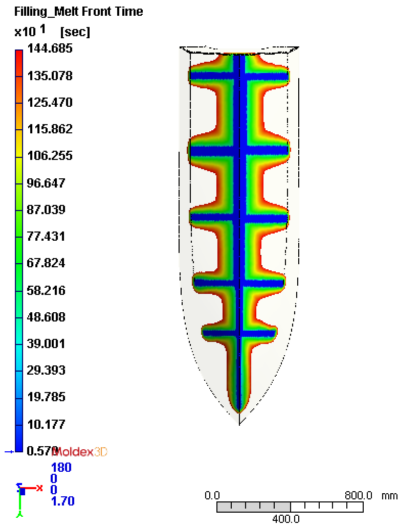
Boat

Moldex3D

Case 1: 改變佈管形式對於船殼灌注

> 改變佈管形式



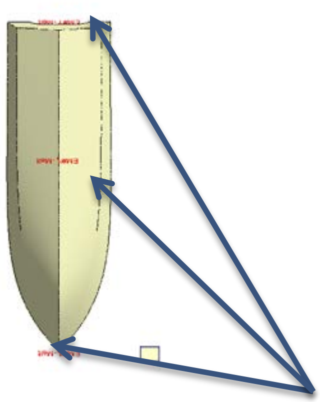


Experiment result

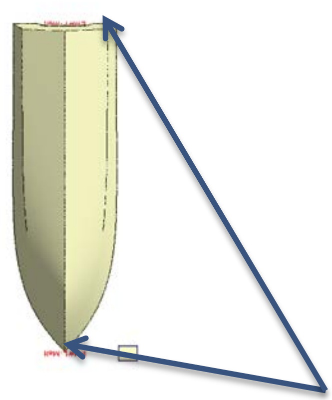
Simulation result

不同的佈管形式

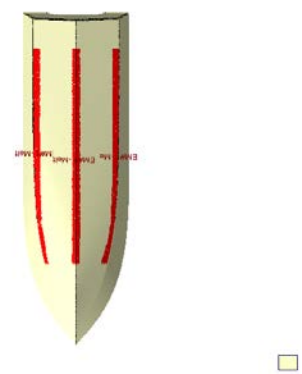
> 以模擬方式評估佈管方式



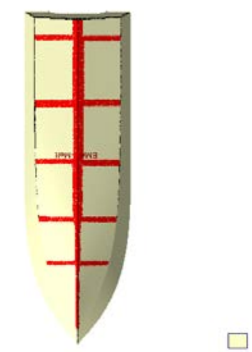
三進澆口方式



兩進澆口方式



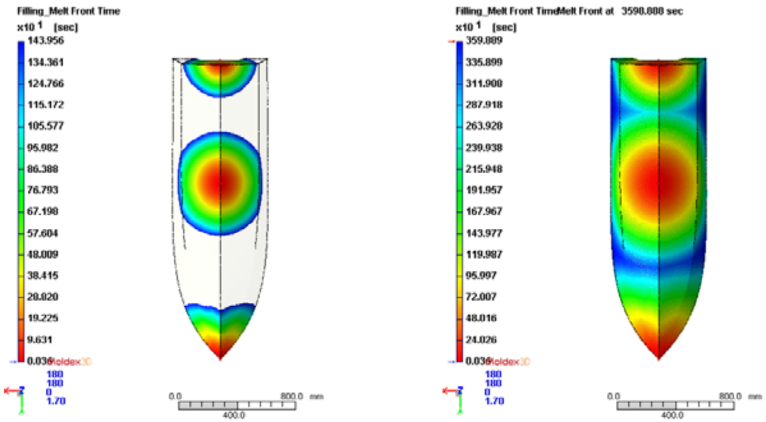
平行型佈管



魚骨型佈管

流動波前結果

> 比較各種進澆的方式



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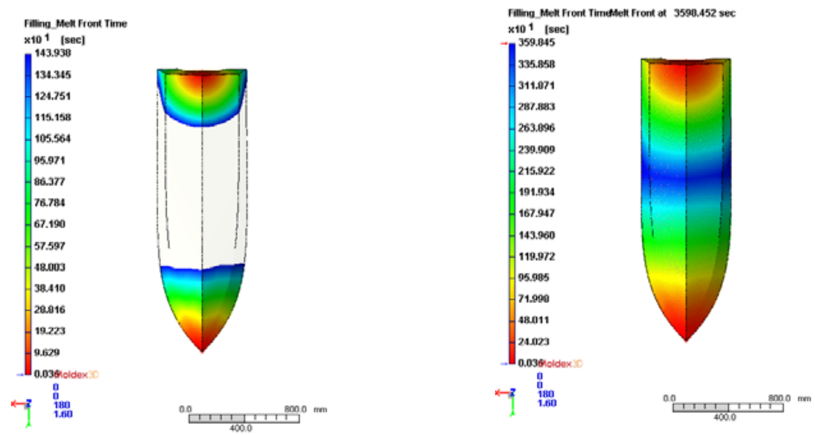

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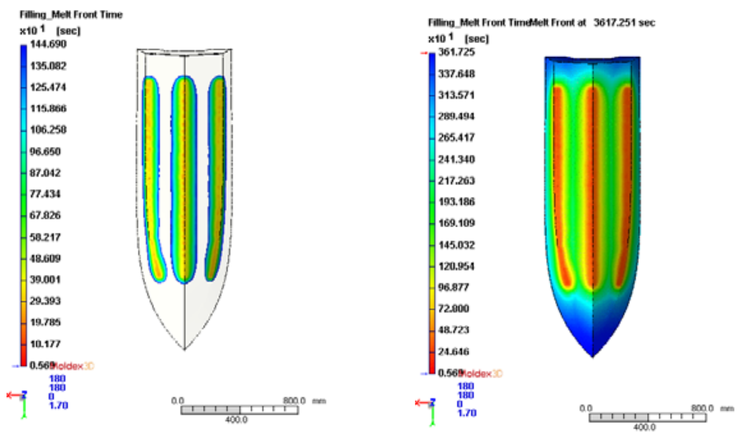
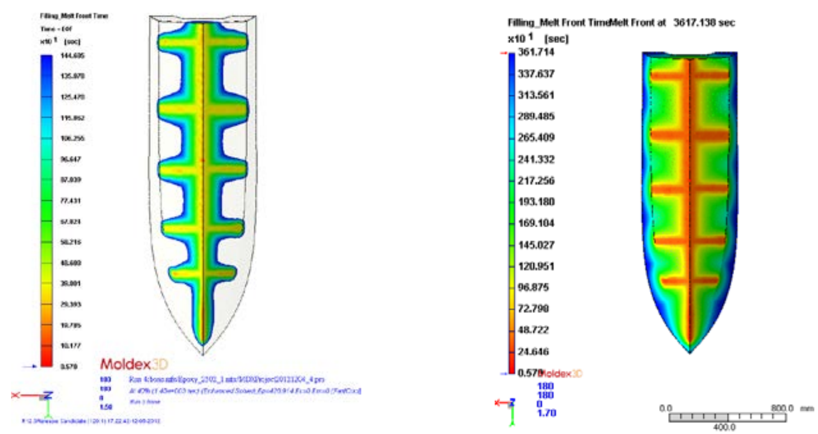


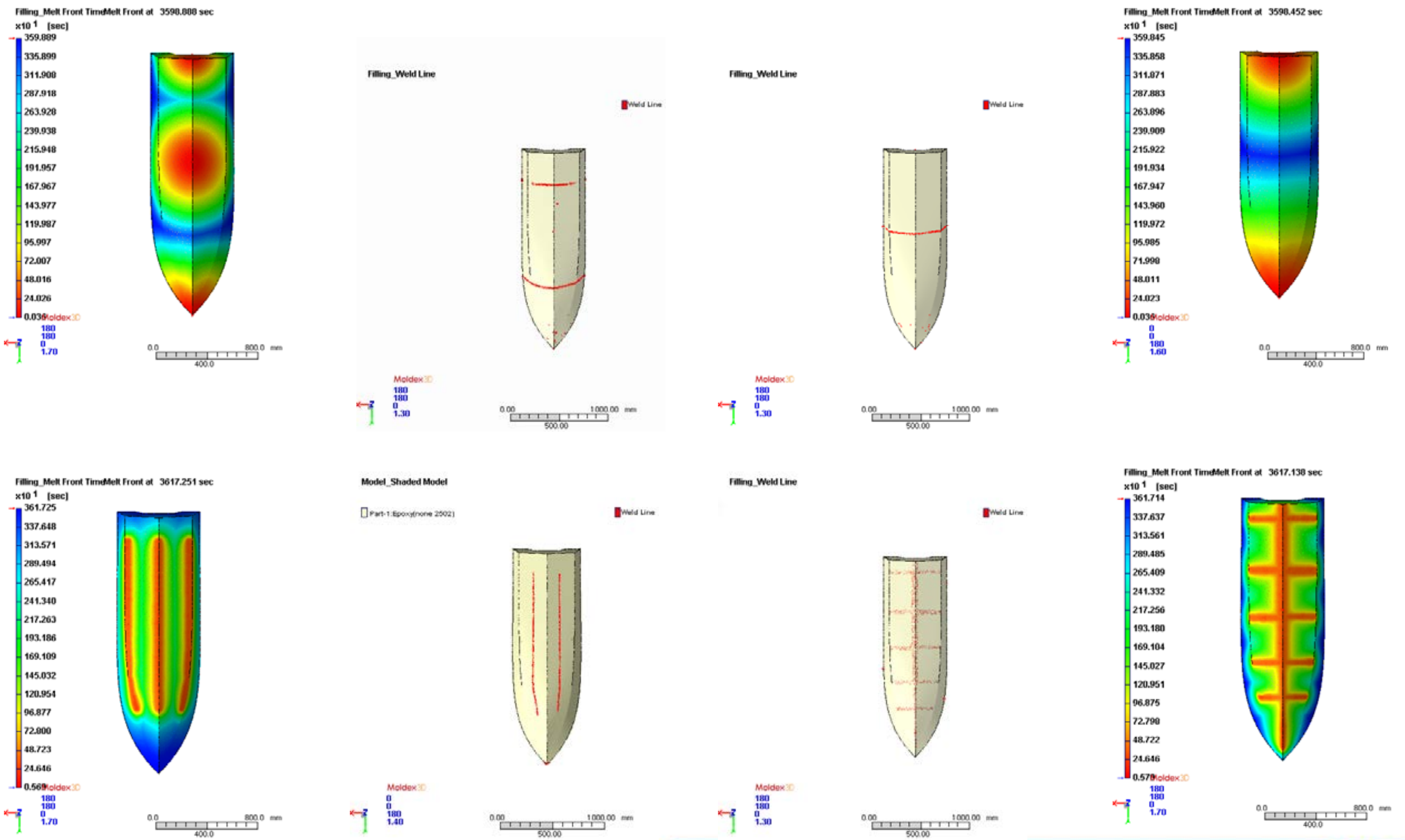
平行型佈管



魚骨型佈管

波前交會線

> 不同佈管方式下波前交會造成波前交會線



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