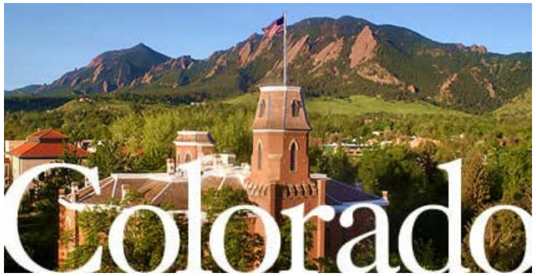
DEM Simulations of Falling Particles Flowing in Crossflow Around a Heated Cylinder



2013 NETL Workshop on Multiphase Flow Science

7-Aug-2013

Dr. Aaron Morris	University of Colorado (post-doc)
Dr. Zhiwen Ma	NREL (co-PI)
Dr. Sreekanth Pannala	ORNL (co-PI)
Prof. Christine Hrenya	University of Colorado (PI)
Dr. Tom O’Brien	retired NETL (co-PI)

Motivation

Concentrating Solar Power

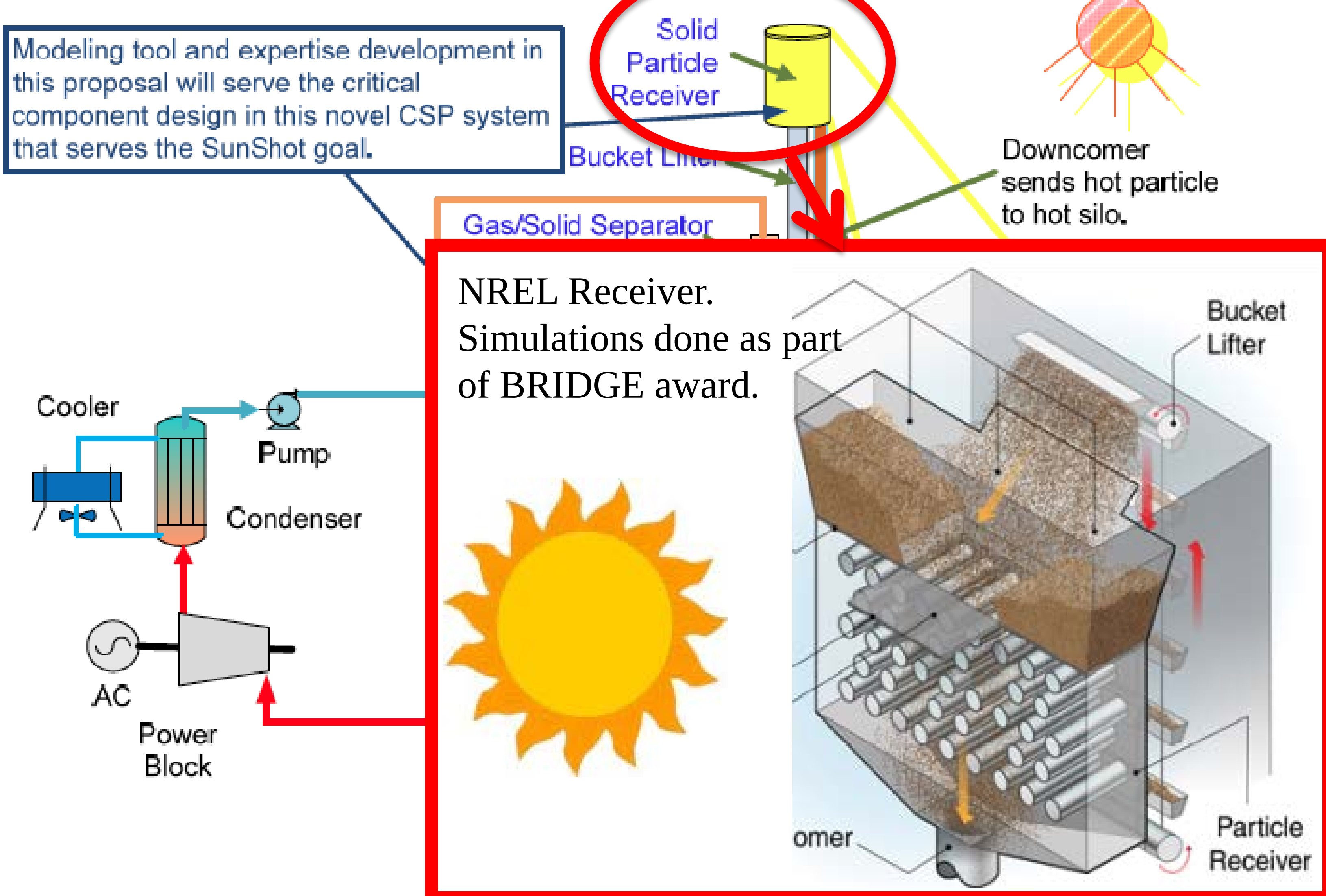
- Solar radiation warms heat transfer fluid (HTF) to power a turbine.
  - *Power tower*
  - *Parabolic mirrors*
  - *Stirling Engines*

PS-10 Power Tower
Seville, Spain

HTF	Pros	Cons
Steam / Oil	High operating temp. Low cost	Poor thermal storage High pressure systems
Molten salts	Good thermal storage	Chemically unstable above 600C.
Solid particles	Good thermal storage High operating temps.	*Heat transfer performance yet to be demonstrated.*

Motivation

CSP design investigated at NREL
as part of the DOE Sunshot Initiative



BRIDGE Project

Objective

- *Develop a fundamental modeling tool that can be used for design of particle receiver: understanding and prediction of heat transfer in solids flows*

Models:

- *DEM: Fundamental model but high computational costs*
- *Continuum: Computationally more efficient but heat transfer models have not been validated*

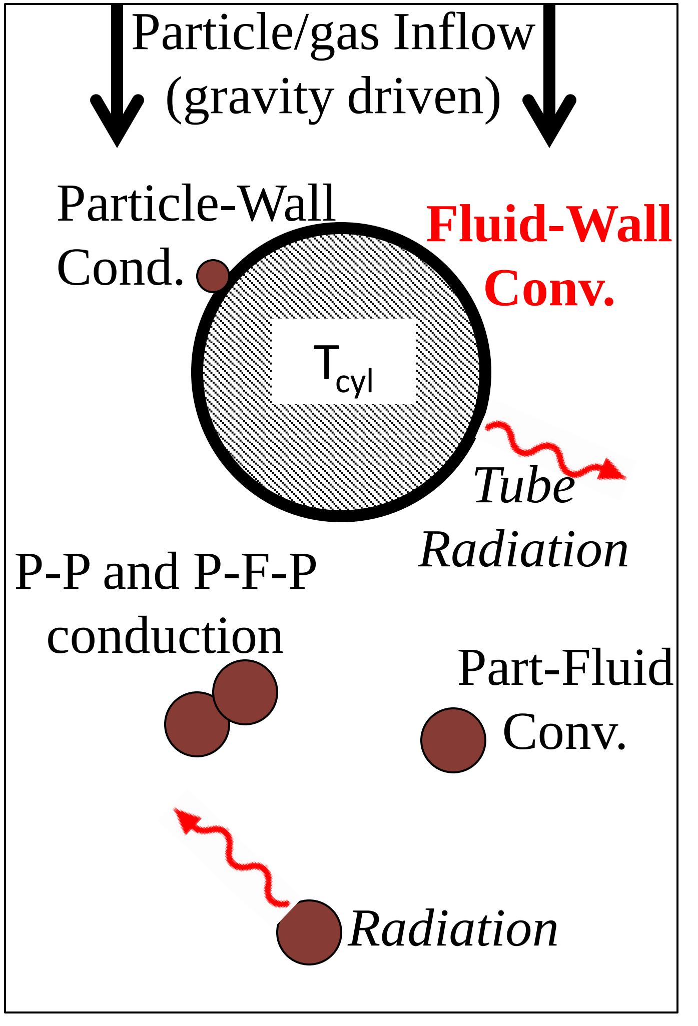
Our Approach:

- Use DEM to generate "ideal" data to validate continuum models
- First step is to study single tube system with MFIX
- Identify relative importance of various heat transfer mechanisms
- Determine heat transfer coefficients
- Distribution of particle temperatures

Single Tube System

Indirect Heat Transfer to Particles

- Interstitial gas warmed by the tube transfers heat to cold particles



Single Tube System

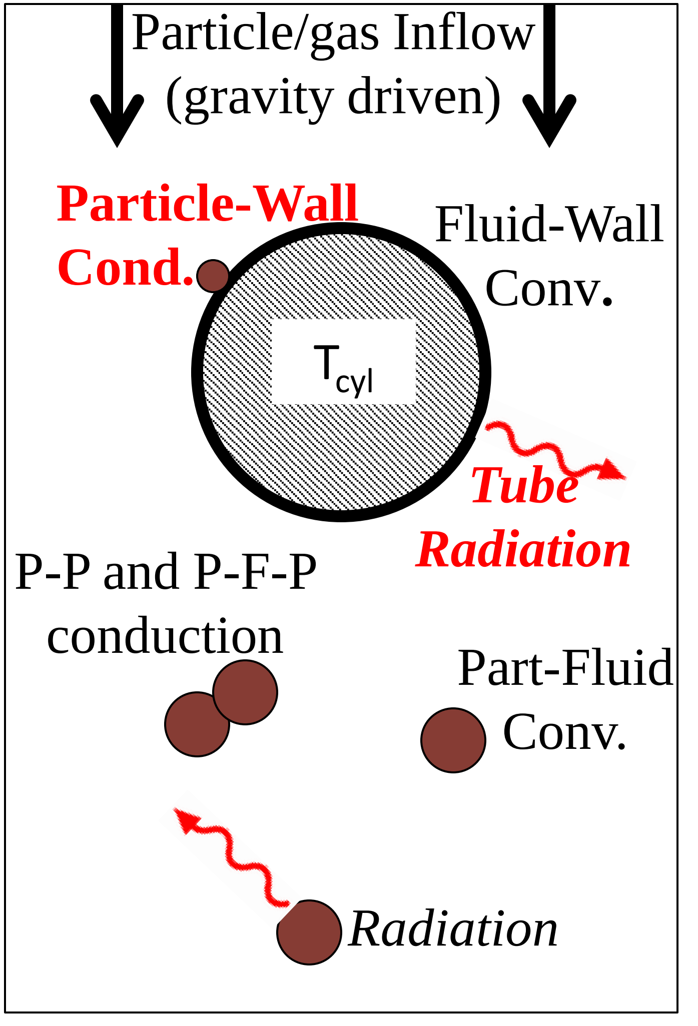
Indirect Heat Transfer to Particles

- Interstitial gas warmed by the tube transfers heat to cold particles

Direct Heat Transfer to Particles

- Particle-wall contact conduction
- Particle-fluid-wall conduction
- *Radiation from tube to the particles*

.



Single Tube System

Indirect Heat Transfer to Particles

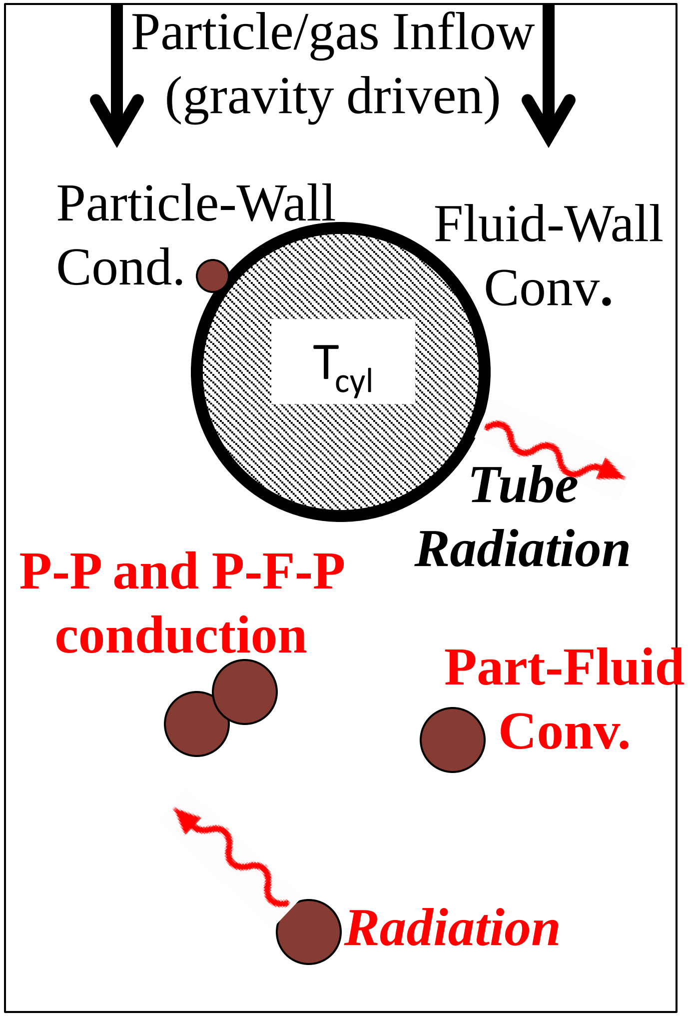
- Interstitial gas warmed by the tube transfers heat to cold particles

Direct Heat Transfer to Particles

- Particle-wall contact conduction
- Particle-fluid-wall conduction
- *Radiation from tube to the particles*

Heat Diffusion

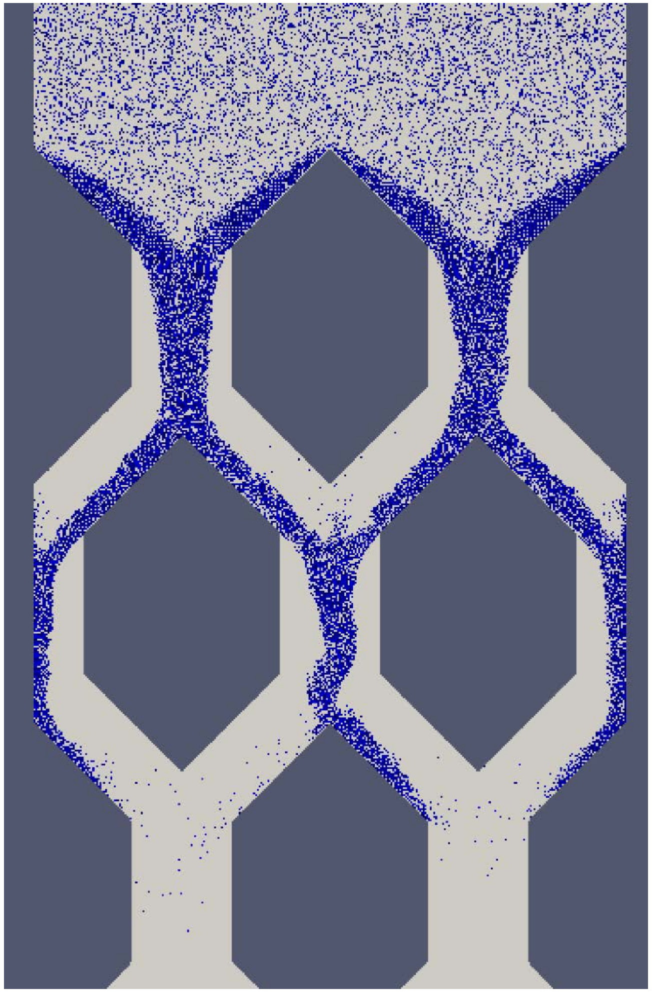
- Convective motion of particles
- Particle-particle contact conduction
- Particle-fluid-particle contact conduction
- Convection between particles and interstitial gas
- *Particle-particle radiation*



Computational Tool

MFIX-DEM

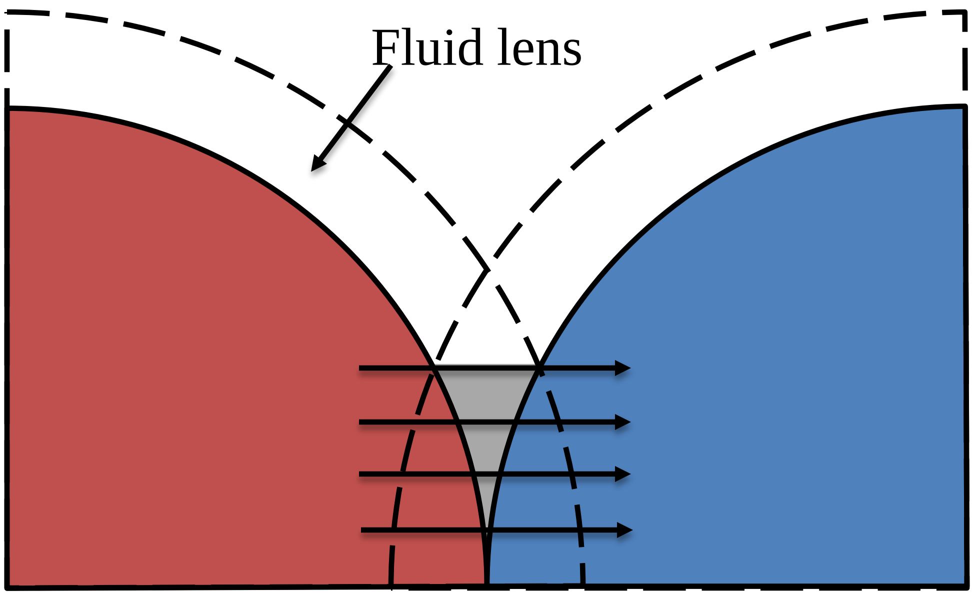
- Use cut-cell implementation
  - Construct complicated geometries
- Heat transfer models
  - Particle-particle conduction
  - Particle-fluid-particle conduction
  - Particle-fluid convection
- Added heat transfer mechanisms
  - Particle-wall conduction
  - Particle-fluid-wall conduction



Model

Conduction through interstitial fluid

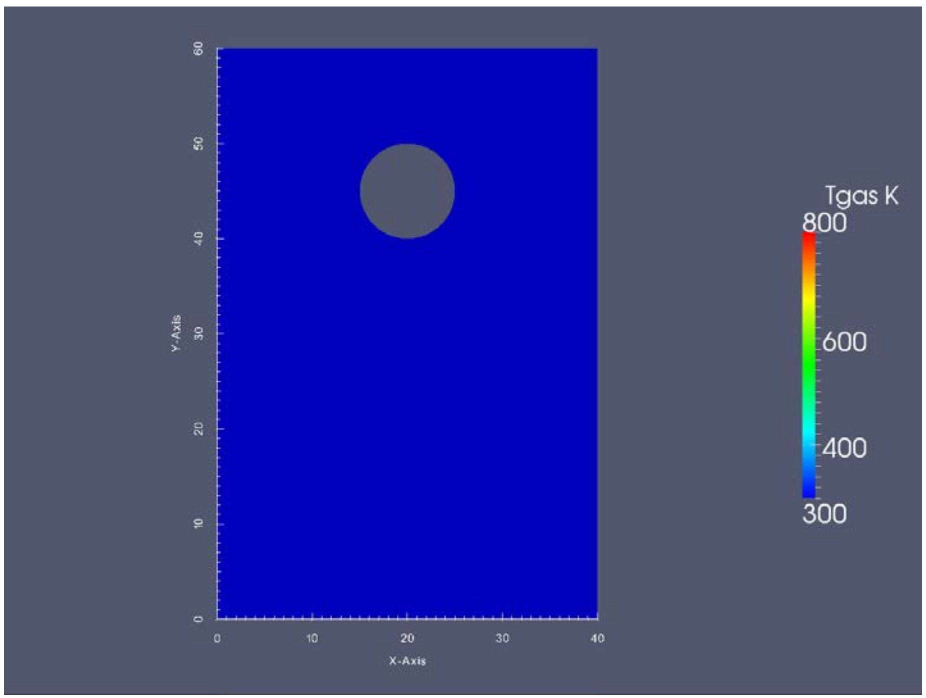
- A way of accounting for heat transfer since through interstitial gas because DEM does not resolve fluid on particle scale.
- Interstitial fluid enhances conduction by increasing contact area.
- Plays a significant role in particle heating.
- Rong and Horio (1999)
- Extended to particle-wall conduction



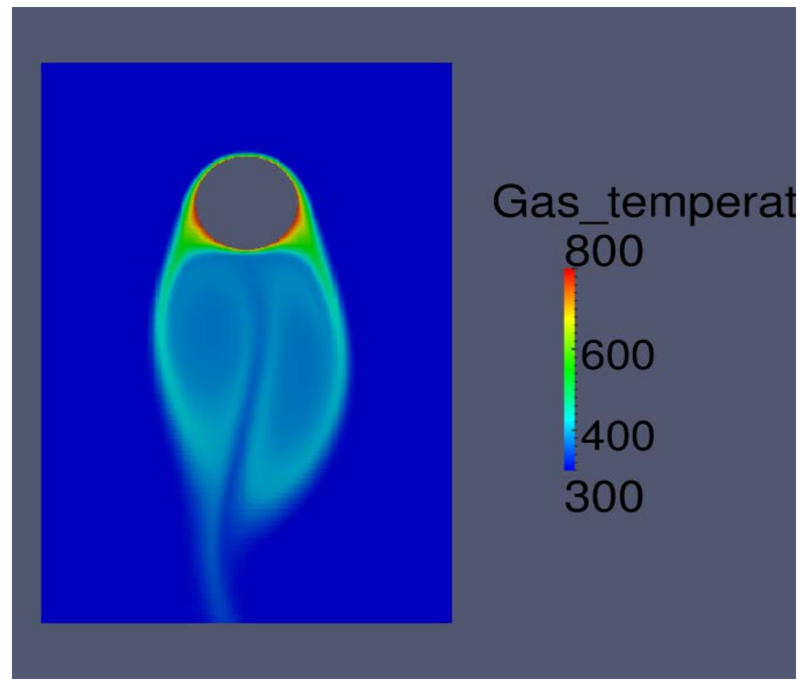
Gas phase only

Convective heat transfer

- Natural convection dominates without particles
- Flow not symmetric about cylinder center line
- Unsteady vortices can affect particles for dilute flows



With Gravity



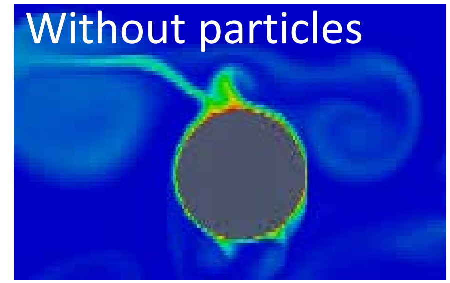
No Gravity

Dilute Inflow – No particle-wall conduction

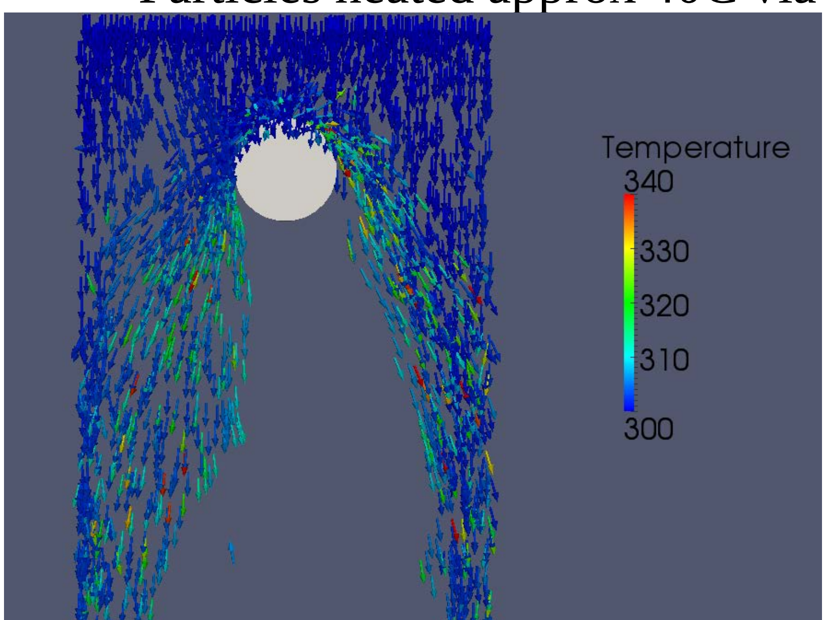
Run parameters

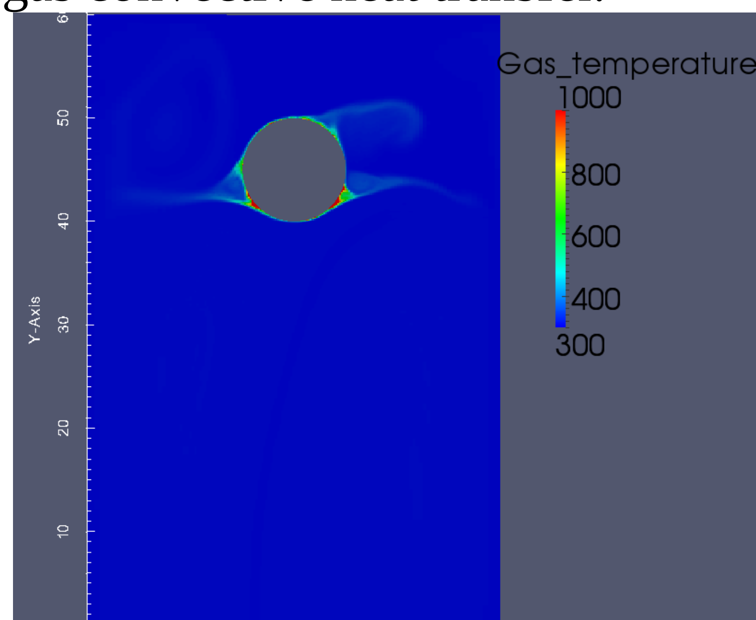
- $\varphi_{\text{inlet}} = 0.1\%$; $D_p = 400\mu\text{m}$; $\varepsilon = 0.9$; $D_{tube} = 10\text{cm}$; $q_{tube} = 7.5$ kW/m2

Findings



- Gas flow is unsteady
  - Vortex shedding and natural conv.
- Particle motion is unsteady
  - Coupled to gas in the wake and particles respond to vortex shedding
- Particles heated approx 40C via only gas convective heat transfer.





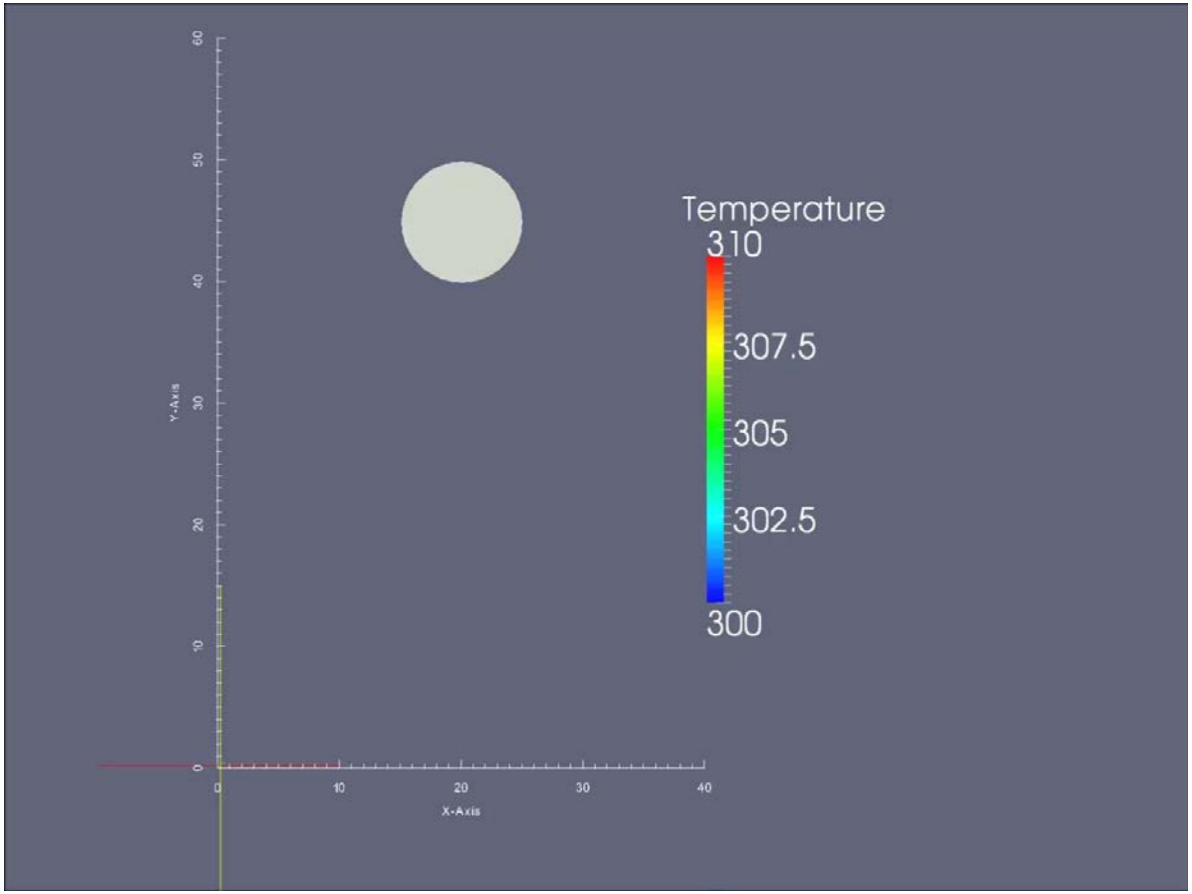
Dense Inflow

Run Parameters

- T_{tube} = 800K; φ_{inlet} = 20%; D_p = 400μm ; ε = 0.9; D_{tube}= 10cm

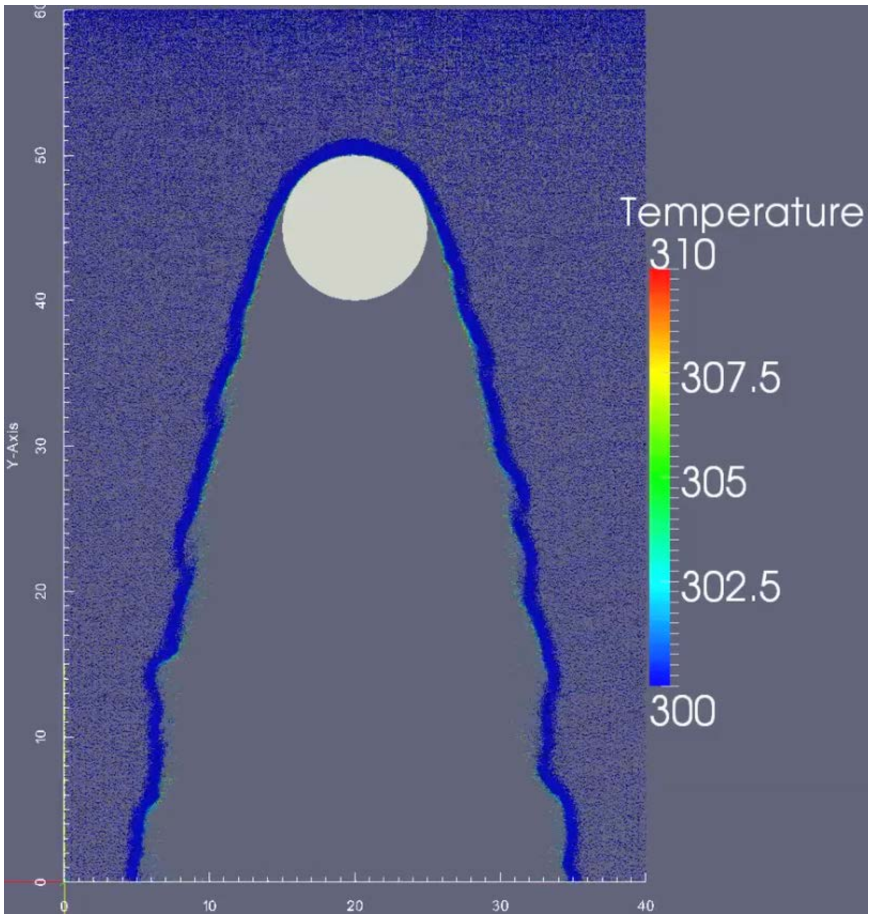
Findings

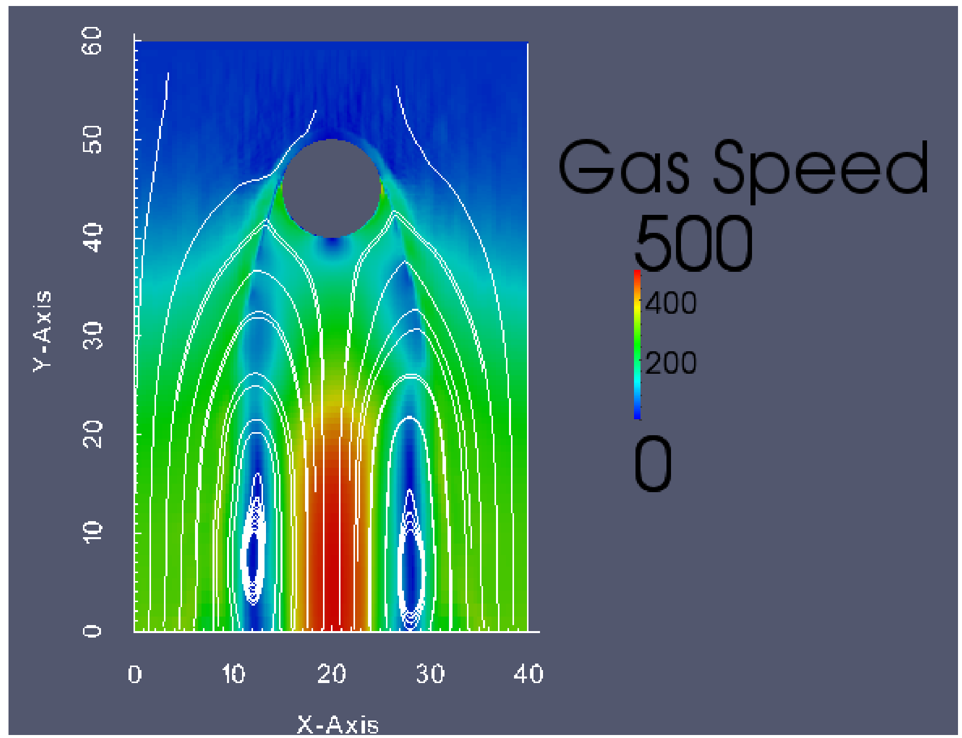
- Dense lens of particles forms around tube
- The lens sheds off the tube and shields particles from the wake area.



Single tube simulations – Dense Inflow

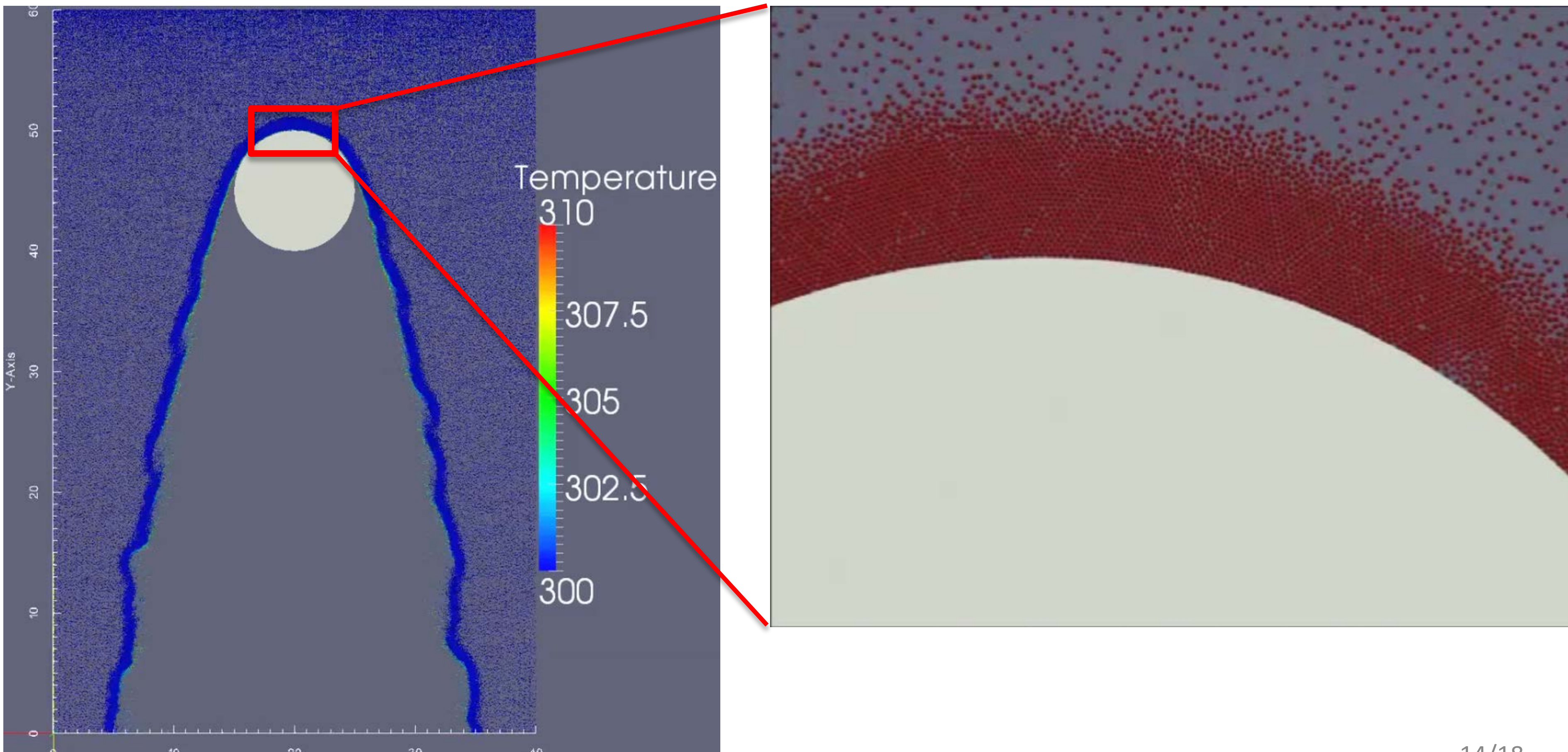
- No particles in wake. Gas is more symmetric. Natural convective eddies dampened.
- Enduring contacts with wall





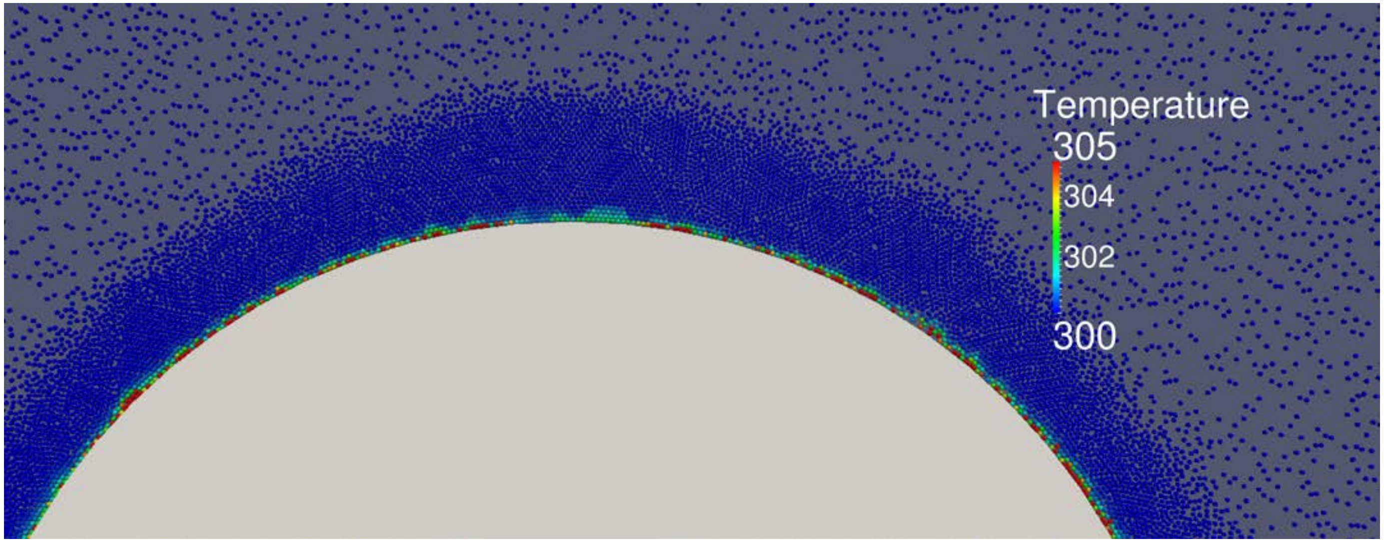
Single tube simulations – Dense Inflow

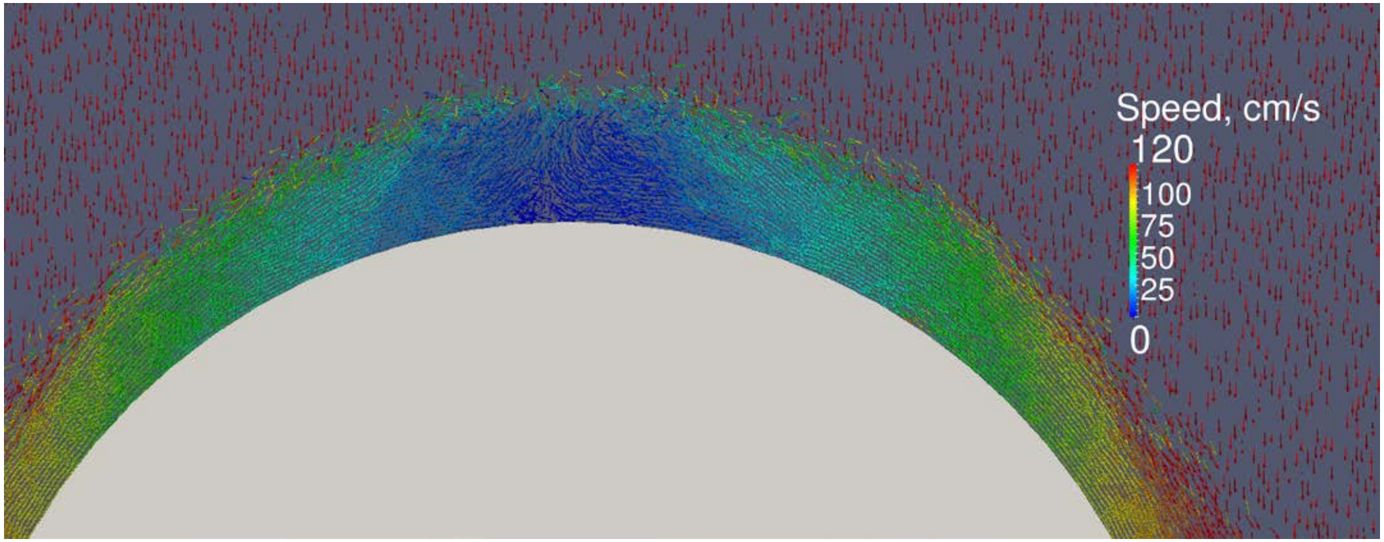
- No particles in wake. Gas is more symmetric. Natural convective eddies dampened.
- Enduring contacts with wall
- Particle-wall conduction is important.



Single Tube – Dense Inflow

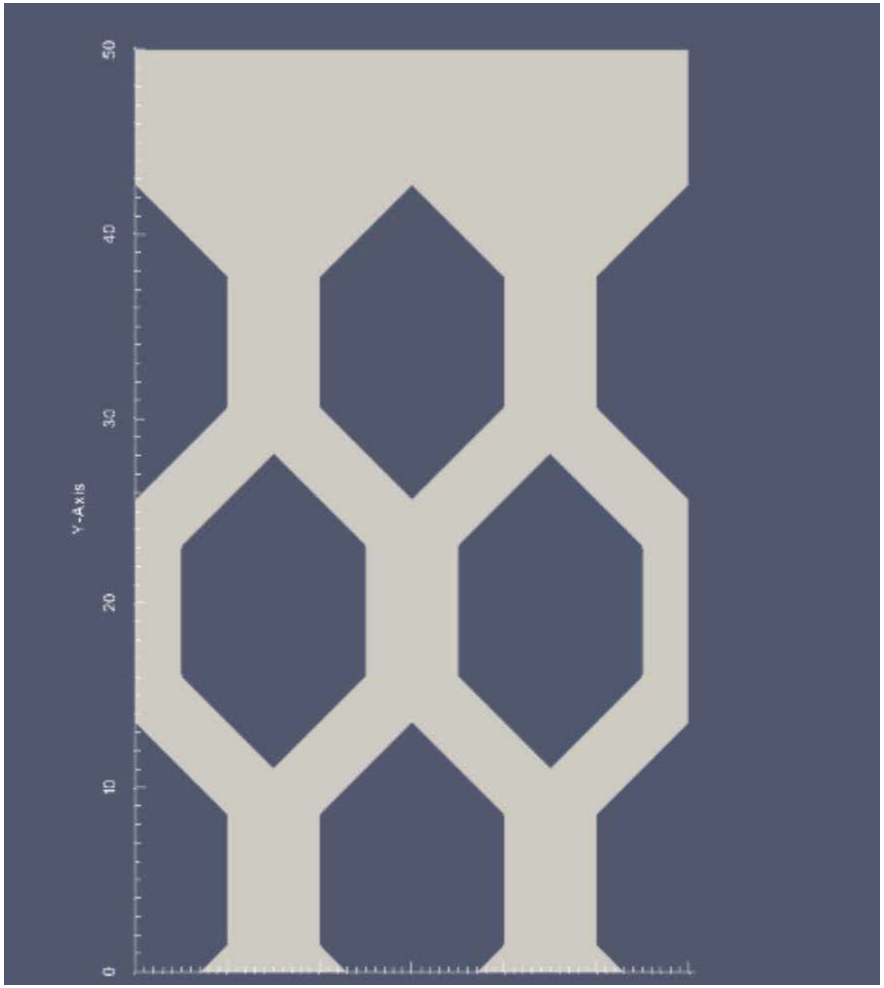
- Only particles in first several layers are heated.
- No particle-wall conduction. Particles do not stagnate.

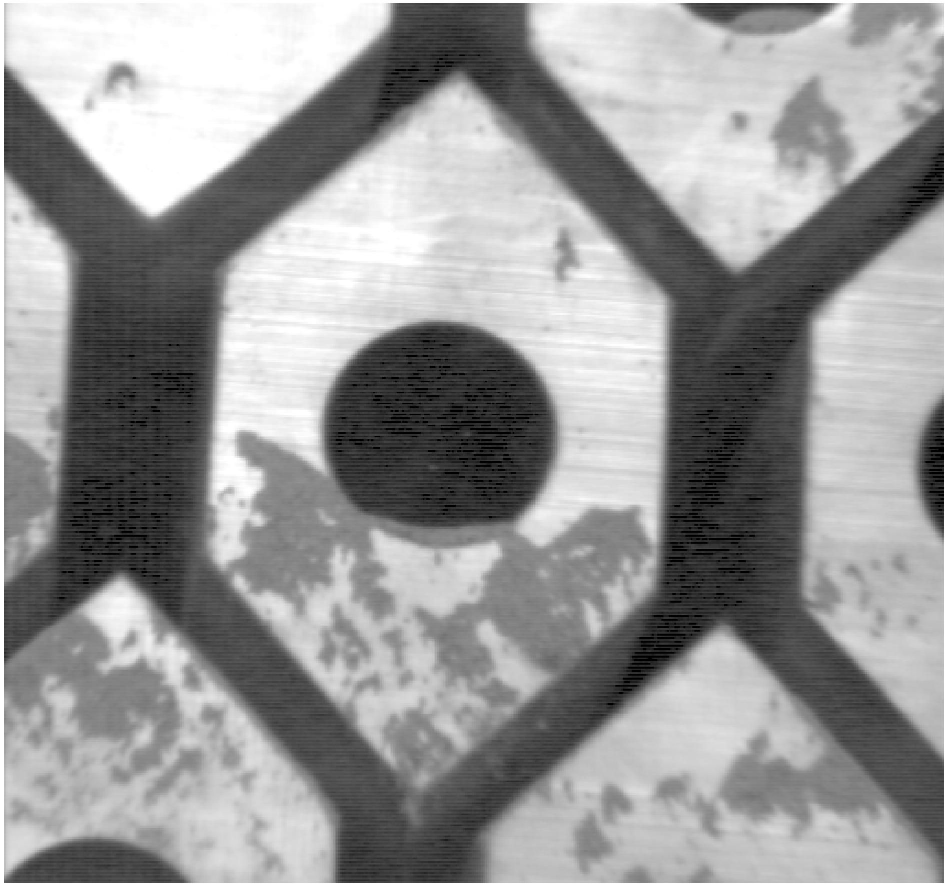




Future Work

- Simulations of more complicated receiver designs with arrays of hexagonal heat transfer tubes (some employing Titan at ORNL).
- Experiments done by Alan Wang and Prof. Fan at Ohio State University





Conclusions

- MFIX-DEM has been used to simulate particles falling over a cylinder.
- For dilute flows the particle motion is affected by unsteadiness in the gas.
  - Unsteady particle motion in cylinder wake
  - Contact conduction negligible
  - Convective heat transfer with gas is dominant mechanism
- For dense flows the particle motion dampens gas unsteadiness
  - Thick lens of particles forms around the cylinder
  - Enduring contacts where particle-particle and particle-wall conduction may be significant
- Model development:
  - Adding particle-wall heat transfer models
  - Using DEM cutcell algorithm to simulate complicated geometries with arrays of heat transfer tubes

Acknowledgements

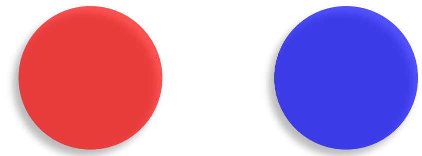
Thank you to Dr. Jordan Musser, Dr. Rahul Garg, Dr. Sofiane Benyahia, and Dr. Jeff Dietiker for their assistance during a visit to NETL funded by the BRIDGE award.

Computations were performed on the supercomputer Titan at ORNL through a OLCF discretionary allocation.

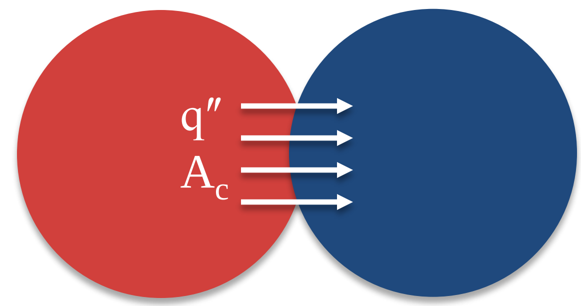
This work was graciously funded by BRIDGE Award EE00005954 under the DOE Sunshot initiative.

Backup Slide

Particle-particle conduction



- Cond. across contact area.
- Small Biot numbers (isothermal)
- This mechanism is **negligible** for dilute flows.
- Batchelor and O'Brien (1977)



Particle-wall conduction

- **Significant** for enduring contacts
- Sensitive to contact area and contact model
- Batchelor and O'Brien