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Extensible Volume-of-Fluid Solver for Phase-Change Heat Transfer

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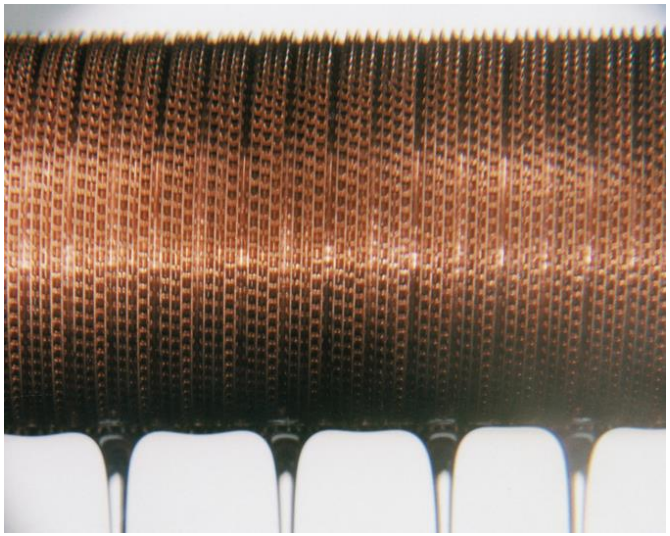
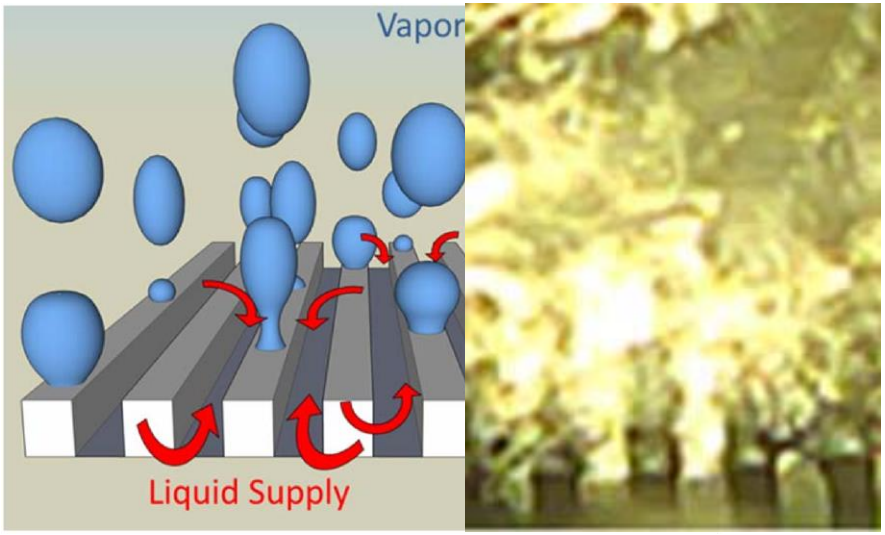
Need for Phase Change Simulation Tools

- Steam generation: 40% of USA **primary energy**, 72% rejected to ambient through condensation
- Phase change is often efficiency bottleneck, analytic solutions only for simplest configurations
- Need robust simulation tools for diverse phase change processes in emerging enhanced geometries



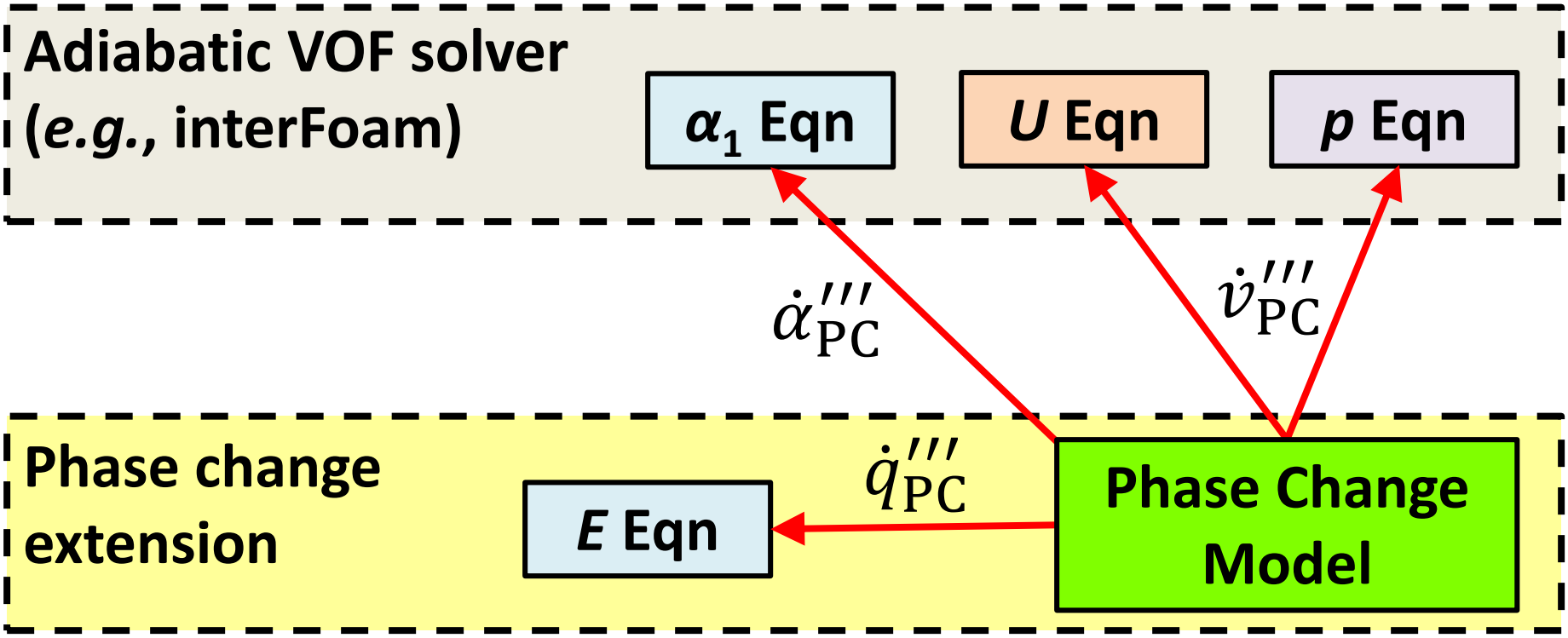
Enhanced Condenser
(Wieland Group, 2013)



Enhanced Boiling
(Cooke and Kandlikar, 2011)

Interface Capturing Formulations

Standard approach: couple energy equation and phase change source terms with adiabatic flow formulation



Interface Capturing Formulations

Standard approach: couple energy equation and phase change source terms with adiabatic flow formulation

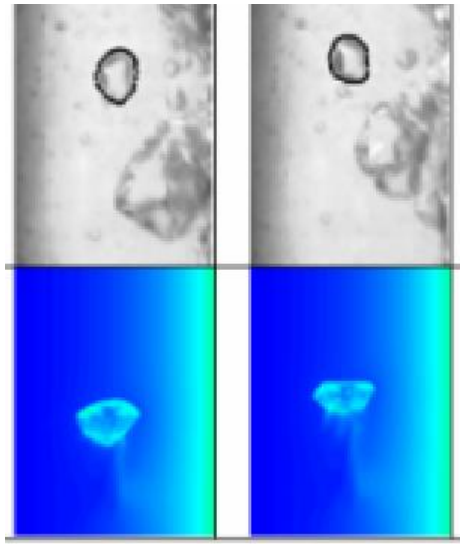
Empirical Rate Parameter

$$\dot{q}'''_{\mathrm{PC}} = r(1-\alpha_1)\rho_{\mathrm{V}}\frac{T-T_{\mathrm{sat}}}{T_{\mathrm{sat}}}$$

Flow boiling (Yang *et al.*, 2008)

Adapted Correlation

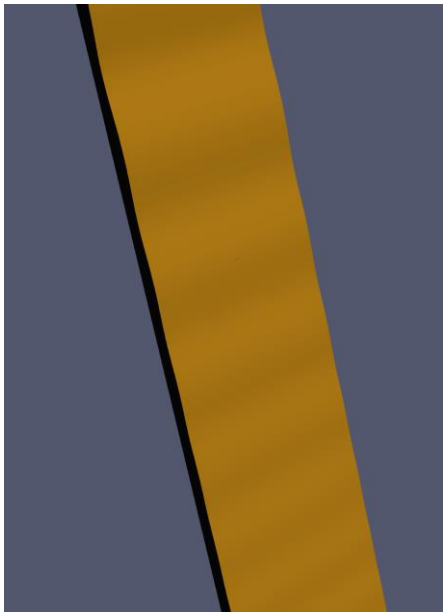
$$\dot{q}'''_{\mathrm{PC}} = \bar{h}(T-T_{\mathrm{sat}})$$



Bubble condensation (Jeon *et al.*, 2009)

Saturated Interface

$$\dot{q}'''_{\mathrm{PC}} = (\rho c_{\mathrm{p}})\frac{(T-T_{\mathrm{sat}})}{\Delta t}$$



Film condensation (Rattner & Garimella, 2014)

Need for Extensible Phase Change Solver

- Prior formulations fit in common framework: energy equation & phase change source terms
- **but**, nearly all studies implement whole new solver
  - Repeated development and validation efforts
  - Limited code availability and maintenance

Project goal: Implement flexible VOF-based solver for diverse phase-change heat transfer processes

"Common framework for phase change simulations"

VOF Phase Change Solver Overview

- VOF Phase change solver based on *interFoam*

Continuity $\frac{\partial u_i}{\partial x_i} = \dot{v}_{PC}$

Momentum $\rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \mu_{eff} \frac{\partial^2 u_i}{\partial x_i \partial x_j} + f_i$

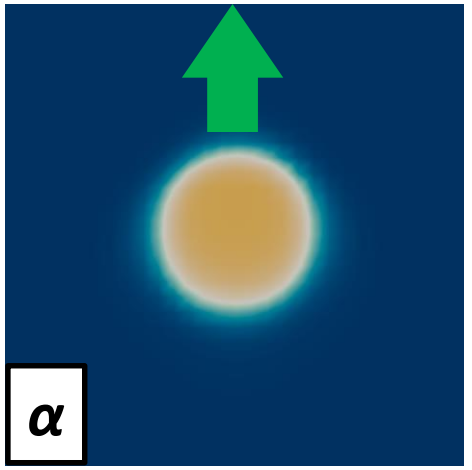
Phase $\frac{\partial \alpha}{\partial t} + \frac{\partial}{\partial x_i}(u_i \alpha) = \dot{\alpha}_{PC}$

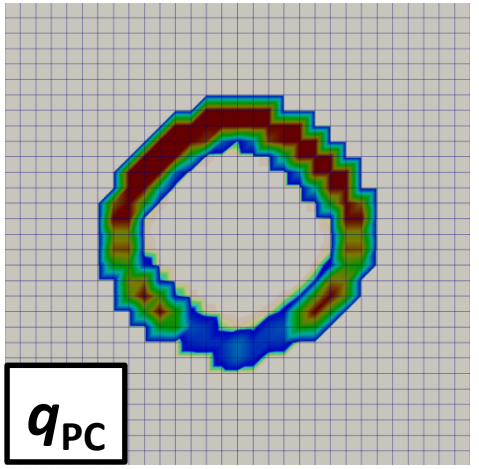
Energy $\frac{\partial (\rho h)}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}\left[k_{eff} \frac{\partial T}{\partial x_i} \right] - \dot{q}'''_{PC}$

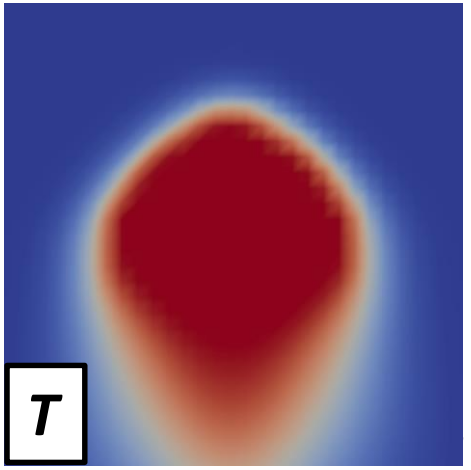
- Selectable f_σ (Brackbill et al., 1992; Raeini et al., 2012)
- Selectable fluid property calculation (Marschall et al., 2012)
- Multistep method implemented for energy equation (for conduction / advection timescale mismatch)

Phase Change Solver Algorithm

1. Initialize case and phase change model
2. **WHILE** $t < t_{end}$ **DO**
    1. Update Δt for stability
    2. Update fluid and turbulence properties
    3. Update phase change model ($\dot{q}_{pc}$, $\dot{v}_{pc}$, $\dot{\alpha}_{pc}$)
    4. Phase equation (α_1) sub-cycle
    5. **DO** Pressure-velocity correction loop
        1. Form u equation
        2. PISO algorithm
            1. Obtain and correct φ
            2. Solve p-Poisson equation
            3. Correct u
    6. **LOOP**
    7. Update $i(T)$
    8. **DO** Energy Loop
        1. Solve i equation
        2. Update $T(i)$
    9. **LOOP**
3. **LOOP**







thermalPhaseChangeModel Class

- Phase change models extend **thermalPhaseChangeModel** (Similar to turbulence models)
- Must implement:
  - **Q_pc**() (*heat source*)
  - **PCV**() (*dilatation, default available*)
  - **alpha1Gen**() (*liquid volume fraction source, default available*)

- Implementations for:
  - Interface equilibrium (Rattner and Garimella, 2014)
  - Empirical rate parameter (Yang *et al*., 2008)
  - Interfacial resistance (Kunkelmann and Stephan, 2009)
  - None (debugging)

Example Phase Change Model Implementation

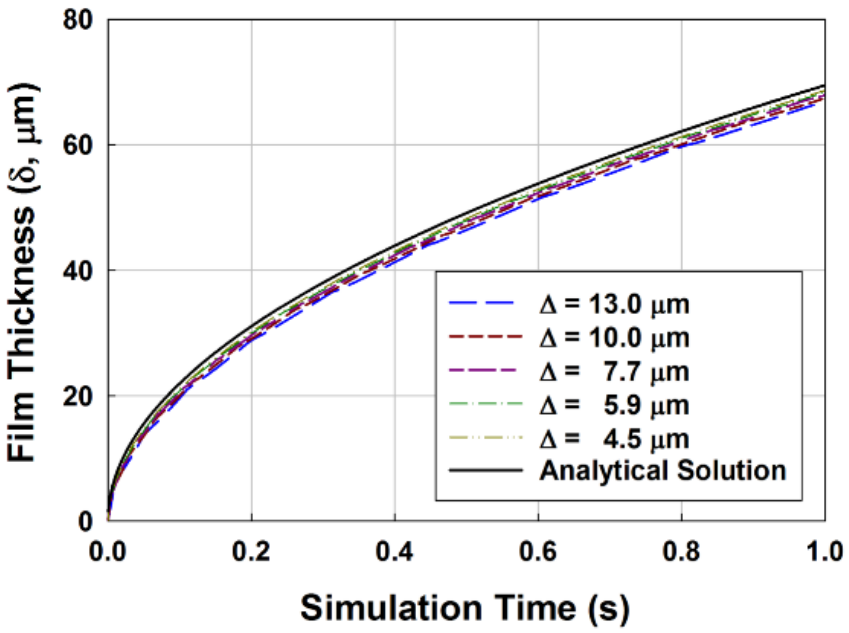
- Empirical rate parameter model (Yang et al., 2008)

```
//Evaluates phase change heat source term field
void Foam::thermalPhaseChangeModels::Yang::calcQ_pc() {
   const dimensionedScalar& rhol = twoPhaseProperties_.rho1();
   const dimensionedScalar& rhov = twoPhaseProperties_.rho2();

   Q_pc_ = pos(T_-T_sat_)*h_lv_*rl*alpha1_*rhol
           *((T_-T_sat_)/T_sat_)
         + neg(T_-T_sat_)*h_lv_*rv*(1.0-alpha1_)*rhov
          *((T_-T_sat_) / T_sat_);  }

//Updates model parameters from user specified input file
bool Foam::thermalPhaseChangeModels::Yang::read(
const dictionary& thermalPhaseChangeProperties) {
   thermalPhaseChangeModel::read(thermalPhaseChangeProperties);
   thermalPhaseChangeProperties_.lookup("rl") >> rl;
   thermalPhaseChangeProperties_.lookup("rv") >> rv;
   return true;   }
```

Validation Cases (1)

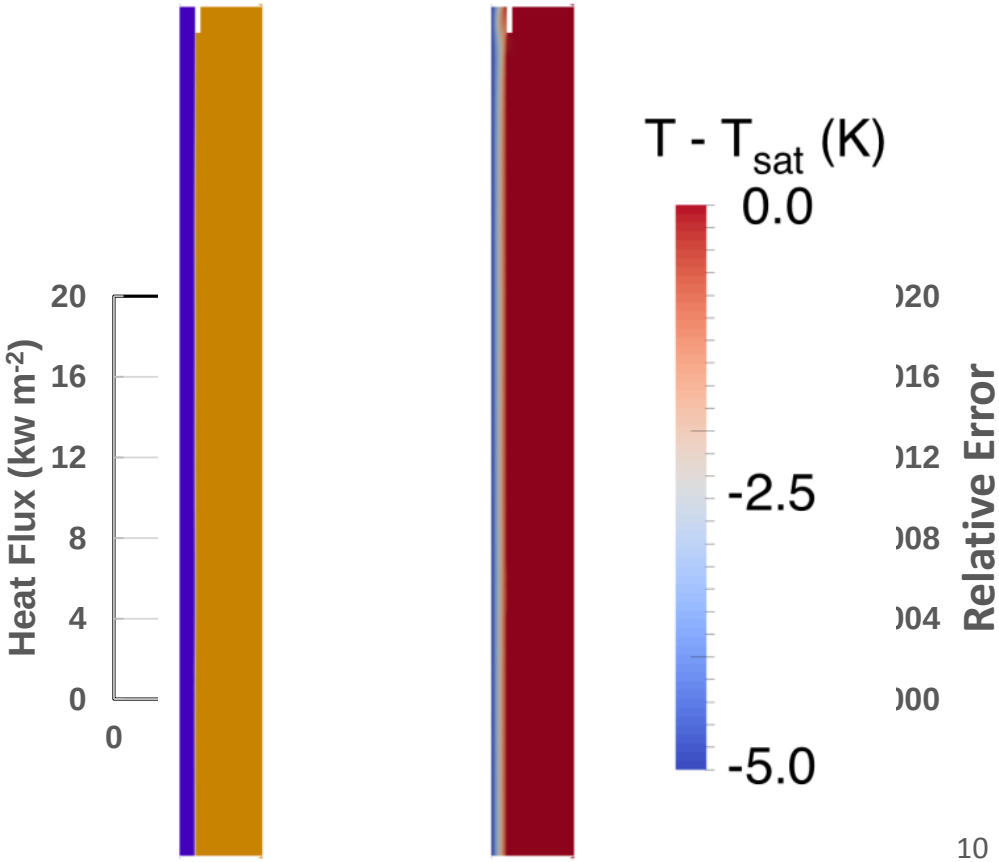
Horizontal Film condensation

- Linear convergence ($E = 0.36\Delta^{1.05}$)



Smooth Falling Film Evaporation / Condensation

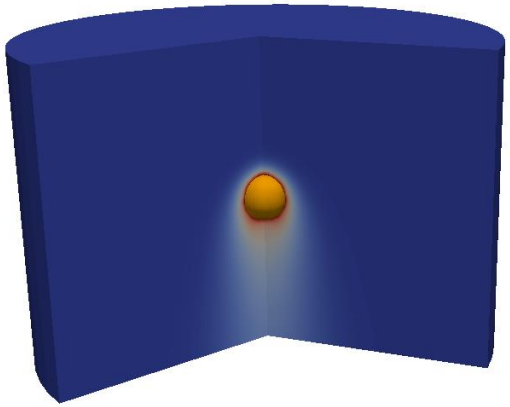
- Error < 1.2% over large range of grids

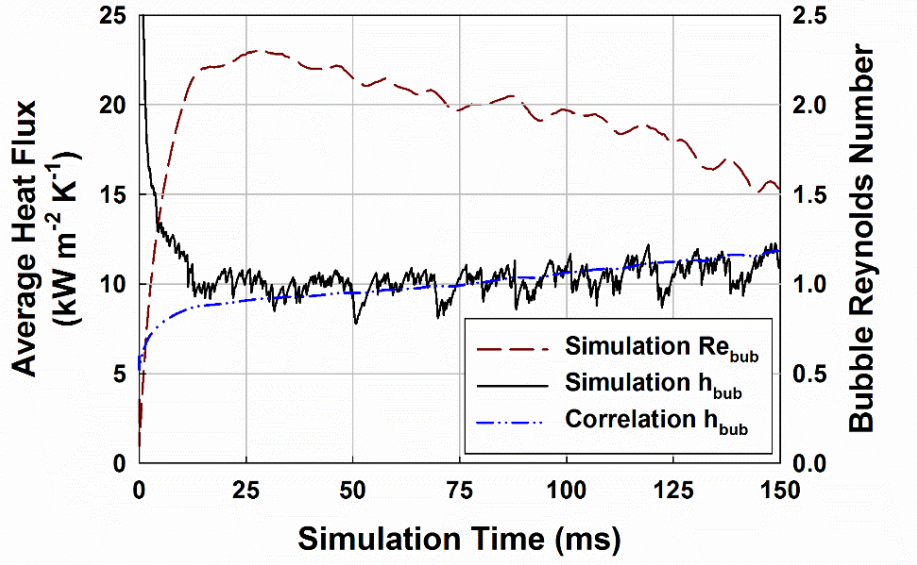


Validation Cases (2)

Rising Bubble Condensation

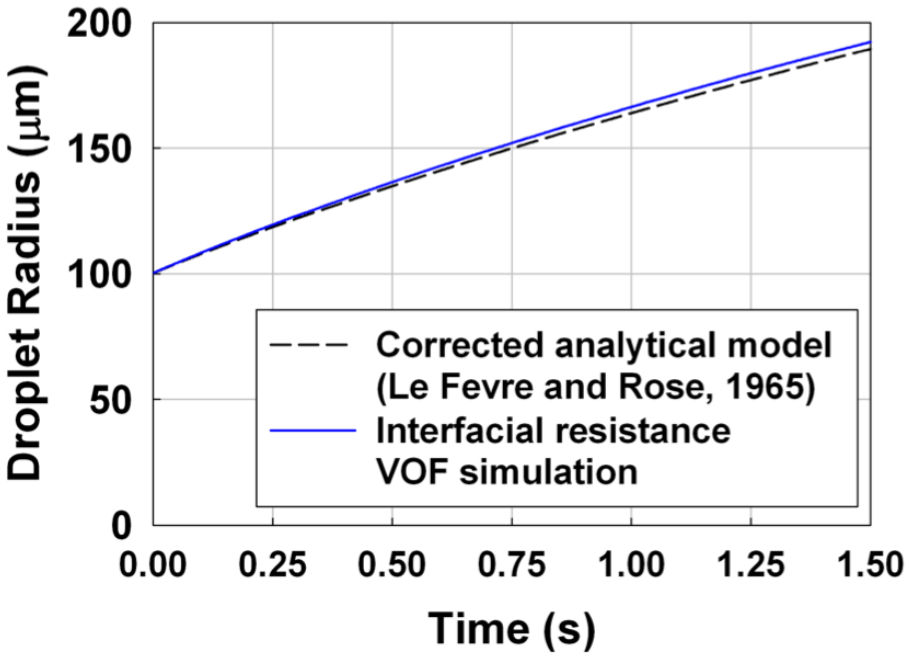
- h_{bub} agreement: 5.6%





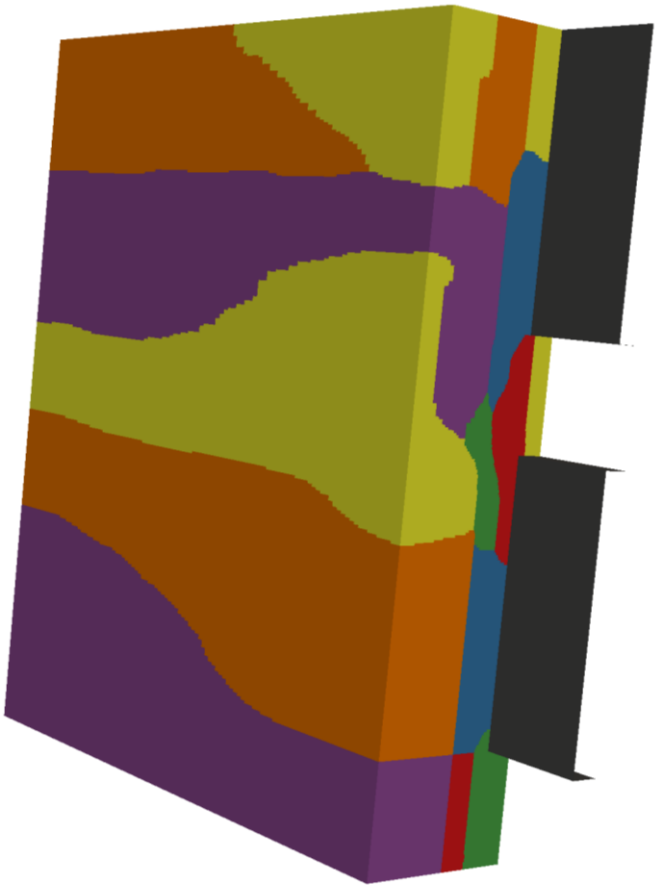
Single droplet condensation

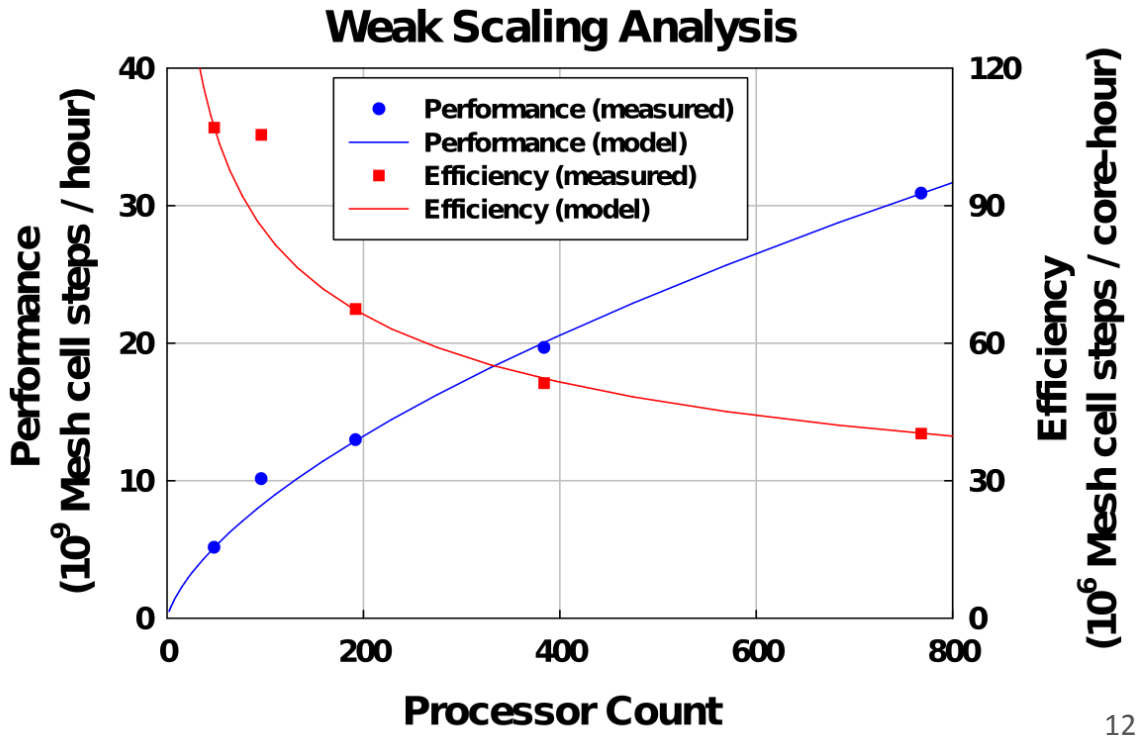
- Interfacial resistance model needed for contact-line PC
- 3% radius change error during growth



Scaling Performance

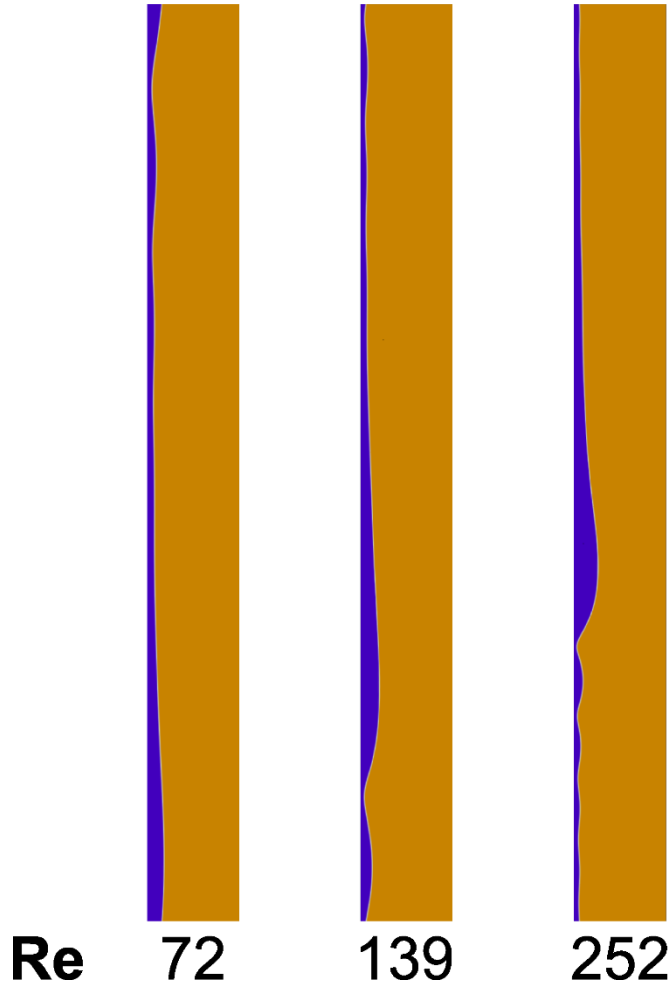
- Model problem: Falling film absorption
- MPI-based domain decomposition parallelization

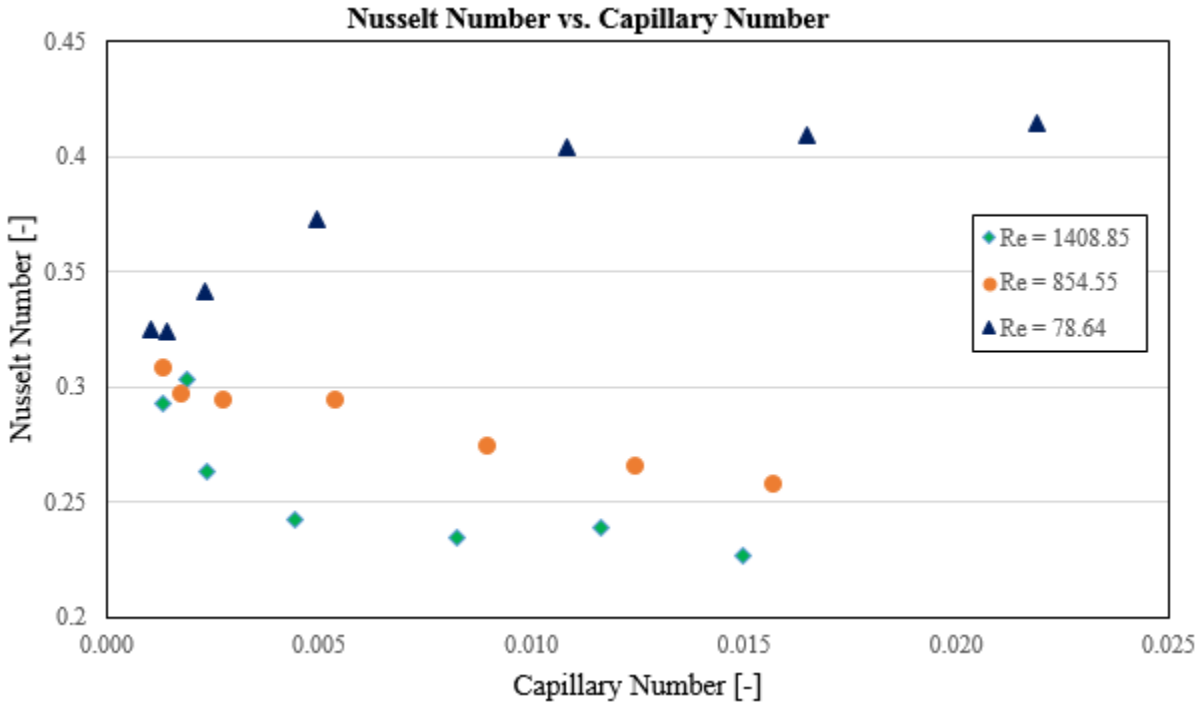




Application: Wavy Film Phase Change

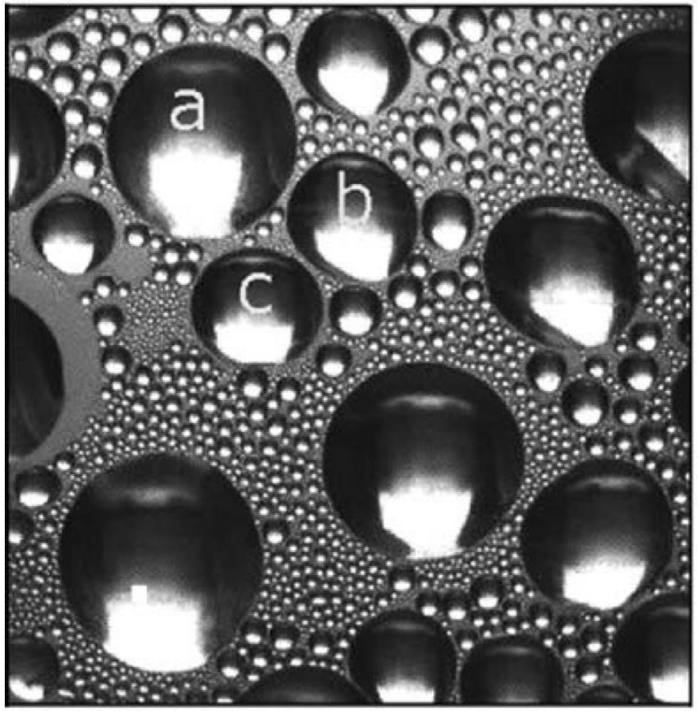
- 2D simulations of wavy falling film heat transfer
- First studies to measure effect of σ on heat transfer



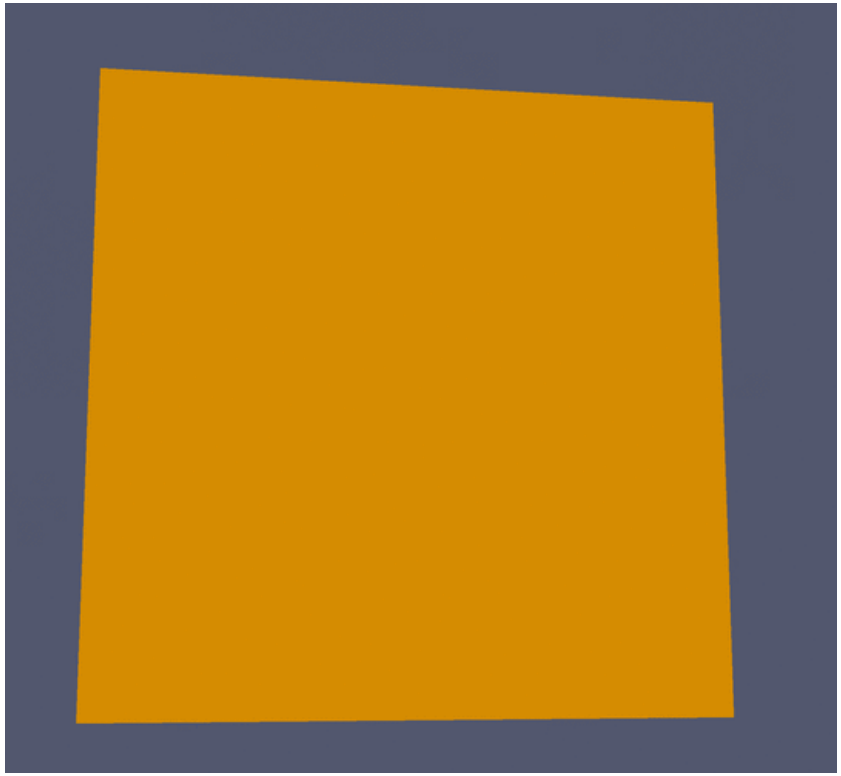


Applications: Dropwise Condensation

- High heat flux condensation mode on non-wetting surfaces (10× filmwise): promising for power plant applications
- Previous studies model drops as rigid particles (no dynamics)

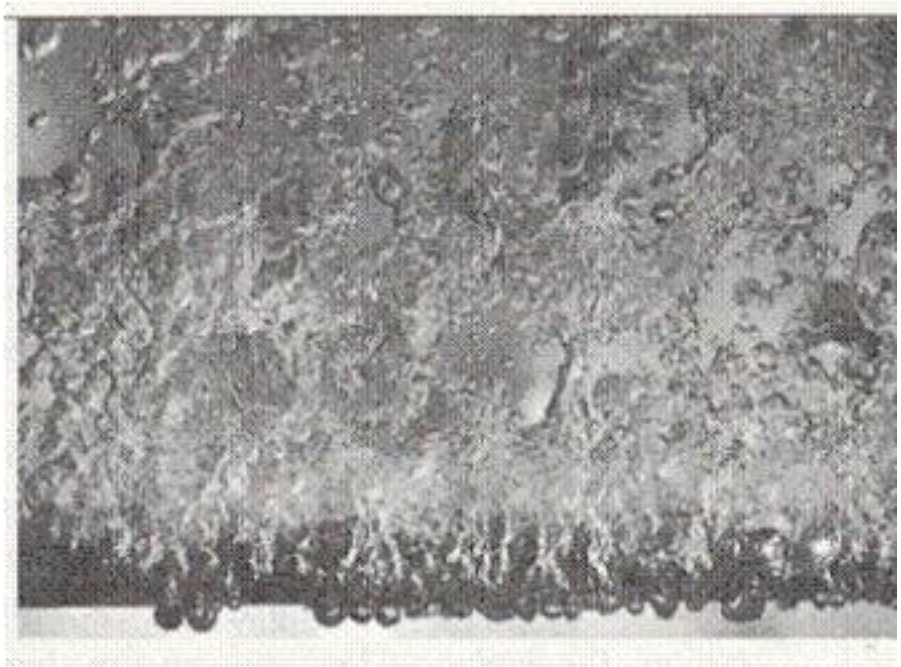


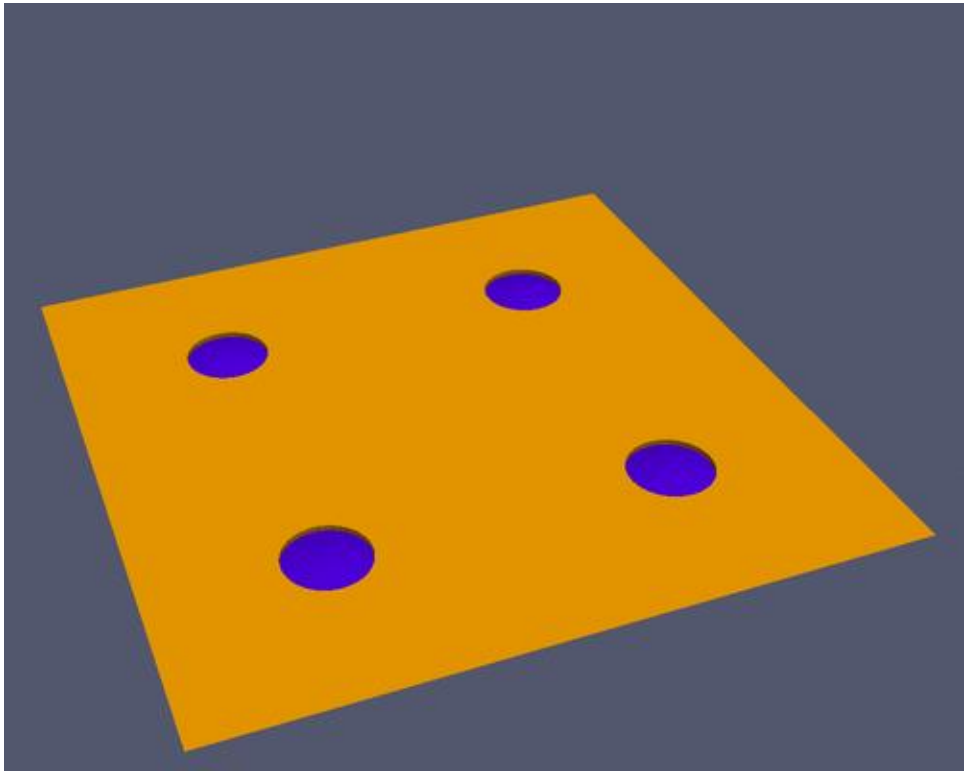
Sikarwar *et al*. (2010)



Applications: Nucleate Boiling

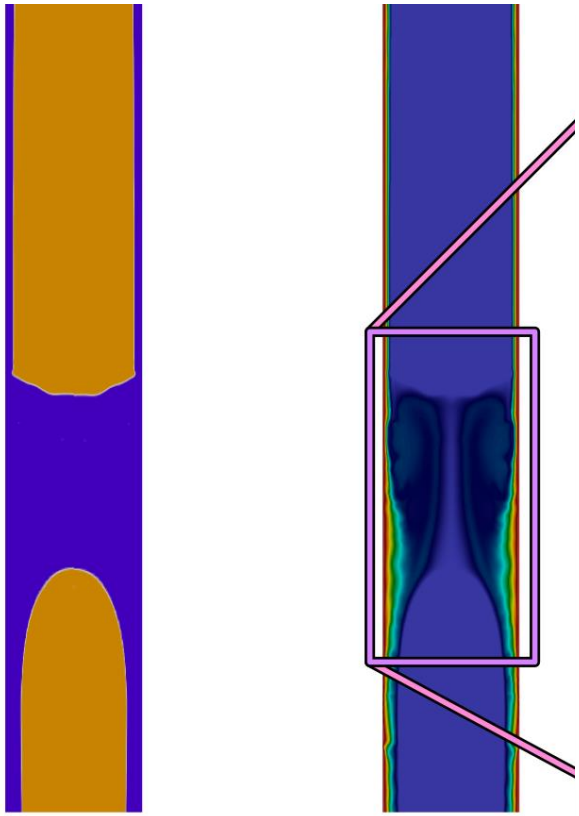
- In boiling, phase change primarily occurs in bubbles growing from imperfections in surface
- Analytical theory limited to individual bubbles
- In practice: strongly interacting nucleation sites

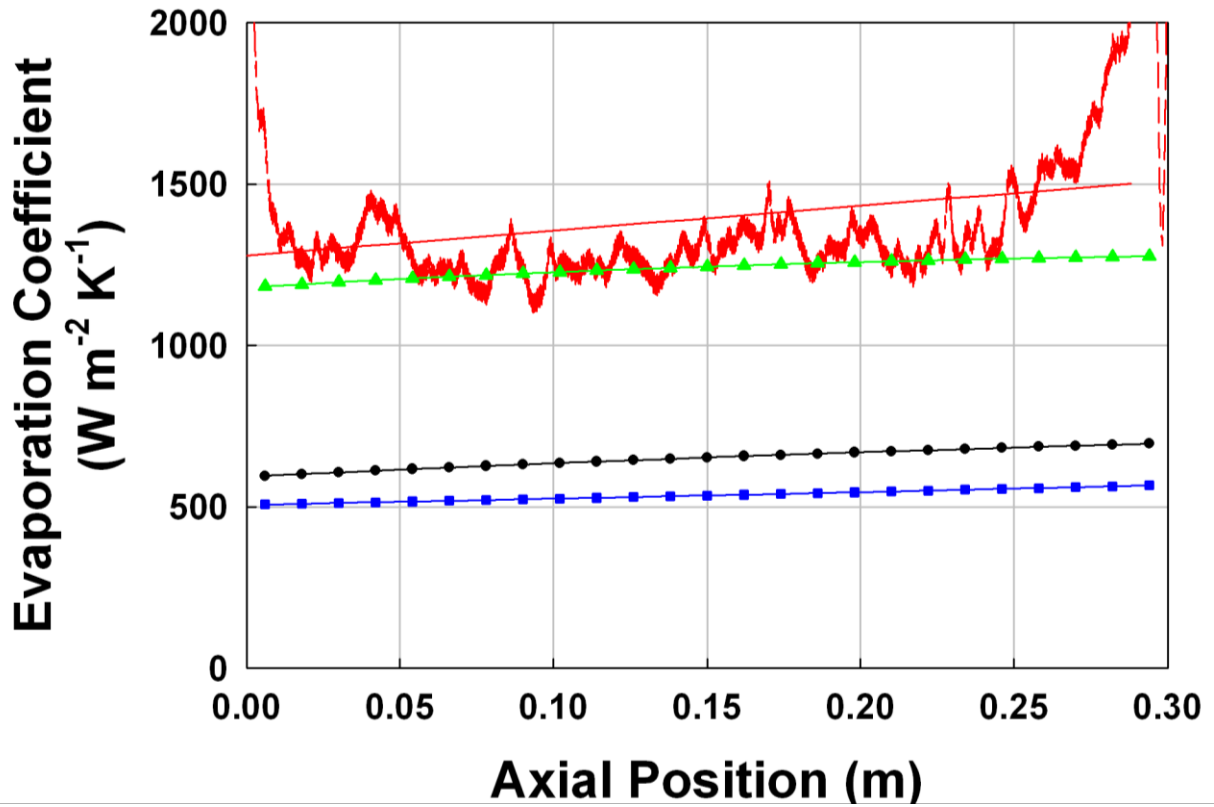




Applications: Taylor Flow Evaporation

- Simulation of coupling-fluid-heated evaporating Taylor flow
- Informed new wake-region heat transfer model





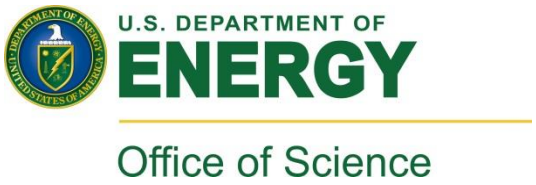
Summary

- **interThermalPhaseChangeFoam**: Extensible solver for liquid-vapor phase change processes
- Runtime selectable phase-change models: Yang *et al*., 2008; Kunkelmann & Stephan, 2009; Rattner & Garimella, 2014
- Validation cases for: Stefan problem, Nusselt problem, wavy film heat transfer, rising bubble condensation, droplet condensation on surface
- Applications in: wavy film HT, dropwise condensation, nucleate boiling, flow evaporation…

- Solver, libraries, tutorials, validation test scripts @ https://github.com/MahdiNabil/CFD-PC

Thank You

- Sponsors:



- Solver code and tutorials available @

https://github.com/MahdiNabil/CFD-PC

(OpenFOAM libraries V2.4.0)