Enhancing Steam-Side Heat Transfer via Microdroplet Ejection using Inorganic Coatings

Project ID: FE0031675

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Outline

- Overview
- Lattice Boltzmann Method
- Results & future goals
- Mini Condenser System

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- **Overview**
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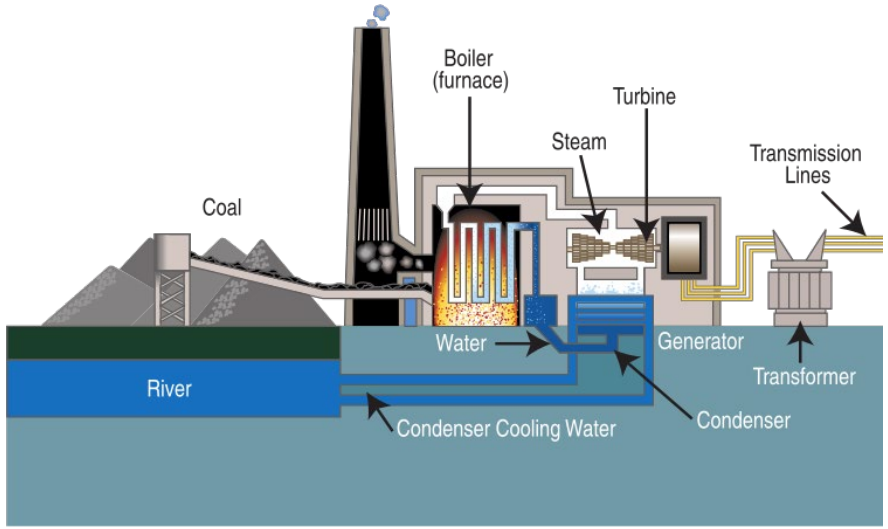
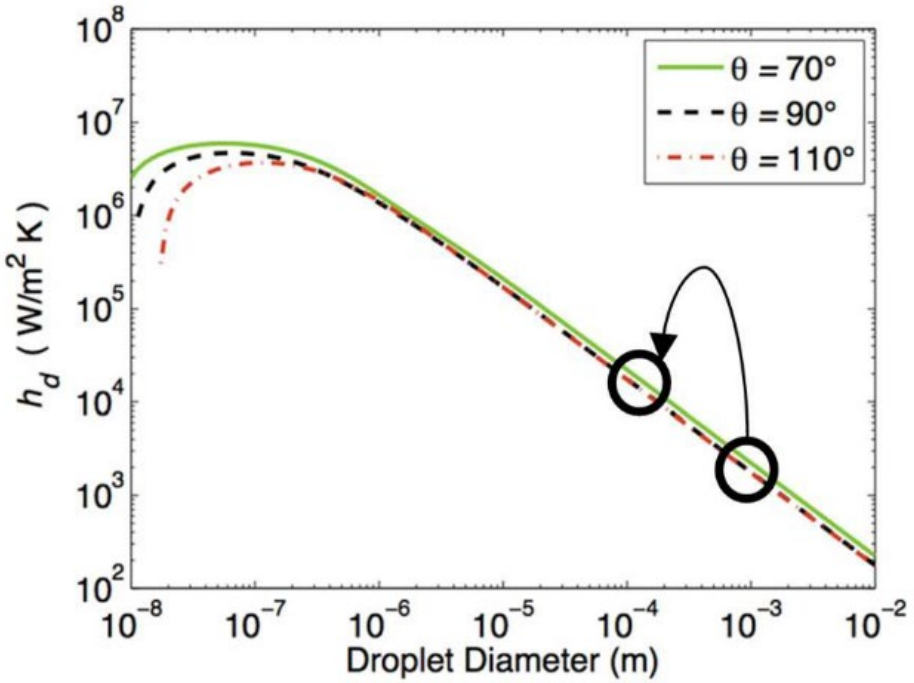
Motivation

- Power generation in the US is the primary source of water usage in the country

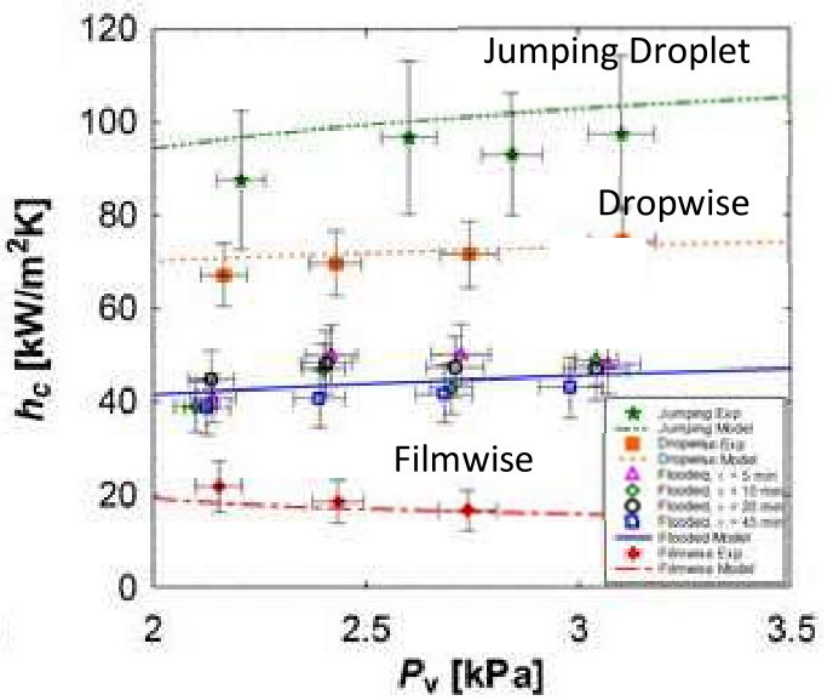


- Reduce water consumption approaches:
  - Increase condenser efficiency
  - Retrofit plant to recirculating or dry condenser
  - Recycle water withing the plant for other applications

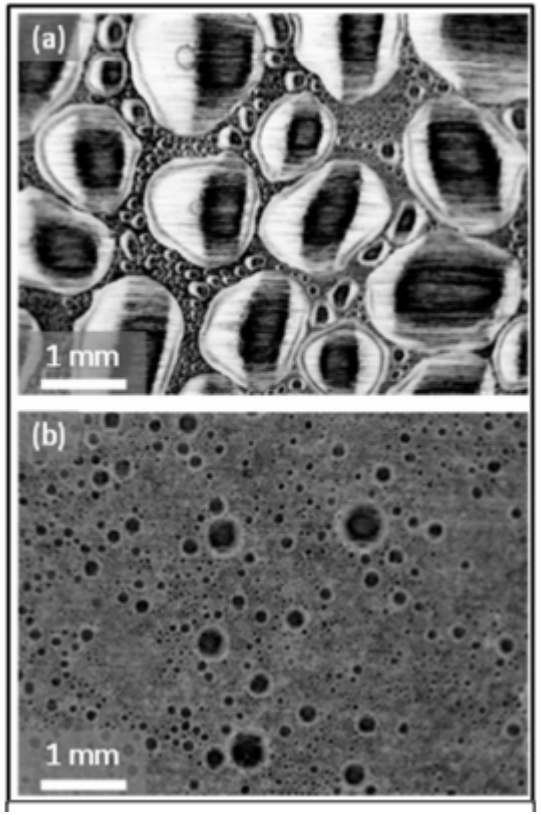
Increasing condenser efficiency



H. Mendoza, et al. (2014)



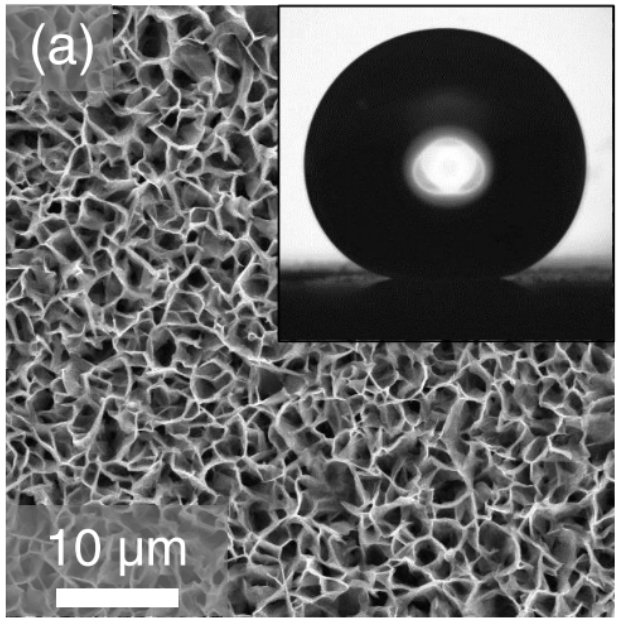
N. Miljkovic , et al. (2013)



- Increase condenser efficiency by increasing shell-side heat transfer coefficient using Nelumbo's droplet ejection coatings

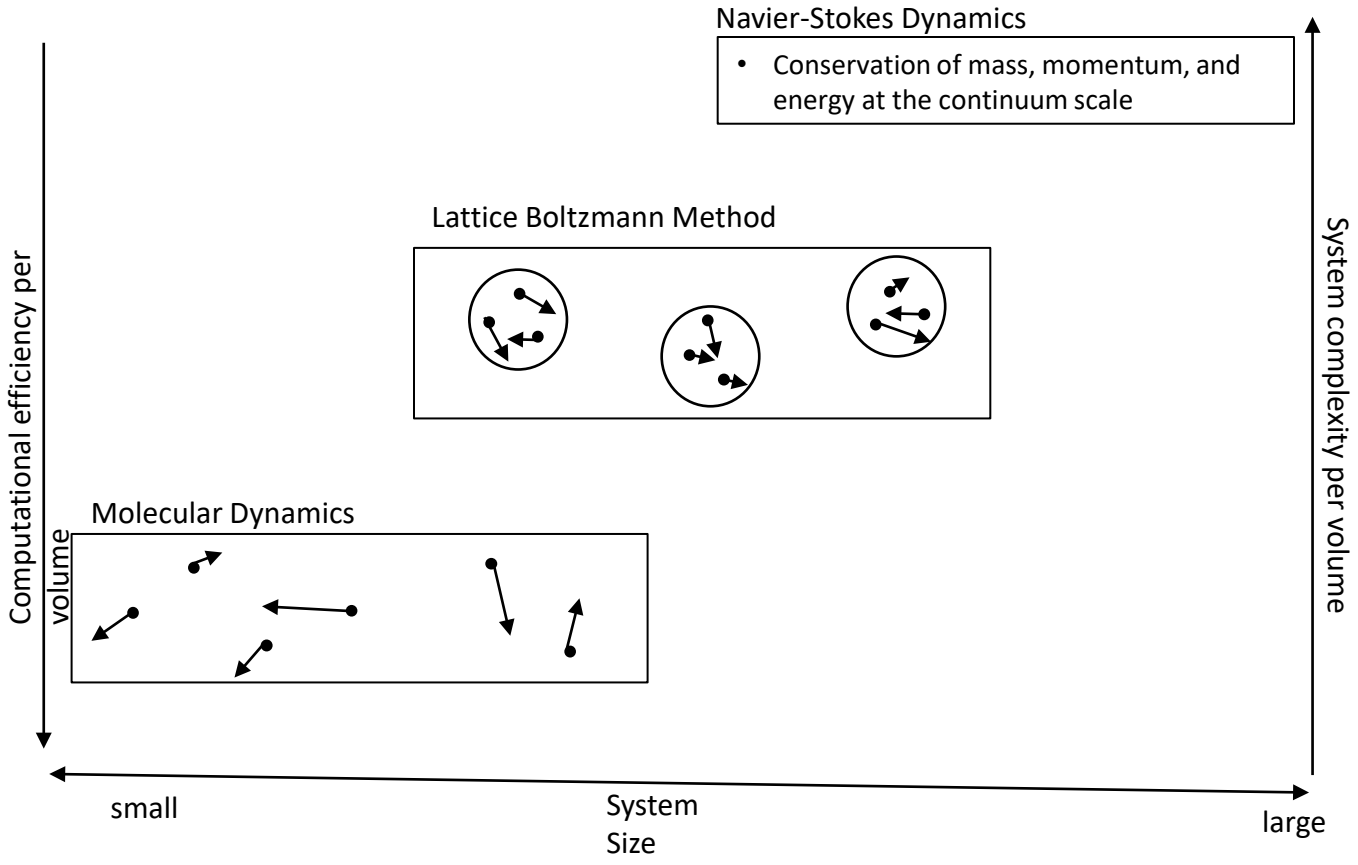
Droplet Dynamics Model

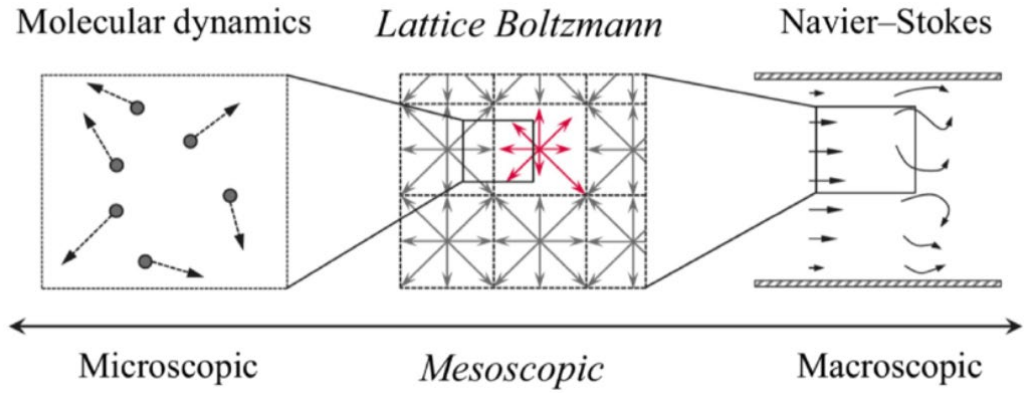
- LBL deliverable is to develop a microscale droplet dynamics based thermal model for Nelumbo's inorganic coatings on the condenser surface to understand the physics of thermal transport of their coating and guide further design



L. Brockway, et al. (2017)

Simulations of fluid flow at different scales

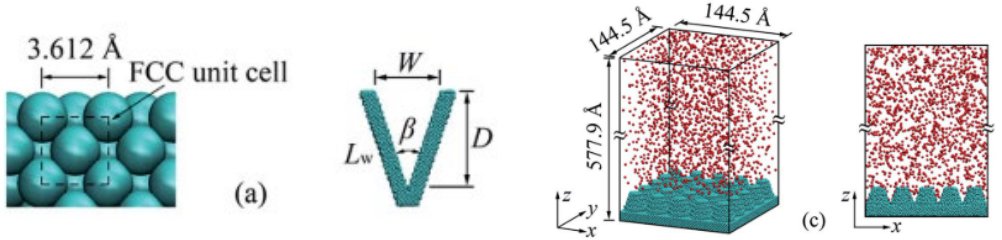




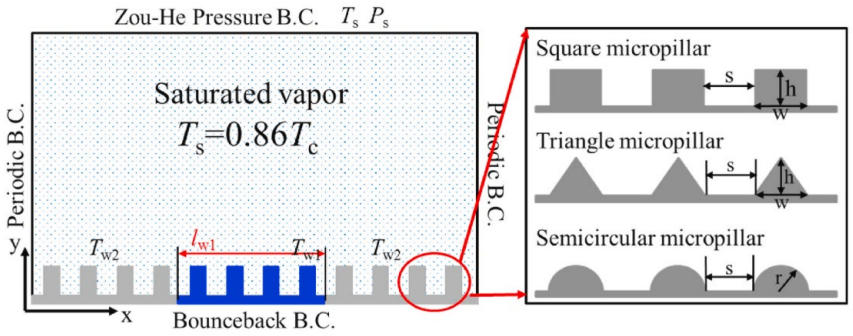
Saito et al. (2017)

Droplet Dynamics Model

- Simulations that have focused on both nucleation and growth are done using MD, where the length scales aren't applicable
- 2D LBM used to model dropwise condensation heat transfer to investigate effects of surface wettability, surface microstructure and subcooling degree on the condensate dynamic behaviors.
- *Goal: Extend LBM to 3D, with features like Nelumbo's reentrant jumping droplet surfaces*



N. Dong, et al. (2018)



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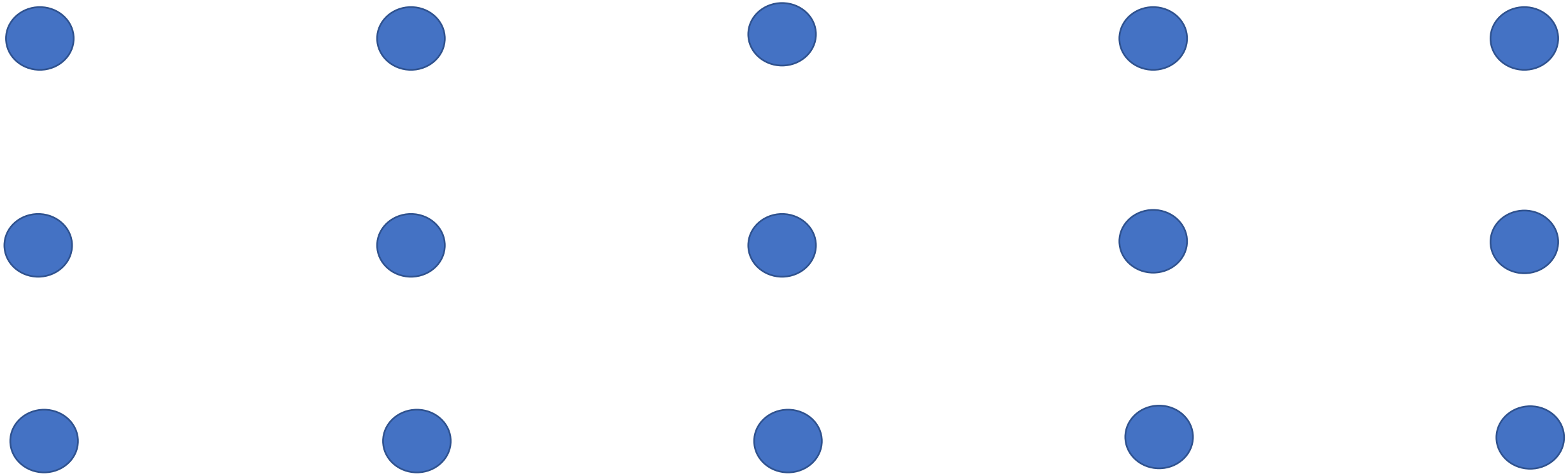
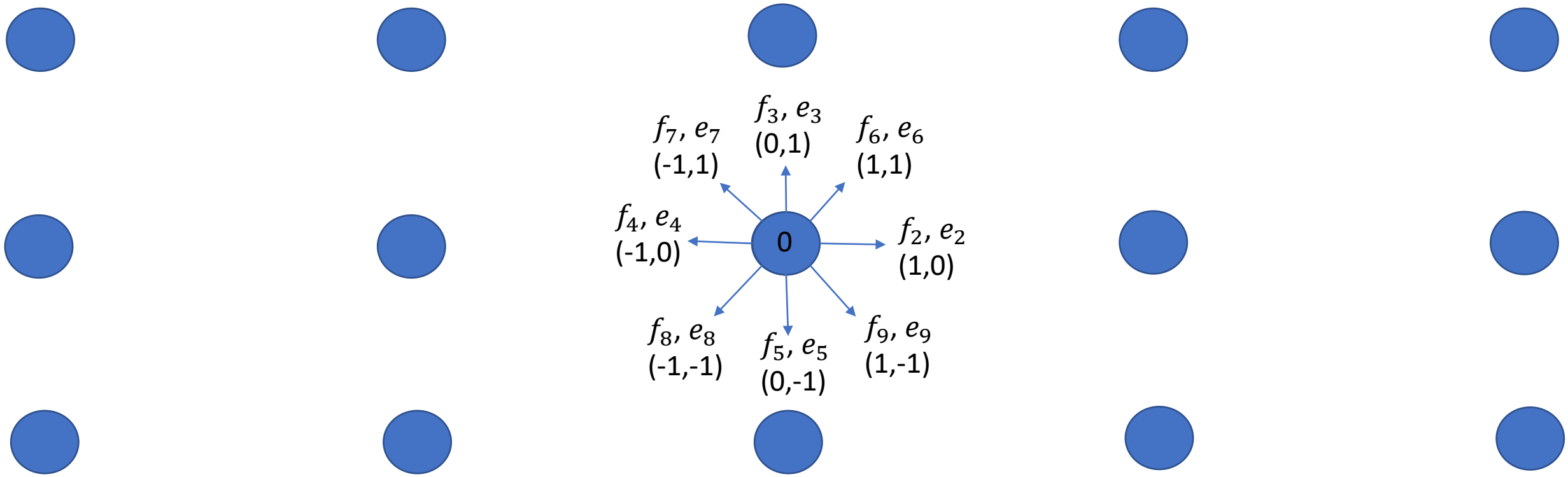
- **Lattice Boltzmann Method**
- Results & future goals
- Mini Condenser System

The nodes represent your system



The nodes represent your system

- Here, we are using a D2Q9 system



Macroscopic density & velocity

- Lattice Fluid Density

$$\rho = \sum_{i=1}^{9} f_i$$

- Lattice Fluid Velocity

$$\mathbf{u} = \frac{1}{\rho} \sum_{i=1}^{9} f_i \, \boldsymbol{e_i}$$

Governing Equation

$$\underbrace{f_i(x + e_i\delta_t, t + \delta_t) = f_i(x + t)}_{\text{Streaming}} \underbrace{- \frac{1}{\tau}\left[f_i(x,t) - f_i^{eq}(\rho, u^{eq})\right]}_{\text{Collision}}$$

- Collisions of the fluid particles is considered as a **relaxation towards a local Equilibrium**, in the D2Q9 case, towards the equilibrium distribution function. Here, $f_i^{eq}(\rho, u^{eq})$ is the Bhatnagar-Gross-Krook (BGK) approximation

$$f_i^{eq}(\rho, u^{eq}) = w_i\rho(\boldsymbol{x})\left(1 + 3\boldsymbol{e_i u} + \frac{3}{2}(\boldsymbol{e_i u})^2 - \frac{3}{2}\boldsymbol{u}^2\right)$$

Force on Fluid Component

- Force on component σ:

$$\mathbf{F}_\sigma(\mathbf{x}) = -G\psi_\sigma(\mathbf{x},t)\sum w_a\psi_{\bar{\sigma}}(\mathbf{x}+\mathbf{e}_a\Delta t,t)\mathbf{e}_a = -G\rho_\sigma\sum_{i=1}^{9} w_i\rho_{\bar{\sigma}}e_i$$

  - $\bar{\sigma}$ indicates the other fluid component.
  - $\psi_\sigma = \rho_\sigma$ and $\psi_{\bar{\sigma}} = \rho_{\bar{\sigma}}$

- Strength of the interaction potential between component is a Green's function:

$$G(x-x') = \begin{cases} 0, |x-x'| > c \\ g, |x-x'| = c \end{cases}$$

Macroscopic velocity

- Before collision, the fluid velocity on a lattice node x is

$$\boldsymbol{u}(\boldsymbol{x}) = \frac{1}{\rho(\boldsymbol{x})} \sum_i f_i(\boldsymbol{x}) \boldsymbol{c}_i$$

- In the absence of a force, collision leaves the momentum and velocity invariant (never changing). The only mechanism that can change the fluid velocity during collision is a body force:

$$\boldsymbol{u}^\star(\boldsymbol{x}) = \frac{1}{\rho(\boldsymbol{x})} \sum_i f_i^\star(\boldsymbol{x}) \boldsymbol{c}_i = \frac{1}{\rho(\boldsymbol{x})} \sum_i f_i(\boldsymbol{x}) \boldsymbol{c}_i + \frac{\boldsymbol{F}(\boldsymbol{x}) \Delta t}{\rho(\boldsymbol{x})}$$

* denotes post-collision

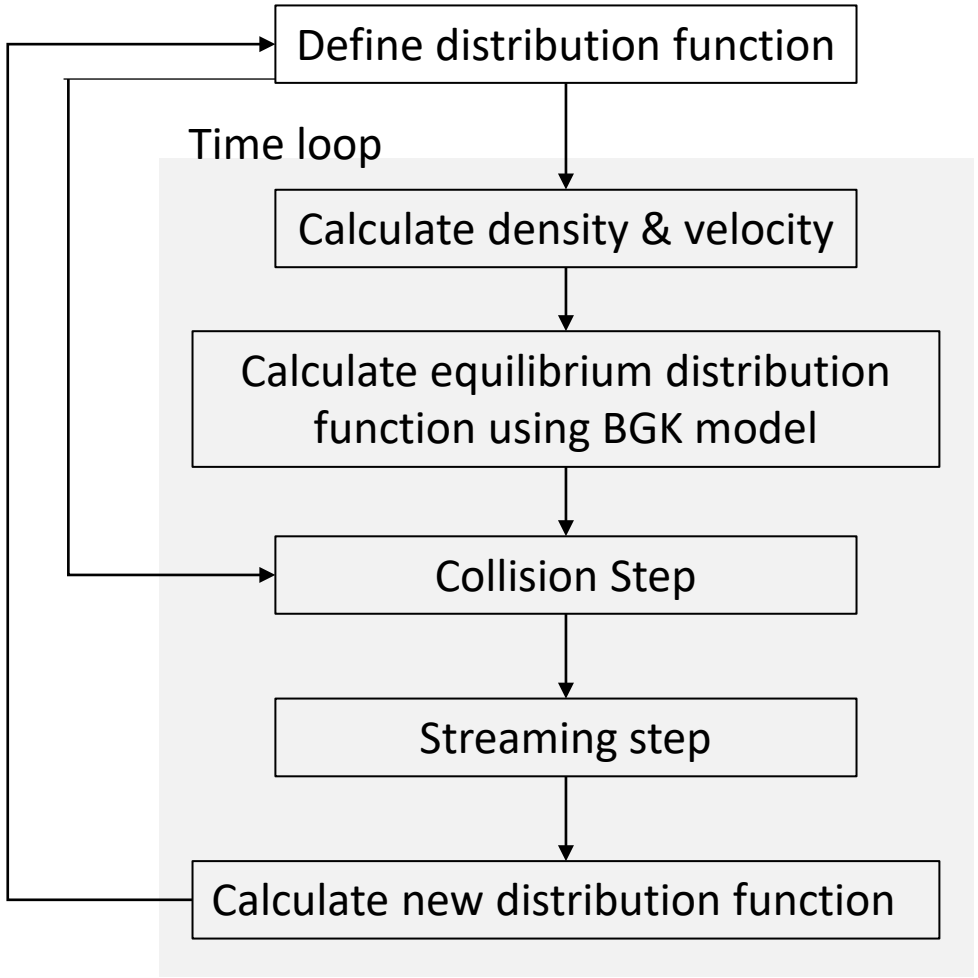
- We know that a the physical fluid velocity during a time step is the average of the pre-and-post-collision velocities:

$$\boldsymbol{u}_\mathrm{f}(\boldsymbol{x}) = \frac{\boldsymbol{u}(\boldsymbol{x}) + \boldsymbol{u}^\star(\boldsymbol{x})}{2} = \boldsymbol{u}(\boldsymbol{x}) + \frac{\boldsymbol{F}(\boldsymbol{x}) \Delta t}{2\rho(\boldsymbol{x})}$$

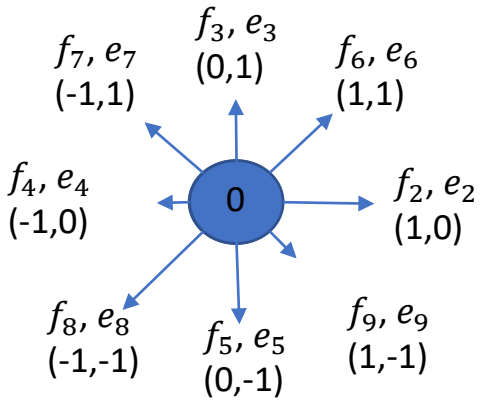
- The equilibrium distribution function is computed from a composite macroscopic velocity (u'=represents the flow of the bulk fluid)

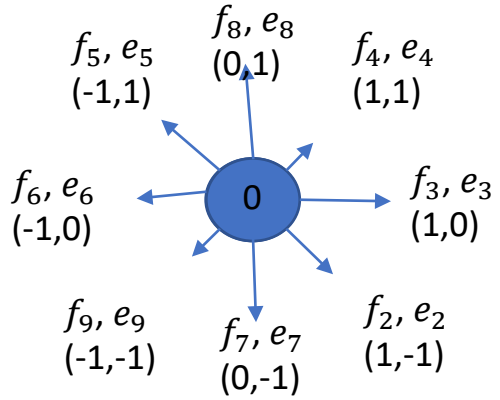
$$\boldsymbol{u}(\boldsymbol{x}) = \mathbf{u}' = \frac{\sum_\sigma \frac{1}{\tau_\sigma} \sum_a f_a^\sigma \mathbf{e}_a}{\sum_\sigma \frac{1}{\tau_\sigma} \rho_\sigma}$$

Outline of LBM

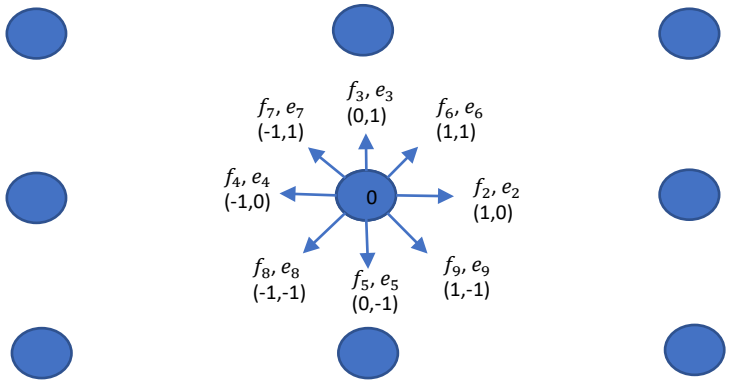


Collision Step:





Streaming Step:



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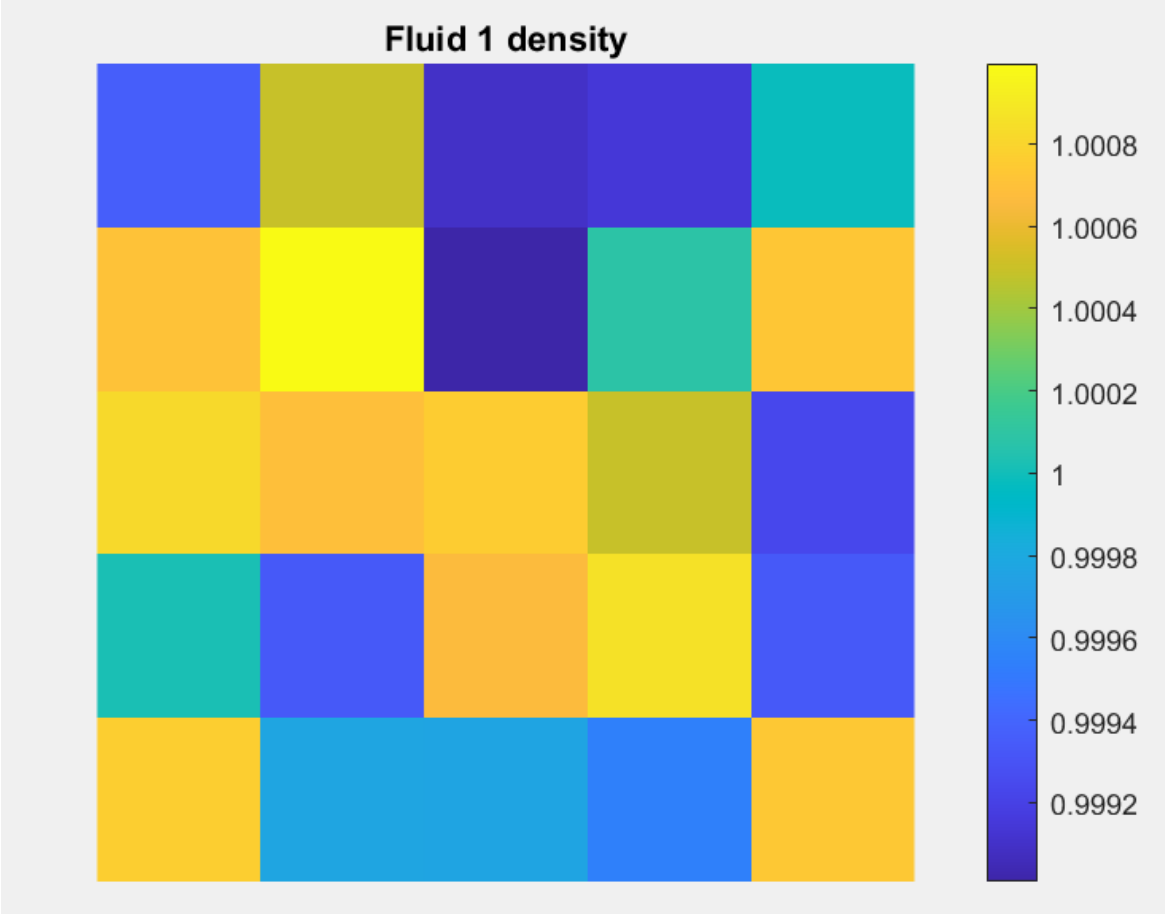
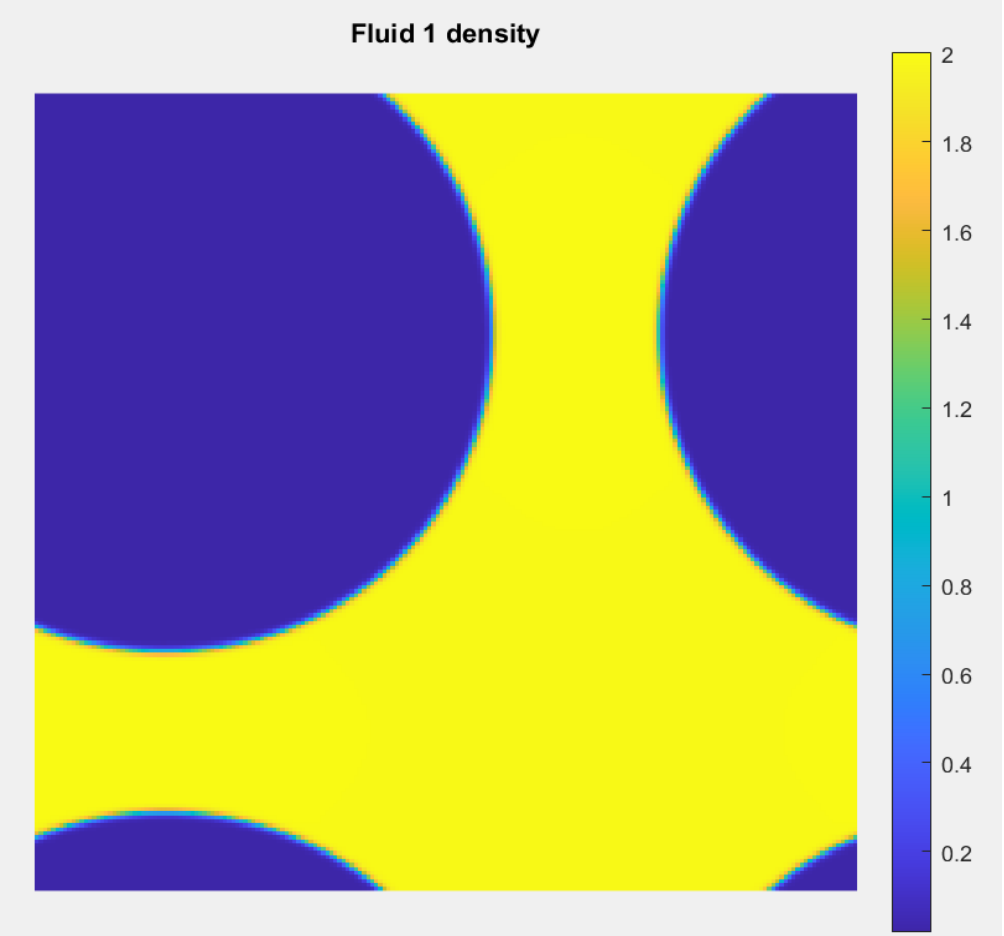
Shan and Chen Simulation Results

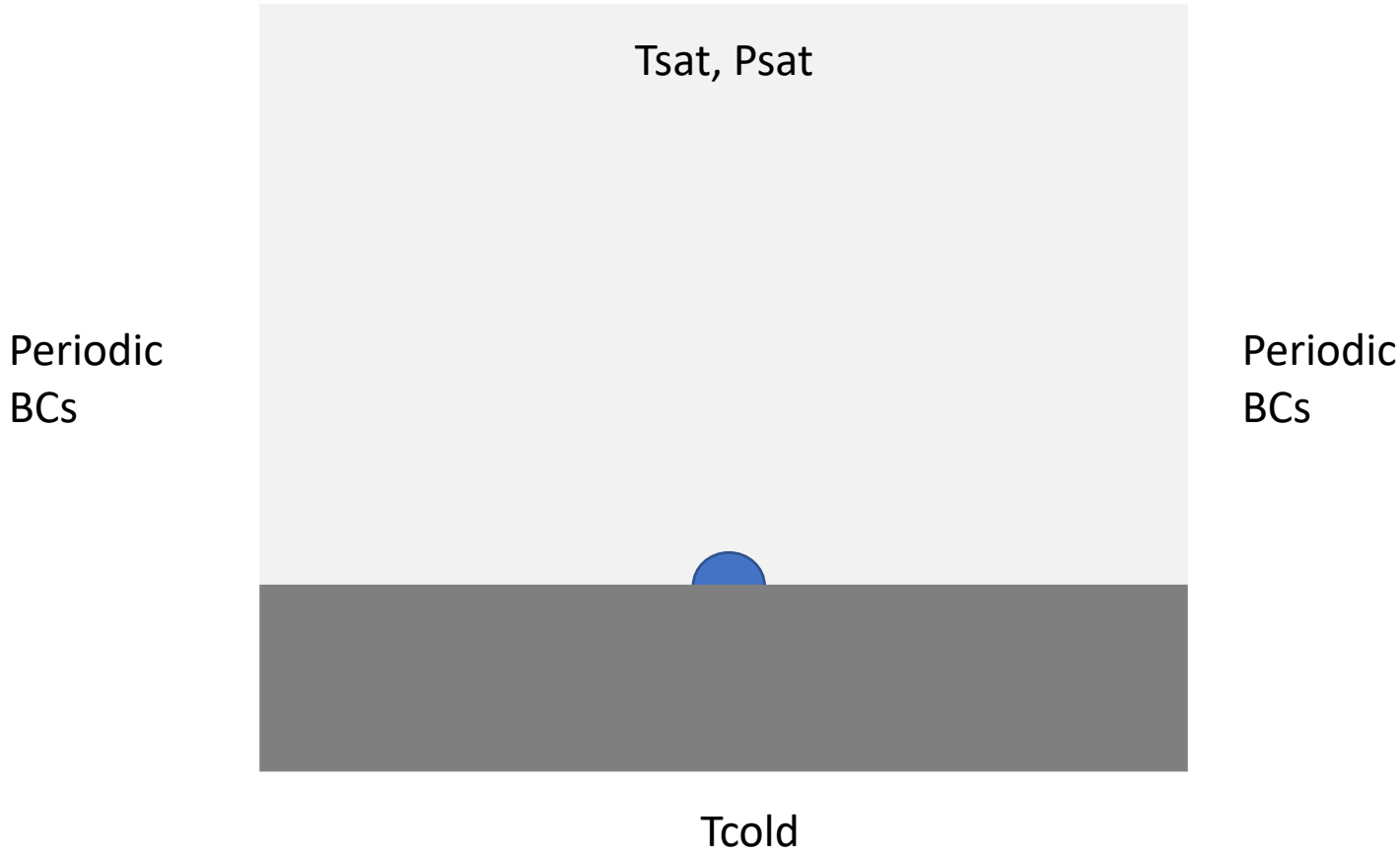
t=0 time steps



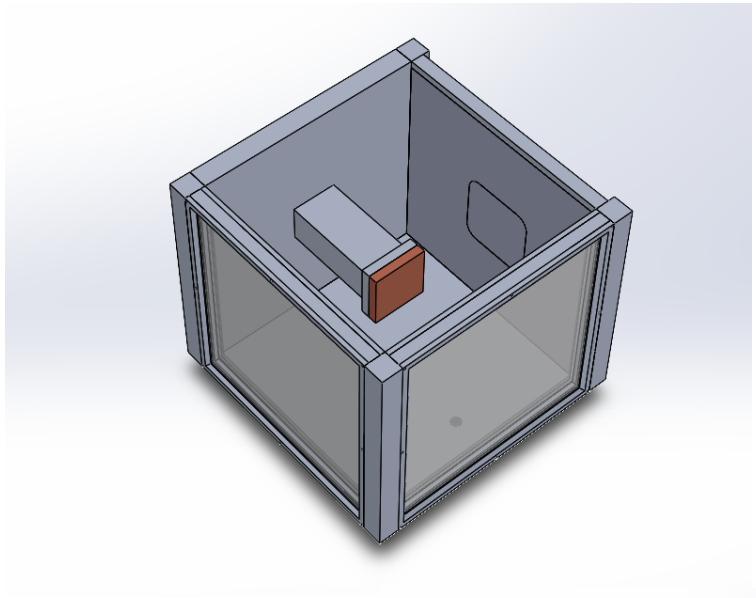
t=80,000 time steps

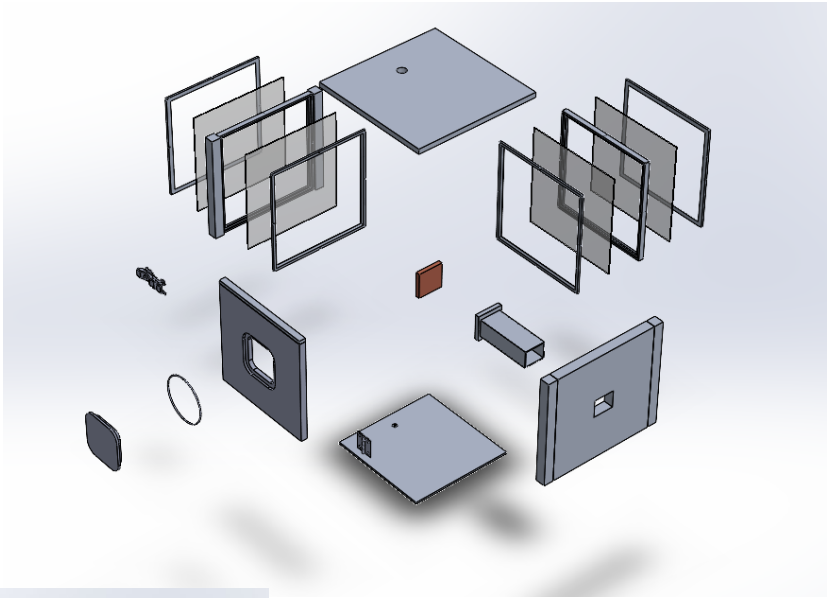


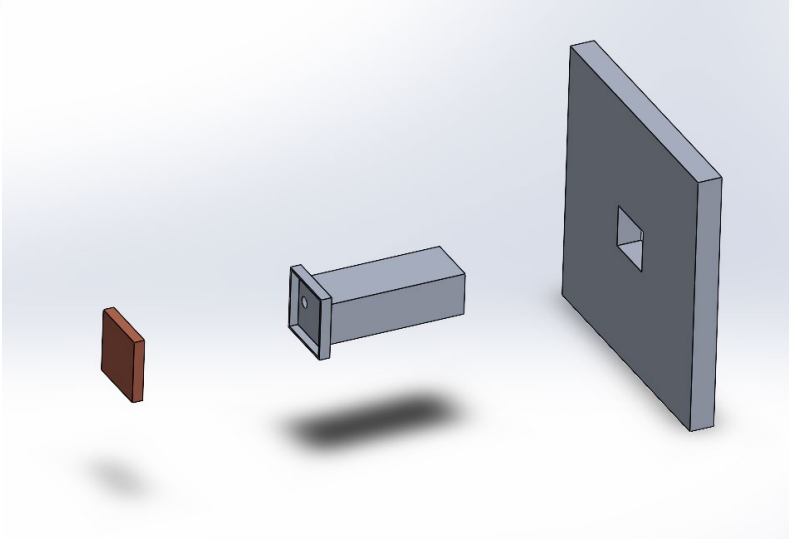
Next Steps on Simulation



Mini Condenser System







Concluding Remarks

- Developed Shan and Chen model as a starting point to LBM
  - Will continue to expand on the model to eventually include reentrant surfaces
- Finalizing design on mini-condenser system for model validation

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