CFD Modeling of the Closed Injection Wet-Out Process For Pultrusion

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Outline

- Definition of Process Challenge
- CFD Model
  - Assumptions
  - Equations
  - Boundary Conditions
  - Building Process
  - Resin Flow Patterns
  - Predictions of Pressure Profiles
- Comparison with Experimental Data
- Conclusions
- Future Work
Typical PU Pultrusion Set-up

What is happening inside the injection box?

What is the box design?
Process Challenge

- What is the internal design of the injection box?
- How can trial and error be eliminated/reduced?
- How can box design be optimized for particular parts and process conditions?
  - Thick vs. thin
  - Line speed
  - Resin properties

- SOLUTION:
  - Develop computational model
  - Compare with detailed experimental work
  - Validate and update model
CFD Model - Assumptions

Micro-scale model of PU resin flow through fibers

To model injection box at macro-scale we must use a phenomenological approach

Resin and reinforcement represented as a moving porous medium (extension of Darcy’s law)

Surface tension effects captured by permeability tensor

Single phase flow and constant viscosity
CFD Model - Equations

Navier-Stokes Equations
\[ \nabla \cdot u = 0 \]
\[ \rho u \cdot \nabla u = -\nabla p + \mu \nabla^2 u + S \]

Source terms describing moving porous medium
\[ S = -\frac{\mu}{K}(u - \varepsilon U) \]

Injection box porosity changes with position
\[ \varepsilon = 1 - V_f(z) \]

Gebart model of permeability
\[ K_z = \frac{2D_I^2}{c} \frac{\varepsilon^3}{(1 - \varepsilon)^2} \]
\[ K_x = K_y = \frac{C_1 D_I^2}{4} \left( \frac{V_{f,\text{max}}}{\sqrt{(1 - \varepsilon)}} - 1 \right) \]
Model Regions & Boundary Conditions

Resin Inlet
\[ p = p_{\text{inj}} \]
\[ \phi = 1 \]

Rovings Entrance
\[ p = p_{\text{atm}} \]
\[ \phi = 0 \]

Rovings
\[ \varepsilon = 1 - \frac{A_{\text{wet}}}{A_{\text{glass}}} \]

Model Exit
\[ w = \varepsilon W_{\text{pull}} \]

Initial Die Section
\[ \varepsilon = \varepsilon_{\text{die}} \]
Building a CFD model - 1

建模几何
Building a CFD model - 2

Build Mesh
Building a CFD model - 3

Add Physics
Building a CFD model – 4

Solve Simulation
Building a CFD model - 5

Look at Results
Resin Flow Patterns
Influence of Glass Fraction

[Graphs showing the influence of glass fraction on pressure, superficial velocity, glass fraction, and permeability.]
Influence of Glass Fraction

- Pressure rise quadratic with glass fraction
- More pronounced at die face than at transducer locations
Pressure Rise in the Injection Box

![Graphs showing pressure rise in the injection box with respect to viscosity, glass fraction, length of box, and height of box.](image)
Tapered Injection Box Setup

- **Resin Injection Port** (Top & Bottom)
- **ROVINGS** 120 4400-Tex PPG 2026
- **Digital Pressure Transducer at Tee Inlet**
- **Digital Pressure Transducer at 5 cm from Die Face**
- **Toggle Clamp and Mounting Bracket** (with alignment pins)
Pressure Profiles in the Injection Box

Pressure rises faster than model prediction
Comparison with Experiments

Simulation predictions lower than experimental data
Rate of rise in pressure higher

Lower viscosity data
Small variation with line speed
Capillary forces now dominate?
Void Fraction

Shorter Injection Box
Higher Glass Fraction

Void Percentage (%) vs. Line Speed (m/min)

- Blue: Good Wetout
- Green: Poor Wetout

Void %

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Conclusions

- **Model inputs include:**
  - Injection box geometry
  - Number & location of ports
  - Injection pressure
  - Line speed
  - Resin viscosity & density, glass fraction & density
  - Permeability defined by glass fraction & flow direction

- **Model outputs include:**
  - Pressure and velocity profiles
  - Composite density

- **Improvements needed:**
  - Improved permeability parameters
    - Do additional experimental measurements
    - Do small-scale flow modelling
  - Add surface tension effects
  - Consider ‘encapsulation’ vs. ‘filament wet-out’
Future work

- Micro-scale modeling
  - Surface tension effects
  - Viscosity
- Experimental
  - Permeability measurements
  - Pultrusion trials
- New Materials
  - CFM
  - Engineered fabric
- New Geometries
  - Thicker parts
  - Round parts
  - ‘Consolidated’ wet-out
- Cure/Exotherm Mapping
2D Pultrusion Die Modeling
Die Exotherm: 6mm Thick Profile
Zone 1 = 330 F (165 C)
Cure/Exotherm Mapping: 6 mm Profile
18 IPM, Zone 1=330 F (45.7 cm/min, 165 C)
Questions???

Thank you for your attention and interest