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Encapsulation and Porous Imbibition Models of Curing Epoxy

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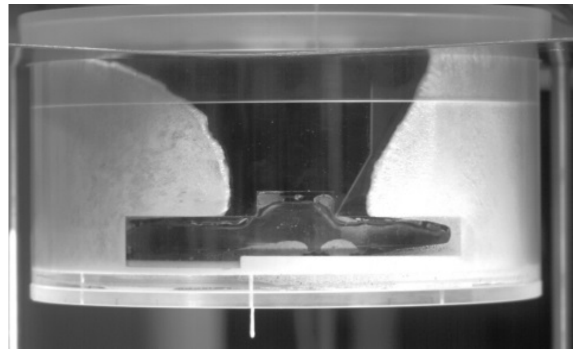
Motivation

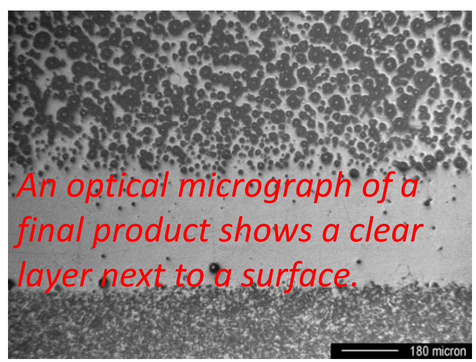
- Purpose: Protecting electronic parts from shock and vibration
- Achieved with thorough infiltration of encapsulants – complete coverage is key

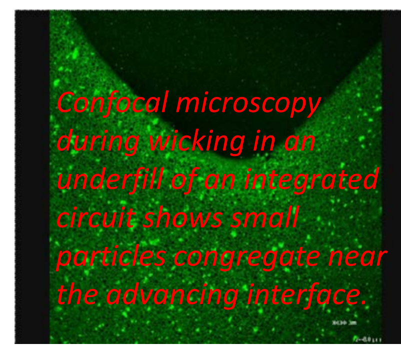
https://www.masterbond.com/tds/ep17ht-100



Foam encapsulation

- Typical defects: Voids, cracks, delamination, fillers migration – need to detect it





Use numerical modeling to predict the extent of infiltration

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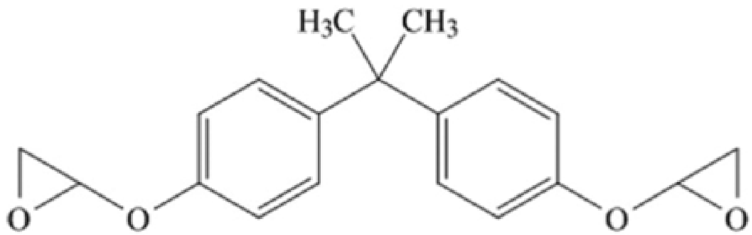
Material Description – Encapsulant

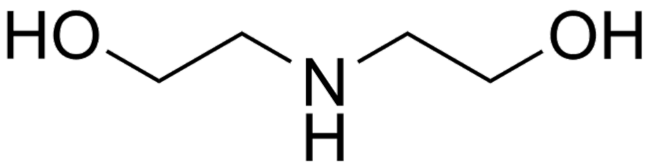
Epoxy resin

Epon™ 828 – Diglycydyl Ether of Bisphenol A



Curing Agents

Diethanol-amine – DEA

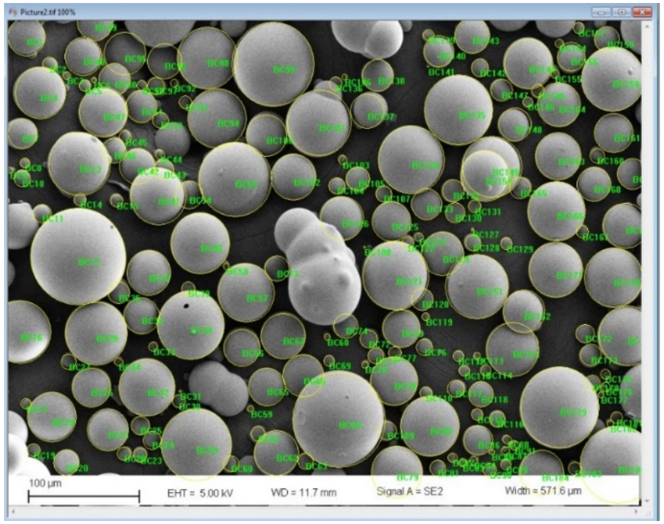


The combination is chosen for its desired mechanical and dielectric properties

Filler

Glass micro-balloons – GMB

Filler is added to made the material lighter, softer and more compressible



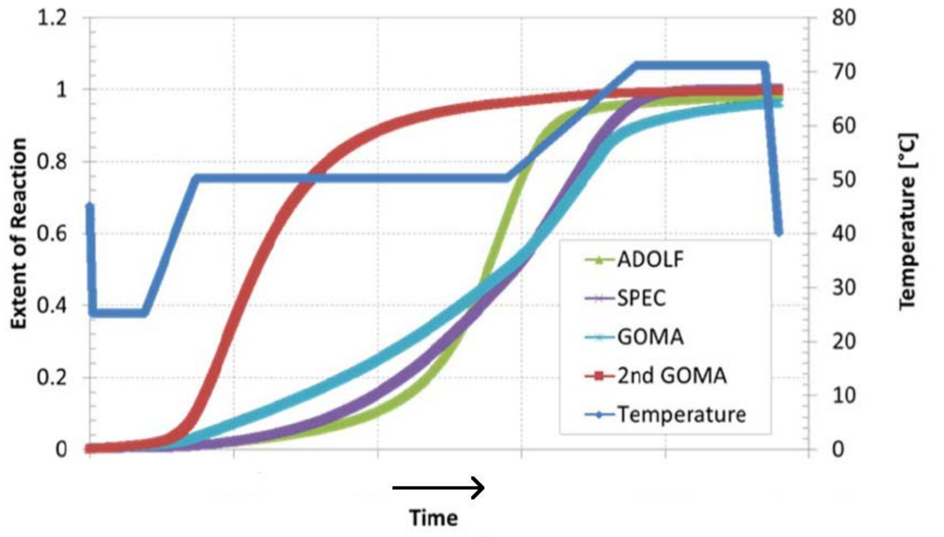
The material is engineered for performance and processing condition

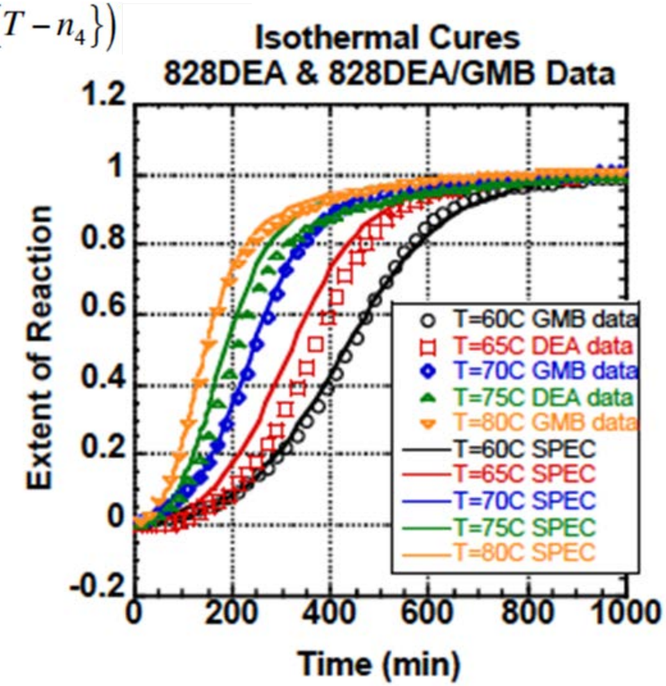
Curing Kinetics

- ***Exothermic reaction*** → heat of reaction can be determined with Differential Scanning Calorimetry (DSC) during isothermal cure
- Extent of reaction is determined by ***integrating heat flow***
- Various kinetic models fit to data (Epon™ 828 cured with DEA): SPEC model best fit with and without added GMB

$$\frac{dx}{dt} = \frac{k_o \exp(-E_a/RT)}{(1+wa_{shift})^{\beta}}(b+x^m)(1-x)^n$$

$$n = n_1 + n_2 \tanh(n_3\{T-n_4\})$$

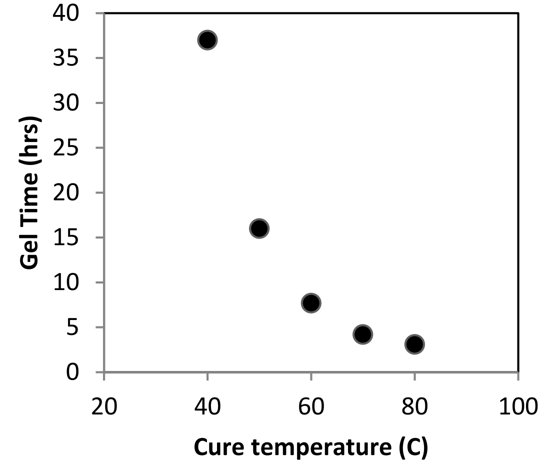


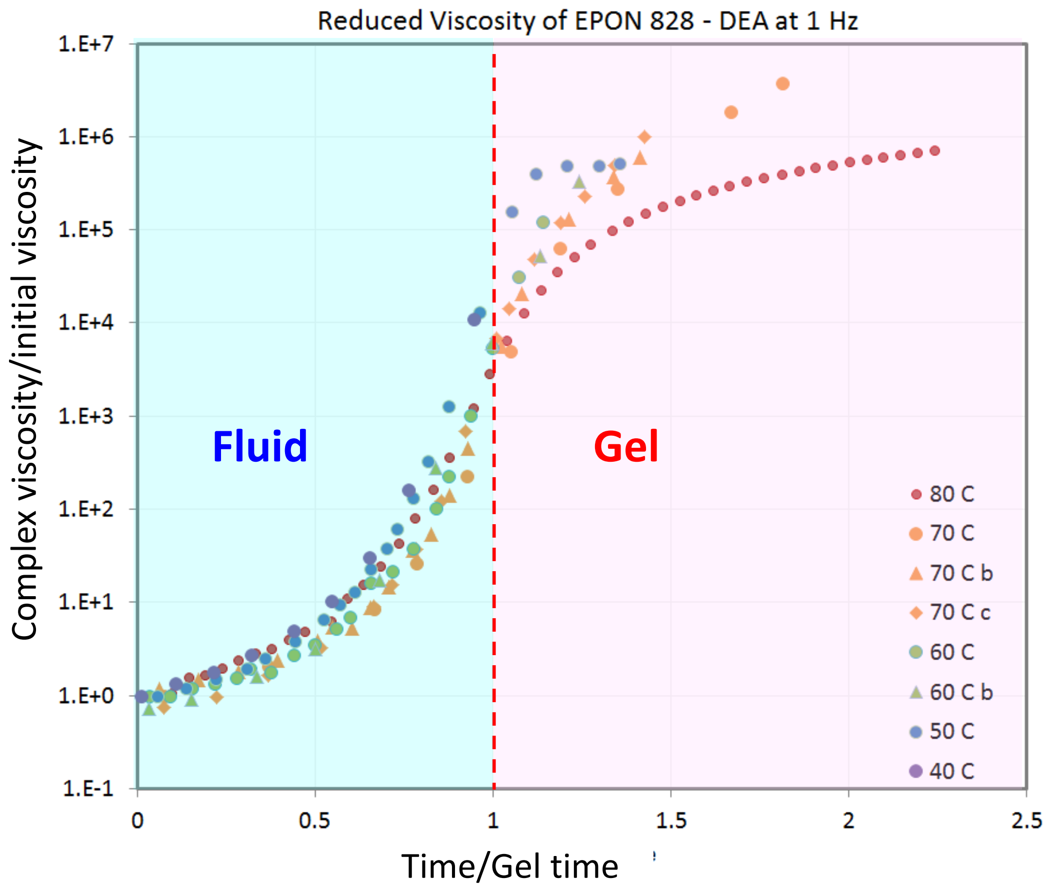


As curing progresses toward gel point, viscosity rises

Viscosity Rise During Cure

Measured with ARES rheometer using disposable parallel plates (25mm). Isothermal experiment
Challenging due to length of time for experiments, sudden high stresses at cure

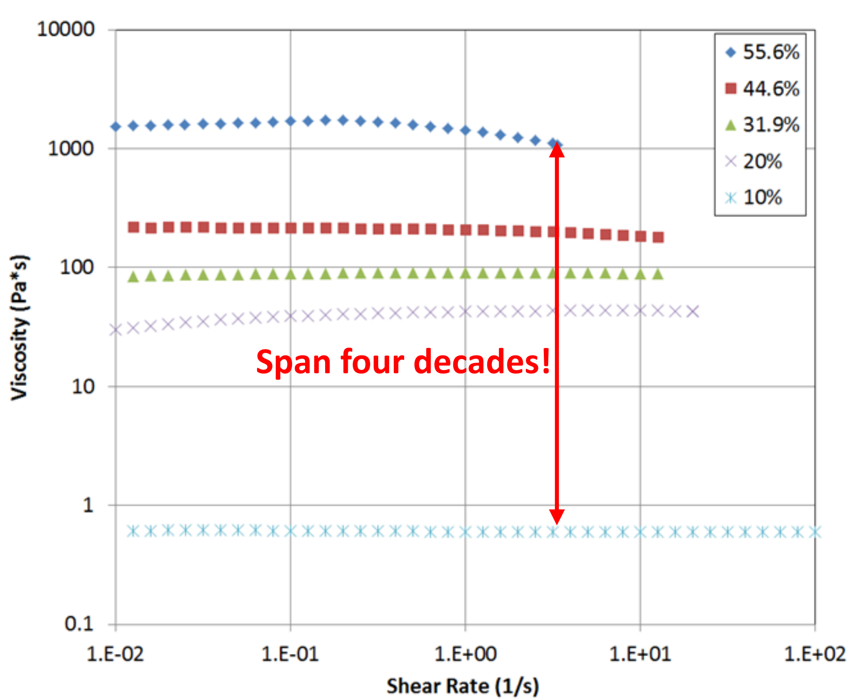




- Modulus vs. frequency collected at each time point throughout cure
- Initial viscosity and final shear modulus are both ***dependent on cure temperature***
- Collapse of data when ***scaled by gel time and initial viscosity*** at that temperature.

GMB Particles Effect

Measured vs. shear rate using AR-G2 rheometer, double gap cylinder geometry – *particle migration less of a concern than cone-on-plate geometry*



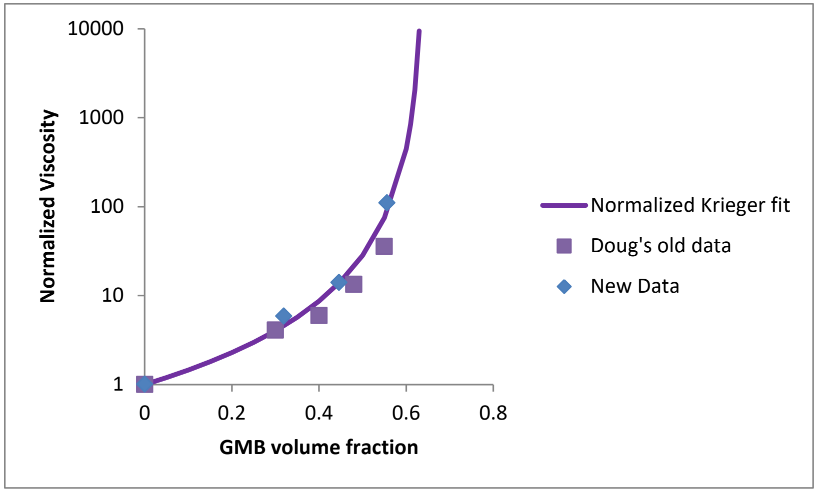
Epon + GMB

No shear-rate dependence!

Parameters for New Krieger model
ϕ_{max}= 0.64
n= 2.2

$$\eta = \eta_0 \left(1 - \frac{\phi}{\phi_{max}}\right)^{-n}$$

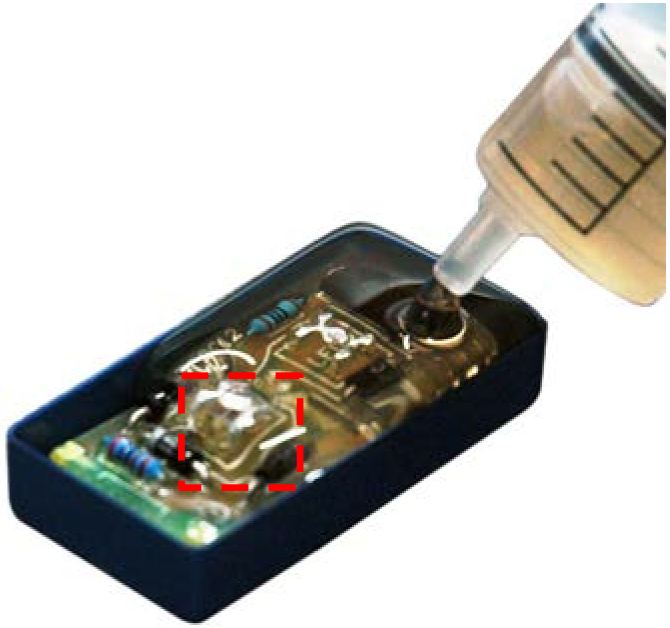
In model η_0 is taken to be the curing continuous phase viscosity

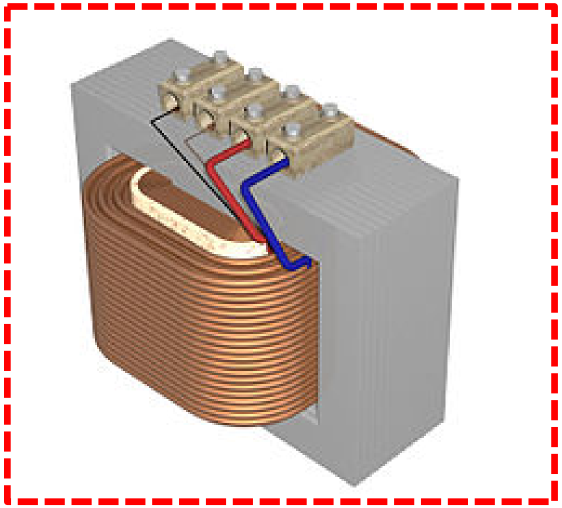


Old data on parallel plates compared to new in the double gap cylinder. Little if any effect of slip.

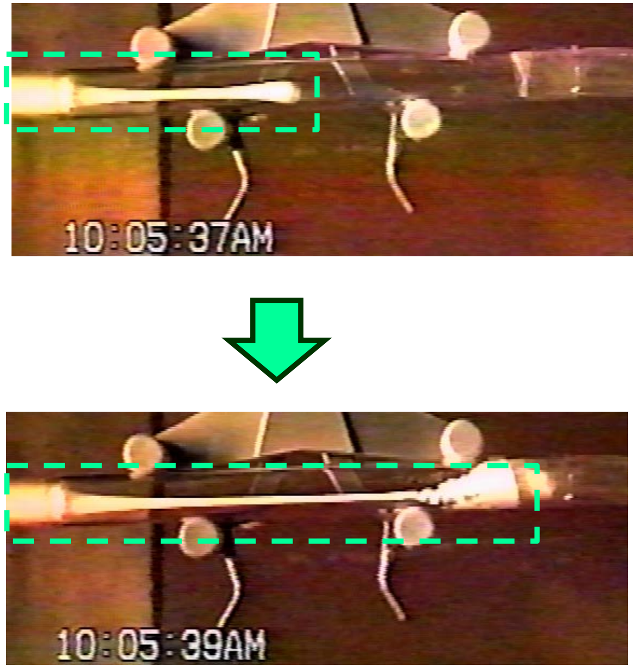
Target of Encapsulation: Winding

Encapsulation of electronic circuits





https://en.wikipedia.org/wiki/Transformer

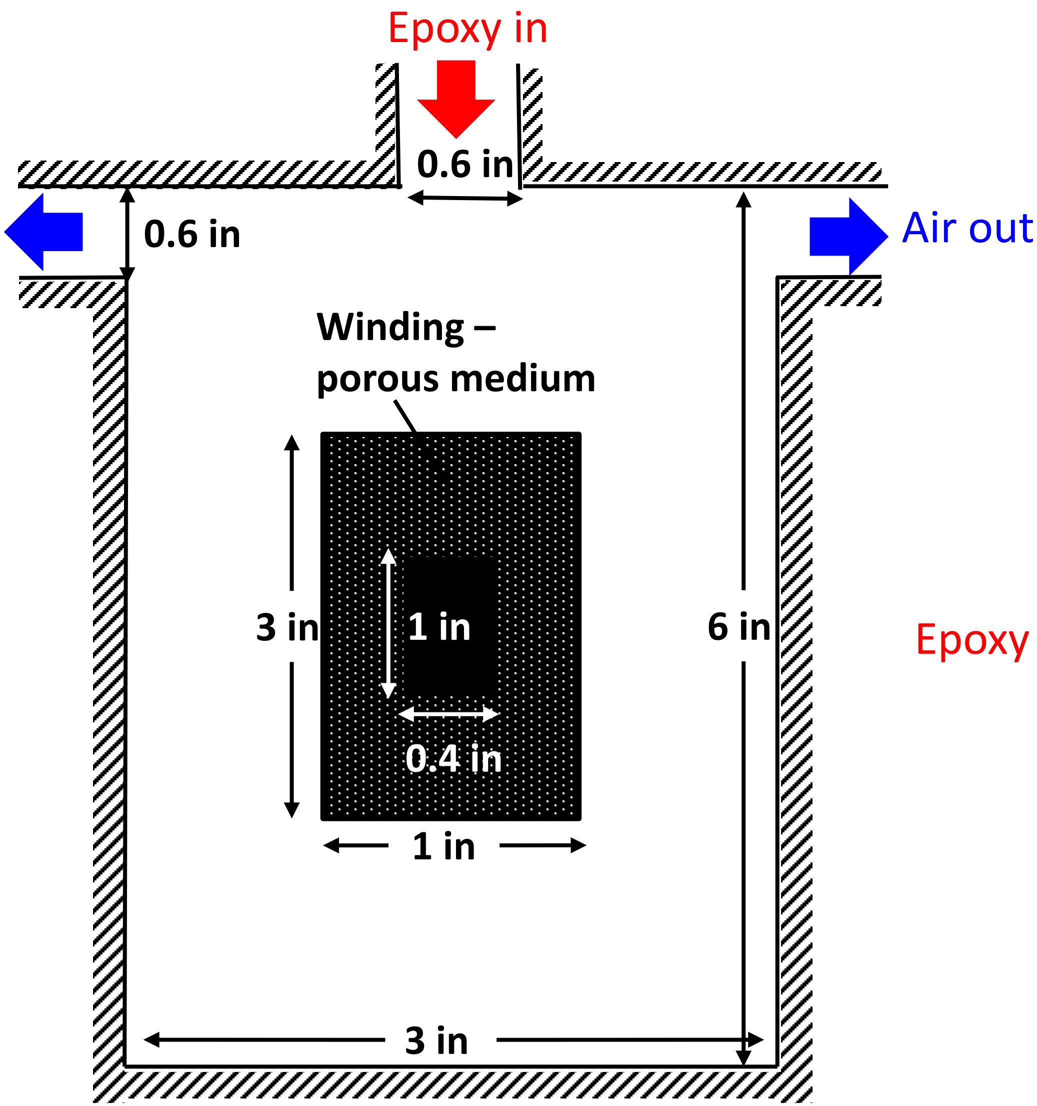


http://www.electrolube.org/technical-articles/2013/09/27/resins-for-potting-and-encapsulation/

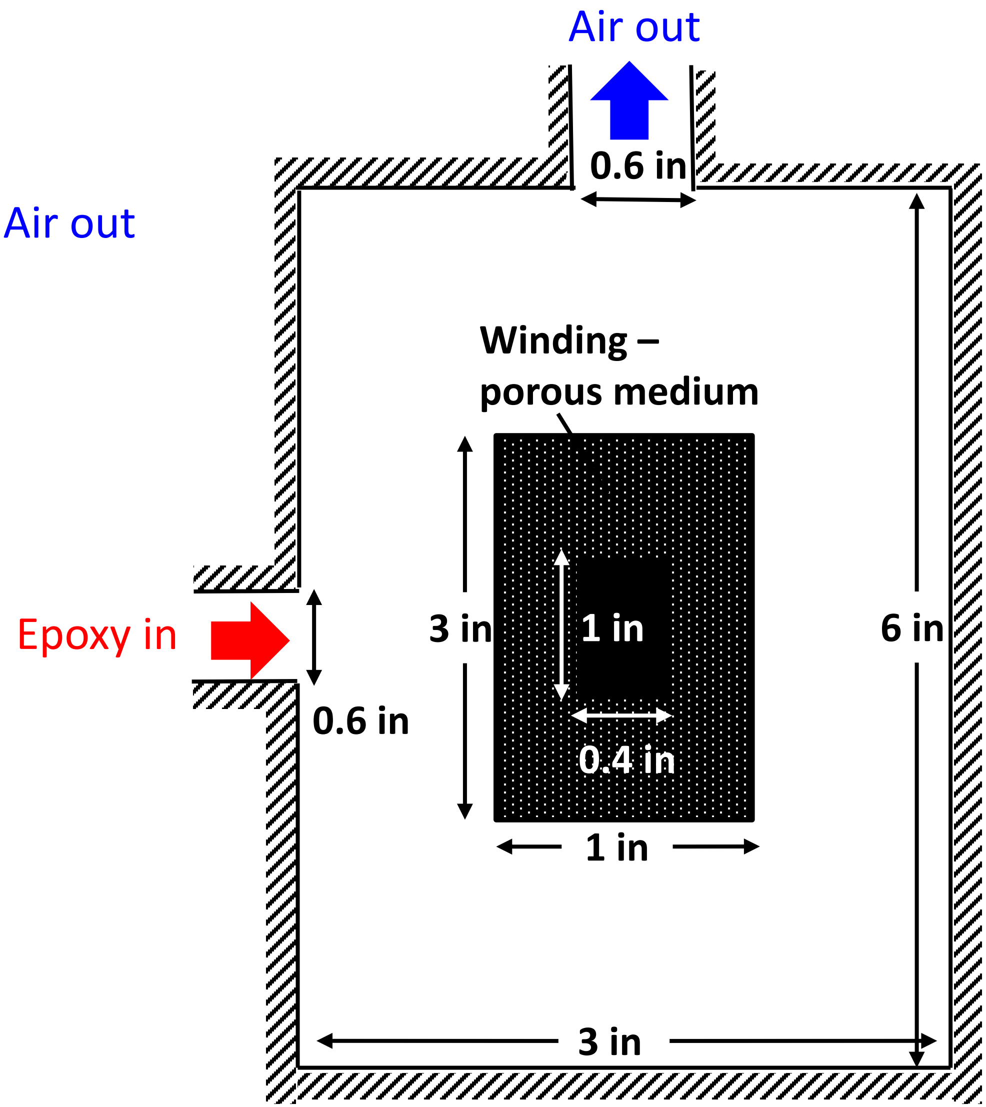
- ***The container with the transformer to be filled with curing epoxy***
- ***The model will not resolve flow in small features – approximate as porous medium***

Two Proposed Processes – Model Geometry

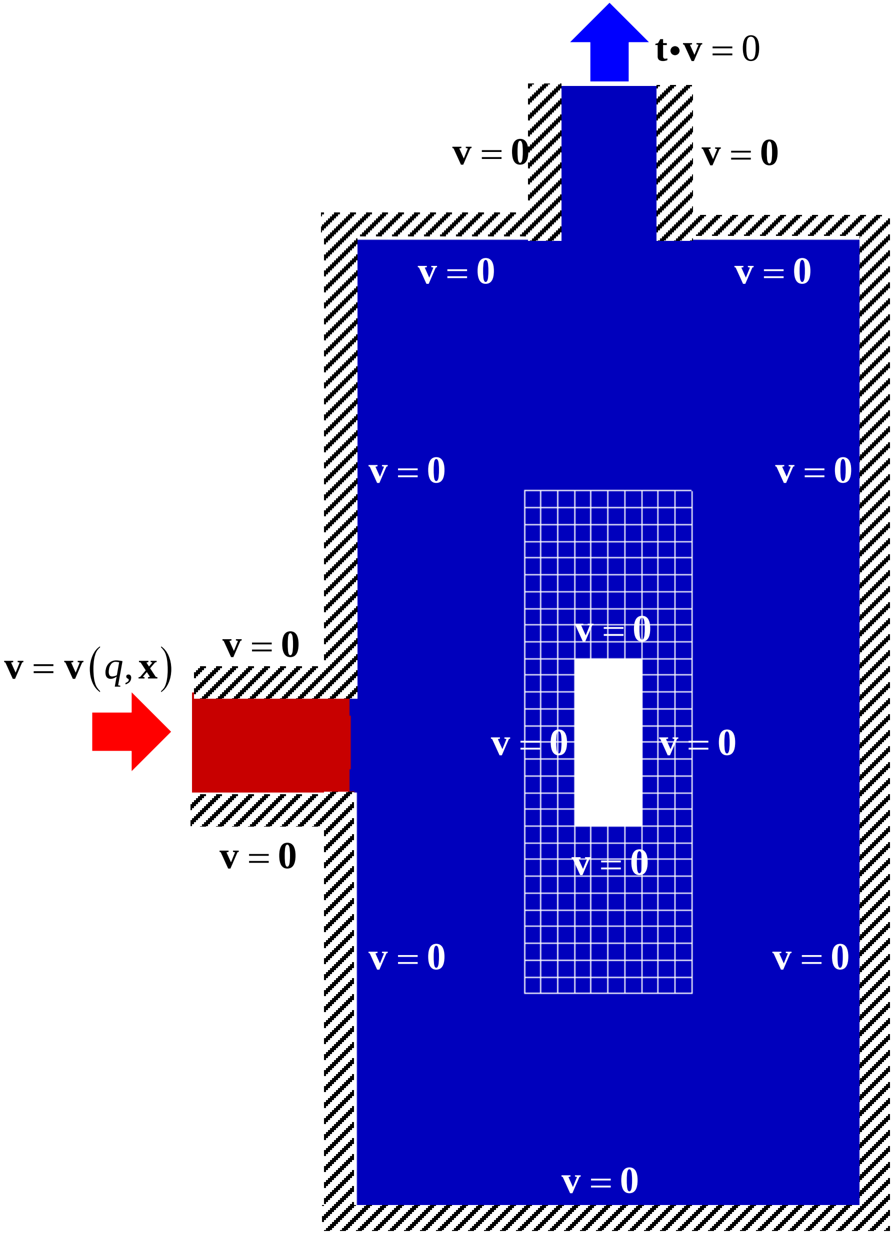
Gravity-driven Flow



Pressure-driven Flow



The Model – Governing Equations



Mass Conservation

$$\nabla \bullet \mathbf{v} = 0$$

Momentum Conservation

Container region – continuous medium

$$\rho\left[\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\bullet\nabla\mathbf{v}\right] = \rho\mathbf{g} + \mathbf{f}_{st} - \nabla p + \mu\nabla^2\mathbf{v}$$

Winding region – porous medium

$$\rho\left[\frac{1}{\phi}\frac{\partial \mathbf{v}}{\partial t} + \frac{1}{\phi^2}\mathbf{v}\bullet\nabla\mathbf{v}\right] = \rho\mathbf{g} + \mathbf{f}_{st} - \nabla p + \mu_B\nabla^2\mathbf{v} + \frac{\mu}{k}\mathbf{v}$$

Brinkmann equation

Interface Tracking

$$\frac{\partial F}{\partial t} + \mathbf{v}\bullet\nabla F = 0$$ ***Level set method***

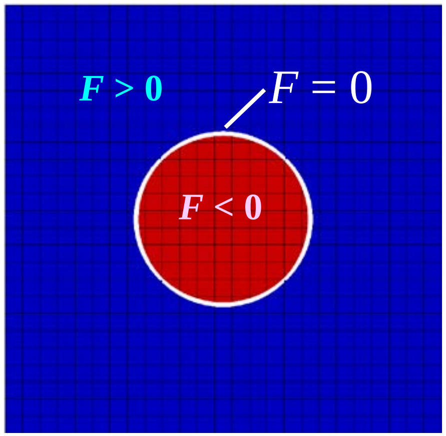
$F < 0$ **Epoxy**

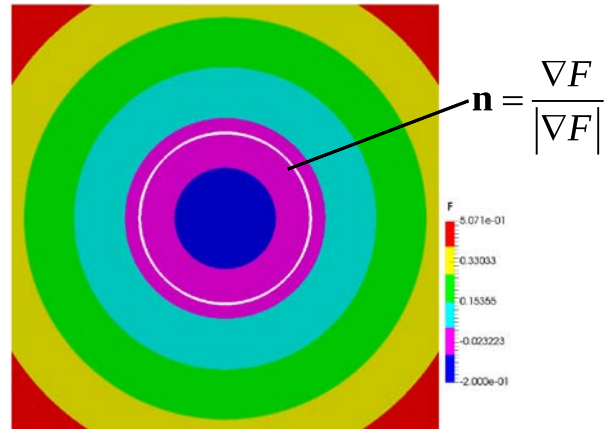
$F > 0$ **Air**

Interface Tracking via Level Set Equation

Osher and Sethian, *J. Comp. Phys.* 1988

- F is defined as **signed distant function** from interface → $F = 0$ signifies interface position
- F field is advected with fluid velocity





Continuum surface force

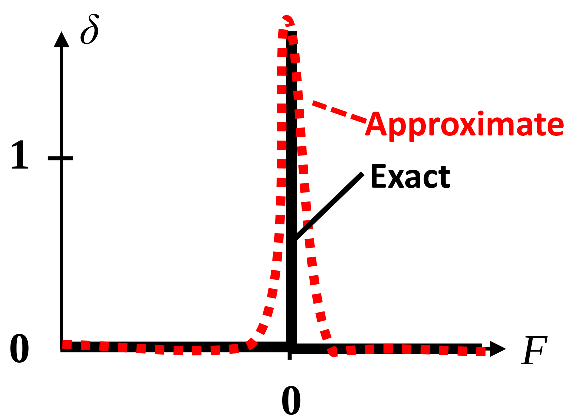
$$\mathbf{f}_{st} = \sigma\left(\nabla_{II} \bullet \mathbf{n}\right)\mathbf{n}\delta$$

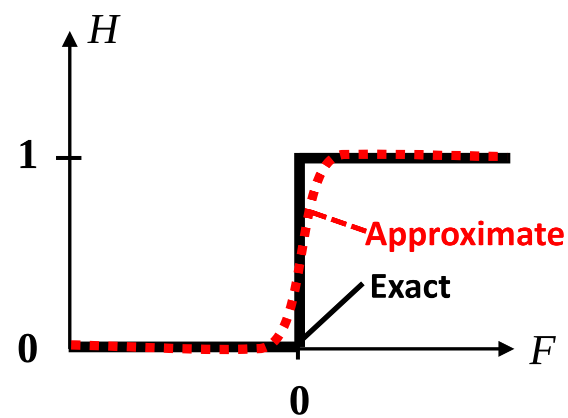
Surface force → volume force

Property averaging

$$\mu(F) = \mu_{\text{epoxy}}(1-H) + \mu_{\text{air}}H$$

$$\rho(F) = \rho_{\text{epoxy}}(1-H) + \rho_{\text{air}}H$$





Sharp interface → diffuse interface

Viscosity Model of Epoxy

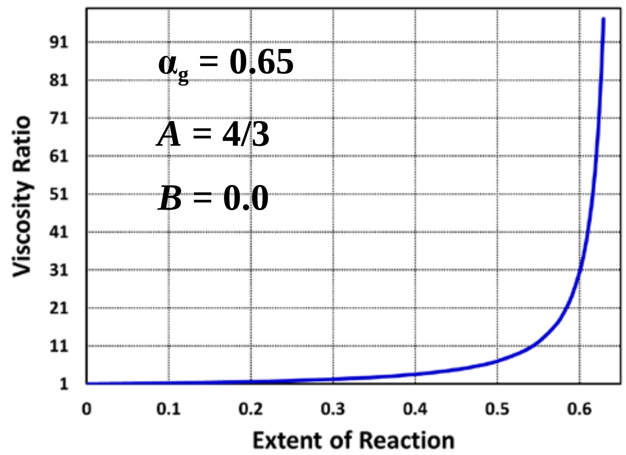
Viscosity rise due to curing reaction

$$\mu = \mu_0 \exp\left[\frac{E}{RT}\right]\left\{\frac{\alpha_g}{\alpha_g - \alpha}\right\}^{A+B\alpha}$$

Arrhenius dependence

Cure/gel point

Extent of reaction

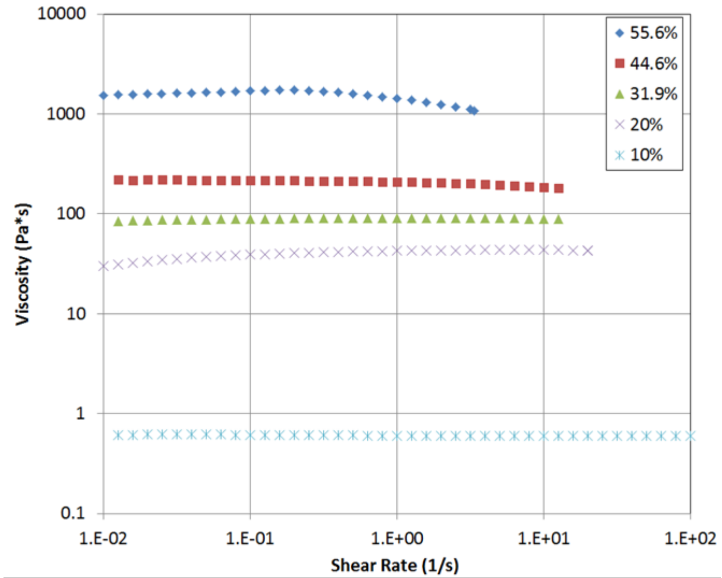


Reaction kinetic model

$$\frac{d\alpha}{dt} = \left(k_1 + k_2\alpha^m\right)\left(1-\alpha\right)^n$$

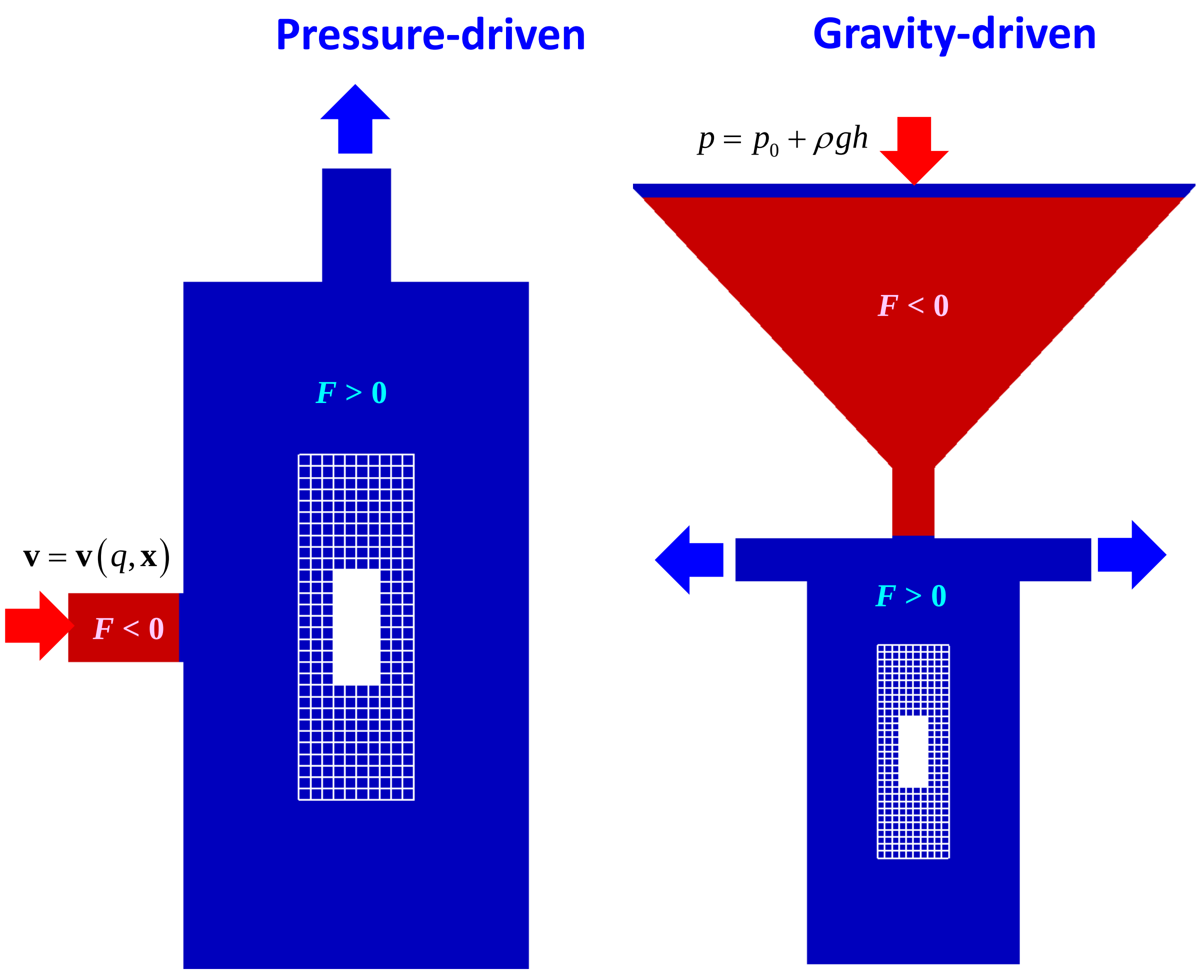
No shear-rate dependence

Negligible viscoelastic effect in early stage of curing



Epon + GMB

Model Summary



Mass Conservation

$$\nabla \cdot \mathbf{v} = 0$$

Momentum Conservation

Cup region – continuous medium

$$\rho\left[\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right] = \rho\mathbf{g} + \mathbf{f}_{st} - \nabla p + \mu\nabla^2\mathbf{v}$$

Winding region – porous medium

$$\rho\left[\frac{1}{\phi}\frac{\partial \mathbf{v}}{\partial t} + \frac{1}{\phi^2}\mathbf{v}\cdot\nabla\mathbf{v}\right] = \rho\mathbf{g} + \mathbf{f}_{st} - \nabla p + \mu_B\nabla^2\mathbf{v} + \frac{\mu}{k}\mathbf{v}$$

Interface Tracking

$$\frac{\partial F}{\partial t} + \mathbf{v}\cdot\nabla F = 0$$

Viscosity Model

$$\mu = \mu_0 \exp\left[\frac{E}{RT}\right]\left\{\frac{\alpha_g}{\alpha_g - \alpha}\right\}^{A+B\alpha}$$

$$\frac{d\alpha}{dt} = \left(k_1 + k_2\alpha^m\right)\left(1-\alpha\right)^n$$

- ***Unknowns: Velocity, pressure, level set field, and extent of reaction***
- ***Solved with finite element method via Goma 6.0***

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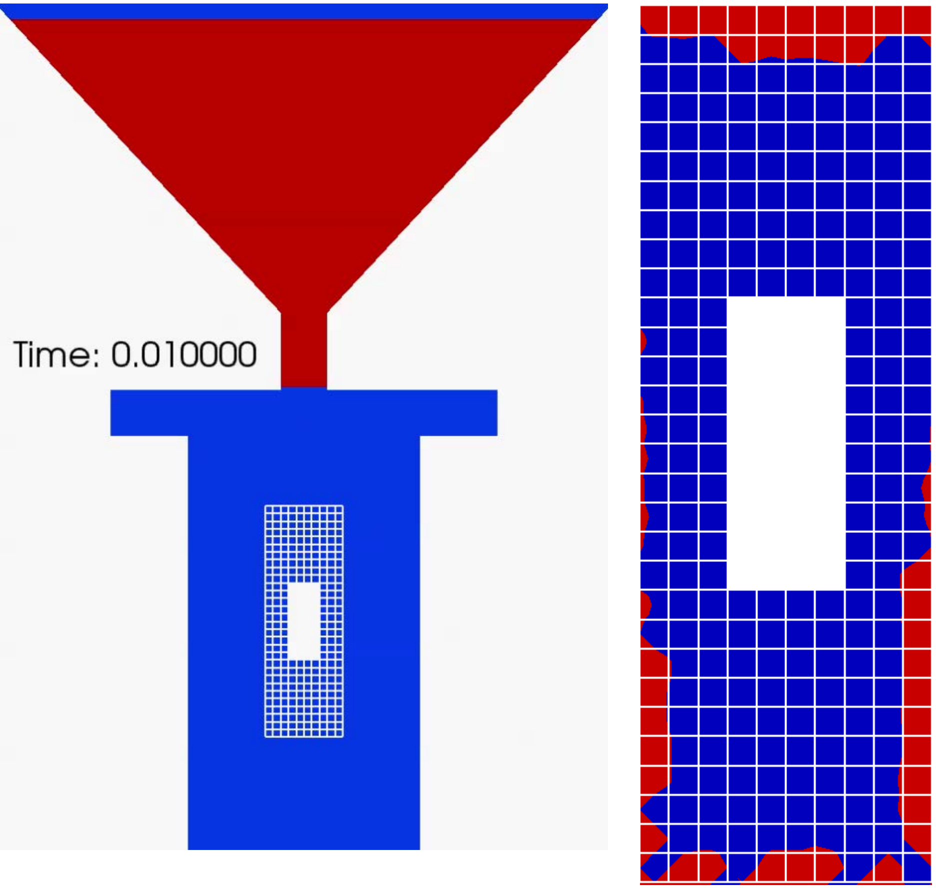
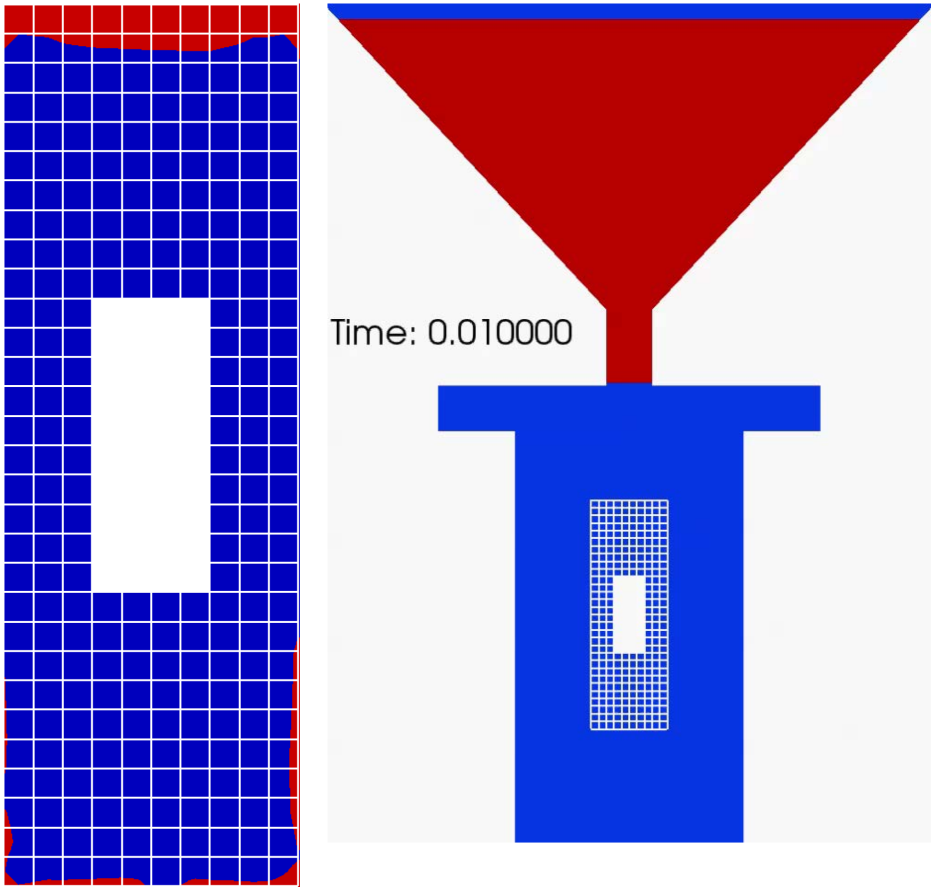
Result – Gravity Driven Flow

μ_0 = 100 Poise – GMB Content < 20%



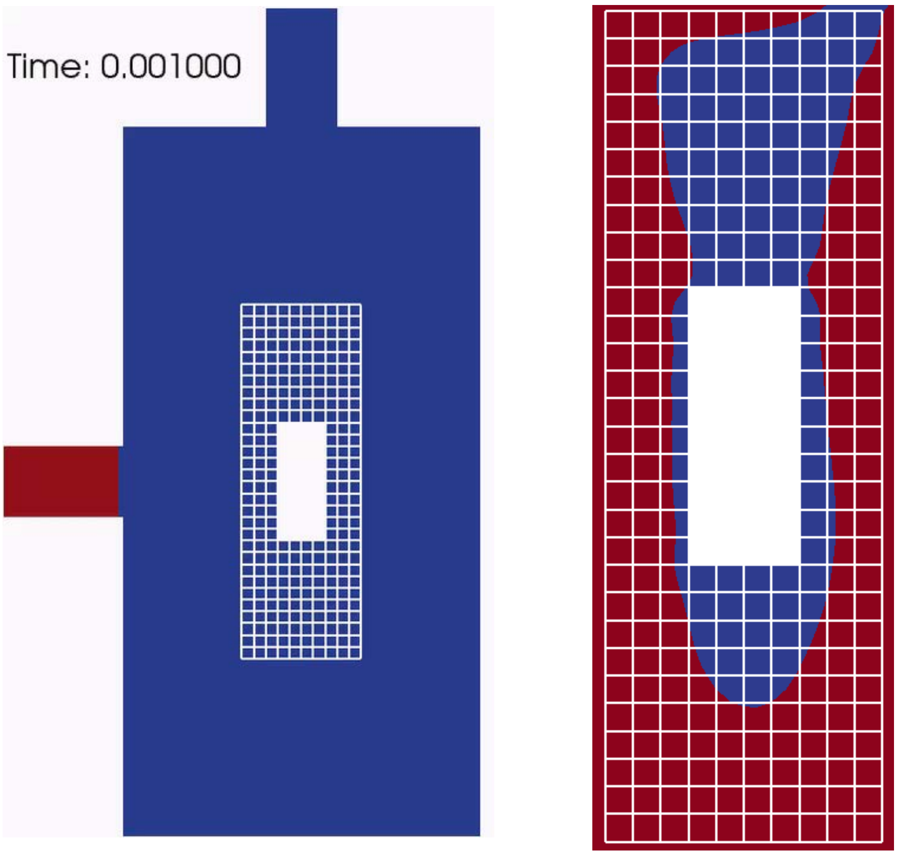
μ_0 = 1000 Poise – GMB Content ~ 39%



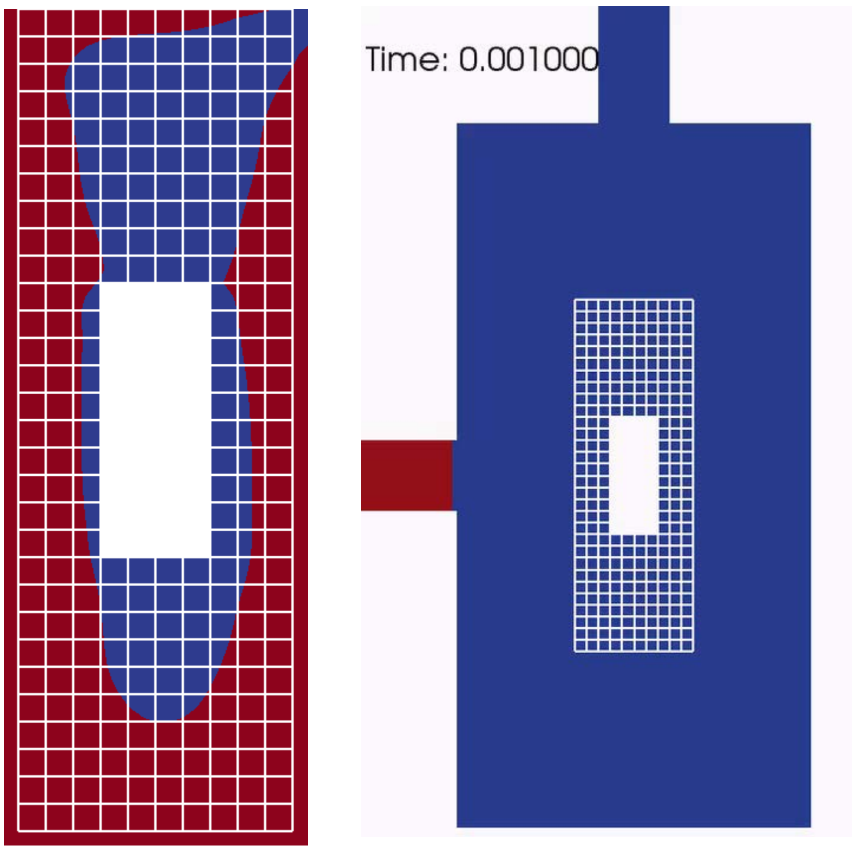
- Top surface gets filled first due to impingement
- Resistance from winding leads to buckling instability of the liquid jet
- Flow instability of air is a challenge

Result – Pressure Driven Flow

μ_0= 100 Poise, Q = 2 cm^2/s



μ_0= 100 Poise, Q = 10 cm^2/s



- Higher flow rate fills up cup faster but need to wait for imbibition
- Porous infiltration is about the same

Future Work

- More experimental characterization of epoxy wicking in the winding region → capillary pressure – saturation relationship
- Better handle on air flow
- Faster curing – more appreciable viscosity rise
  - Non-isothermal curing
- More realistic permeability model
  - Anisotropic permeability
  - Curing-dependent permeability

https://goma.github.io/