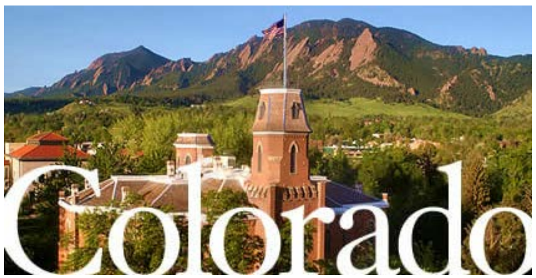
# *Using Solid Particles as Heat Transfer Fluid for use in Concentrating Solar Power (CSP) Plants*




## *DOE CSP Program Review, 24 Apr 2013*


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

# Team Members

**Christine Hrenya**
**University of Colorado**
*Continuum and DEM models of solids flows*

**Zhiwen Ma**
**NREL**
*Concentrating Solar Power (CSP) plants*

**Aaron Morris**
**University of Colorado**
*High-performance computing, Gas-solid modeling (beginning 3/15/13)*

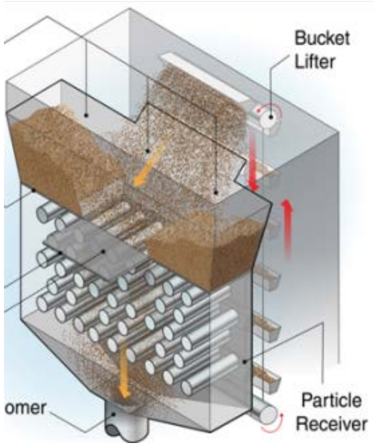
**Tom O’Brien**
**Consultant (retired NETL)**
*MFIX multiphase models*

**Sreekanth Pannala**
**ORNL**
*High-performance computing, including MFIX*

# BRIDGE Project

## Objective

*Fundamental modeling tool that can be used for design of particle receiver: understanding and prediction of heat transfer in solids flows, including radiation*




## Why fundamental (no empirical / adjustable parameters)?

<u>Previous findings:</u>

(i) for rotating heated tumblers, high-heat capacity particles are heated faster for lower conductivities of the interstitial medium [1]

(ii) for shear flows along an unbounded, inclined plate, the thermal conductivity of dilute flows increases with shear rate [2] while the opposite occurs for denser flows [3]

⇒ non-intuitive behavior call for first-principles models

- empiricism is costly and time-consuming
- empiricism not reliable for extrapolation

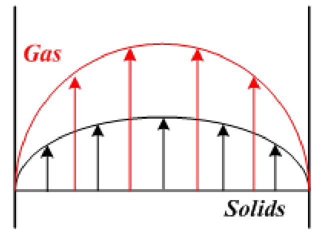
**Less CPU time**

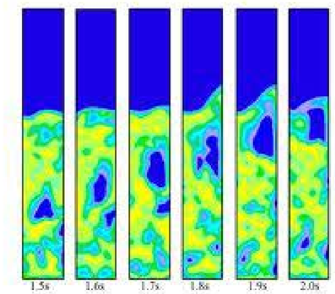
# Modeling Approaches: Various Scales

## Two-fluid Model (TFM)

- Gas = continuum
  (averaged over *many* particles)
- Solids = continuum

$$\frac{\partial}{\partial t}\left(\varepsilon_s \rho_s \mathbf{V}_s\right) + \nabla \cdot \left(\varepsilon_s \rho_s \mathbf{V}_s \mathbf{V}_s\right) = \nabla \cdot \boxed{\boldsymbol{\tau}_s} + \varepsilon_s \rho_s \mathbf{g} + \boxed{\mathbf{F}_{drag}}$$

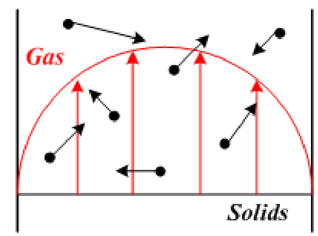


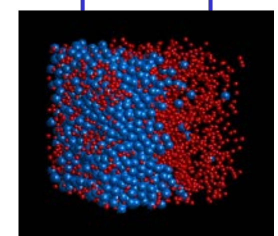




## Discrete Element Model (DEM)

- Gas = continuum
- Solids = discrete

$$m_i \frac{d\mathbf{V}_{si}}{dt} = m_i \mathbf{g} + \mathbf{F}_{ci} + \boxed{\mathbf{F}_{drag,i}}$$



**More detail, Fewer closures**

Typical CPU times for DEM

Serial processor: $O(10^5$ particles)

Parallel processors: $O(10^8$ particles)

→ *ORNL facility*

→ *MFIX DEM (and continuum): parallelized*

| $d_p$ | $N_p$ in 1 cup |
|---|---|
| 100 μm (sand) | |
| 50 μm | |

# Model Development for Solar Collector

**Our Approach**

- *Use DEM simulations as "Ideal Experiment" to test continuum theory*

**Computational Tool: MFIX** *(Multiphase Flow with Interface eXchanges)*

- *public, cost-free, open-source code from DOE NETL*
- *DEM model: conduction, convection and radiation (part-part only)*
- *continuum model: conduction and convection*

**Continuum Models: State of the Art**

- *No validation to date for conduction, convection, or radiation*
- *caveat 1: flow instabilities difficult to deal with (similar to turbulence)*
- *caveat 2: possible large gradients in solids flow variables (requires higher-order model)*

**Steps**

- *Single-tube system, no radiation: generation of DEM validation data, and comparison with continuum predictions*
- *Two-tube system, with radiation: generation of DEM validation data, and comparison with continuum predictions*
- *Prototype receiver, with radiation: assess relative importance of radiation on particle absorber heat transfer*

# Tasks

1. **Model Verification / Validation for Non-Radiative Heat Transfer (BP1)**

2. **Initial Assessment of MFIX Radiation Model (BP1)**

3. **Verification of DEM Radiation Model and Generation of DEM validation data (BP2)**

4. **Implementation, Verification, and Validation of Continuum Radiation Model (BP2)**

5. **Simulation of Prototype Particle Receiver with Radiative Heat Transfer (BP3)**

*Note: The end date for Year 1 has recently been updated by DOE from 11/15/13 to 2/14/14.*

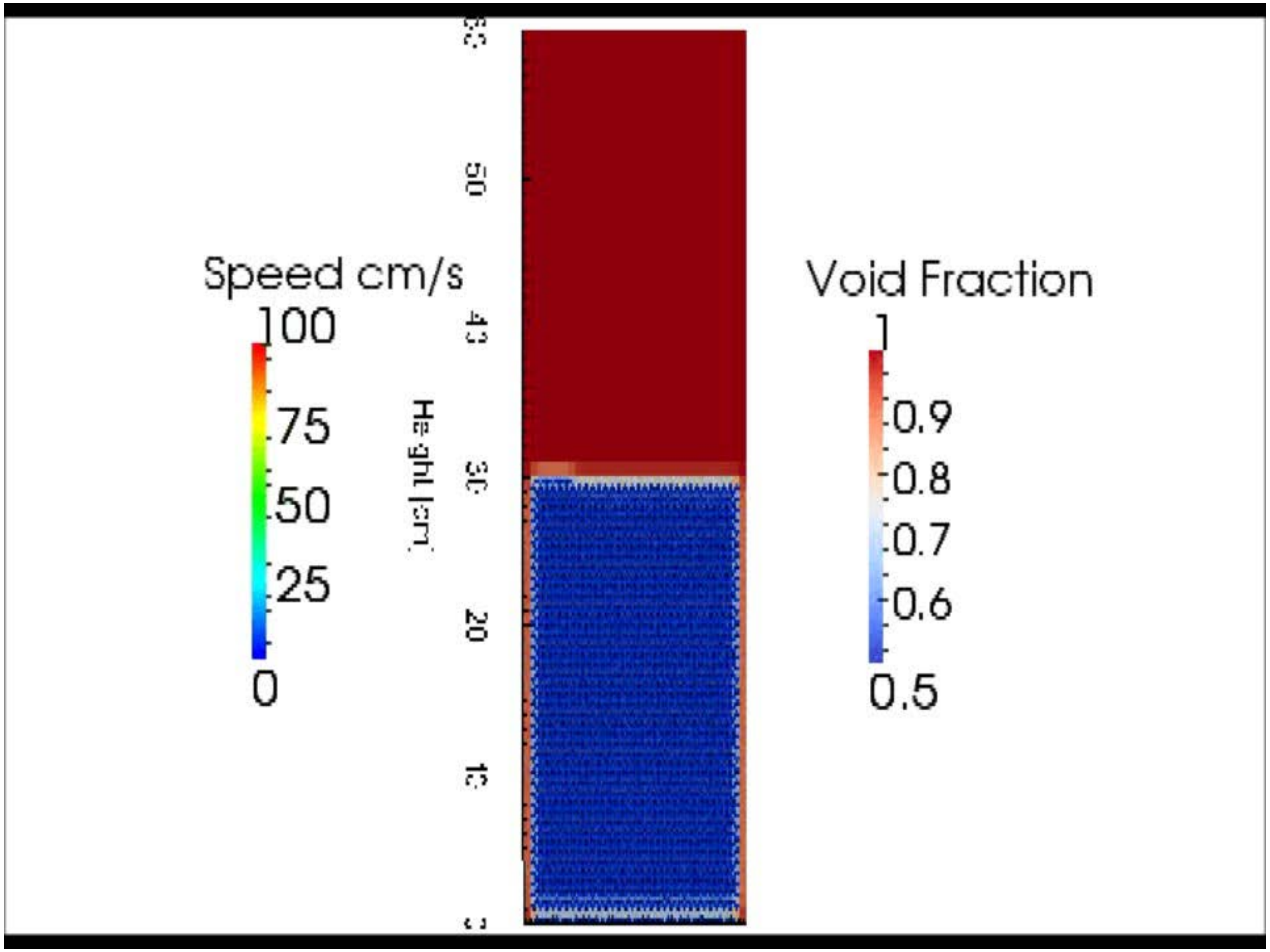
## Current MFIX Modeling Efforts

- Fully coupled two-phase flow.
- Solid phase modeled by either continuum or DEM solver.
- Heat transfer models for solid and fluid phases.
  - Particle-particle conduction.
  - Particle-fluid-particle conduction.
  - Particle-fluid convection.
  - Particle-particle radiation.
- Parallelized for supercomputers.

# Current Modeling Efforts

## Preliminary DEM Simulations

- Fluidized bed with central jet.
  - Fully coupled phases, no heat transfer.



# Univ. Colorado and ORNL Supercomputing Facilities

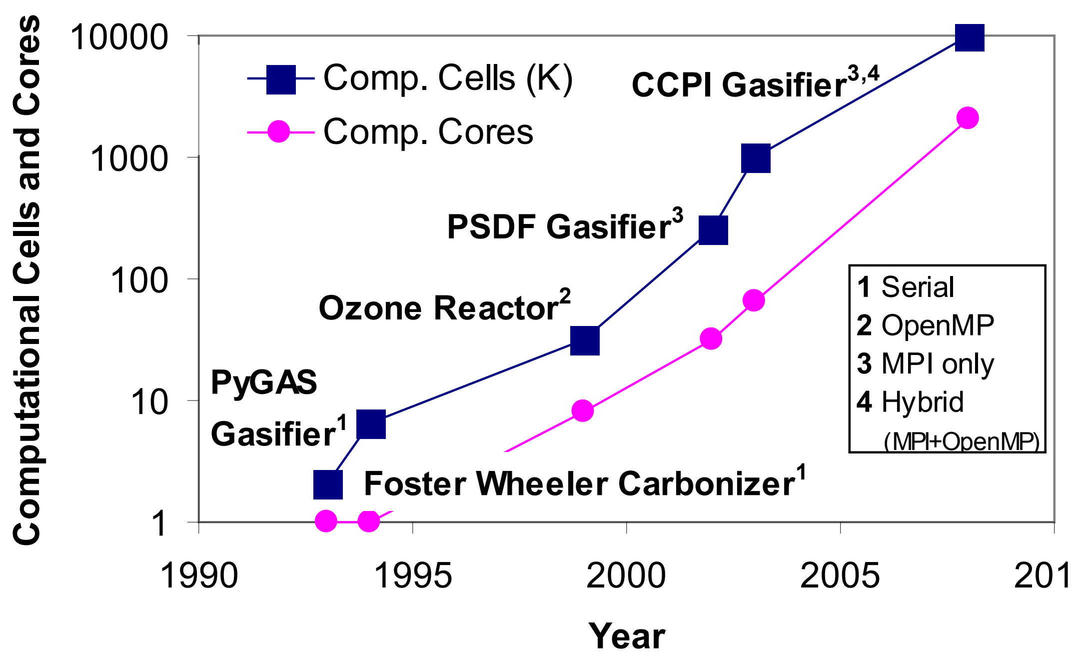
| Janus (Univ. Colorado) | Titan (ORNL) |
| --- | --- |
| 16,416 cores | 299,008 cores |
| Hex-core 2.8Ghz Intel Westmere processors | 16-core AMD Opteron 6274 processors + GPUs |
| 24GB RAM per node | 32GB + 6GB RAM per node |
| 184 teraflops | 20 petaflops |

# Parallel Supercomputing on MFIX

## DEM

- Parallelization is a new addition (Gopalakrishnan and Tafti, 2013)
- Strong scalability and can simulate millions of particles.

## Continuum



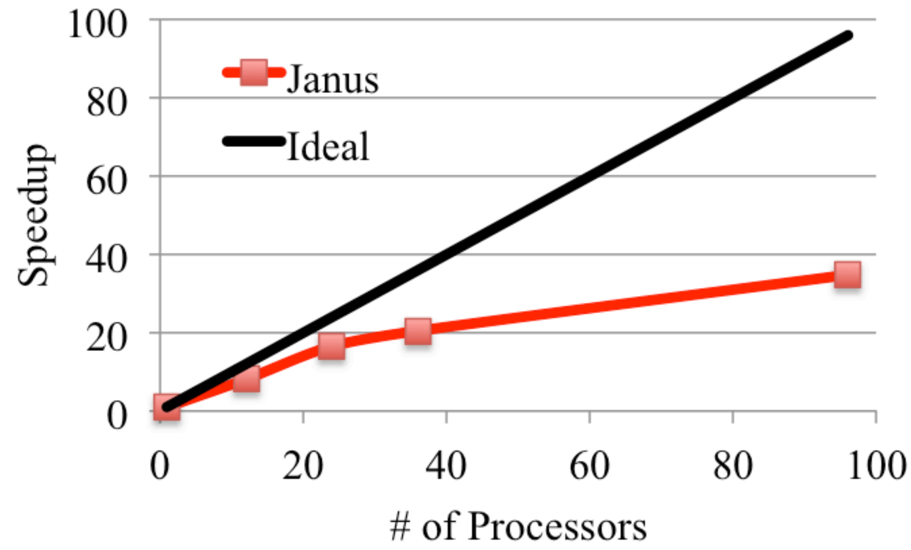

P. Gapalakrishnan, D. Tafti, (2013) "Development of parallel DEM for the open source code MFIX", in *Powder Tech.*, **235**, pp 33-41

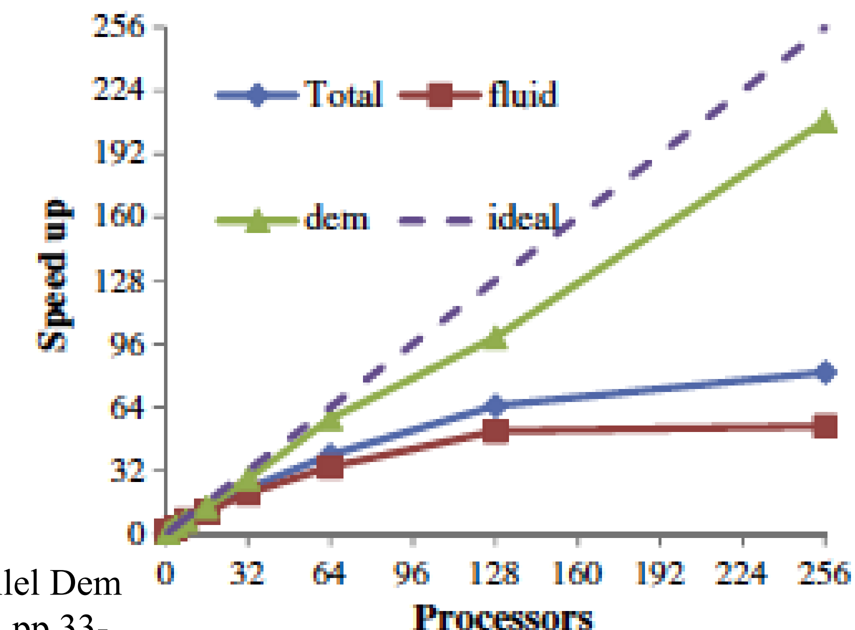
# Current Modeling Efforts

**Preliminary DEM Simulations**

- Fluidized bed with central jet.
  - Fully coupled phases.
  - No heat transfer.

- Bubbling bed parallel speed-up test on Janus supercomputer.
  - Simulated 140,400 particles
    - » 2.56 mil particles in [1]
  - 30 minutes to simulate 0.1s with 24 processors.
  - Approx. half a cup of 1mm diameter particles.
  - Approx. 1tablespoon for 500 μm particles.



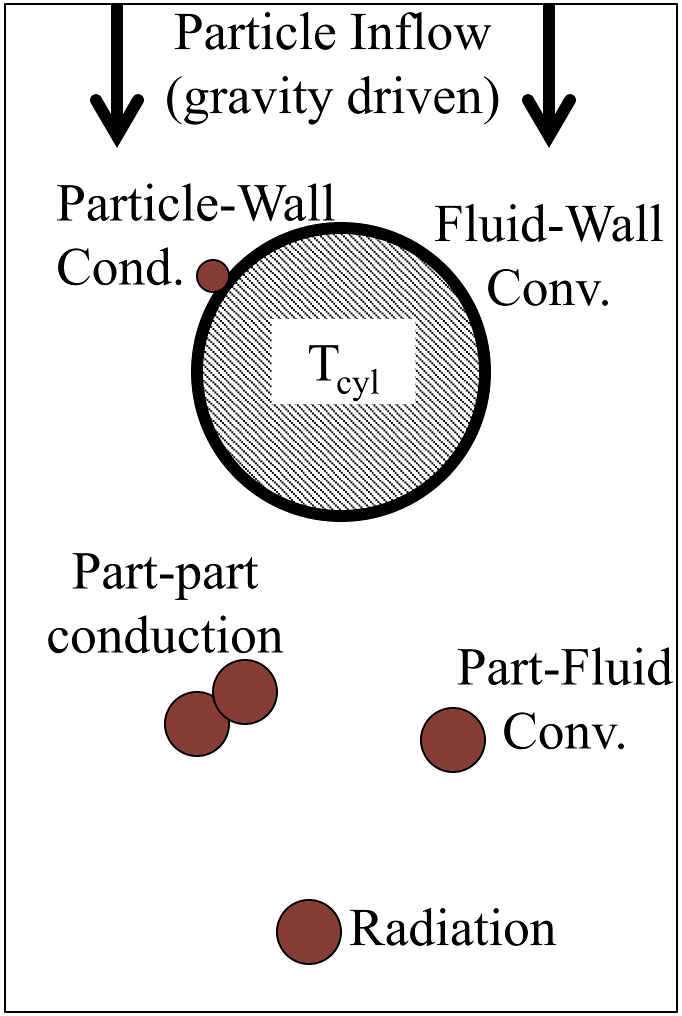




P. Gapalakrishnan, D. Tafti, (2013) "Development of parallel Dem for the open source code MFIX", in *Powder Tech.*, **235**, pp 33-

# Current Modeling Efforts:  Single-Tube System

**DEM Solution with Heat Transfer**

- Identify relative importance of various heat transfer mechanisms.
- Determine heat transfer coefficients and distribution of particle temps.
- Comparison to particle flow/ heat transfer experiments.
- Verification of future continuum model.



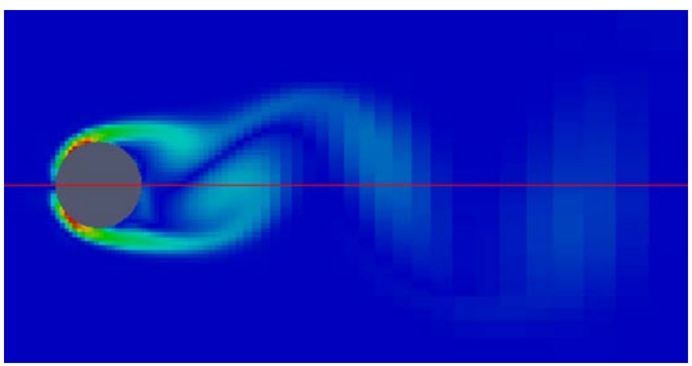
# Progress Towards Single Tube DEM

## MFIX Modifications

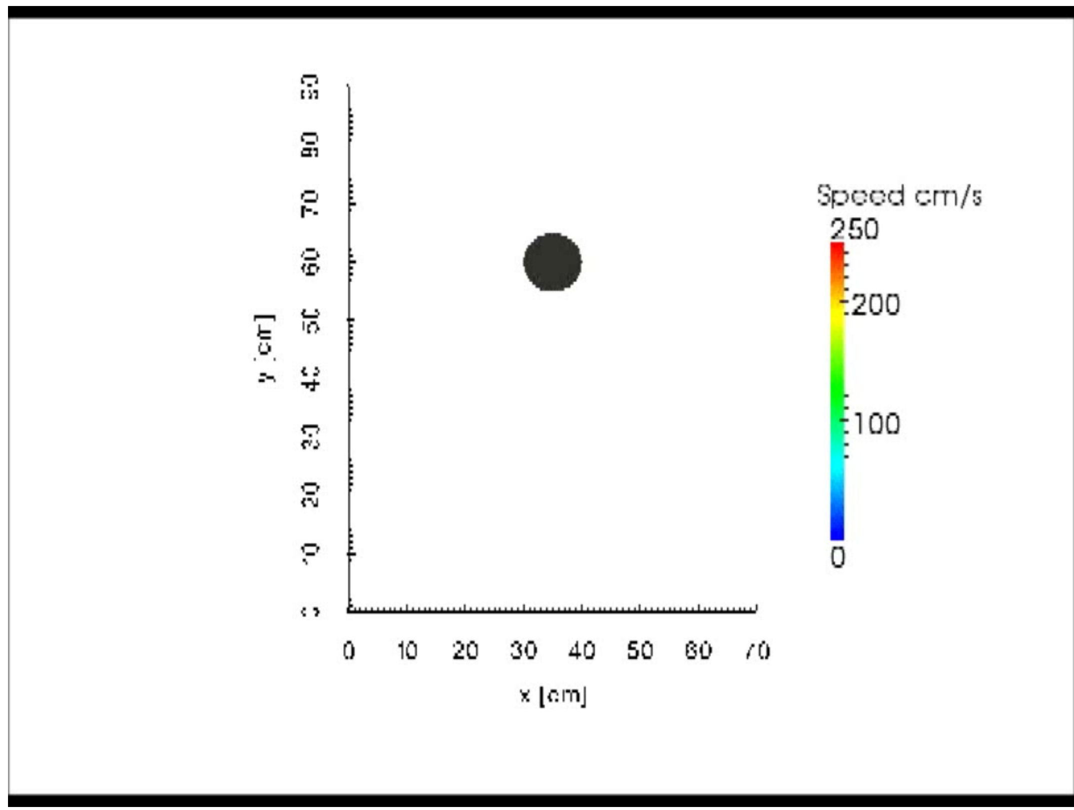
- Need to implement hot wall B.C.(MFIX currently has only adiabatic walls for DEM).
- Cutcell algorithm for flow over internal geometries is still under development.

## Input Parameters

- Tube size, shape, heat flux, particle properties



Gas only
Vorticity field

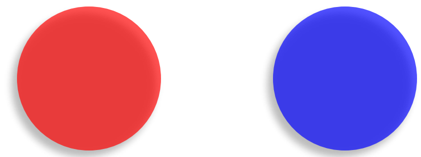


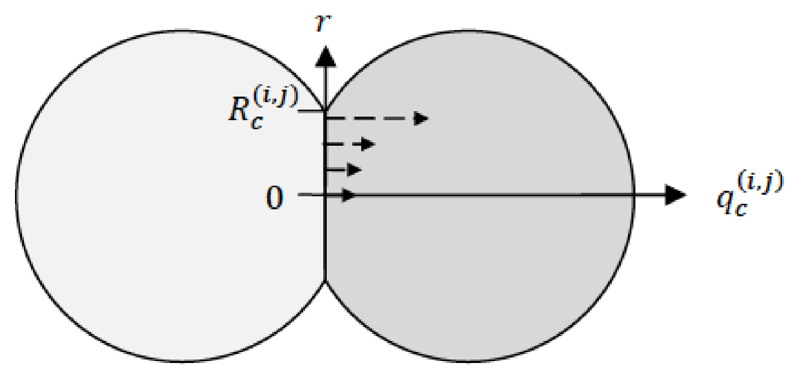

Solids only

# Heat Transfer Mechanisms in MFIX

**Particle-Particle Conduction**

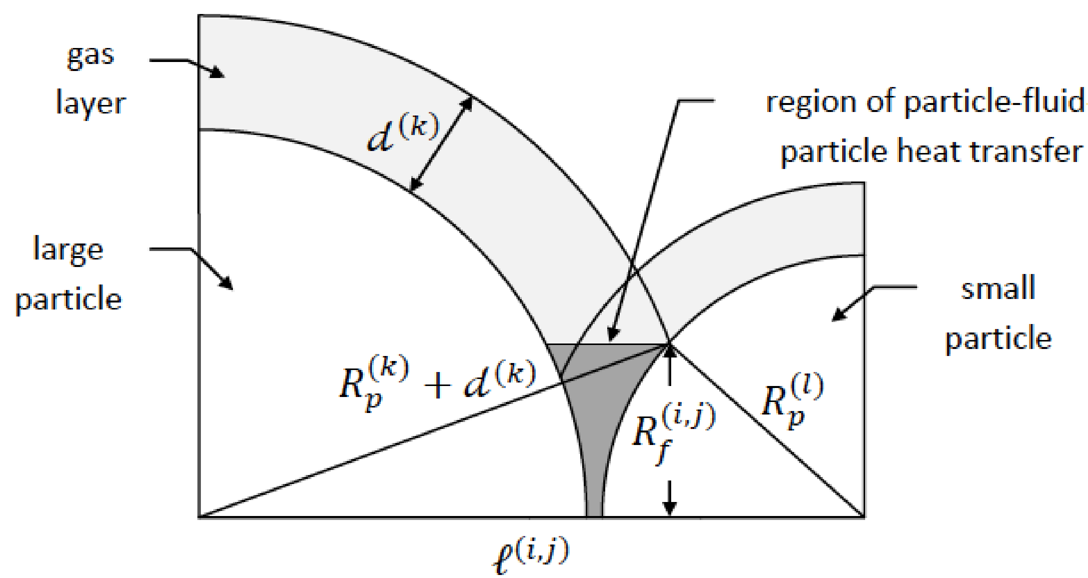
- Cond. across contact area.
- Small Biot numbers
- Normally not important bc collisions are brief and contact areas are small.
- Collision duration is important





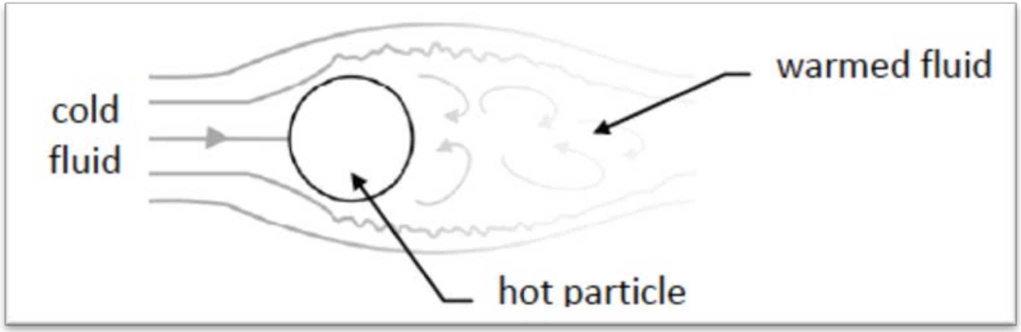

**Particle-Fluid-Particle Conduction**

- Conduction across interstitial fluid in gap.
- Assumes heat transfer is in direction along axis connecting part. centers.
- Polydispersity



# Heat Transfer Mechanisms in MFIX

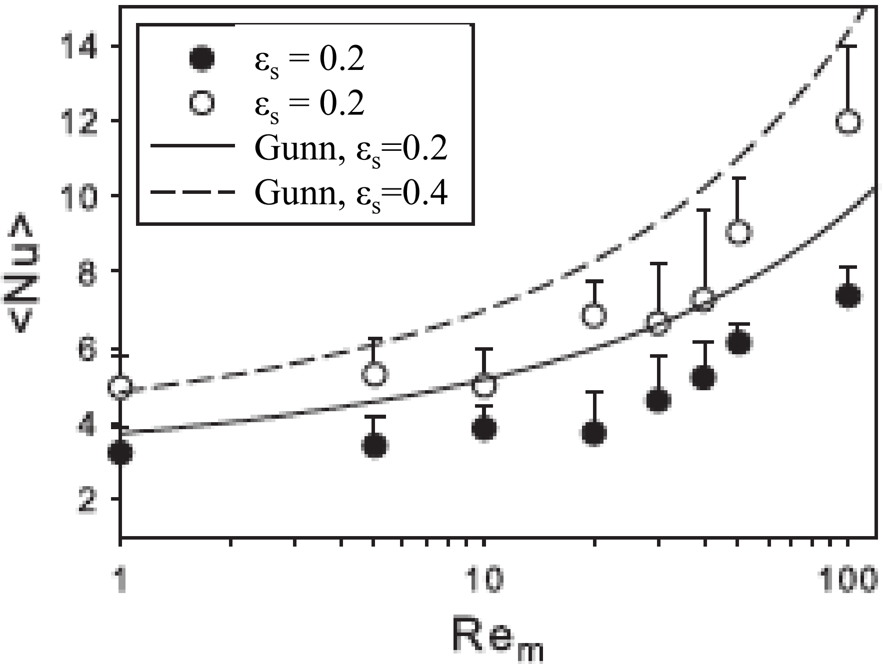
## Particle-Fluid Convection




- MFIX Uses Nusselt number correlations (1952).
- Correlations were derived from single particle systems and should be improved when the particle volume fraction is high.
- Can use LBM or Gunn's correlations for improved Nusselt number at higher volume fractions.
- Expected to be significant heat transfer mechanism.

$$\langle \text{Nu} \rangle = \frac{h_{conv}}{\kappa_g / 2R_p}$$

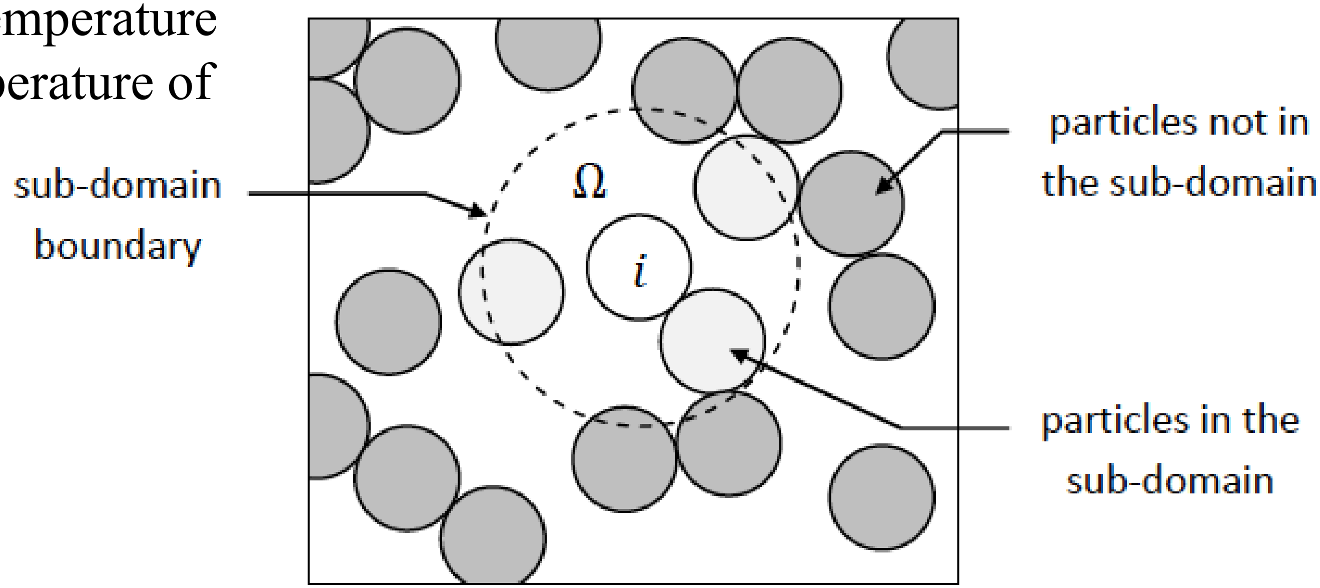
$$\text{Re} = \frac{\rho_g \varepsilon_g \left\| \mathbf{V}_g - \mathbf{V}_p \right\| 2R_p}{\mu_g}$$



# Heat Transfer Mechanisms in MFIX

**Particle-Particle Radiation**

- Best approach would compute view factors between all particles/walls with all other particles and solve radiative balance equations.
  - Computationally expensive – MFIX uses simplified model
- Defines region where radiation occurs and uses a correlation to compute an environment temperature.
- Radius of radiation sub-domain = 1.5Dp
- Environment temperature is average temperature of particles within region.



## Summary

- Scalability of parallel MFIX DEM increases with # particles
- Preliminary DEM simulations around single, unheated tube qualitatively correct
- Reviewed heat transfer mechanisms in MFIX
  - Particle-particle conduction
  - Particle-gas-particle conduction
  - Particle-gas convection
  - Particle-particle radiation

## Next Steps…

- DEM  prediction of particle trajectories in flow domain
- Extension of DEM heat transfer to particle-wall contacts
- Single-tube DEM simulation with heat transfer
- Single-tube continuum simulation