Simulation of Phase-Change Fluid Flows for Energy Systems Engineering

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Phase Change Heat Transfer and You

- Great energy density in phase-change processes
  - 1 liter air (100 ➔ 200°C): **96 J**
  - 1 liter water (liquid ➔ vapor at 100°C): **2.2 MJ**
- Key stages in numerous energy intensive processes

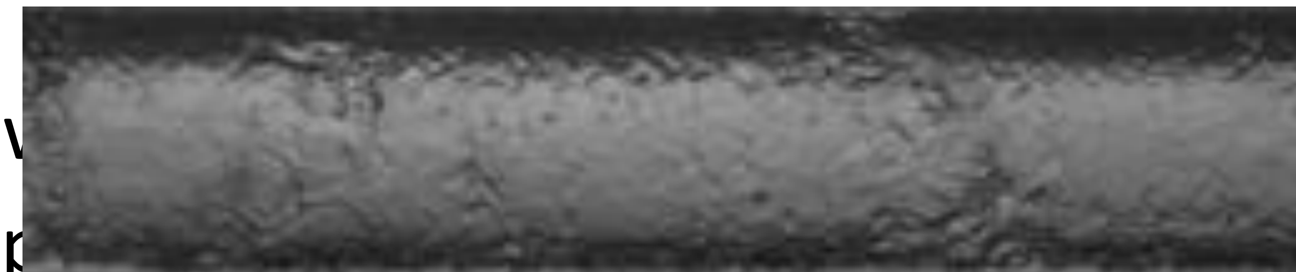
Electricity production
(Steam generation,
Steam condensation)

Air conditioning
(Evaporative cooling,
condensation heat rejection)

Distillation
(Selective condensation)

Challenges of Analyzing Phase Change

- **Multiphase flows**: distinct materials, discontinuities in domain, orientation and interfacial effects, wide range of scales
- Fev
- Exp nited local data



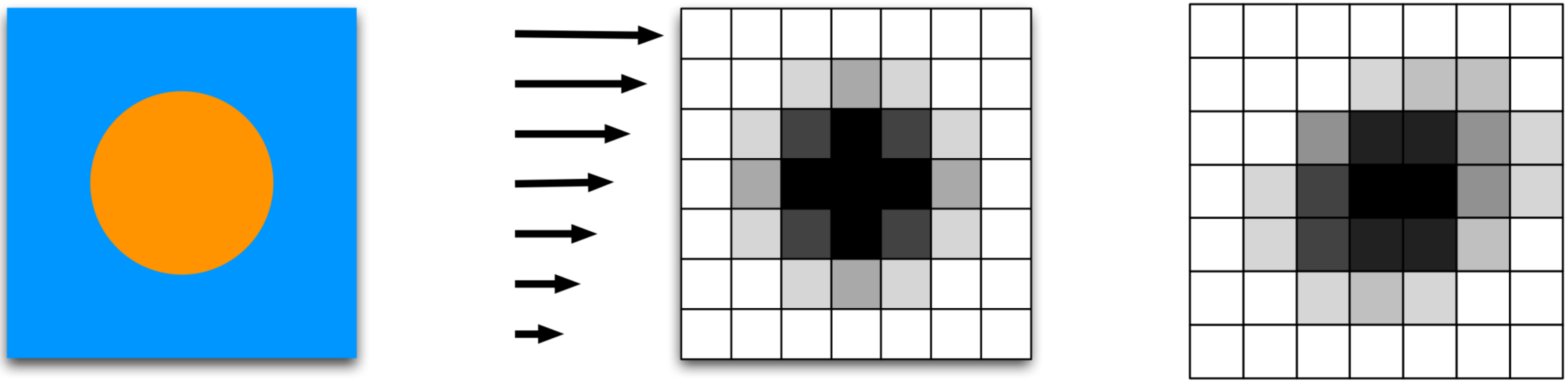
Milkie (2014)

Present research program:

- Direct simulation of phase change transport phenomena

VOF Simulation Approach

- Represent phase fraction in each cell with: $\alpha \in [0,1]$
- Solve advection equation for *α*: $\frac{\partial \alpha}{\partial t} + \frac{\partial}{\partial x_i}(u_i \alpha) = 0$
- Weight fluid properties with *α*: $\theta = \alpha \theta_L + (1-\alpha)\theta_G$
- Volumetric surface tension force in interface cells



Phase Change Formulation

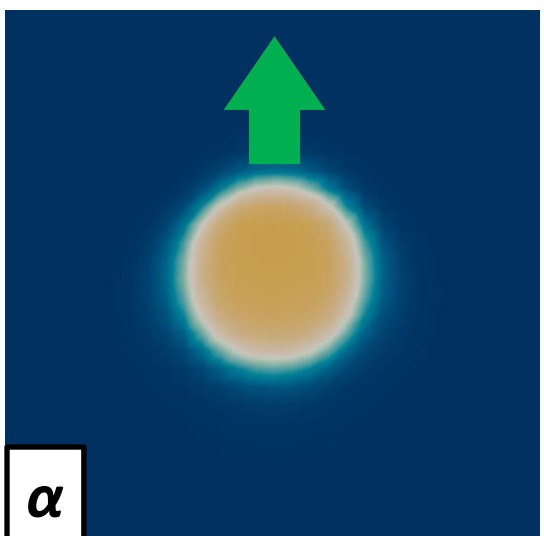
- Phase-change simulations still in their infancy
- New first-principles based scalable phase-change approach to couple (***U***, ***P***, ***α***, ***T***)

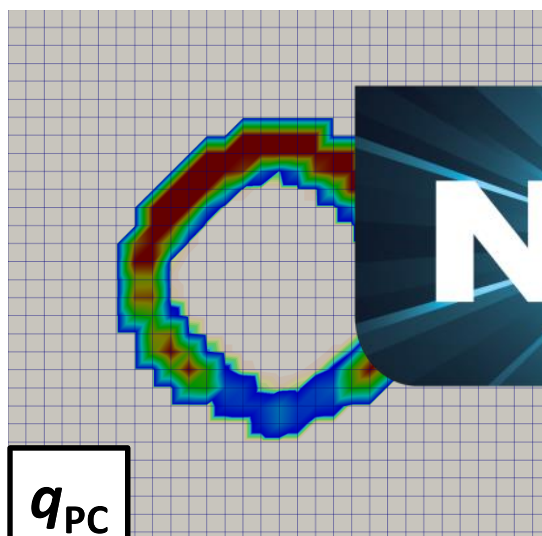
Continuity $$\frac{\partial u_{\mathrm{i}}}{\partial x_{\mathrm{i}}} = \dot{v}_{\mathrm{PC}}$$

Momentum $$\rho \frac{\partial u_{\mathrm{i}}}{\partial t} + \rho u_{\mathrm{j}} \frac{\partial u_{\mathrm{i}}}{\partial x_{\mathrm{j}}} = -\frac{\partial p}{\partial x_{\mathrm{i}}} + \mu_{\mathrm{eff}} \frac{\partial^2 u_{\mathrm{i}}}{\partial x_{\mathrm{i}} \partial x_{\mathrm{j}}} + f_{\mathrm{i}}$$

Phase $$\frac{\partial \alpha}{\partial t} + \frac{\partial}{\partial x_{\mathrm{i}}}\left(u_{\mathrm{i}}\alpha\right) = \dot{\alpha}_{\mathrm{PC}}$$

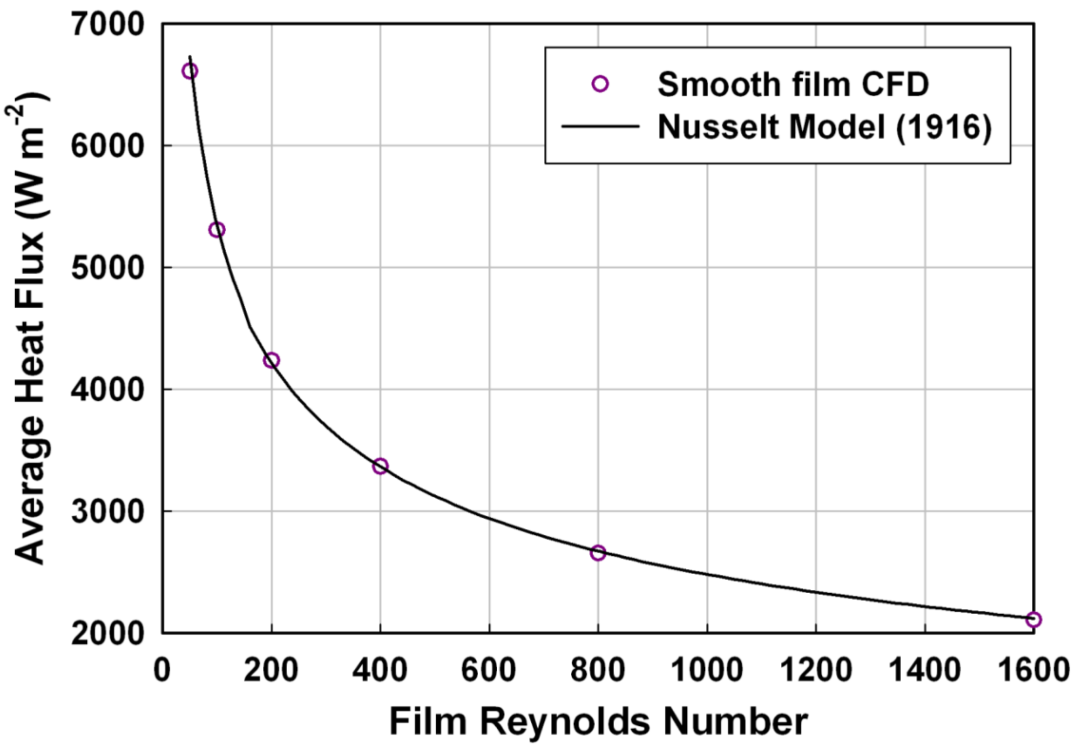
Energy $$\frac{\partial\left(\rho h\right)}{\partial t} + \frac{\partial}{\partial x_{\mathrm{i}}}\left(\rho u_{\mathrm{i}} h\right) = \frac{\partial}{\partial x_{\mathrm{i}}}\left[k_{\mathrm{eff}} \frac{\partial T}{\partial x_{\mathrm{i}}}\right] - \dot{q}'''_{\mathrm{PC}}$$



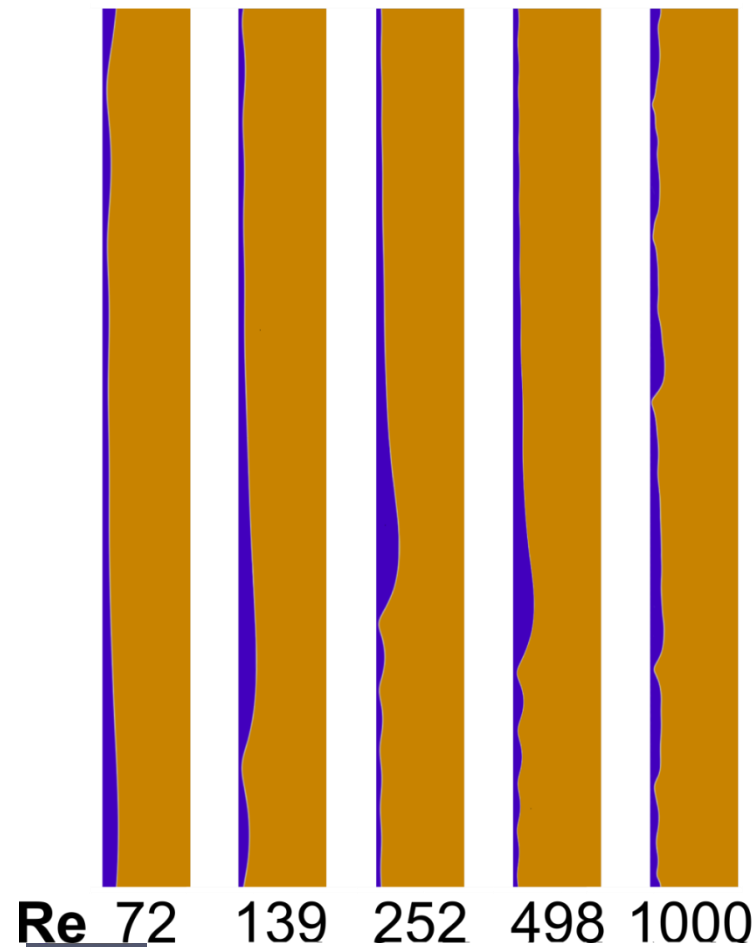


Validation: Falling Film Condensation

- Smooth falling-film condensation – first principles model
- Wavy-film condensation – empirical correlations

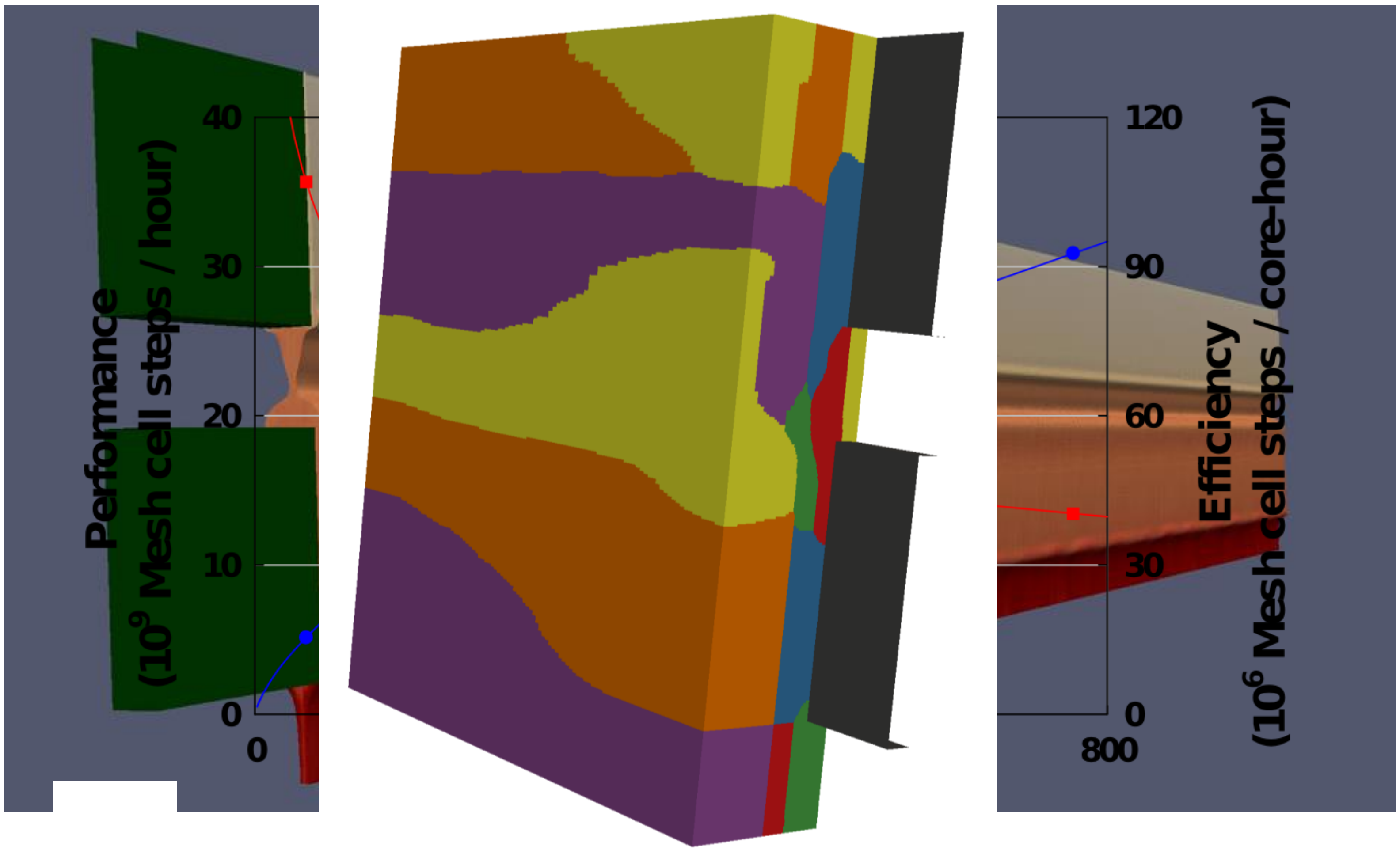


Agreement within 1%



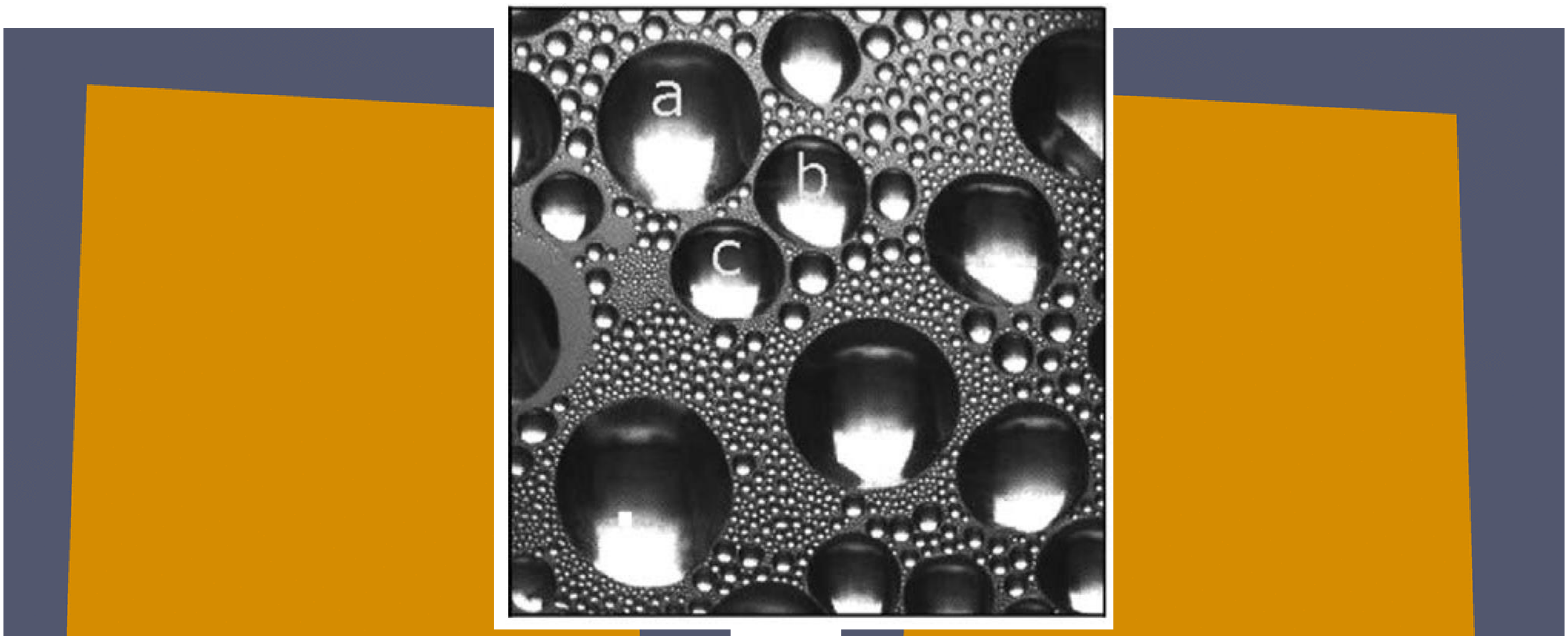
Scaling to HPC Systems

- Model problem: Falling Film Absorption
- MPI-based domain decomposition parallelization



Applications: Dropwise Condensation

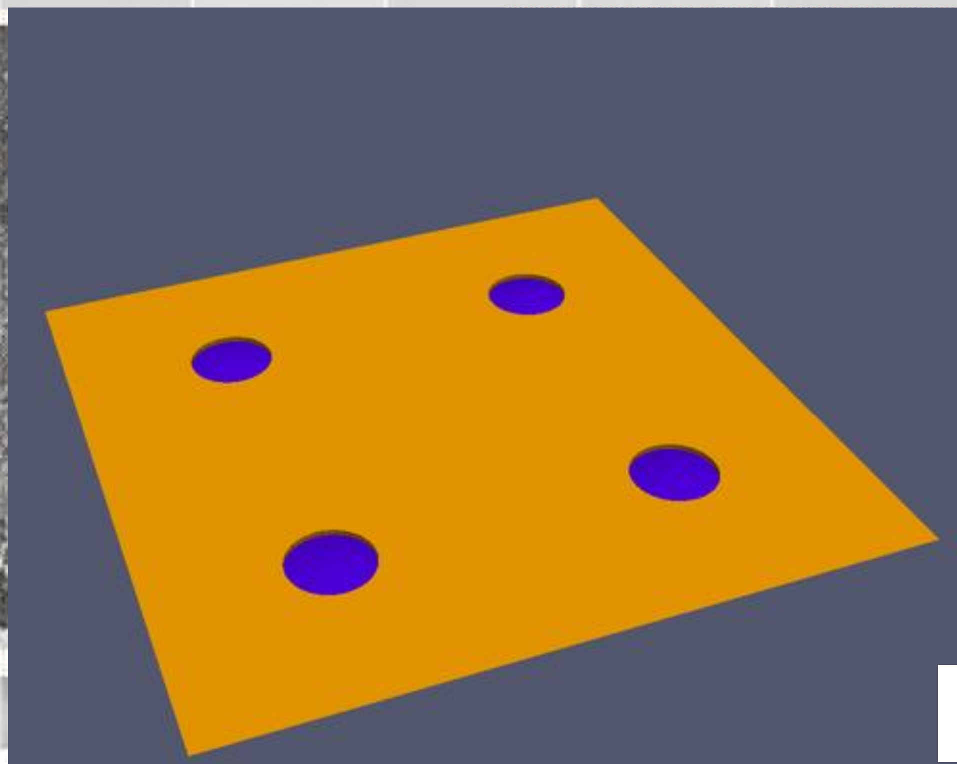
- High heat flux condensation mode on non-wetting surfaces (10× filmwise): promising for power plant applications
- Great range of scales (10^4) → candidate for HPC simulation
- Previous studies model drops as rigid particles (neglect hydrodynamics)

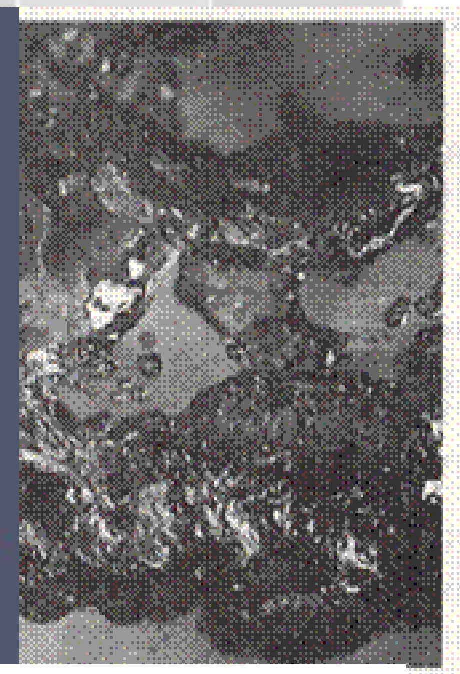


Sikarwar *et al.* (2010)

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

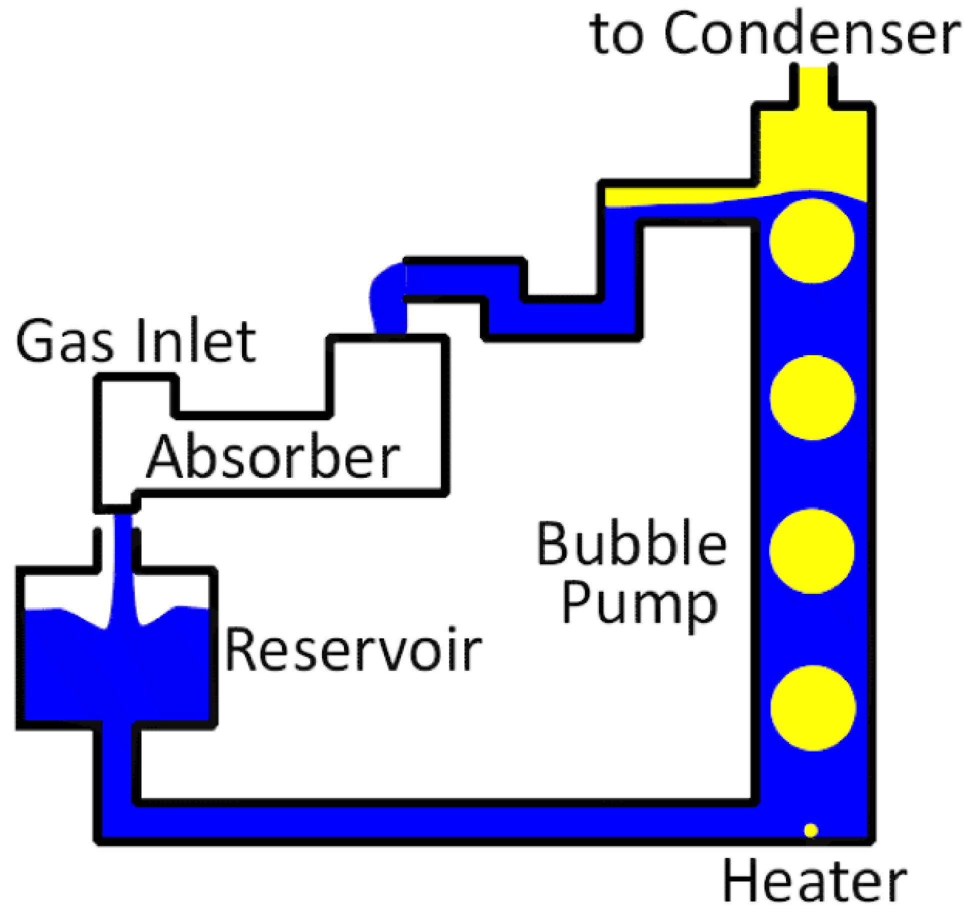




Samuel (2012)

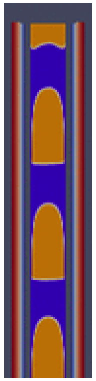
Applications: Taylor Flow Evaporation (1)

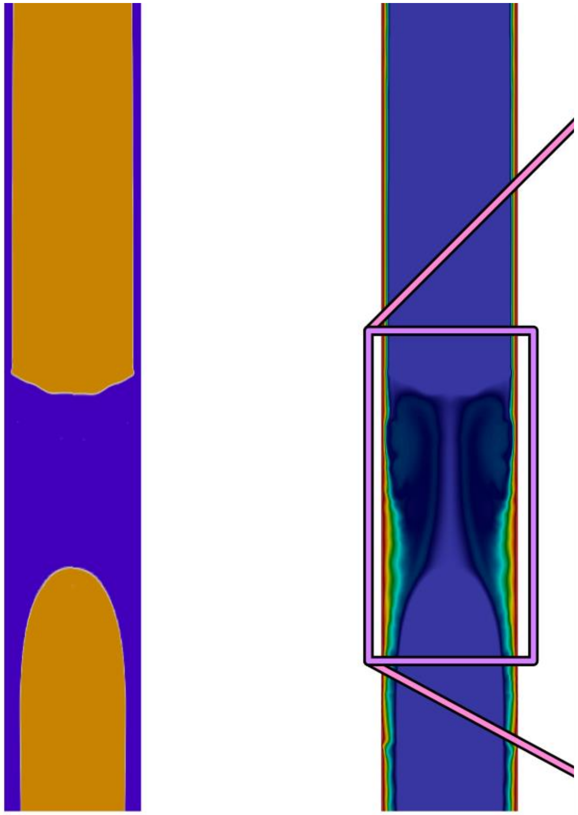
- **Bubble pumps**: passive fluid circulation in diffusion absorption refrigeration cycle
- Experiments ➔ global validation of analytical BP models
- Simulations for more rigorous assessment

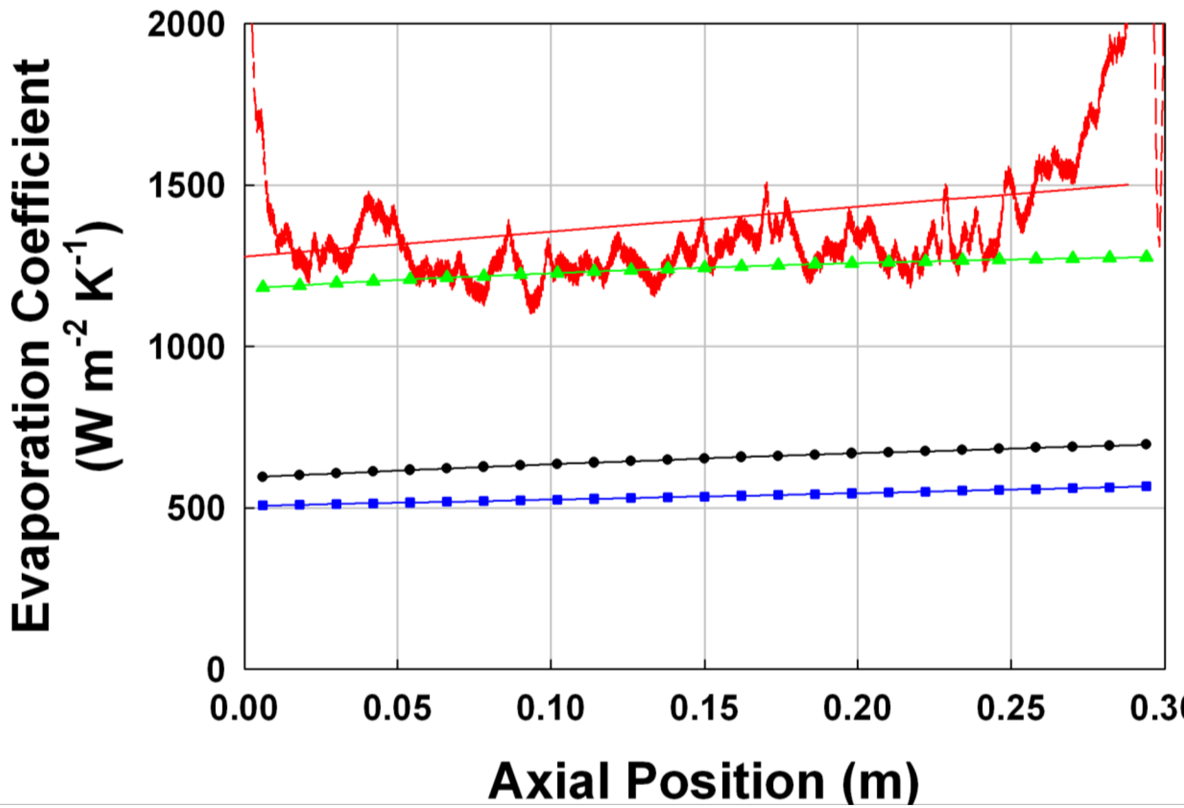


Applications: Taylor Flow Evaporation (2)

- Simulation of coupling-fluid and evaporating flows
- Individual assessment of sub-models: L_b, L_s, U_b, δ_f
- Improved wake-region heat transfer model

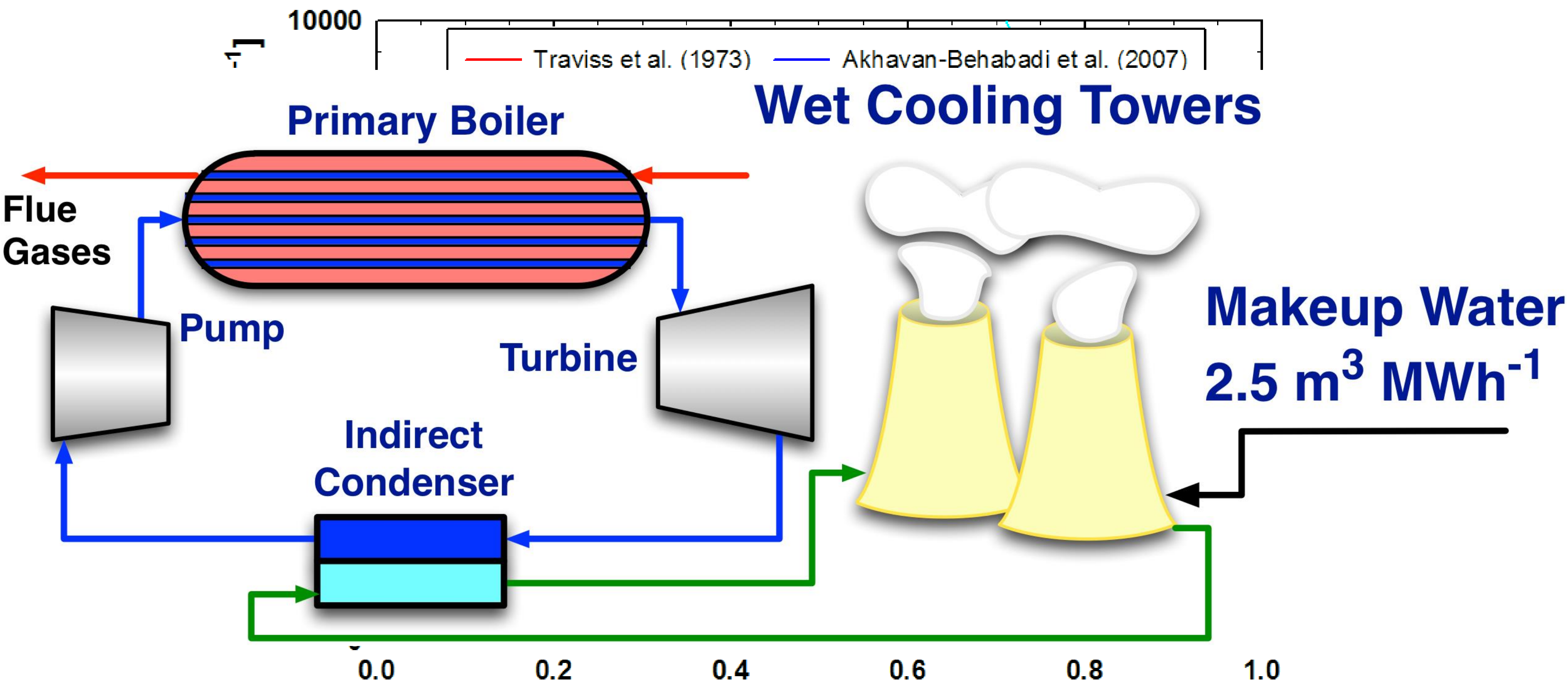






Applications: Air-Cooled Condensers (1)

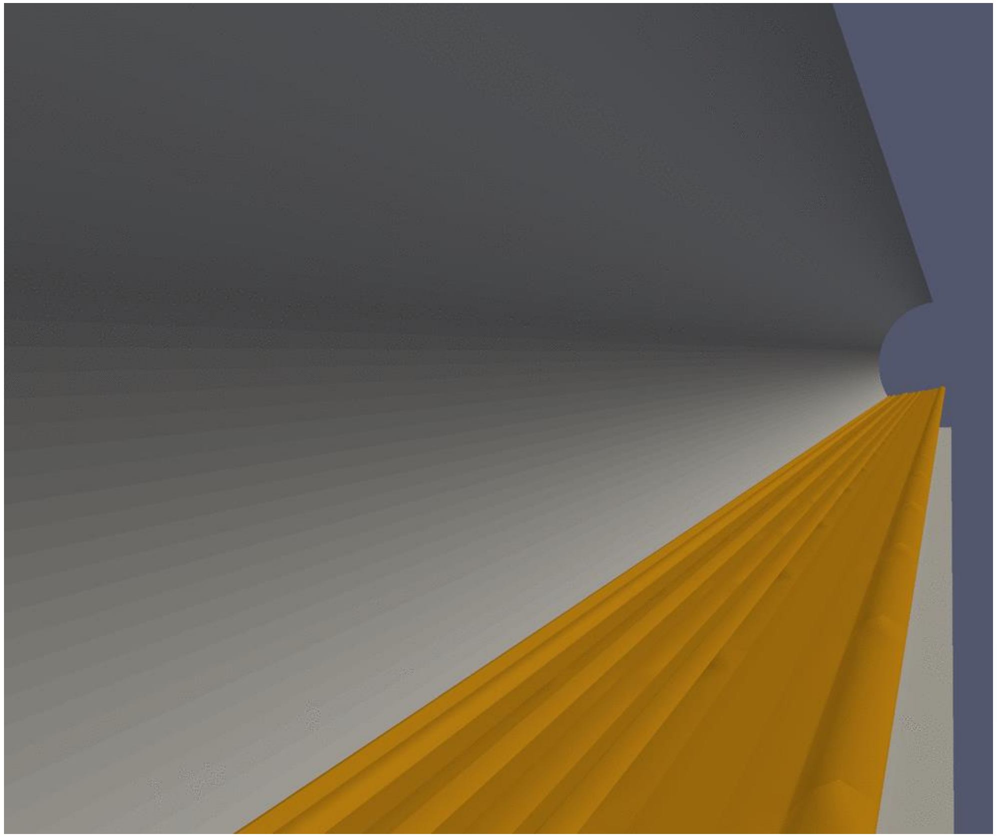
- Power plant condensers account for 38% of US fresh water
- Interest in dry ACCs, but significant engineering challenges
- Steam-side phenomena poorly understood at relevant scales

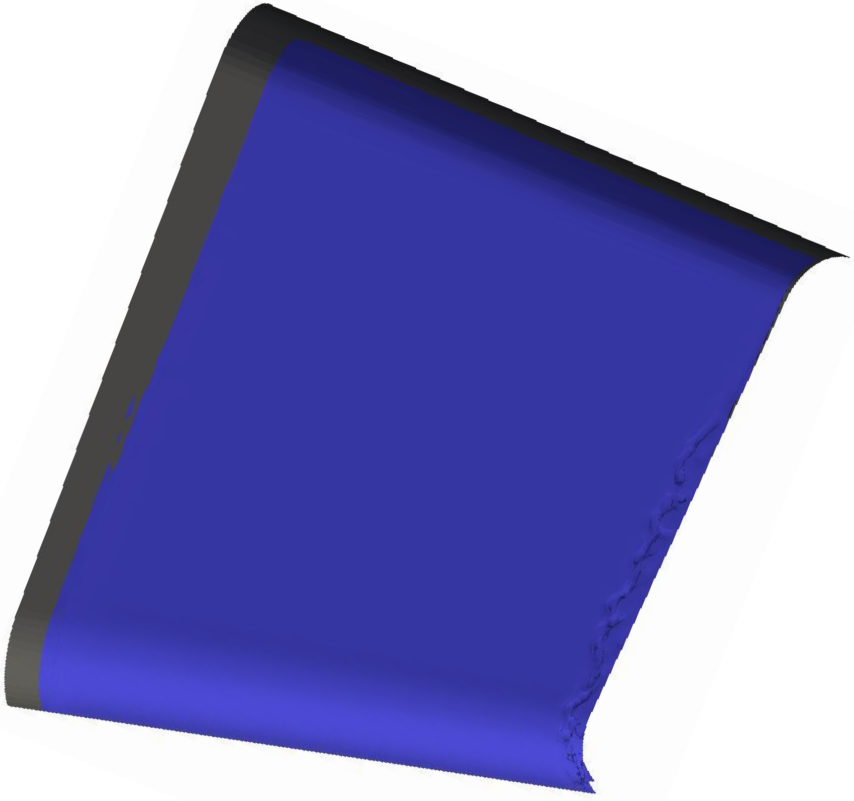


Mahvi *et al.* (2015)

Applications: Air-Cooled Condensers (2)

- Direct simulation of flow condensation in ACC tubes
- Resolve steam-side transport mechanics





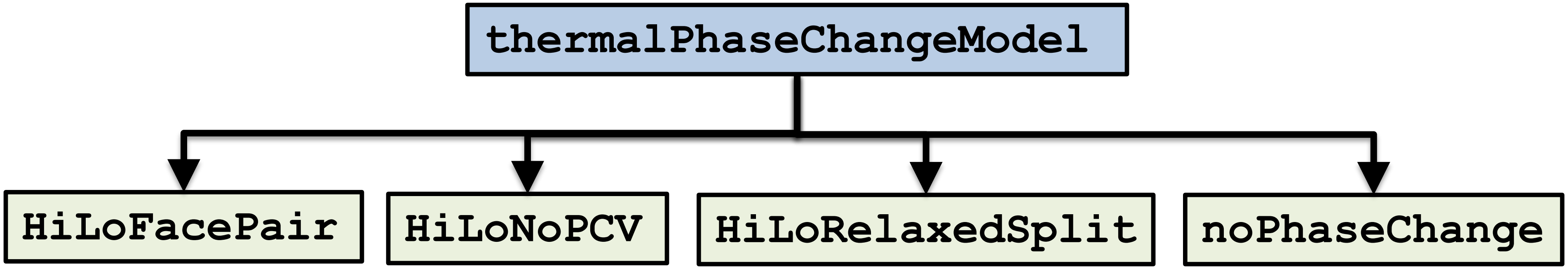
Summary

- Fluid phase change → key transport mechanism for energy technologies
  - **Analytical approaches**: only for simplest cases
  - **Experiments**: cannot instrument full range of scales

- **Validated** and **scalable** formulation developed to directly simulate phase-change phenomena
- Applications in: Falling-film absorption, dropwise condensation, nucleate boiling, flow evaporation…
- Complements experiments to inform engineering models

Next Steps

- Multiple phase-change simulation studies in literature (NIH Syndrome)
- Currently we are open-sourcing our solver https://github.com/MahdiNabil/CFD-PC.git
  - Based in OpenFOAM environment
  - Extensible implementation: select phase-change model at run-time



Thank You

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- Sponsors: