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The Transient Modeling of Single-Bubble Nucleate Boiling in a Sub-Cooled Liquid Using an ALE Moving Mesh

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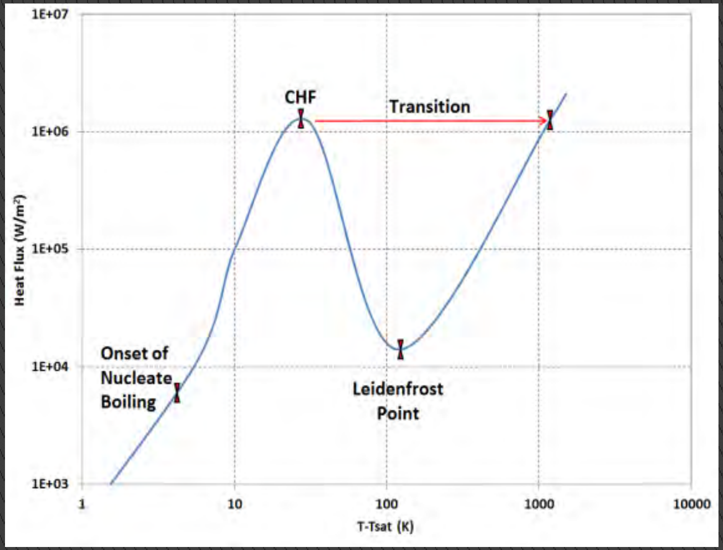
Motivation

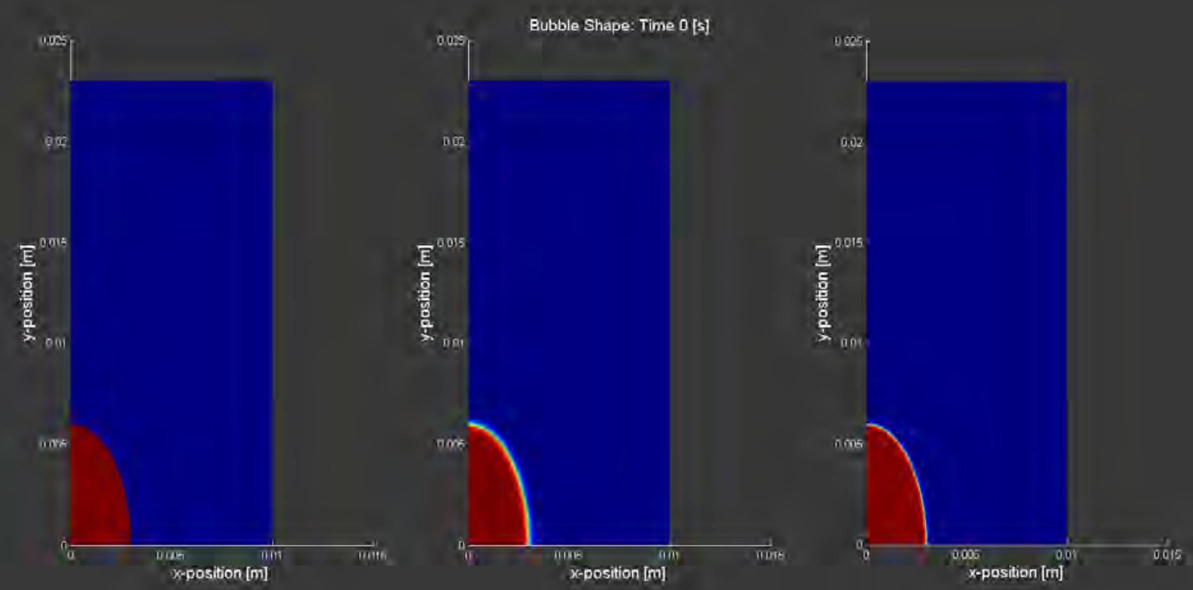
- Power electronics cooling using pool boiling heat exchangers.
- Models are being developed for pool boiling heat transfer with micro-channels in the presence of an acoustic field.
  - Increase critical heat flux (CHF) by delaying transition to film boiling.

Flat plate → 125 W/cm^2
μ-channels → 350 W/cm^2
μ-channels + acoustics → 450 W/cm^2



Photos courtesy of Thomas Boziuk and Ari Glezer
Georgia Institute of Technology – Atlanta, GA

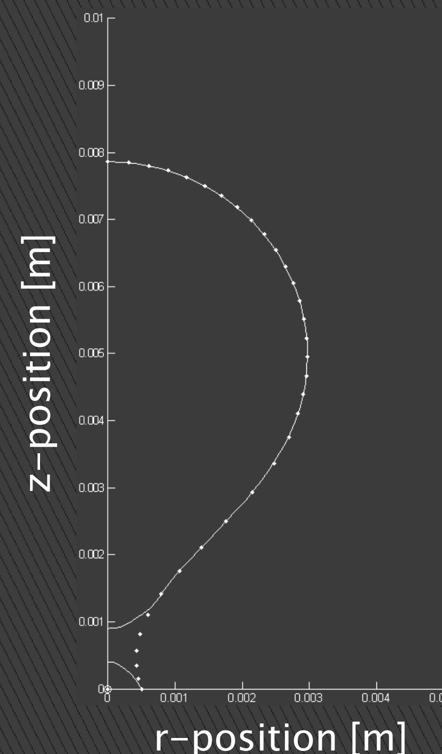
Previous Work



ALE
(Slip BC)

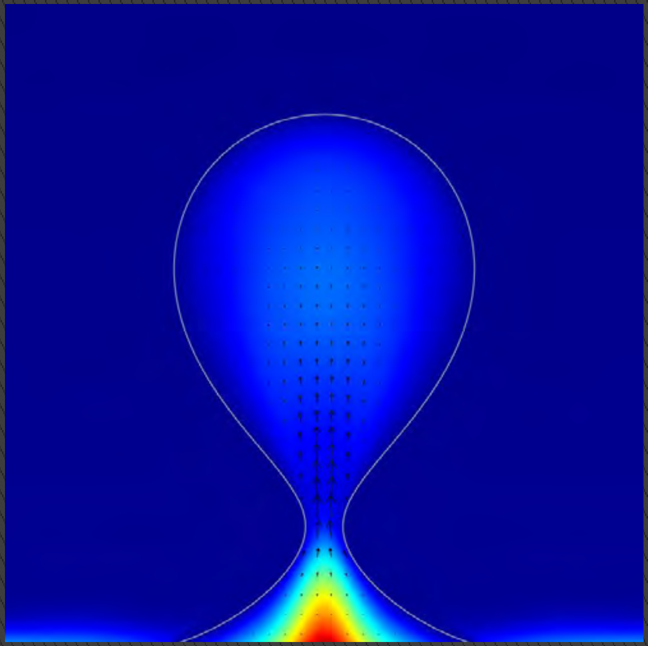
Level-Set
(Slip Length BC)

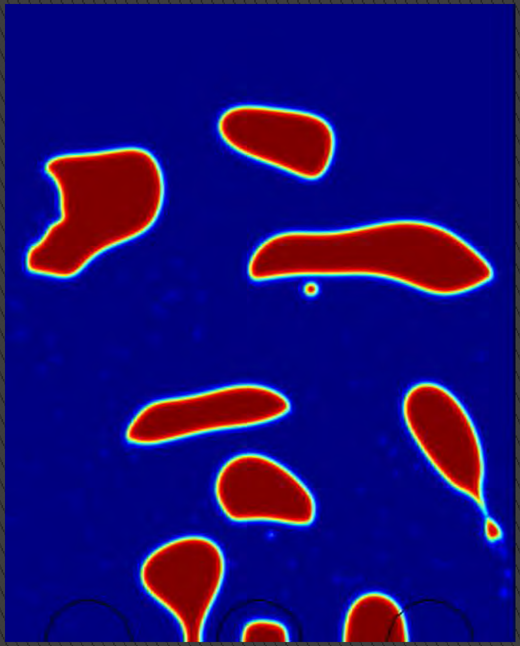
Non-Conservative
Phase-Field
(No-Slip BC)



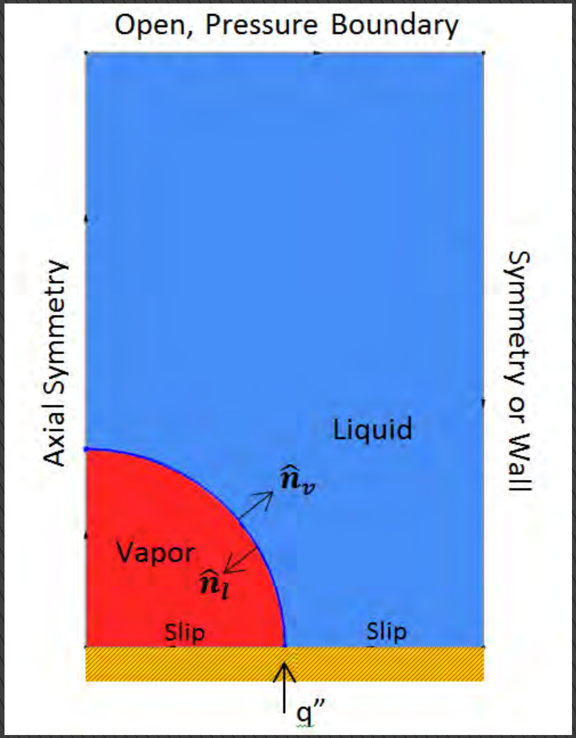
Present Work

- Two boiling models
  - ALE single-bubble boiling
  - Level-set nucleate boiling





ALE Boundary Conditions



Normal-stress boundary condition

$$\left(\underline{\underline{\sigma}}_l - \underline{\underline{\sigma}}_g\right)\hat{n} = \sigma\kappa\hat{n} + P_{recoil}$$

$$\underline{\underline{\sigma}}_{g,l} = \left[-P\underline{\underline{I}} + \eta\left(\nabla\underline{u} + \left(\nabla\underline{u}\right)^T\right)\right]_{g,l} \qquad \kappa = \nabla_s \cdot \hat{n}$$

Interface temperatures

$$T_l = T_v = T_{sat}$$

Vaporization

$$q"_{vaporization} = k_l \nabla T_l \cdot \hat{\boldsymbol{n}}_l + k_v \nabla T_v \cdot \hat{\boldsymbol{n}}_v$$

Interface velocities

$$v_{n,l} = -\frac{q"_{vaporization}}{\rho_l(h_v - h_l)} \qquad v_{n,v} = -\frac{q"_{vaporization}}{\rho_v(h_v - h_l)}$$

$$\left(\underline{\boldsymbol{u}} - \underline{\boldsymbol{u}}\cdot\hat{\boldsymbol{n}}\right)_l - \left(\underline{\boldsymbol{u}} - \underline{\boldsymbol{u}}\cdot\hat{\boldsymbol{n}}\right)_v = 0$$

$$\left(\underline{\boldsymbol{u}}_v \cdot \hat{\boldsymbol{n}}_v - \underline{\boldsymbol{u}}_l \cdot \hat{\boldsymbol{n}}_l\right) + v_{n,l} + v_{n,v} = 0$$

$$u_{n,mesh} = \underline{\boldsymbol{u}}_l \cdot \hat{\boldsymbol{n}}_l + v_{n,l}$$

Level-Set Boundary Conditions

Temperature Recovery Method

$$\dot{m} = C\rho_l\left(\frac{T - T_{sat}}{T_{sat}}\right)$$

Modified Continuity Equation

$$\nabla \cdot \underline{\boldsymbol{u}} = \delta\left(\frac{1}{\rho_v} - \frac{1}{\rho_l}\right)\dot{m}\widehat{\boldsymbol{n}}$$

Interface Tangential Stress

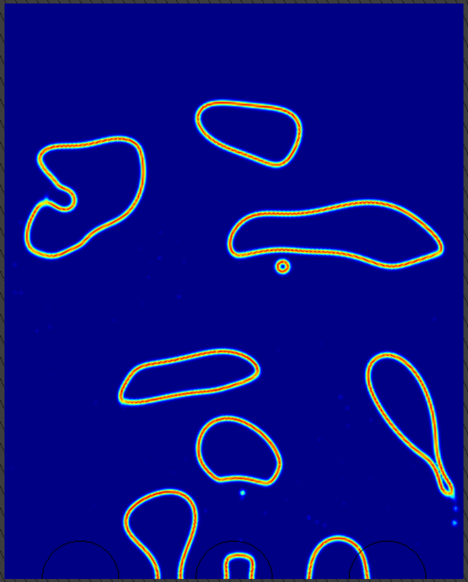
$$\widehat{\boldsymbol{n}} \cdot \left[\mu_l\left(\nabla\underline{\boldsymbol{u}} + \nabla\underline{\boldsymbol{u}}^T\right)_l - \mu_v\left(\nabla\underline{\boldsymbol{u}} + \nabla\underline{\boldsymbol{u}}^T\right)_v\right] \times \widehat{\boldsymbol{n}} = 0$$

Interface Normal Stress

$$-p_l + p_v + \widehat{\boldsymbol{n}} \cdot \left[\mu_l\left(\nabla\underline{\boldsymbol{u}} + \nabla\underline{\boldsymbol{u}}^T\right)_l - \mu_v\left(\nabla\underline{\boldsymbol{u}} + \nabla\underline{\boldsymbol{u}}^T\right)_v\right] \cdot \widehat{\boldsymbol{n}} = \sigma\kappa - \left(\frac{1}{\rho_v} - \frac{1}{\rho_l}\right)\dot{m}^2$$

Heat Source Term

$$\rho_f c_f\left(\frac{\partial \underline{\boldsymbol{u}}_f}{\partial t} + \underline{\boldsymbol{u}}_f \cdot \nabla T_f\right) = \nabla \cdot k_f(\nabla T)_f - \delta\dot{m}h_{lv}$$



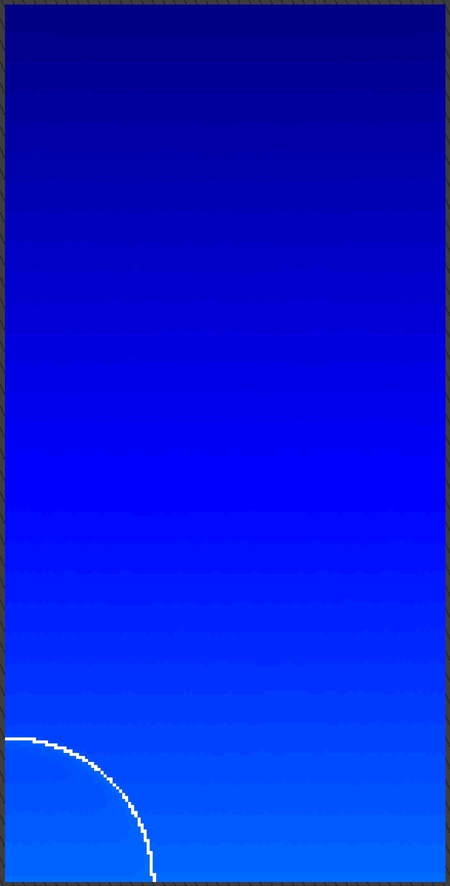
Interface Delta Function

Modified Level-Set Equation

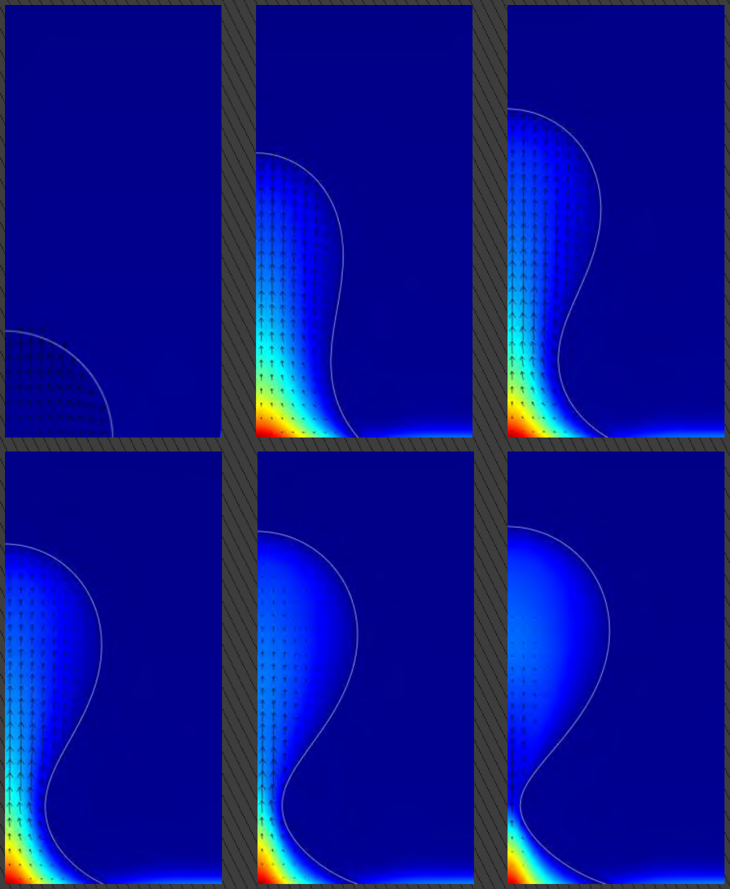
$$\frac{\partial\phi}{\partial t} + \underline{\boldsymbol{U}} \cdot \nabla\phi = 0$$

$$\underline{\boldsymbol{U}} = \underline{\boldsymbol{u}}_f + \frac{\dot{m}}{\rho_f}\widehat{\boldsymbol{n}}$$

ALE Results

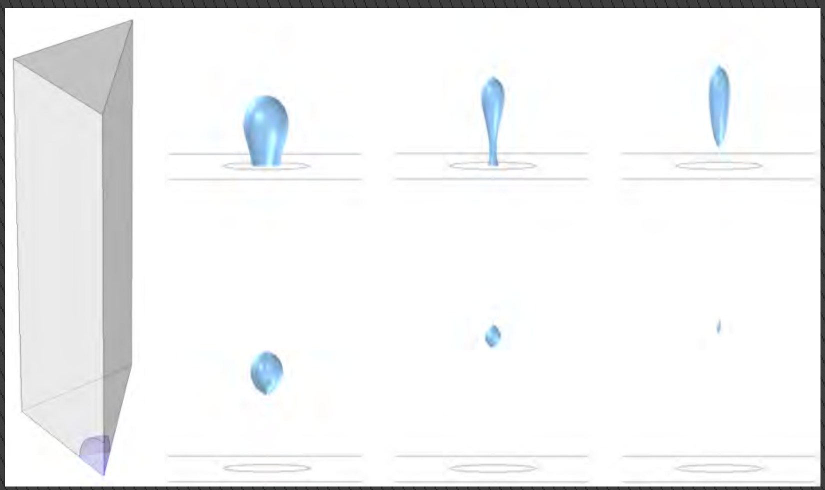


Slip Contact Line

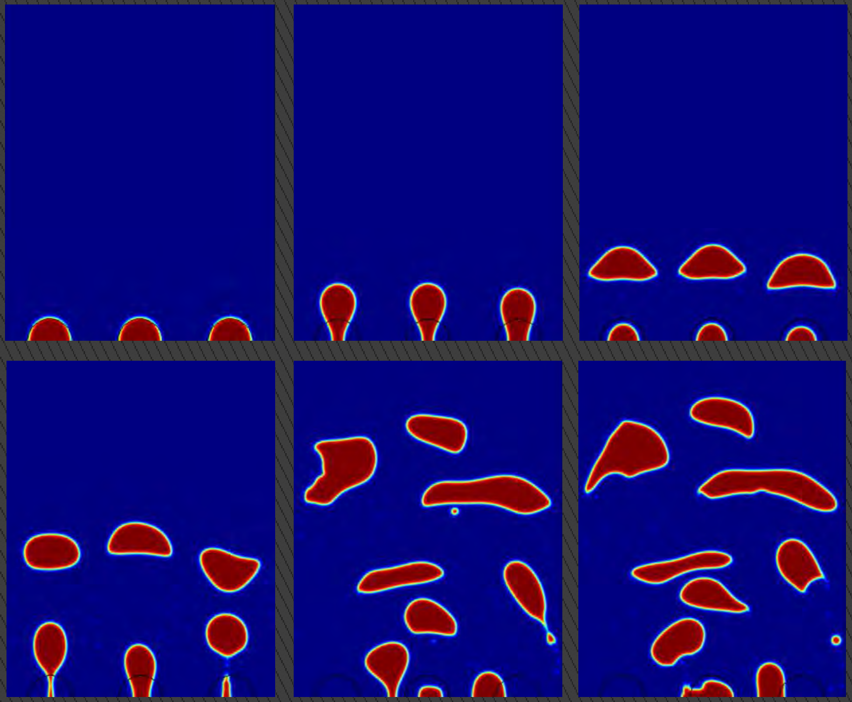


Pinned Contact Line

Level-Set Results

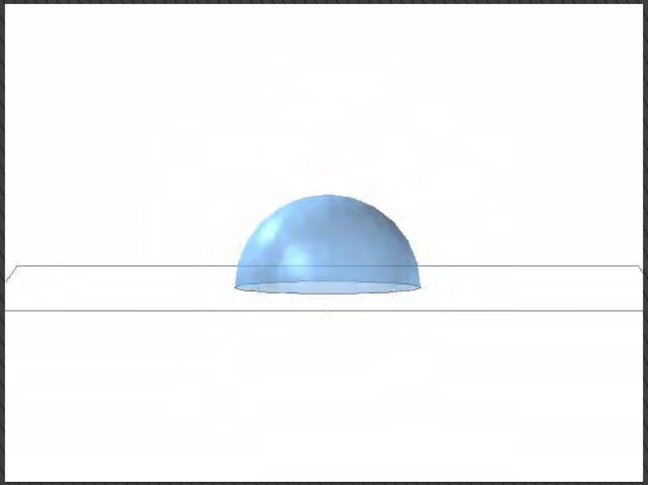


1/8th symmetry



2D Model

Level-Set Results



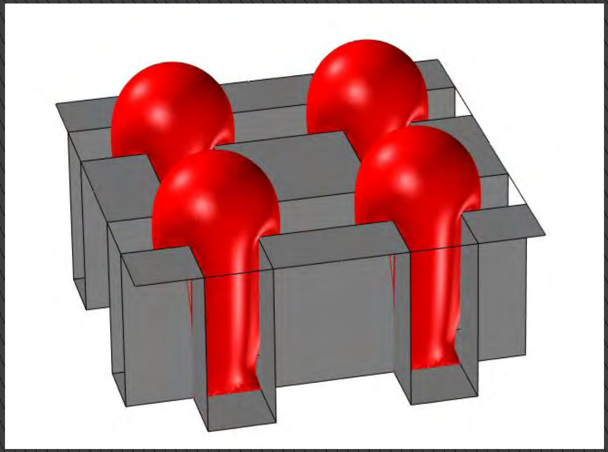
1/8th symmetry

2D Model

Summary

- ALE model is good for modeling dynamics of a single bubble in greater detail.
- Level-set offers the ability to model more complicated bubble interactions at the cost of interface detail.

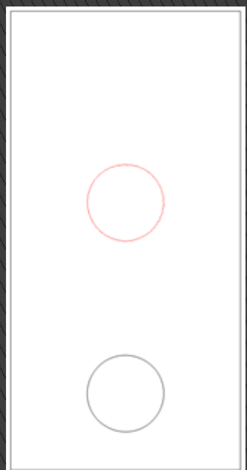
Future Work



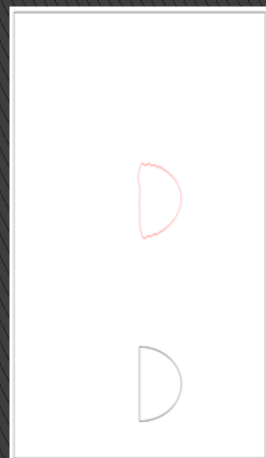
- Combine benefits of ALE and level-set
- Boiling in micro-channels
  - Effects of channel spacing, width, and depth
  - Effects of contact angle
    - Material selection
    - Coatings
- Determine fundamental mechanisms that allow the micro-channels to increase the critical heat flux
- Add effects of acoustics

Questions?

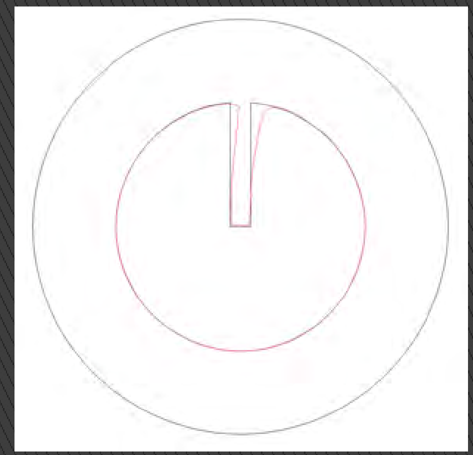
Level-Set Reinitialization Error



Translation

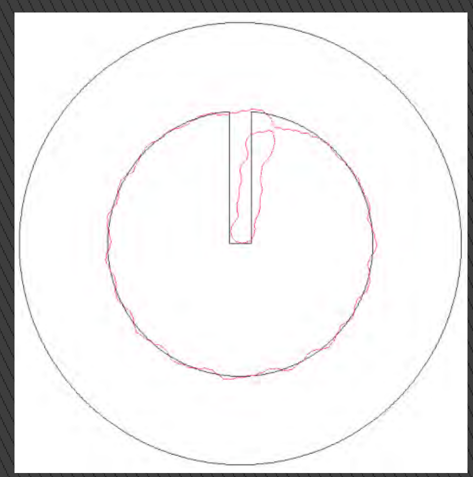


Translation



Rigid-body Rotation

$\gamma = 0.001\ m/s$



$\gamma = 1\ m/s$
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