MODELLING AND VALIDATION OF A NOVEL VACUUM ASSISTED THERMOPLASTIC MELT COMPRESSION IMPREGNATION PROCESS

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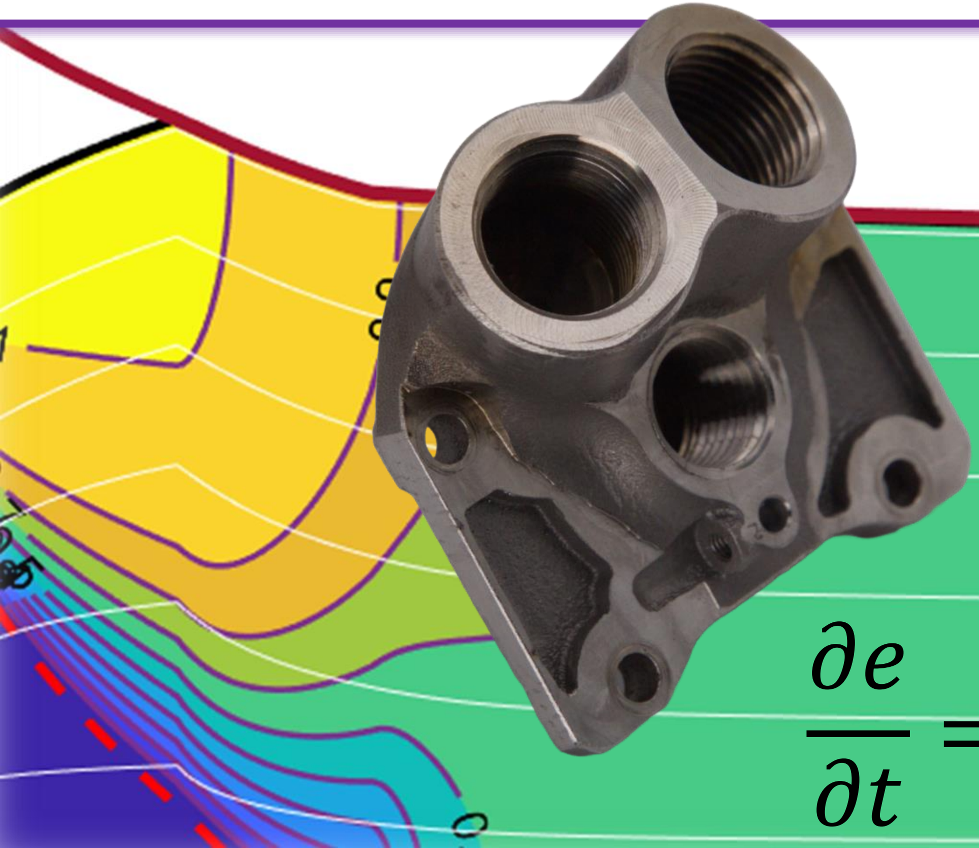
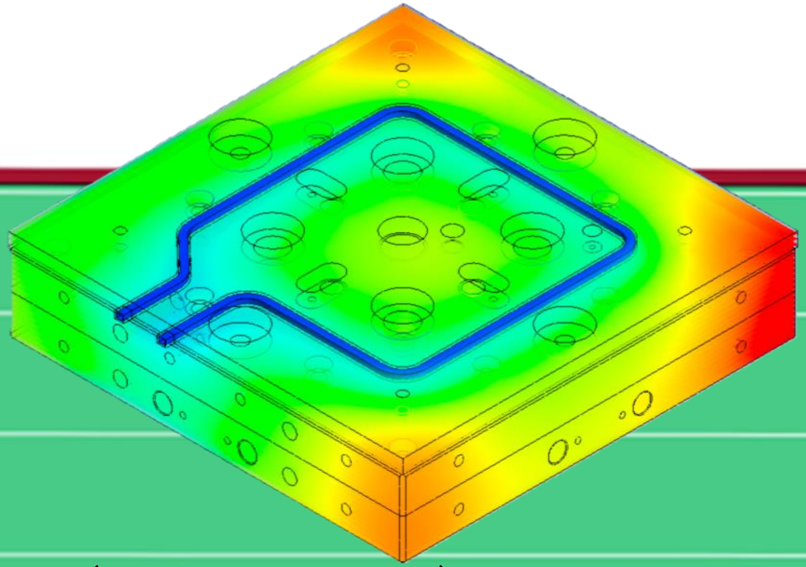
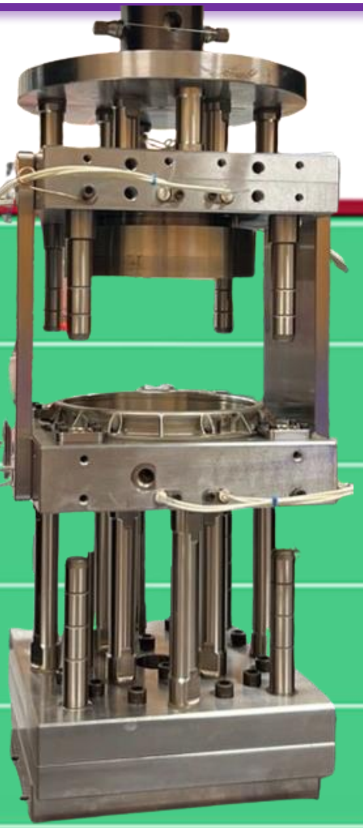






$$\frac{\partial e}{\partial t} = \frac{\partial}{\partial X}\left(D(e)\frac{\partial e}{\partial X}\right) + \frac{Q}{V_s}$$

Introduction

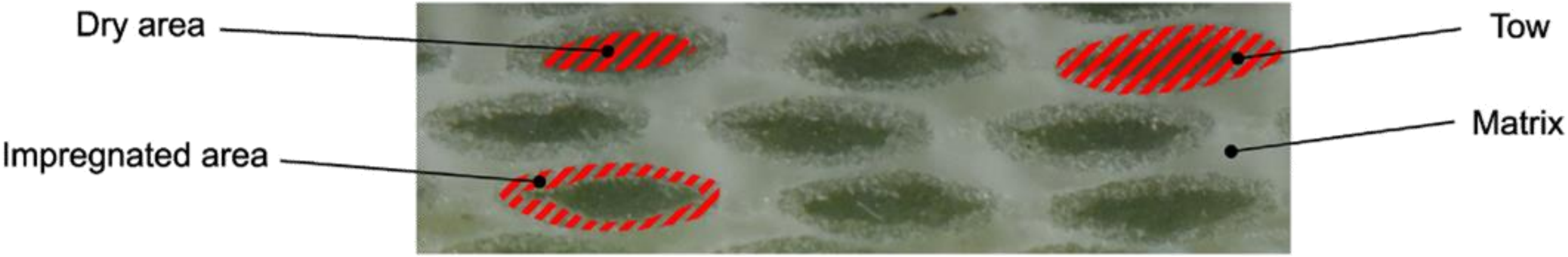
Melt thermoplastic composites offer a range of advantages

- **Mechanical Properties**
  - Good strength, toughness
  - Excellent specific energy absorption
- **Manufacturing**
  - Long shelf life
  - No cure cycle
  - Post forming, overmoulding
- **Environmental**
  - Potential for reuse (thermoform)

BMW 7 Series, Competitive and sustainable thermoplastic composites for automotive applications - JEC (jeccomposites.com)

Primary challenge of melt thermoplastic composite processing is the **high melt viscosity.**

- Slow impregnation process
- Not wetting, no spontaneous intra-tow impregnation
- High pressures required
- Current manufacturing techniques limit design freedom (flat or smooth geometry)



Tow Voids

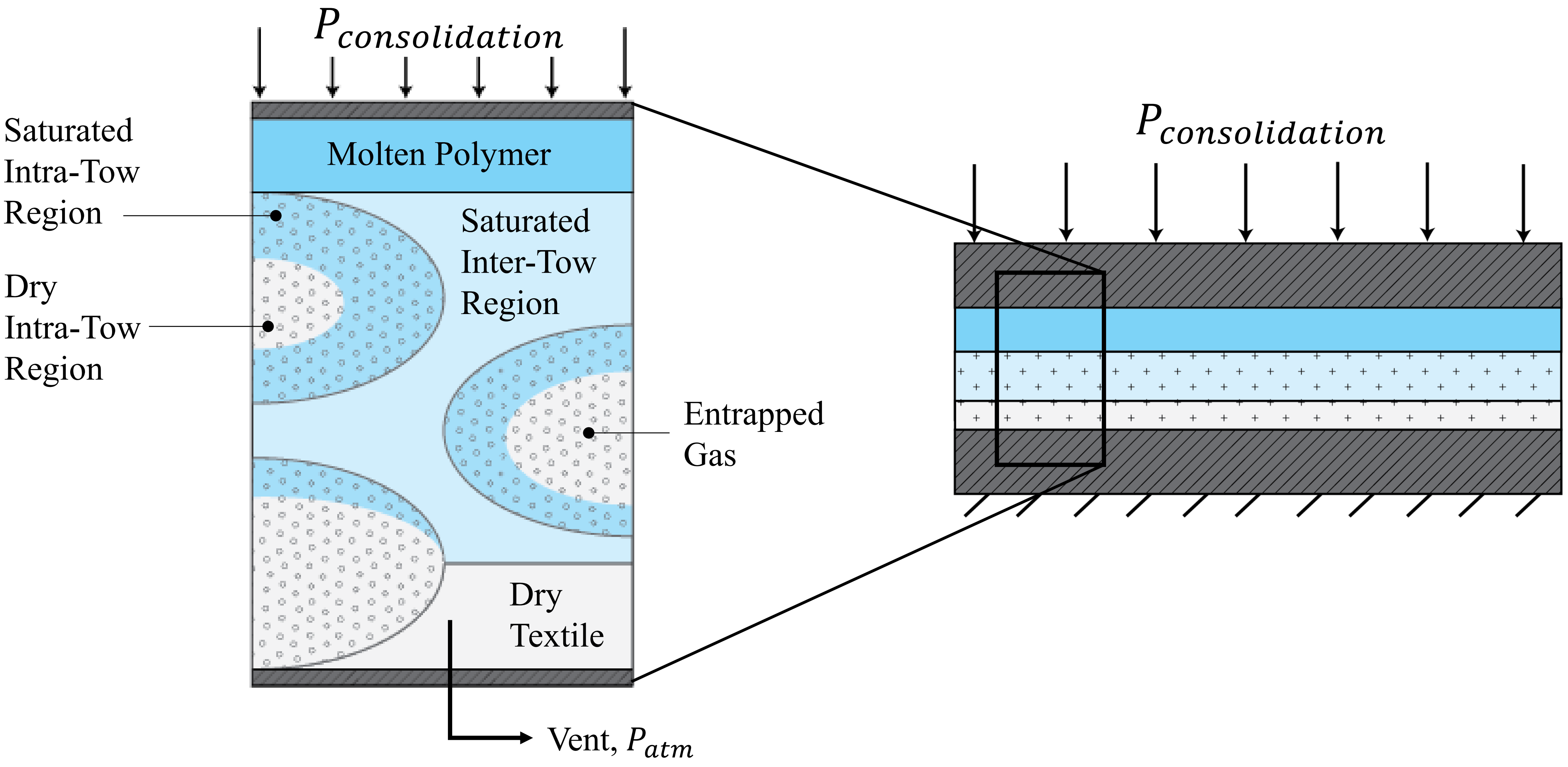
V. Werlen, et al. “**A model for the consolidation of hybrid textiles considering air entrapment, dissolution and diffusion,**” Composites Part A: Applied Science and Manufacturing, v 166, p 107413, 2023

Project Aim

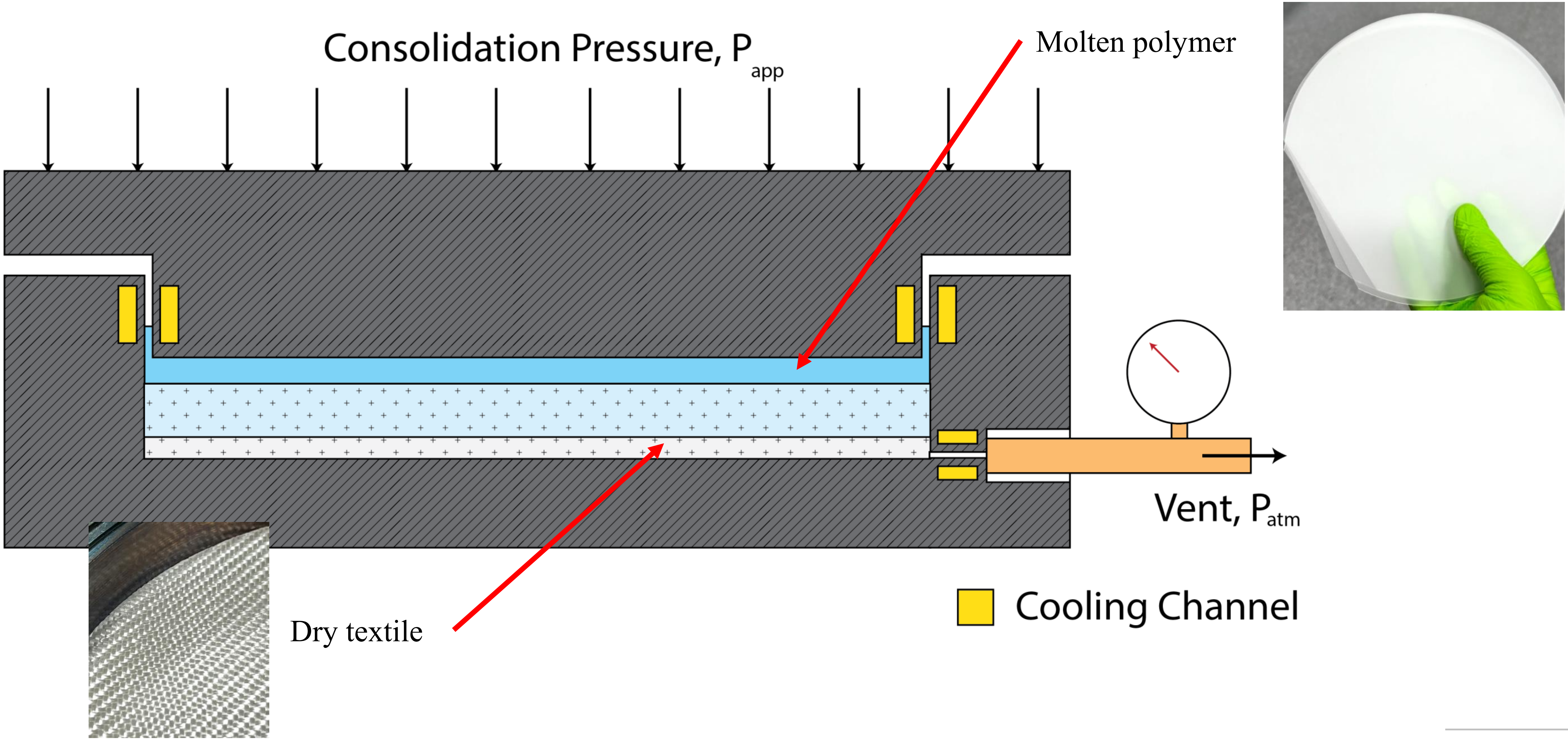
To manufacture continuous fibre thermoplastic melt composites;

- Using woven or stitched textile reinforcements
- Achieving very low void content (<0.1%)
- Use broad range of thermoplastic melts
  - 100 to 10,000 Pa.s range
  - Including Nylon PA6, PEEK/PAEK

Modelling Problem



Equipment Overview



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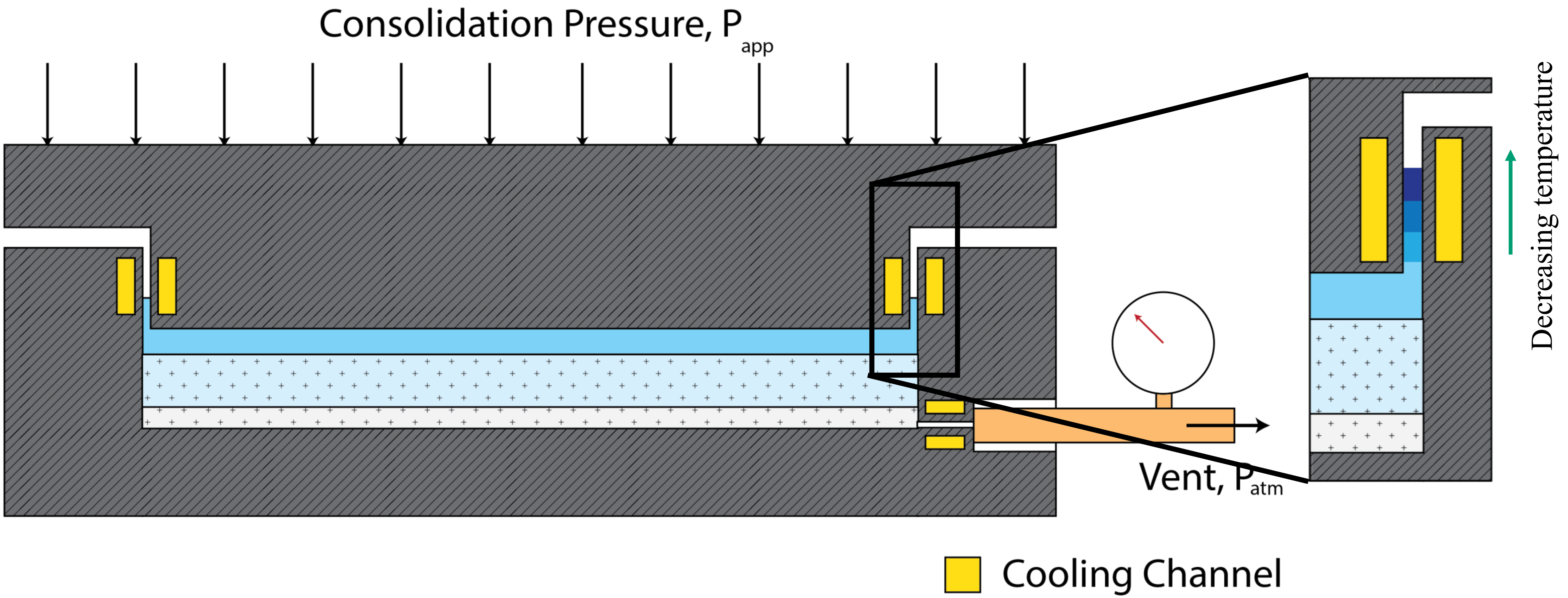
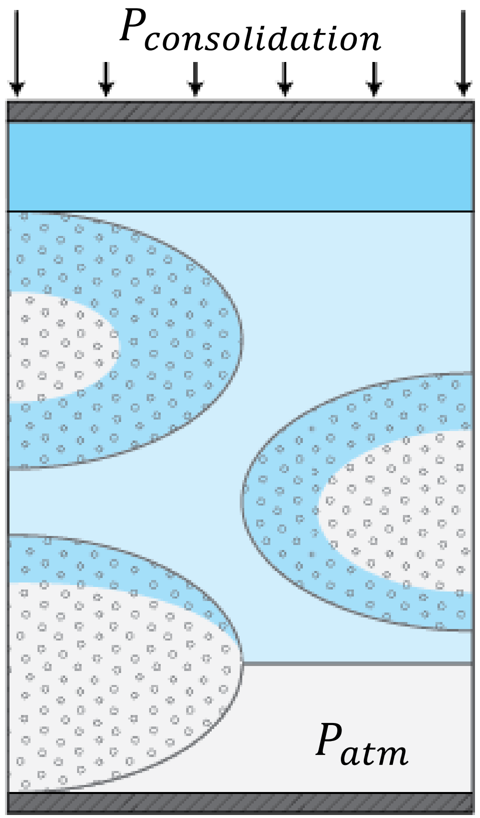
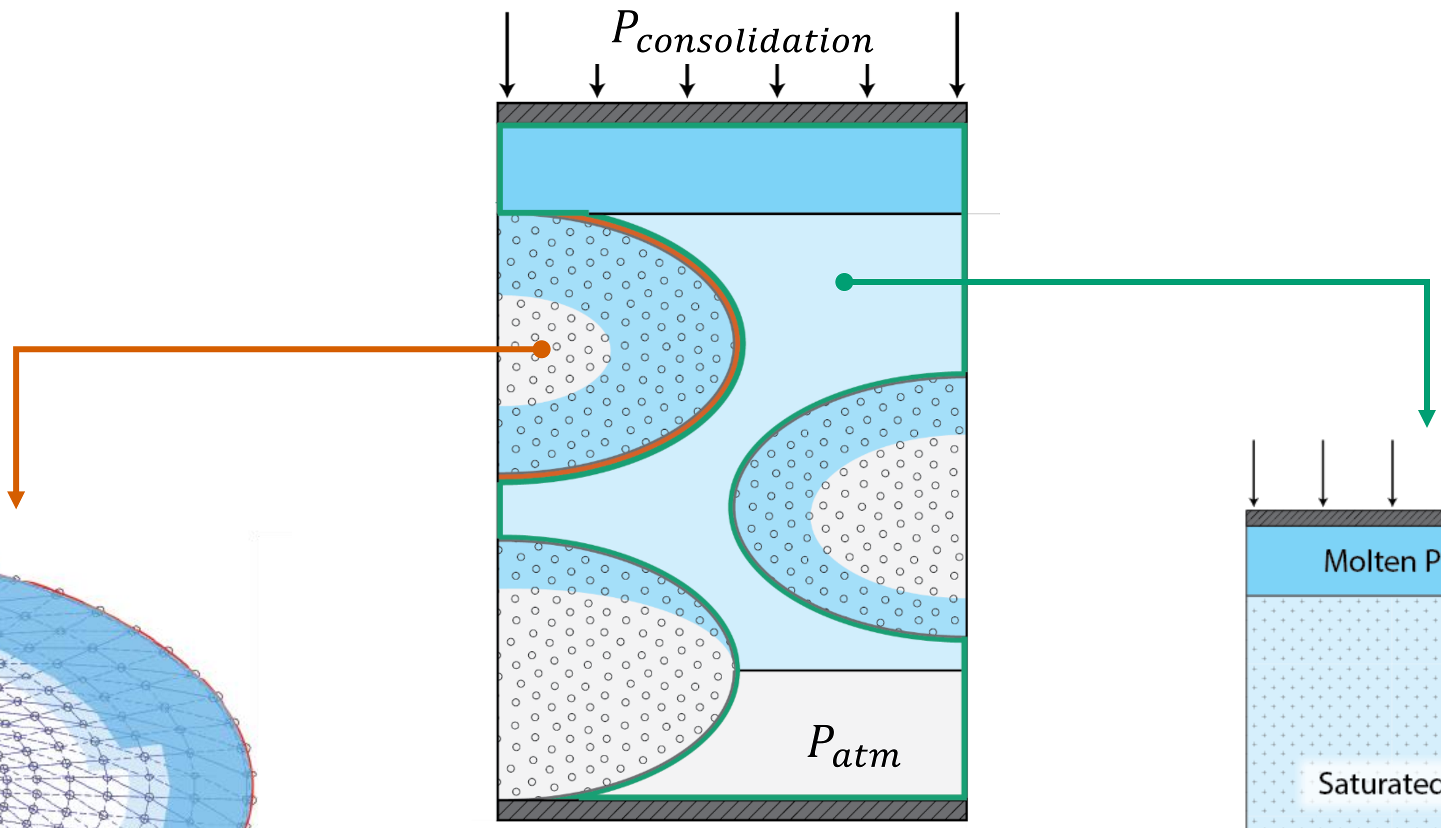


Modelling Strategy

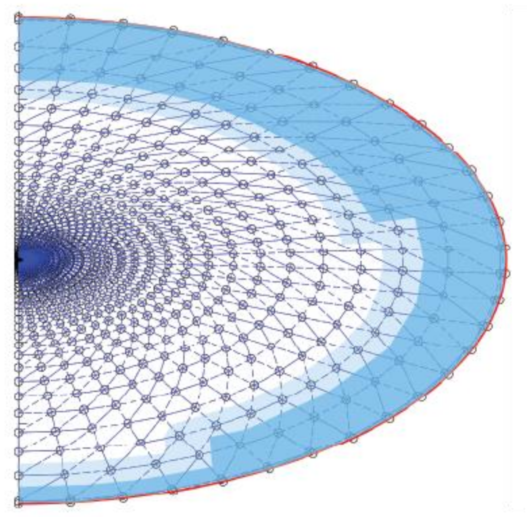


Physical Representation

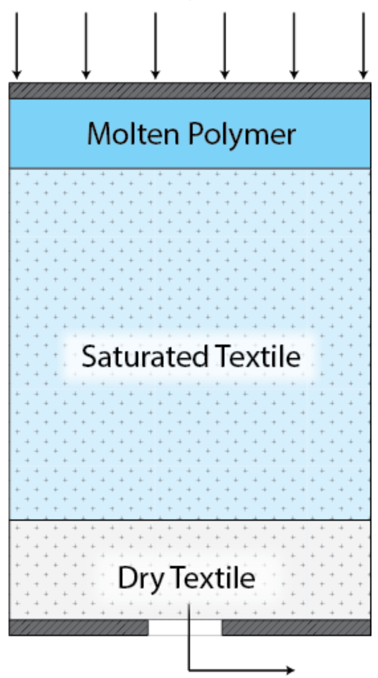
Modelling Strategy



Physical Representation

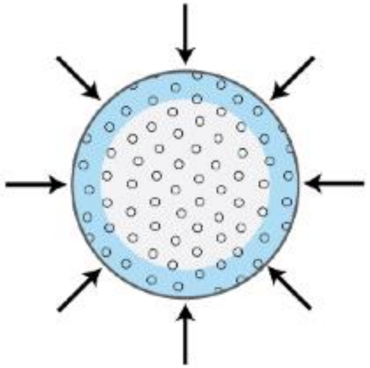


Intra-Tow Model

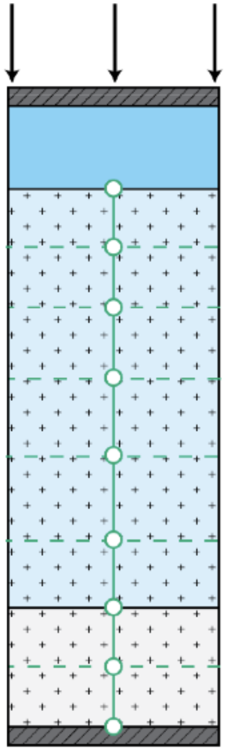


Inter-Tow Model

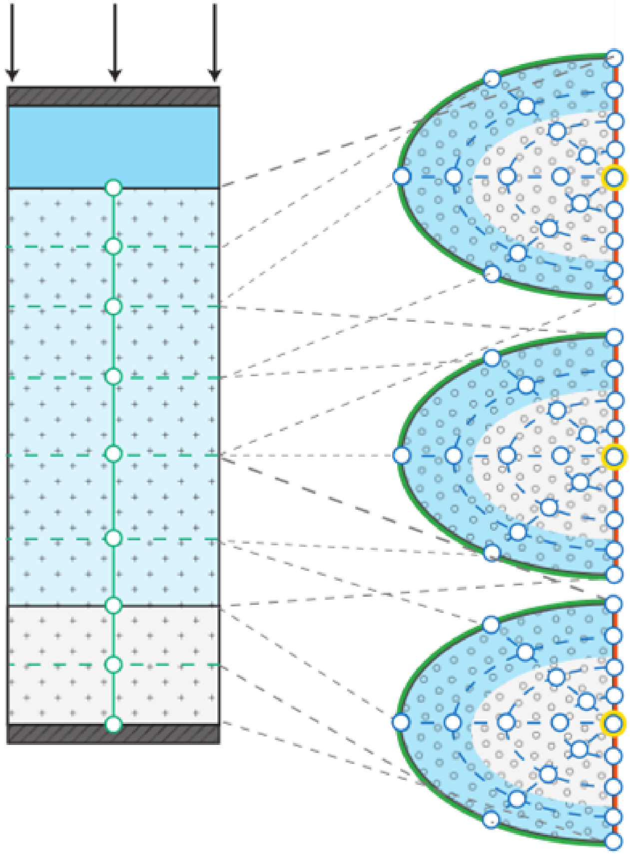
Model Variation Overview



Intra-Tow Model



Inter-Tow Model



Combined Model

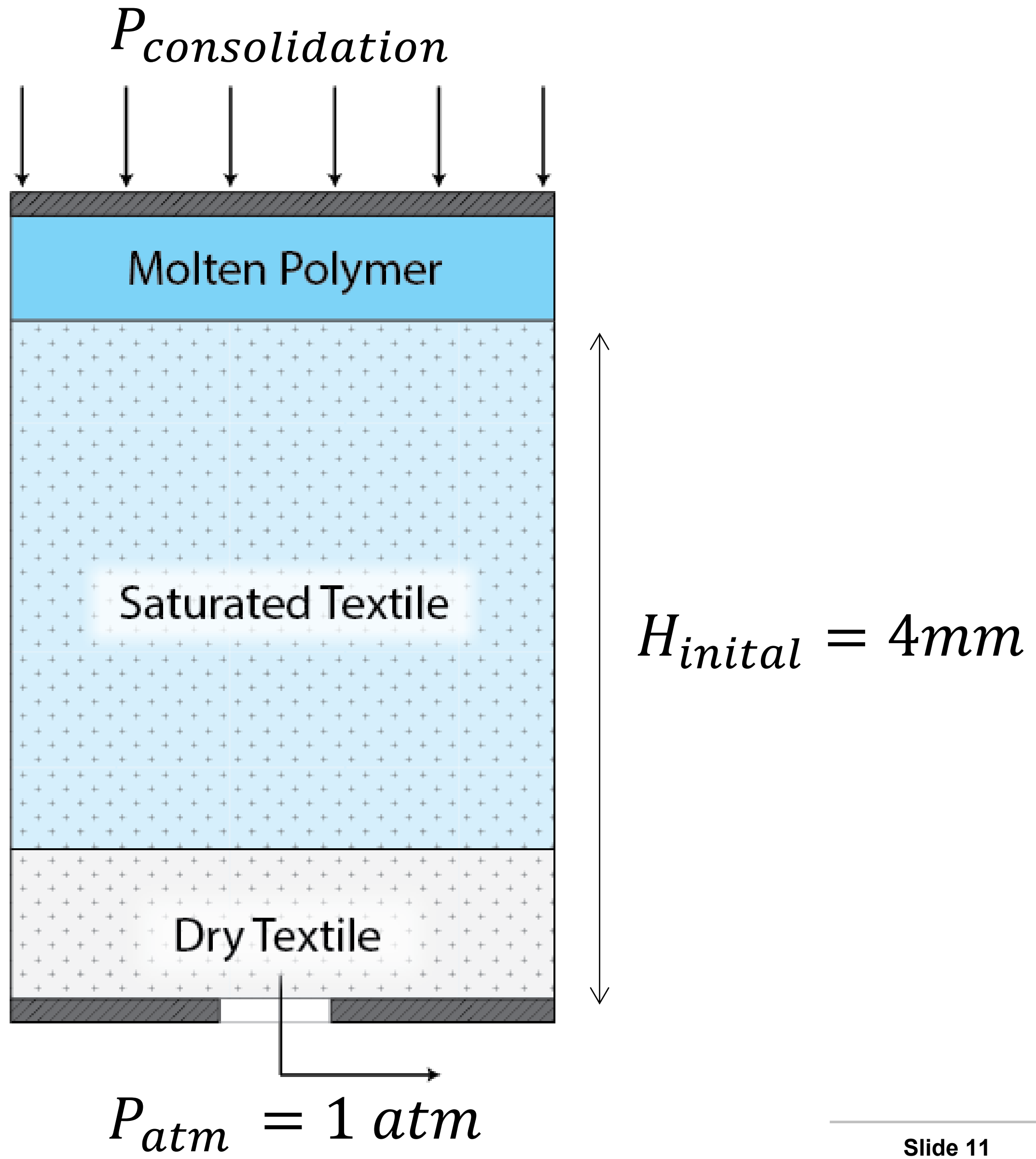
Inter-Tow Model

- Compressible porous textile stack
- Hydromechanically coupled
- Solved in terms of voids ratio (e) rather than fibre volume fraction

Voids Ratio

$$e = \frac{1 - \phi_s}{\phi_s}$$

Solid (fibre) volume fraction



Inter-Tow Model – Governing Equation

Transient Diffusion Equation Terms [1]

Fluid Flux between Inter-Tow and Intra-Tow Models

$$\frac{\partial e}{\partial t} = \frac{\partial}{\partial X}\left(D(e)\frac{\partial e}{\partial X}\right) + \frac{Q}{V_s}$$

Inter/Intra-tow Coupling Term

[1] J. Lee, et al. “**Transverse liquid composite moulding processes for advanced composites material manufacturing,**” Plastics, Rubber and Composites, v 51, n 8, p 373–382, 2022

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Inter/Intra-tow Coupling Term

$$D(e) = -\frac{1}{\mu}(1+e^0)^2\left[\alpha\frac{1}{1+e}K(e)\frac{\partial\sigma(e)}{\partial e}\right]$$

Polymer Viscosity

Inter-Tow Flow Scaling

Textile Stress/Strain Curve

Saturated Textile Permeability

Inter-Tow Flow Scaling Term

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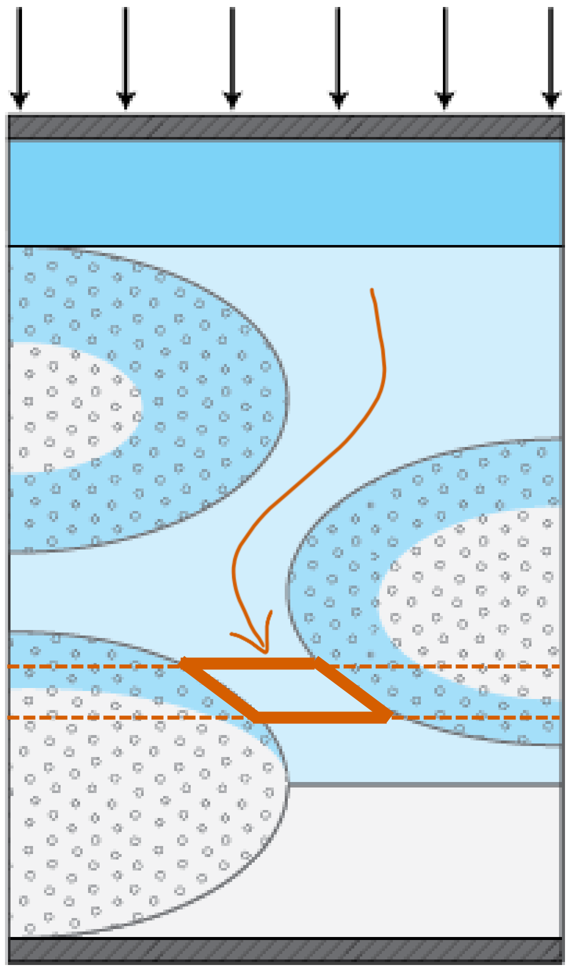
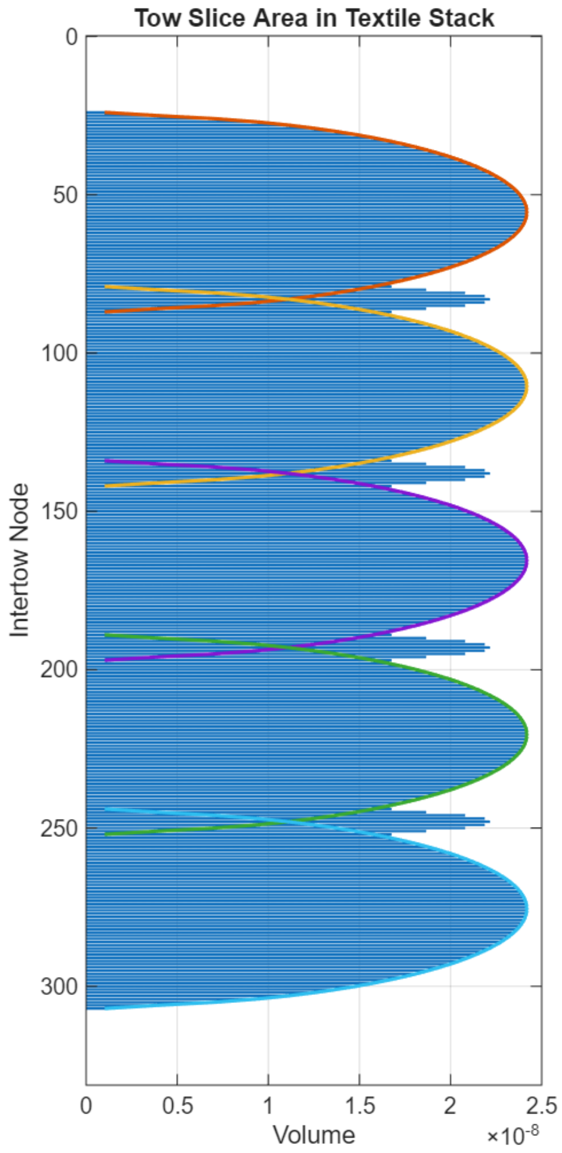
- Inter-tow area reduced due to tows
- Flow velocity locally increases due to reduced inter-tow area

(Right) Tow volume distributed through textile stack

Evaluated on an element-wise basis

$$\alpha = \frac{1}{\phi^{i}_{intertow}} = \frac{V^{i}_{element}}{V^{i}_{element} - V^{i}_{tow\ slice}}$$





Intra-tow Model

- 2D CVFEM method
- Elliptical tow geometry
- Edge nodes (red) are coupled to textile stack polymer pressure

Saturation

Flux between control volumes

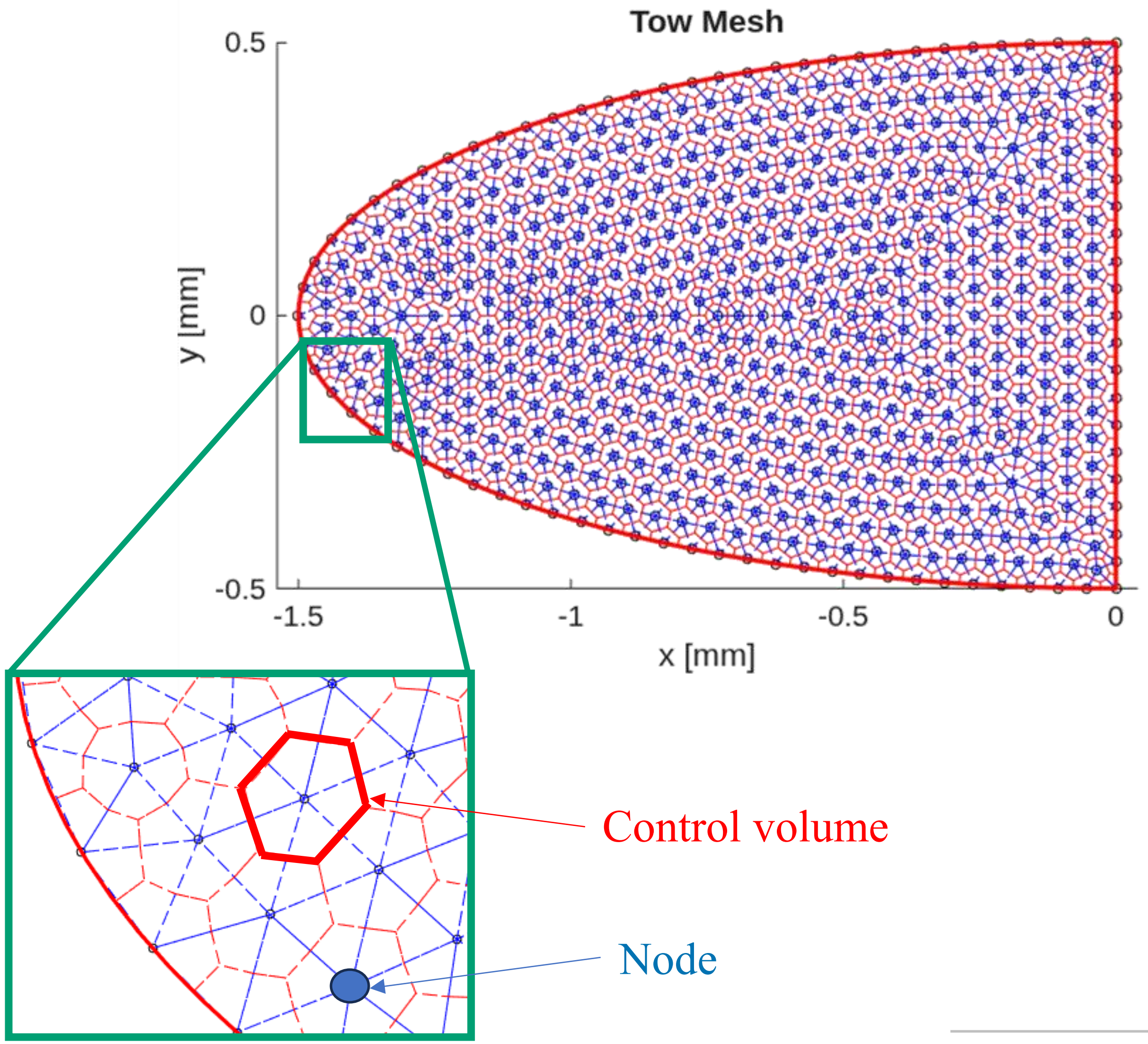
$$\Delta\psi_{CV} = \frac{Q_{CV}}{\phi\, V_{CV}}\Delta t$$

Timestep

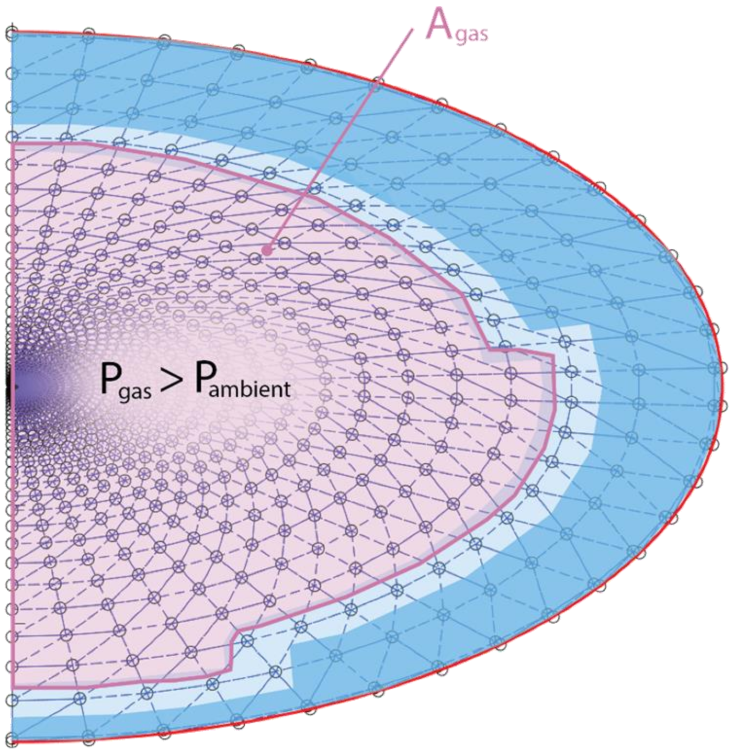
Porosity

Volume of control volume

$$\psi_{CV}(t+\Delta t) = \psi_{CV}(t) + \Delta\psi_{CV}$$



Gas bubbles become entrapped when polymer surrounds the tow's perimeter



Gas Moles

$$P_{gas}(t) = \frac{n(t)RT}{A_{gas}(t)}$$

Length of Flow Front Perimeter

Diffusion Coefficient

Correction Factor

$$\dot{n} = -L_{FlowFront} DG(C_S - C_\infty)\left(1 + \frac{1}{\sqrt{\pi DGt}}\right)$$ [2]

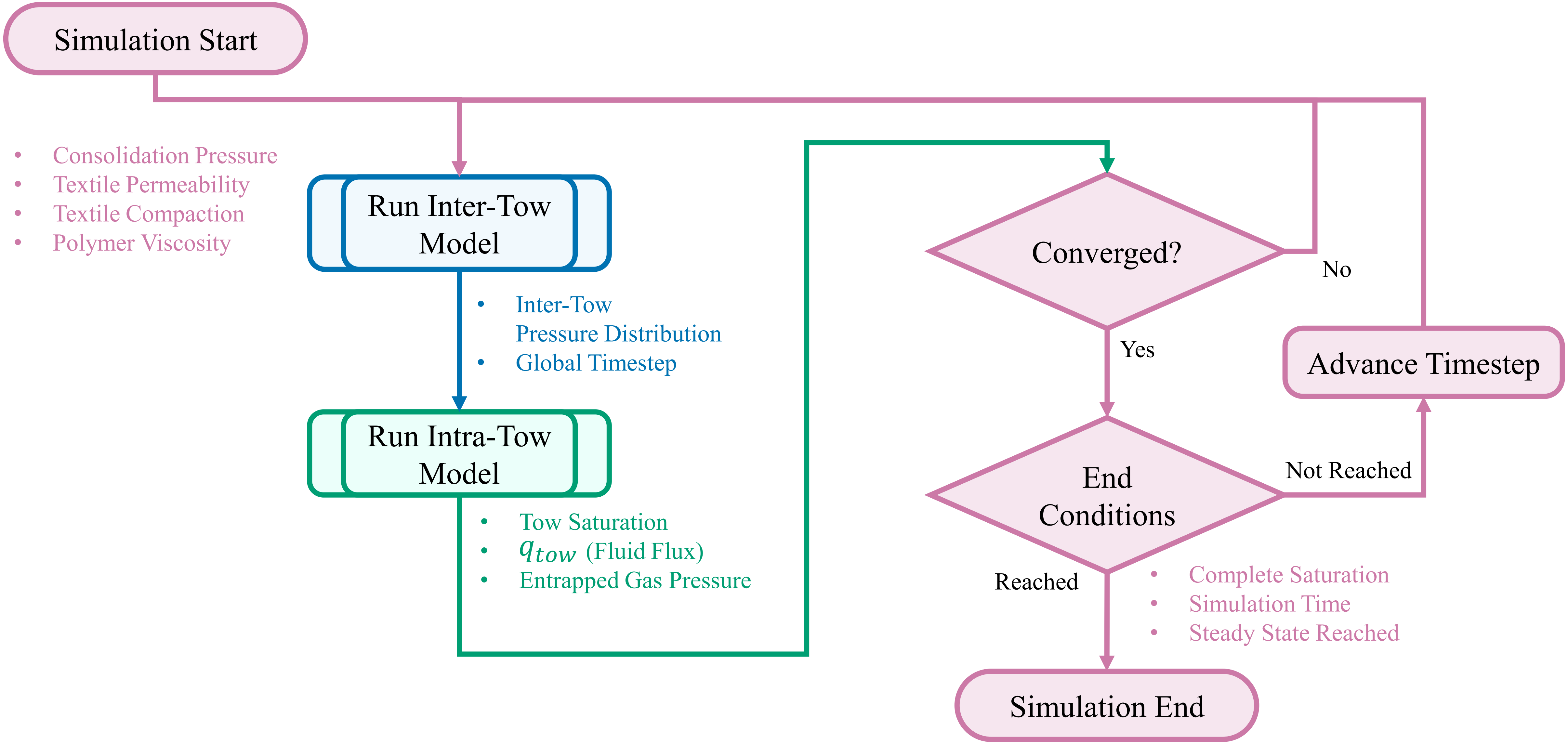
Saturation of gas in polymer at interface

Time

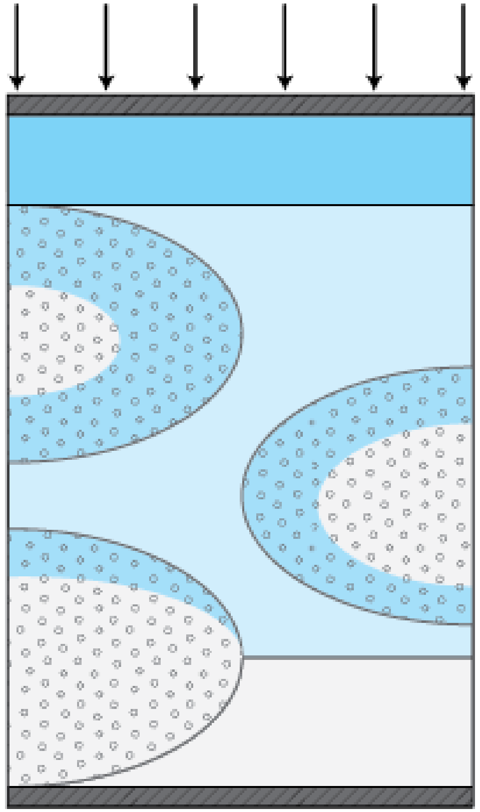
Saturation of gas in polymer at atmospheric pressure

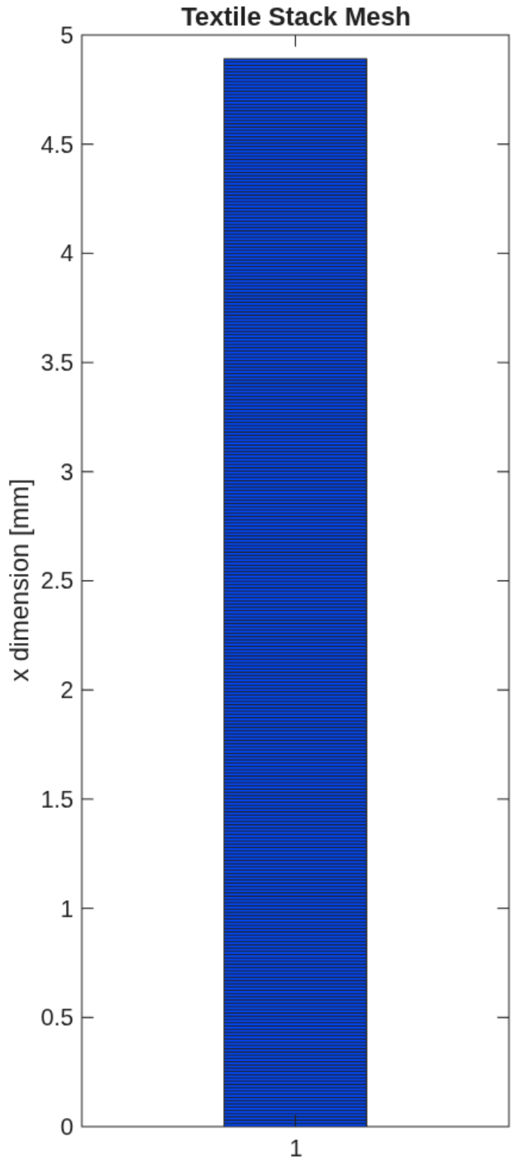
[2] V. Werlen, et al. "**A model for the consolidation of hybrid textiles considering air entrapment, dissolution and diffusion,**" Composites Part A: Applied Science and Manufacturing, v 166, p 107413, 2023

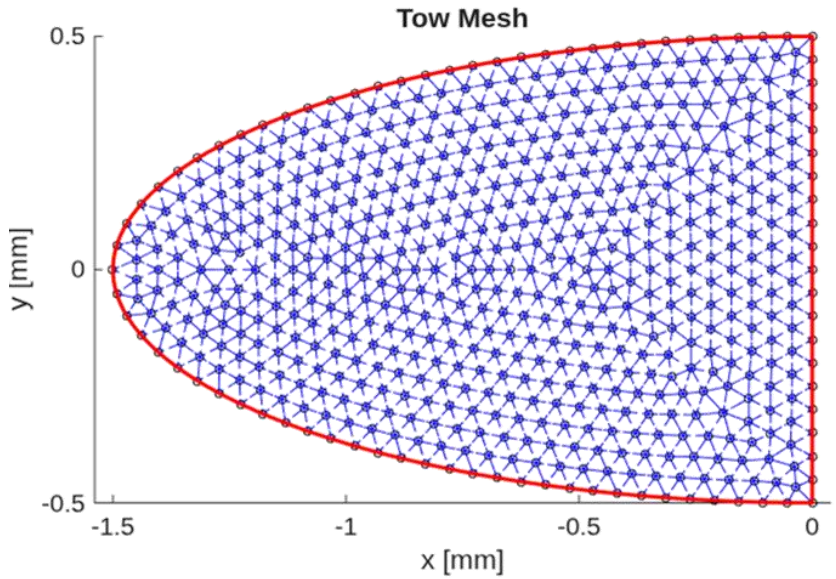
Simulation Procedure Overview



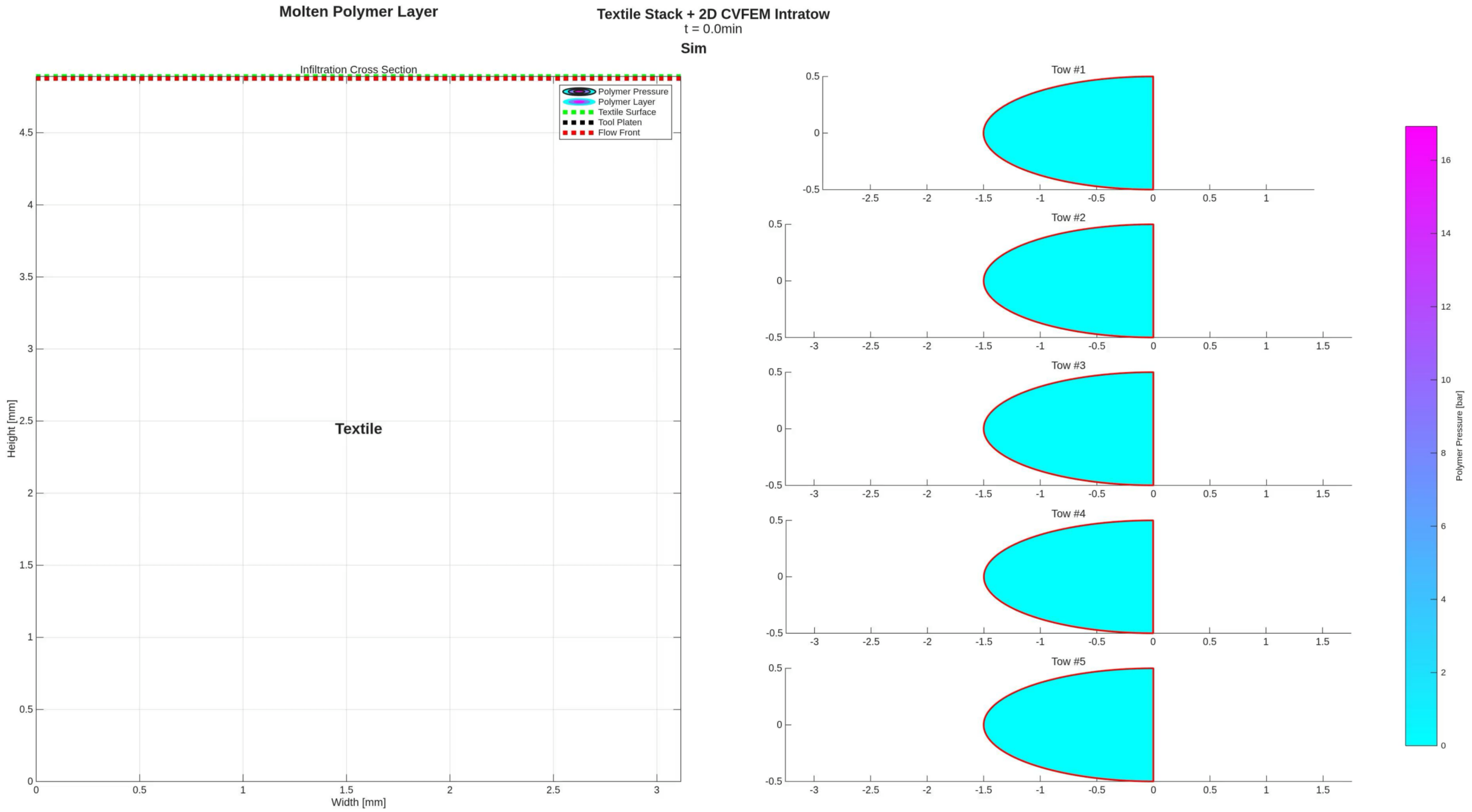
Simulation Example

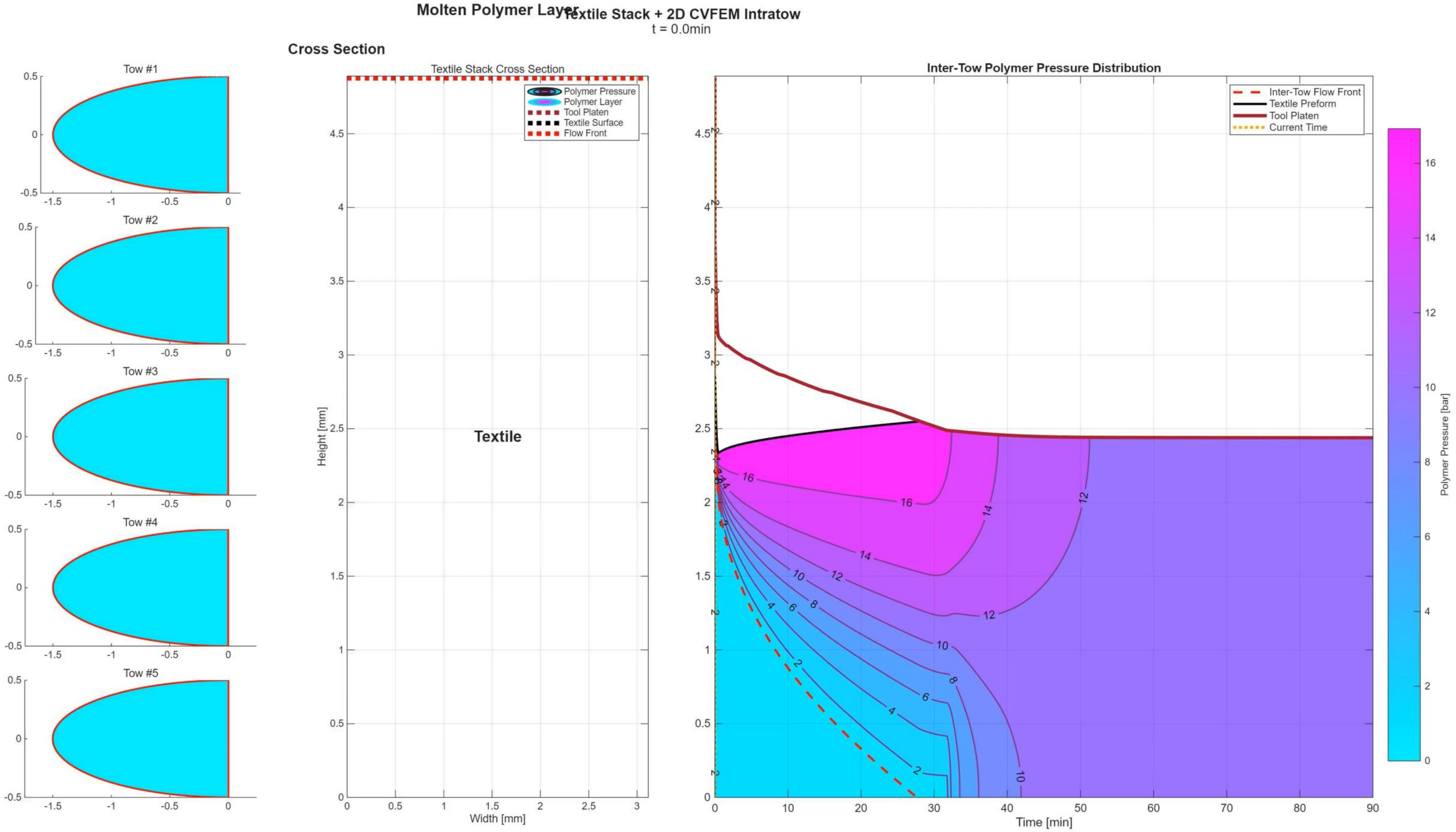






- 5 layers Saertex 444 GSM NCF
- Ultramid B3S (Nylon PA6)
- Temperature = 270C
- Pressure = 16 bar
- No vacuum assistance

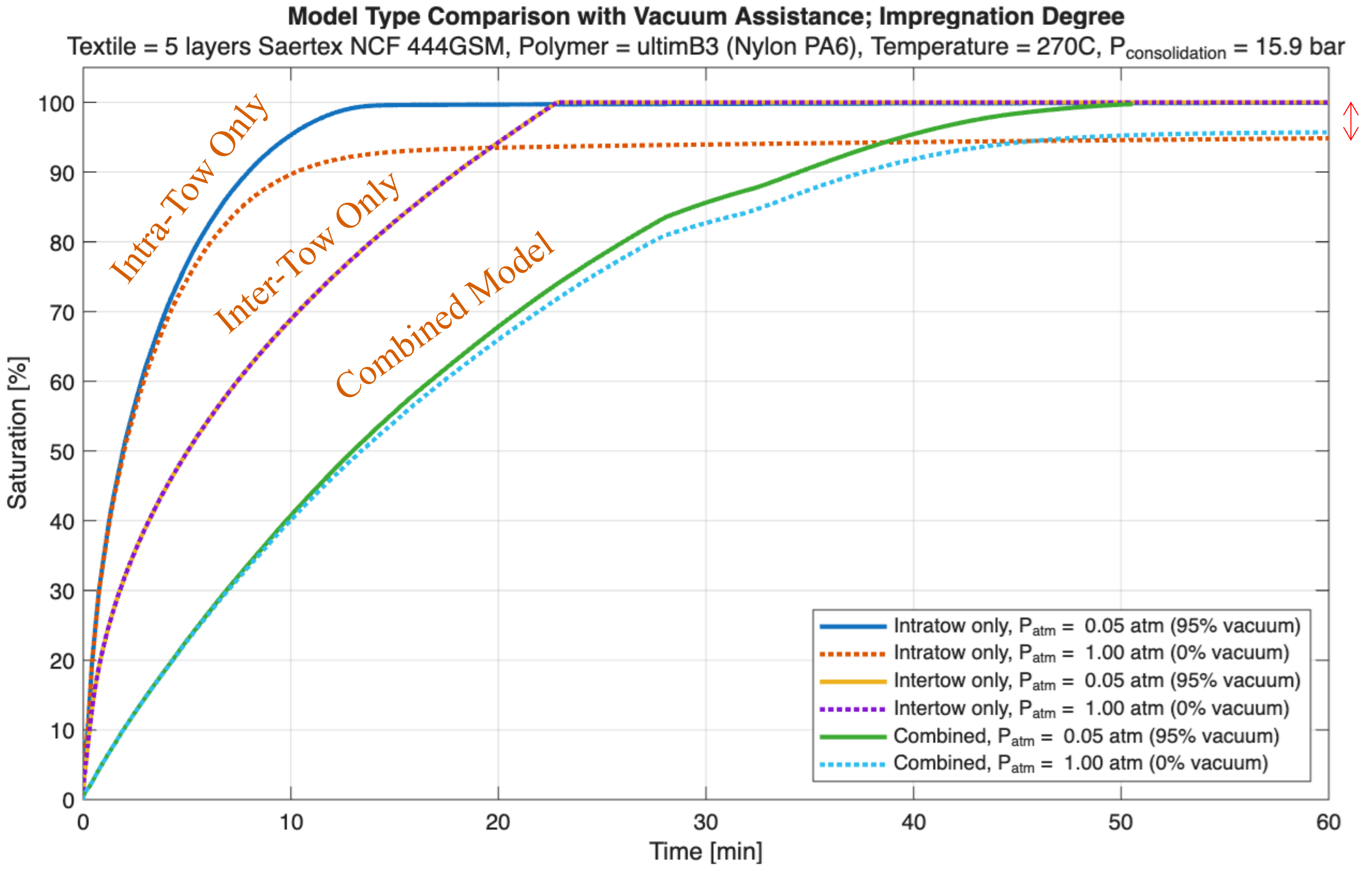

Molten Polymer Layer
Textile Stack + 2D CVFEM Intratow
t = 0.0min
Sim
Infiltration Cross Section
Polymer Pressure
Polymer Layer
Textile Surface
Tool Platen
Flow Front
Textile
Height [mm]
Width [mm]
Tow #1
Tow #2
Tow #3
Tow #4
Tow #5
Polymer Pressure [bar]



Molten Polymer Layer
Textile Stack + 2D CVFEM Intratow
t = 0.0min
Cross Section
Tow #1
Tow #2
Tow #3
Tow #4
Tow #5
Textile Stack Cross Section
Polymer Pressure
Polymer Layer
Tool Platen
Textile Surface
Flow Front
Textile
Height [mm]
Width [mm]
Inter-Tow Polymer Pressure Distribution
Inter-Tow Flow Front
Textile Preform
Tool Platen
Current Time
Time [min]
Polymer Pressure [bar]

Comparison of Models

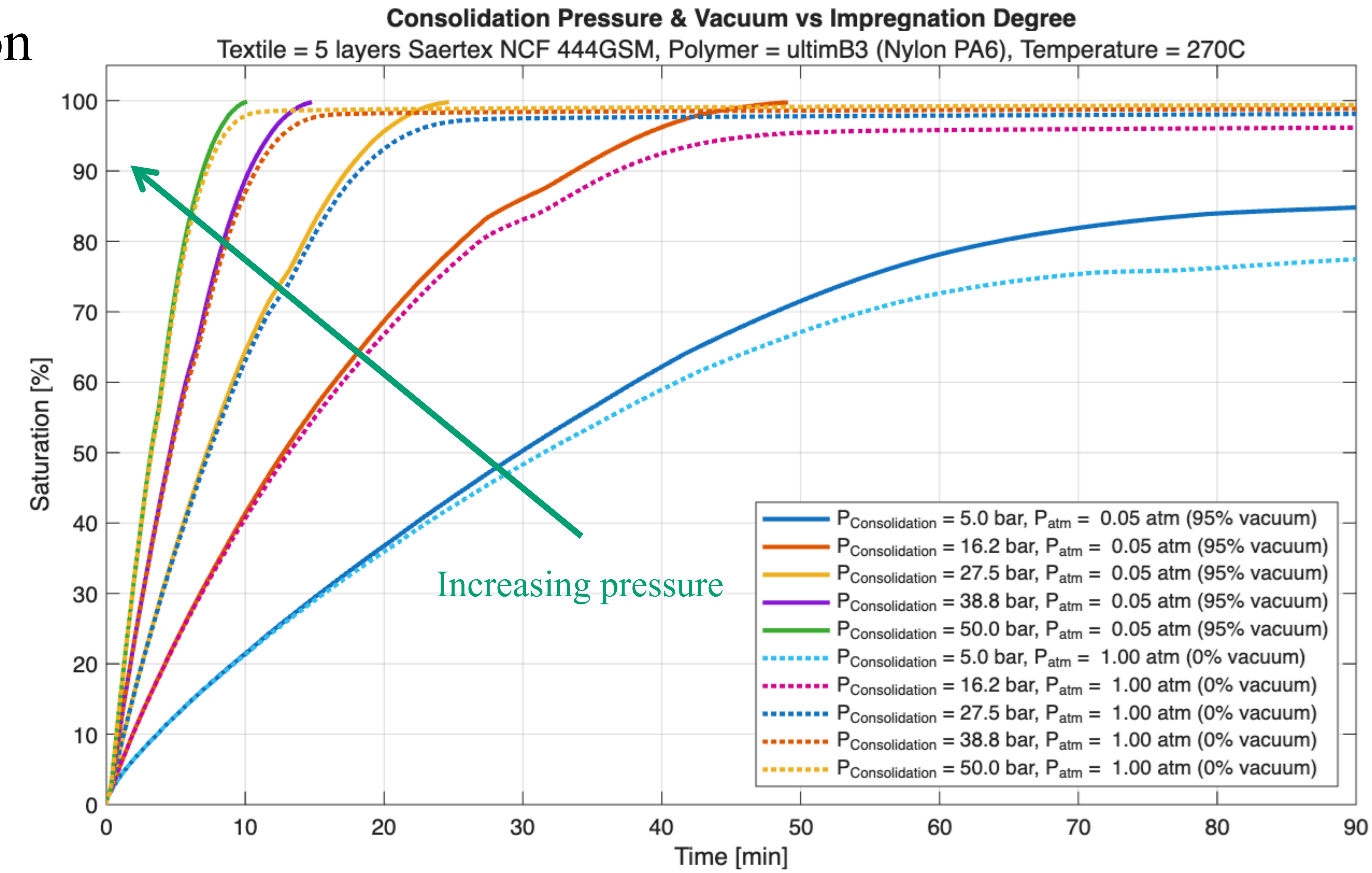
- Vacuum assistance removes voids in tows
- Both "Intra/Inter-Tow only" models estimated a much faster impregnation rate
- "Inter-Tow only" model does not predict any voids
- Steady state impregnation degree of "intra-tow only" and "combined model" is very similar



Parameter Sweep – Consolidation Pressure

Increasing consolidation pressure:

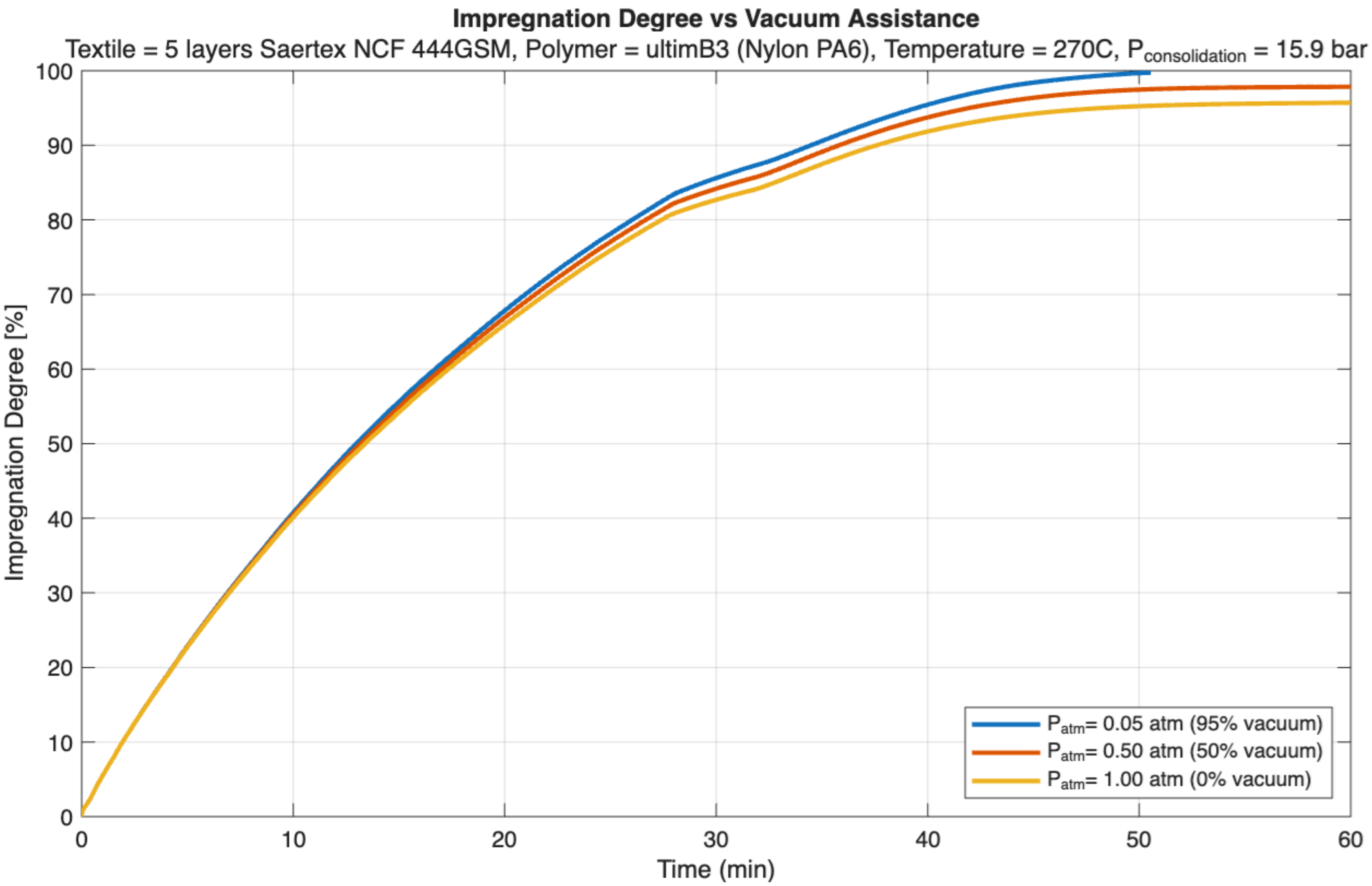
- Improves impregnation rate
- Improves steady state impregnation degree (without vacuum assistance)



Parameter Sweep – Vacuum Assistance

Changing level of vacuum assistance:

- Minimal impregnation rate change
- Primary effect is on steady state impregnation degree

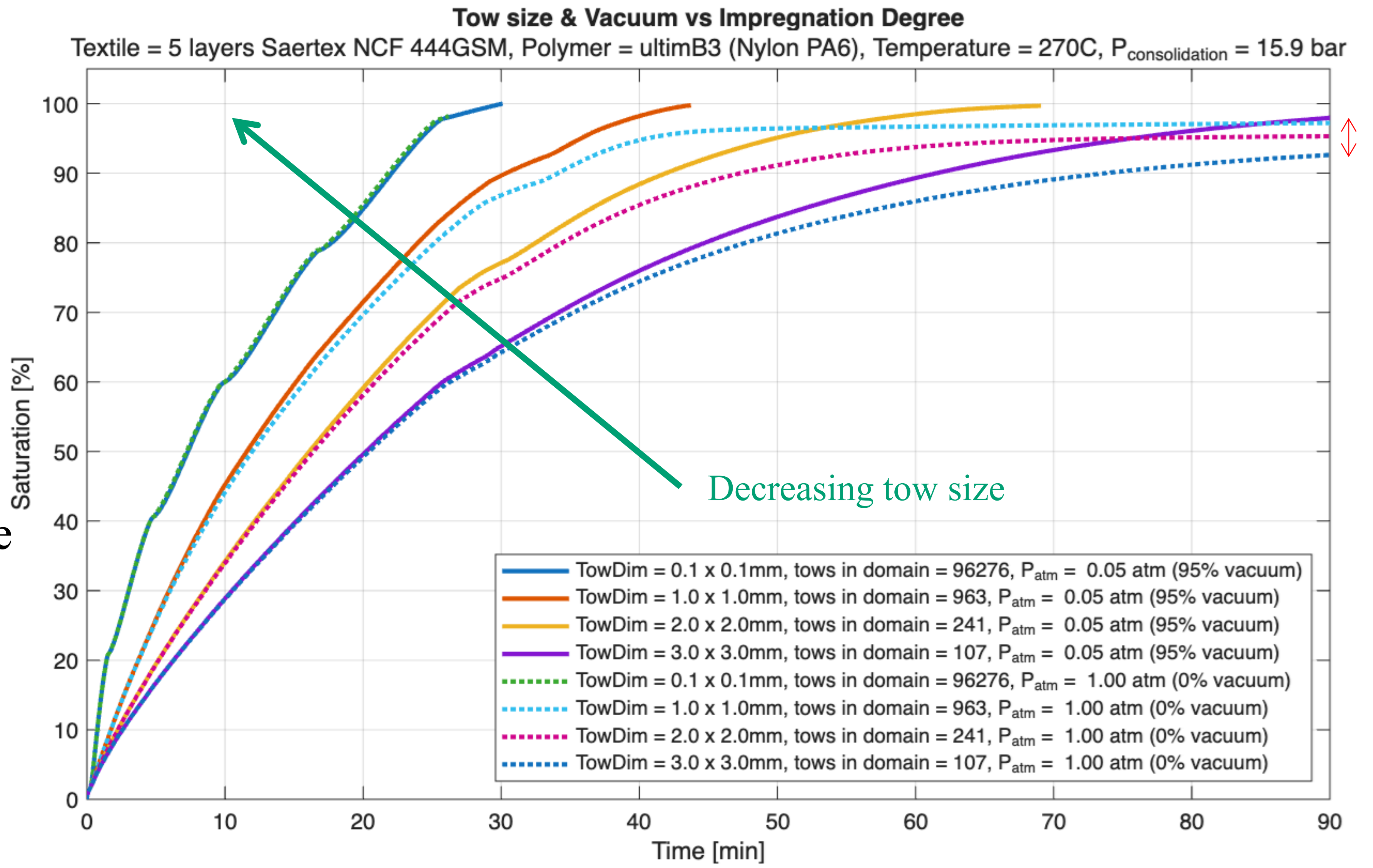


Parameter Sweep – Tow Size

Changing (circular) tow dimensions:

- Normalised textile areal weight
- Constant through thickness permeability

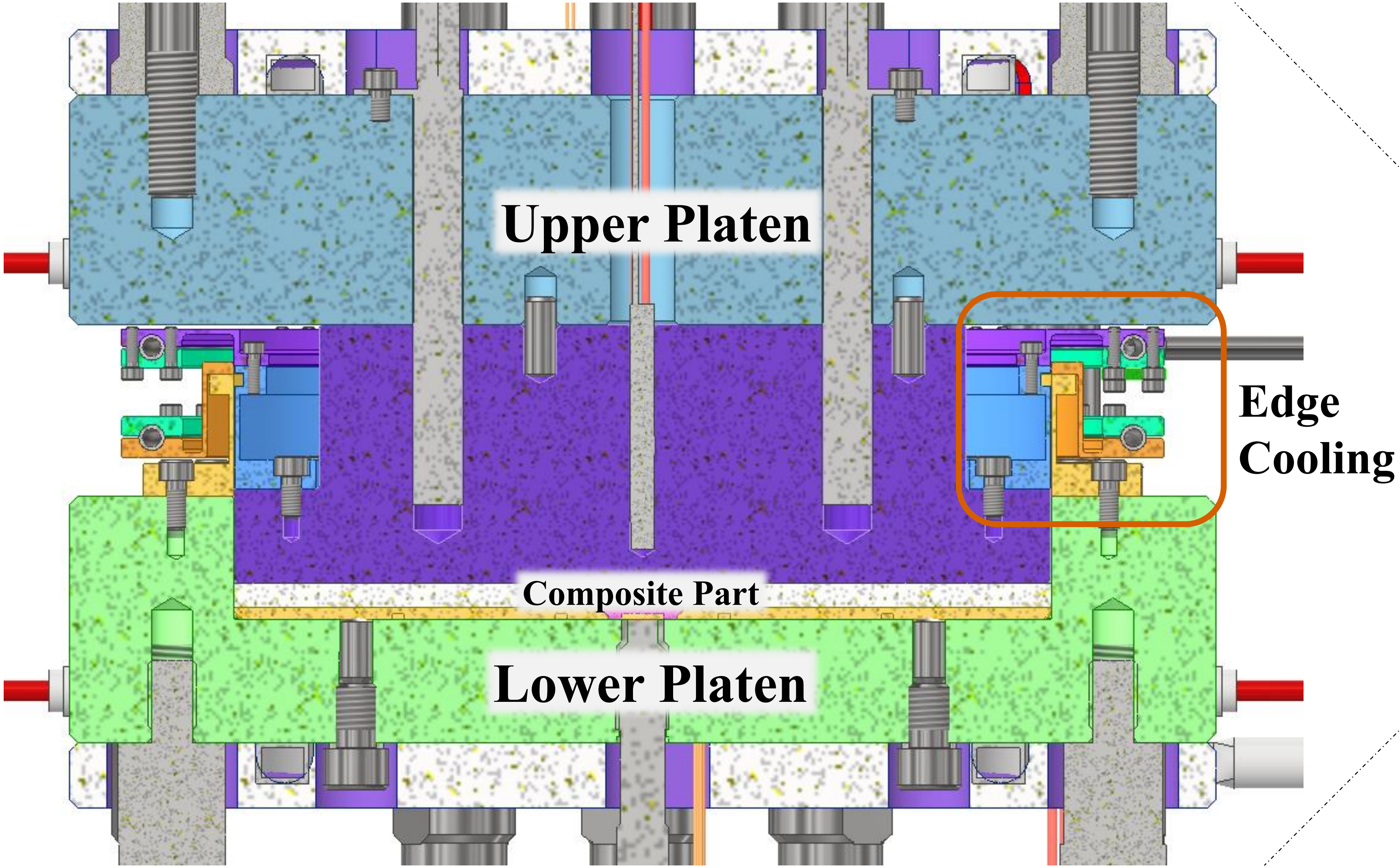
- Smaller tows have improved impregnation rate
- Smaller tows have an improved steady state impregnation degree (without vacuum assistance)

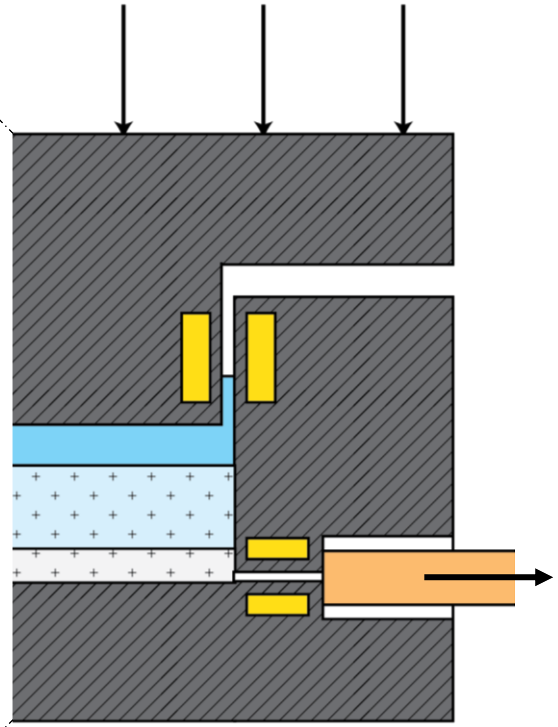


Modelling Summary

- Consolidation pressure significantly affects impregnation rate
- Vacuum assistance is predicted to significantly improve impregnation degree
- Tow size significantly impacts the impregnation rate and influences the steady state impregnation degree without vacuum assistance

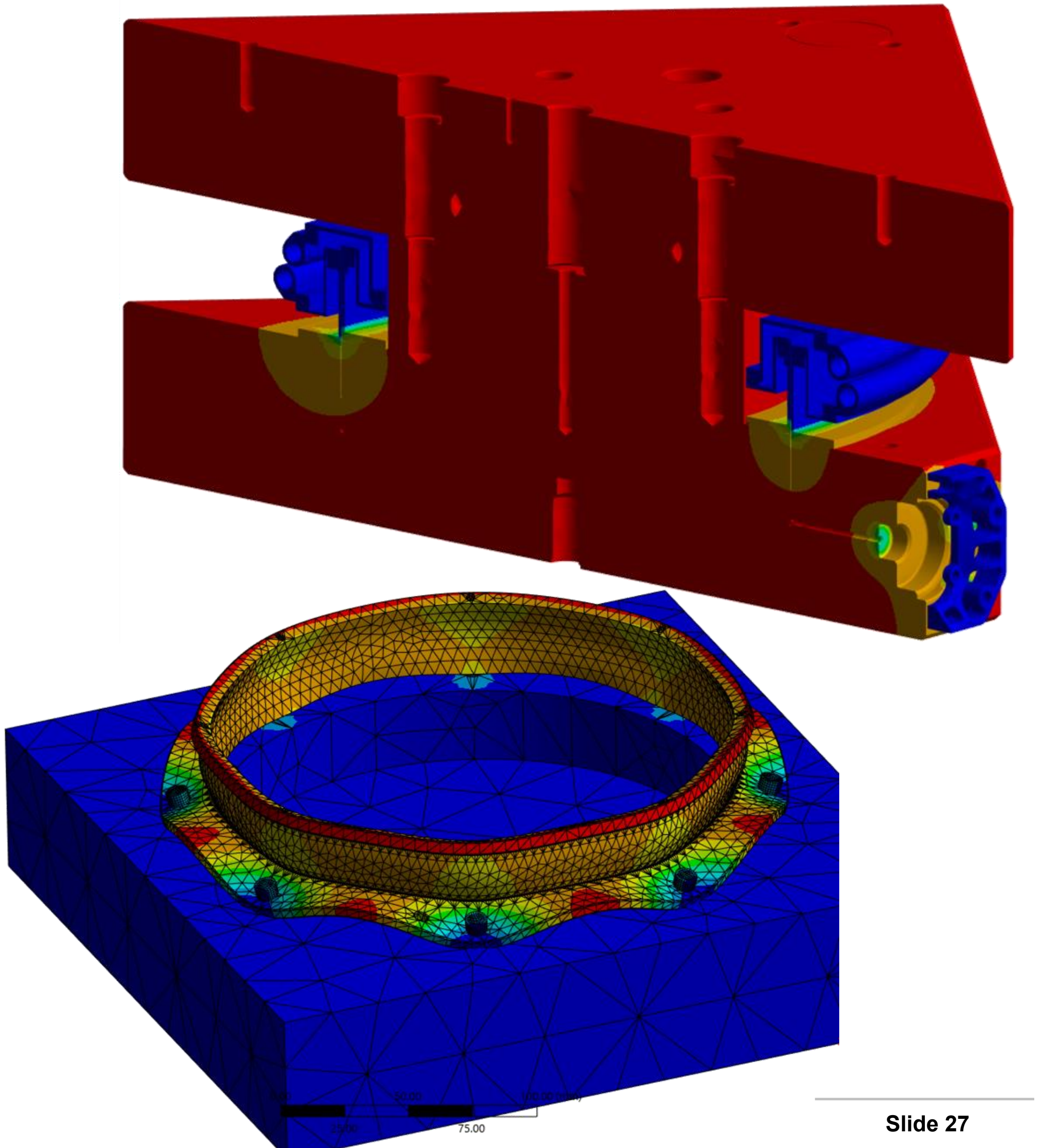
Equipment Overview



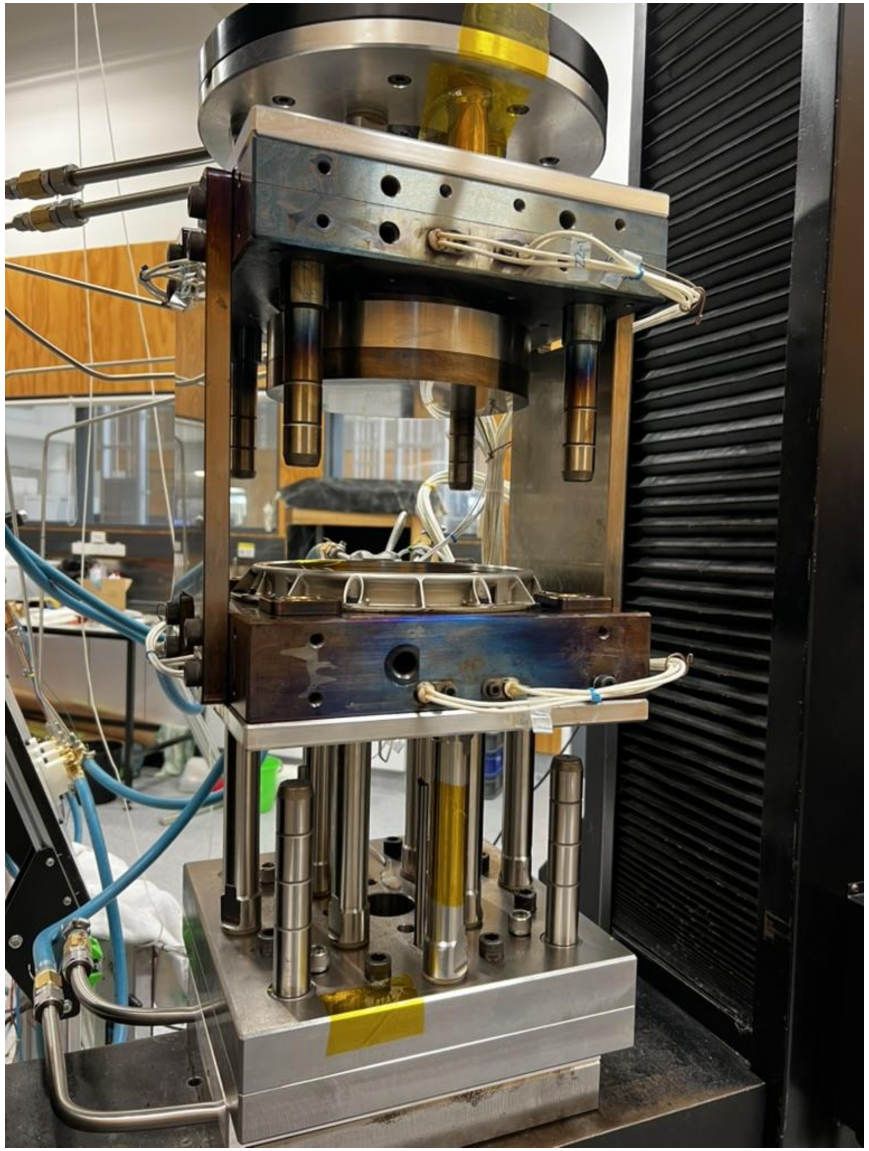


Challenges during Equipment Commissioning

- Mould platen and flange joint stiffness
- Vario-thermal expansion
- Thermal isolation of edge cooling and mounting structure
- Mould platen temperature uniformity
- Edge gap extrusion prevention
- Multiple (four) independently controlled heating zones
- Custom automated controller for sensor and actuator management

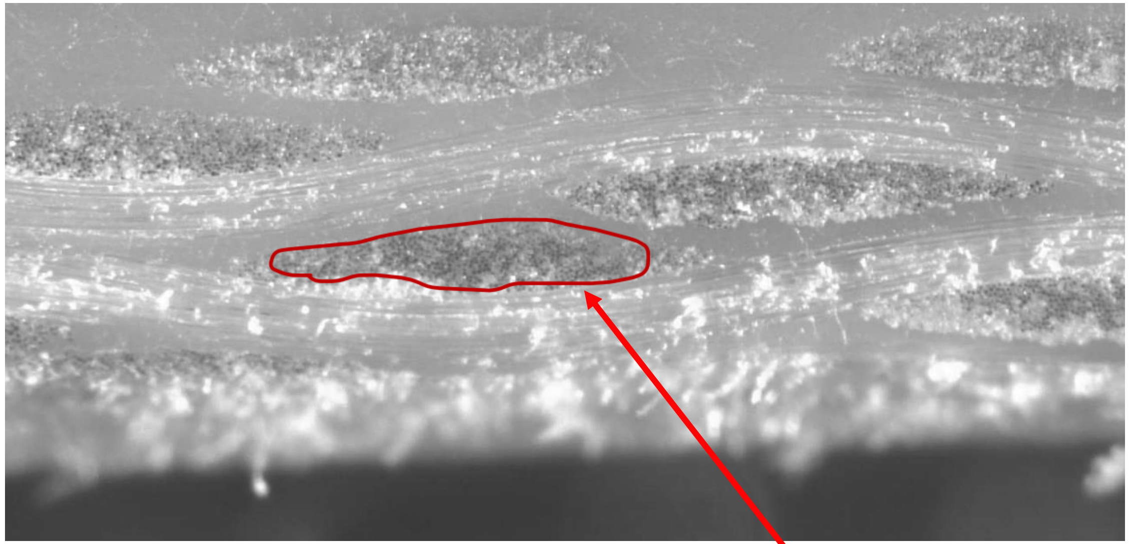


Equipment

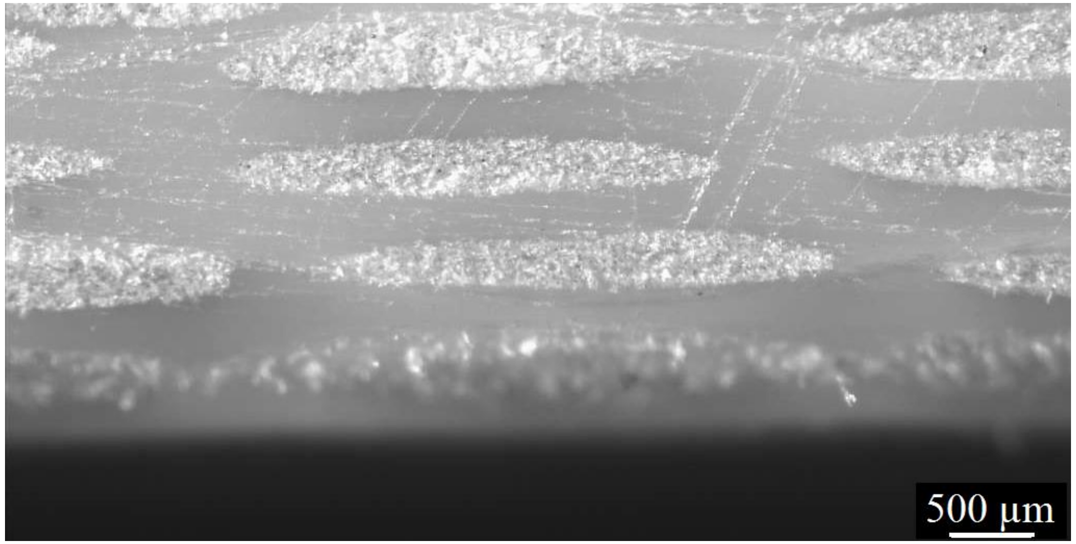


Hot off the press (Instron)!

Experimental results of vacuum assistance during impregnation



Without Vacuum void



Vacuum assistance applied

5 layers 290 GSM glass plain weave, PA6 Nylon @ 1.6 MPa, 270C for 1 hr

Conclusions

- Developed a numerical model for simulating the impregnation of a woven compressible thermoplastic melt composite
  - Deformable textile stack
  - Hydromechanical textile compaction
  - Coupled fluid/pressure transfer between inter/intra-tow domain
- Explored simulation parameters
  - Consolidation pressure significantly affects impregnation rate
  - Vacuum assistance significantly improves impregnation degree
  - Tow size significantly impacts the impregnation rate
- Early experimental results within new tool indicate complete impregnation when using vacuum assistance
- With commissioning nearly complete, will complete textile characterisation, and create detailed experimental datasets for model validation