A THREE DIMENSIONAL DIRECT NUMERICAL SIMULATION METHOD FOR SOLVING HEAT TRANSFER OF PARTICULATE FLOWS

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Outline

1. Introduction
2. Description of the method
3. Simulation results
4. Summary

Introduction

- Numerical simulations of particulate flows with heat transfer:
  - Two-Phase Continuum Model
  - Discrete Particle Model
  - Direct Numerical Simulation (DNS)
- Very little work has been done on particulate flows:
  - Effect of neighboring particles
  - Non-spherical particles
  - Clusters of particle
- Direct Numerical Simulation (DNS) method combined with Immersed Boundary Method (IBM) to study convection heat transfer of particulate flow

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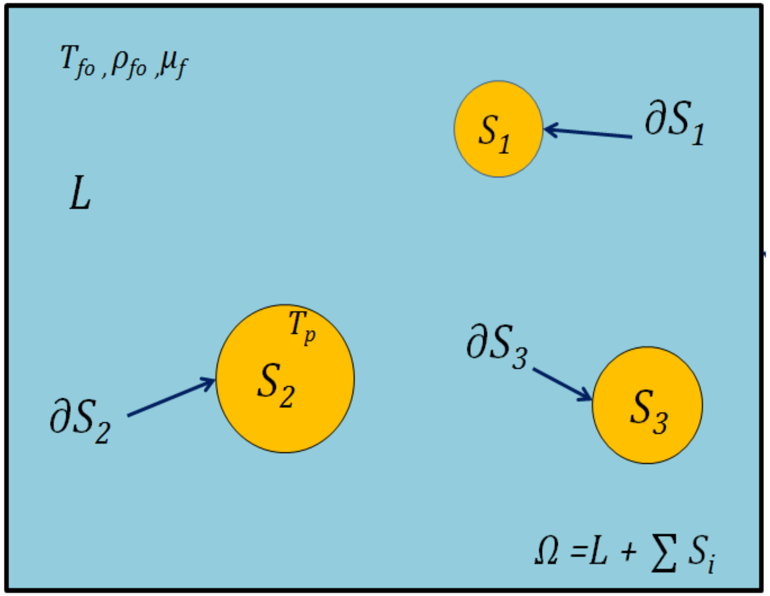
Description of the Method

- Combines DNS and IBM
- Two types of grids are used to solve the solid interactions:
  - Eulerian grid : Flow domain
  - Lagrangian grid :Particles boundaries
- Solid boundary is represented by a virtual boundary with a distribution force
  - Non-slip condition
  - Constant temperature



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Description of the Method

Continuity, Momentum, and Energy Equation

$$\nabla \cdot \mathbf{u} = 0, \quad \mathbf{x} \in \Omega$$

$$\rho_f \frac{\partial \mathbf{u}}{\partial t} + \rho_f \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla \mathbf{p} + \mu_f \nabla^2 \mathbf{u} + \beta_f (T - T_f) \mathbf{g} + \mathbf{f}, \quad \mathbf{x} \in \Omega$$

$$\rho_f c_f \frac{\partial T}{\partial t} + \rho_f c_f \mathbf{u} \cdot \nabla T = k_f \nabla^2 T + q + \lambda, \quad \mathbf{x} \in \Omega$$

$$\beta_f (T - T_f) \mathrm{g} : \text{Bouyancy force}$$

- Fluid velocity and pressure fields
  - Discretization NS equation
- Particle-fluid interaction
  - Immersed boundary method
- Particle-Particle interaction
  - Soft-sphere model
- Particle dynamics
  - Newton’s equation of motion
    - Translational
    - Rotational

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Assumptions

- Boussinesq approximation on the effect of temperature on fluid properties
- Particle has uniform temperature (Bi=0)
- No-slip at the particle surface
- Equal temperatures at the particle surface

Research Goals

- Study heat transfer rate in the presence of neighboring particles
  - Heat transfer of spheres in a packed bed
  - Nusselt number as a function of solid fraction
- Heat transfer rate mixed convection
  - Effect of incident angle
- Heat transfer rate of non-spherical particles

Heat Transfer in Packed Beds

- Gunn's correlations

$$Nu_m = (7 - 10\varepsilon_g + 5\varepsilon_g^2)(1 + 0.7\,\mathrm{Re}_m^{0.2}\,\mathrm{Pr}^{1/3}) + (1.33 - 2.4\varepsilon_g + 1.2\varepsilon_g^2)\,\mathrm{Re}_m^{0.7}\,\mathrm{Pr}^{1/3}$$

  - Porosity range of 0.35-1.0 and Re $\leq 10^5$

- Improvement: Accounting particle shape through numerical simulations

Some Preliminary Results

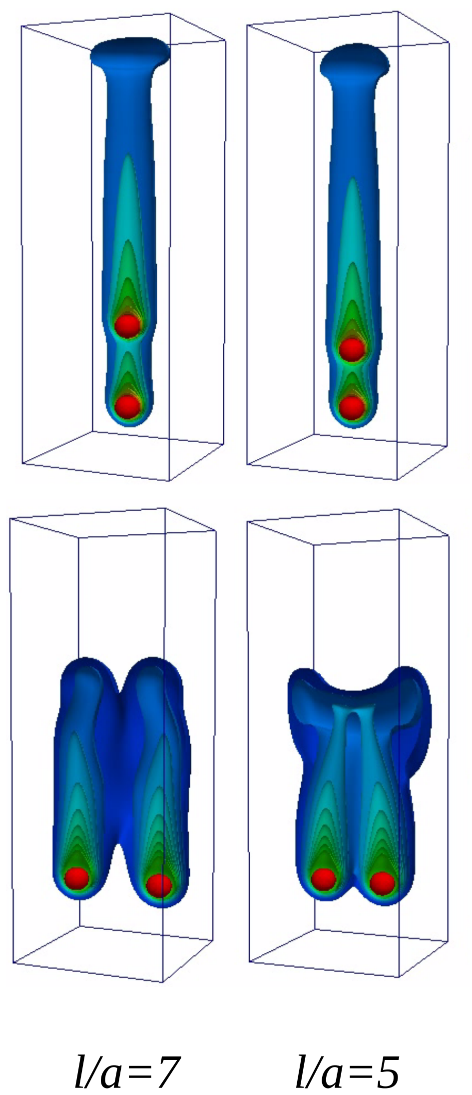
- Heat transfer rate in the presence of neighboring particles:
  - Two horizontal spheres
  - Two vertical spheres
  - Clusters

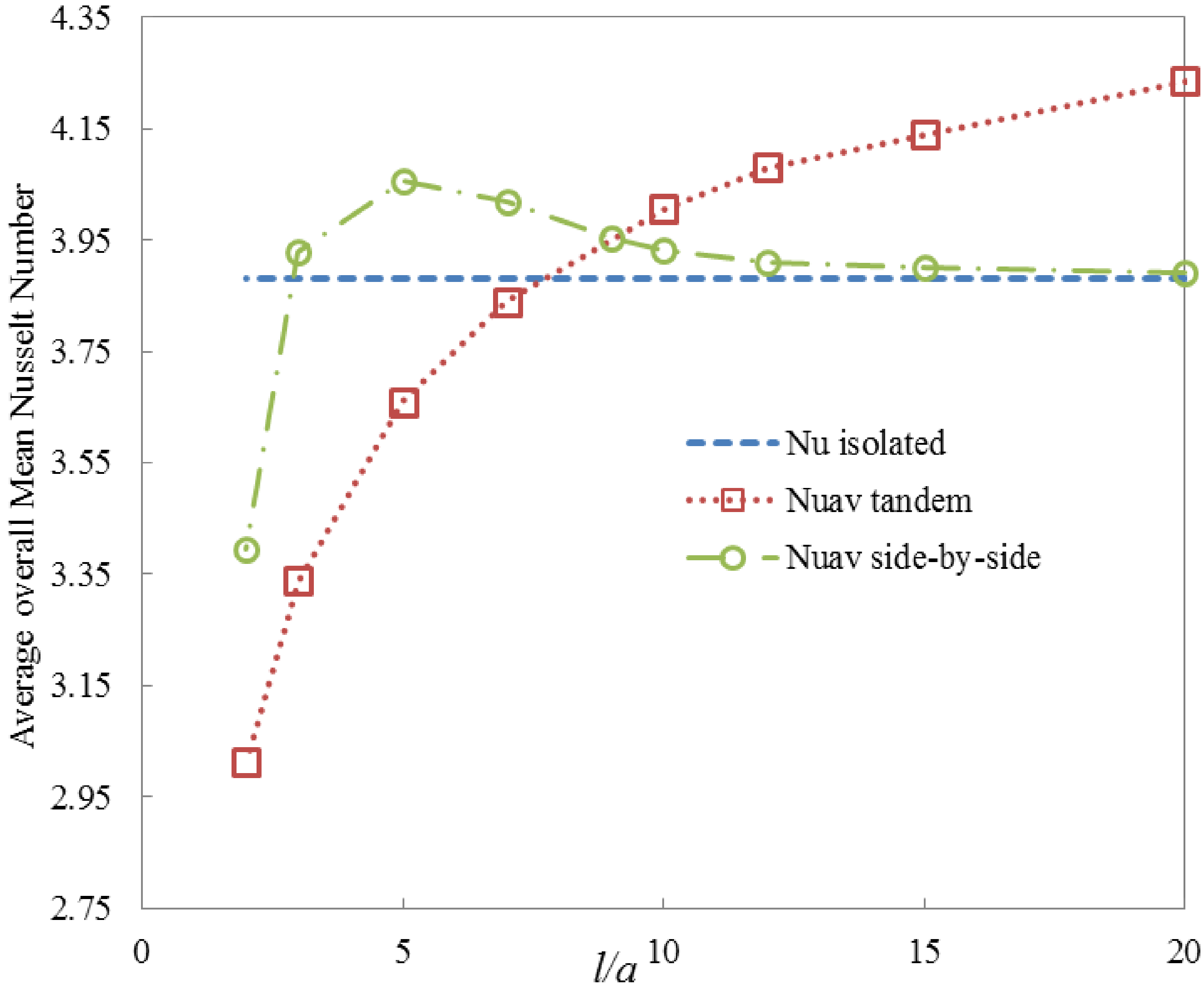
- Heat transfer rate of mixed convection
  - Effect of the incident flow

- Fluidization of particles in a narrow channel

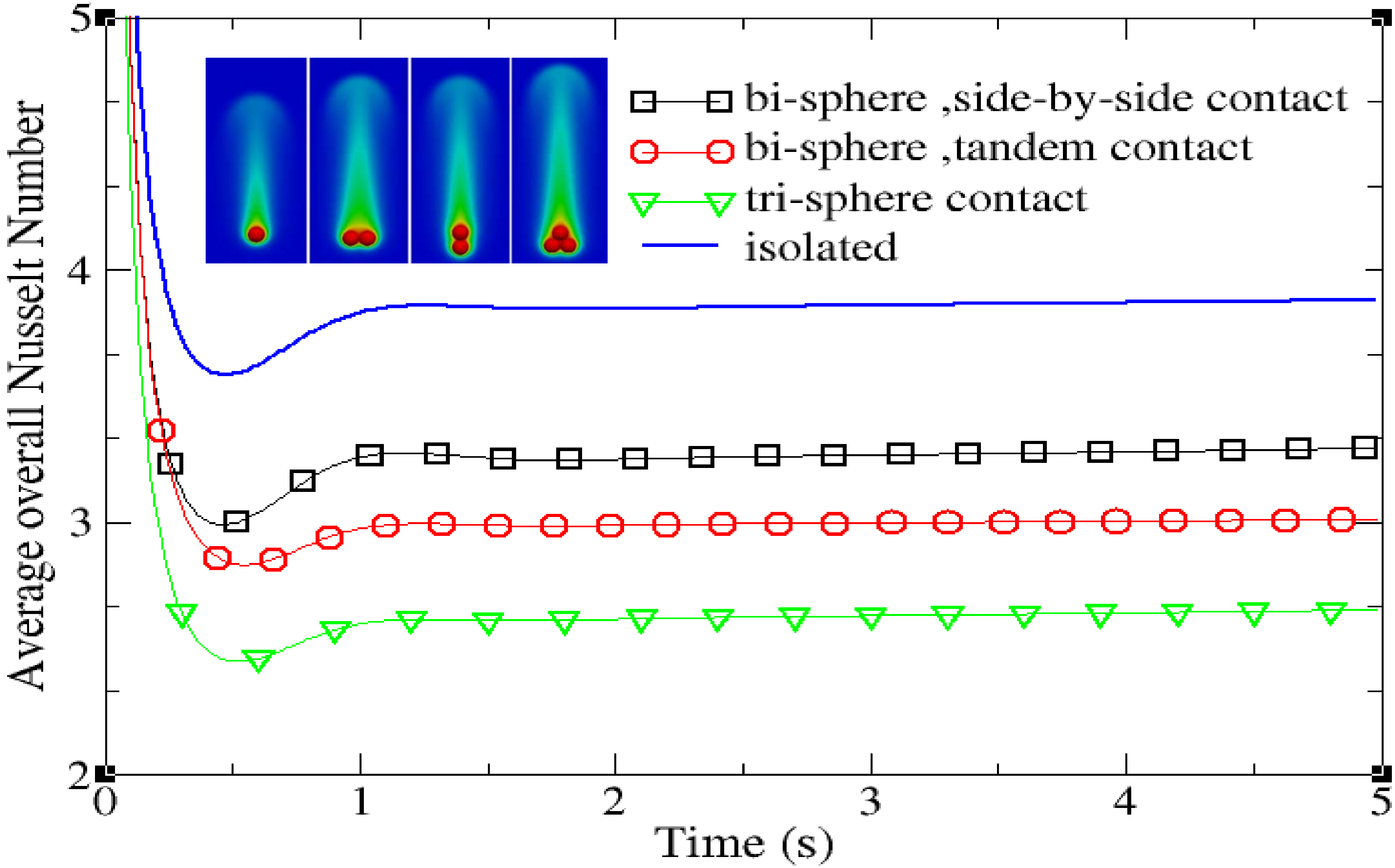
Heat transfer rate in the presence of neighboring particles

Natural Convection Two Horizontal/Vertical Spheres





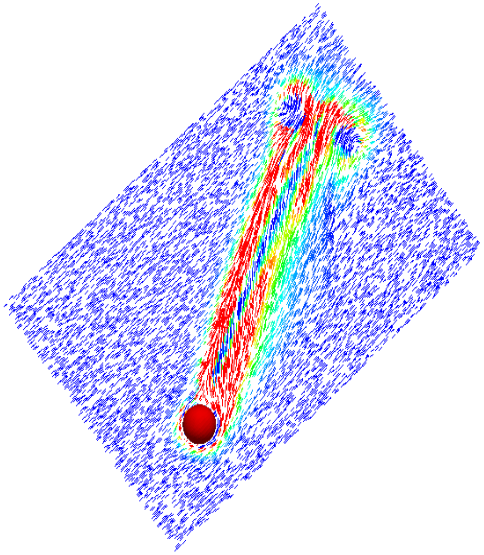
Natural Convection for Clusters (Pr=0.72, Gr=100)

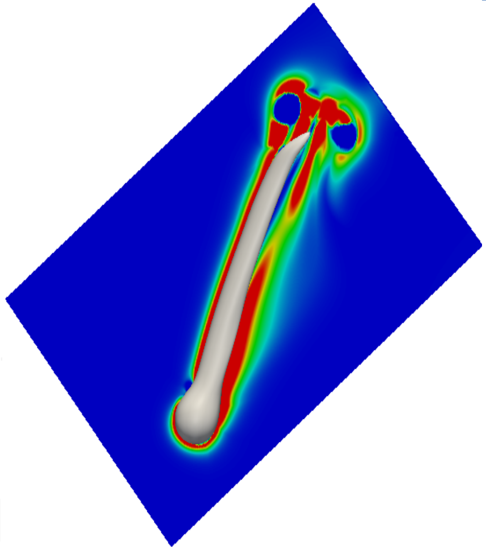


Heat transfer rate of mixed convection

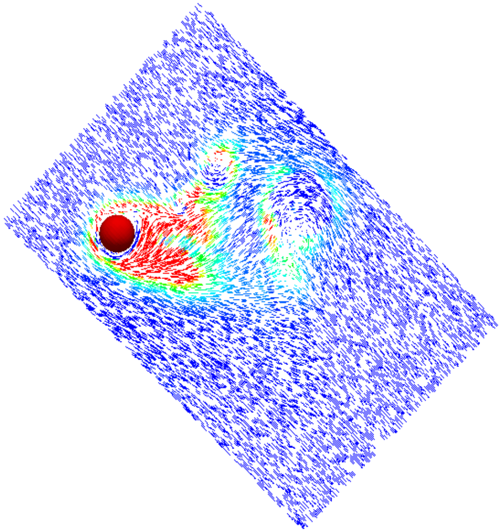
Mixed Convection (Re=100, Ri=5)

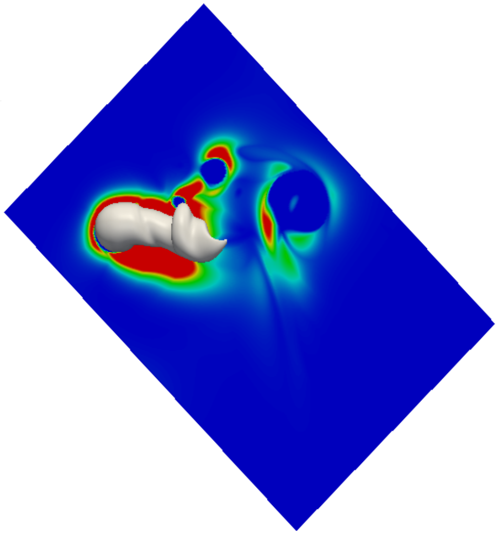
- Aiding Flow (0° – 90°)





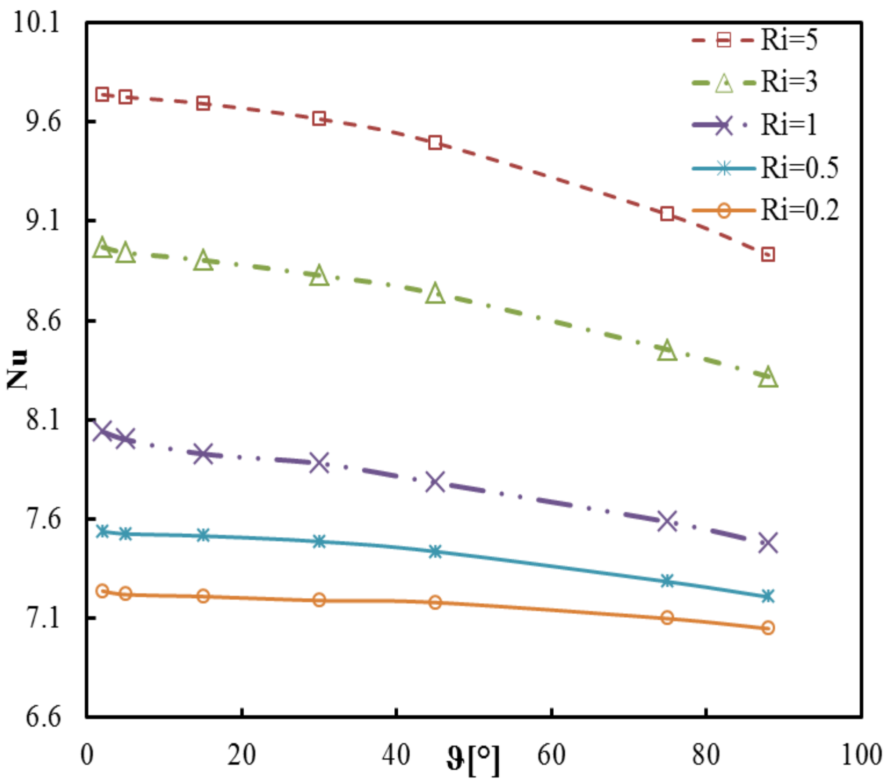
- Opposing Flow (90° – 180°)



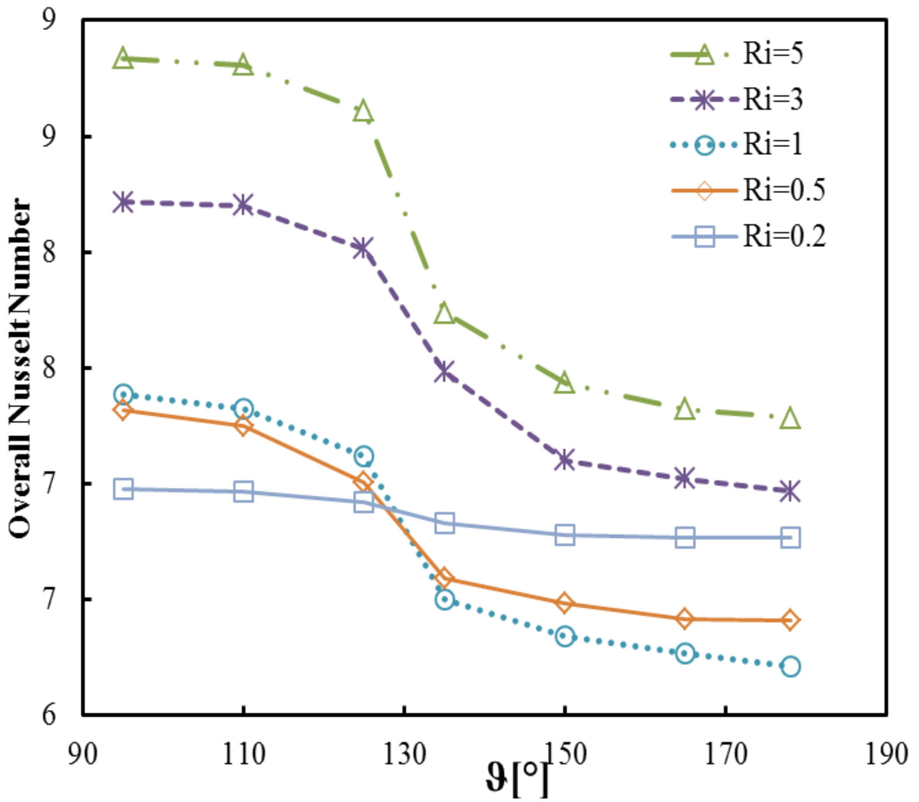


Mixed Convection (Re=100)

Aiding Flow (0º – 90º)



Opposing Flow (90º – 180º)



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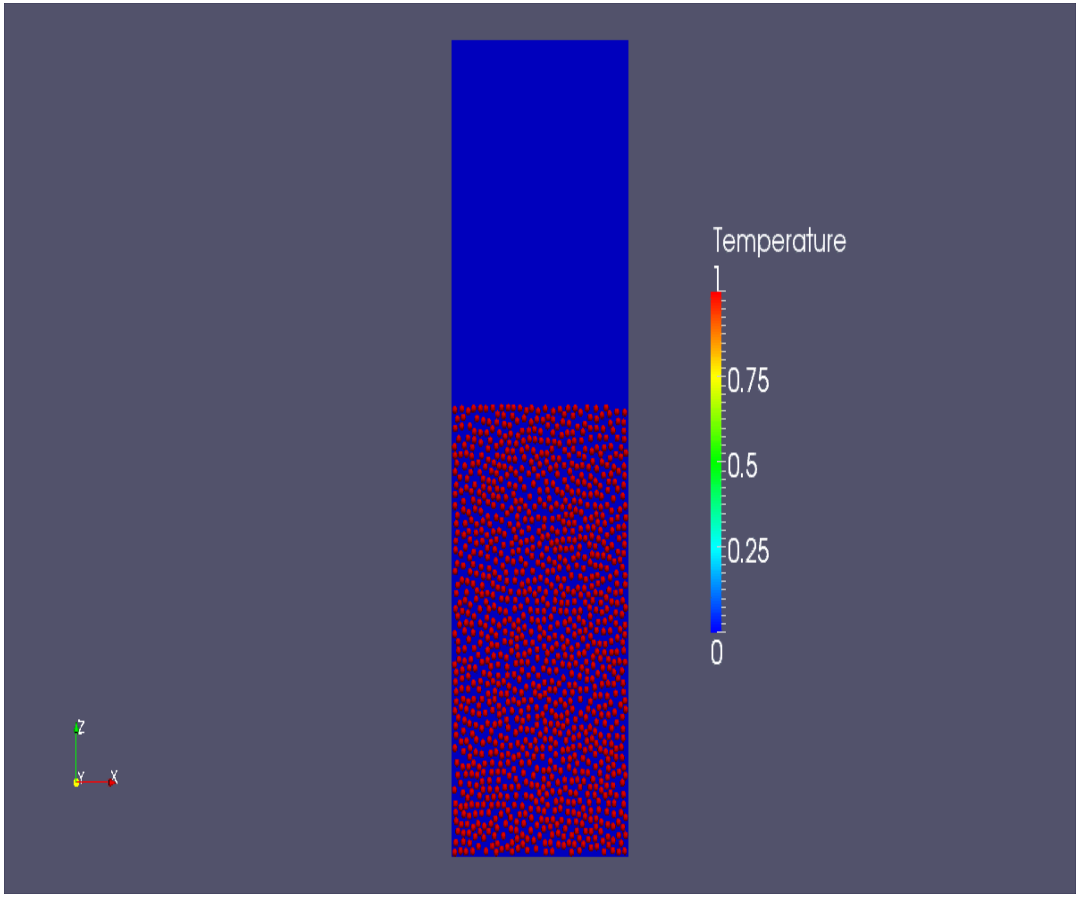
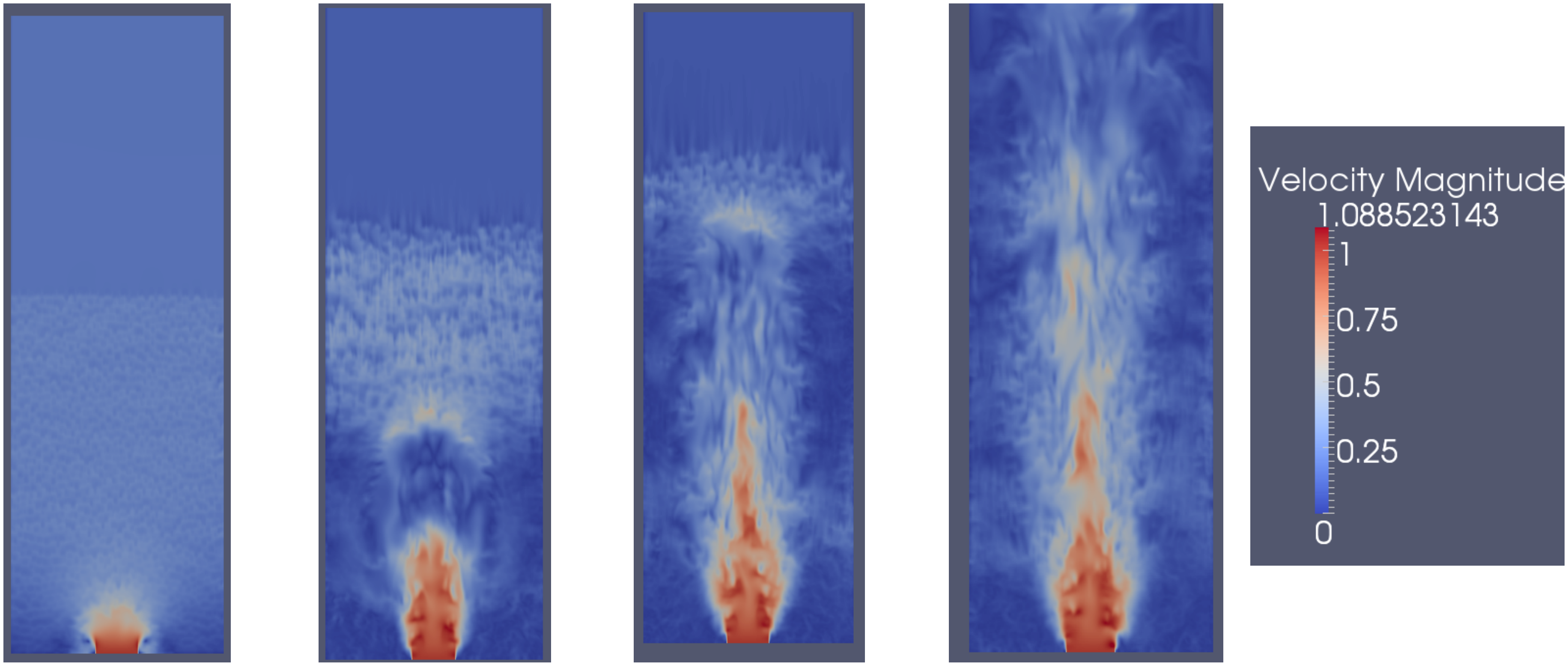
Fluidization of Particles in Narrow Channel

Fluidization of Particles in Narrow Channel

- Number of particles: 1200
- Diameter of particle : 0.3cm
- Dimension of channel: 20x60x1cm
- Fluid density: 1.0 g/cm3
- Particle density:1.5 g/cm3
- Gr=100,Pr=0.72

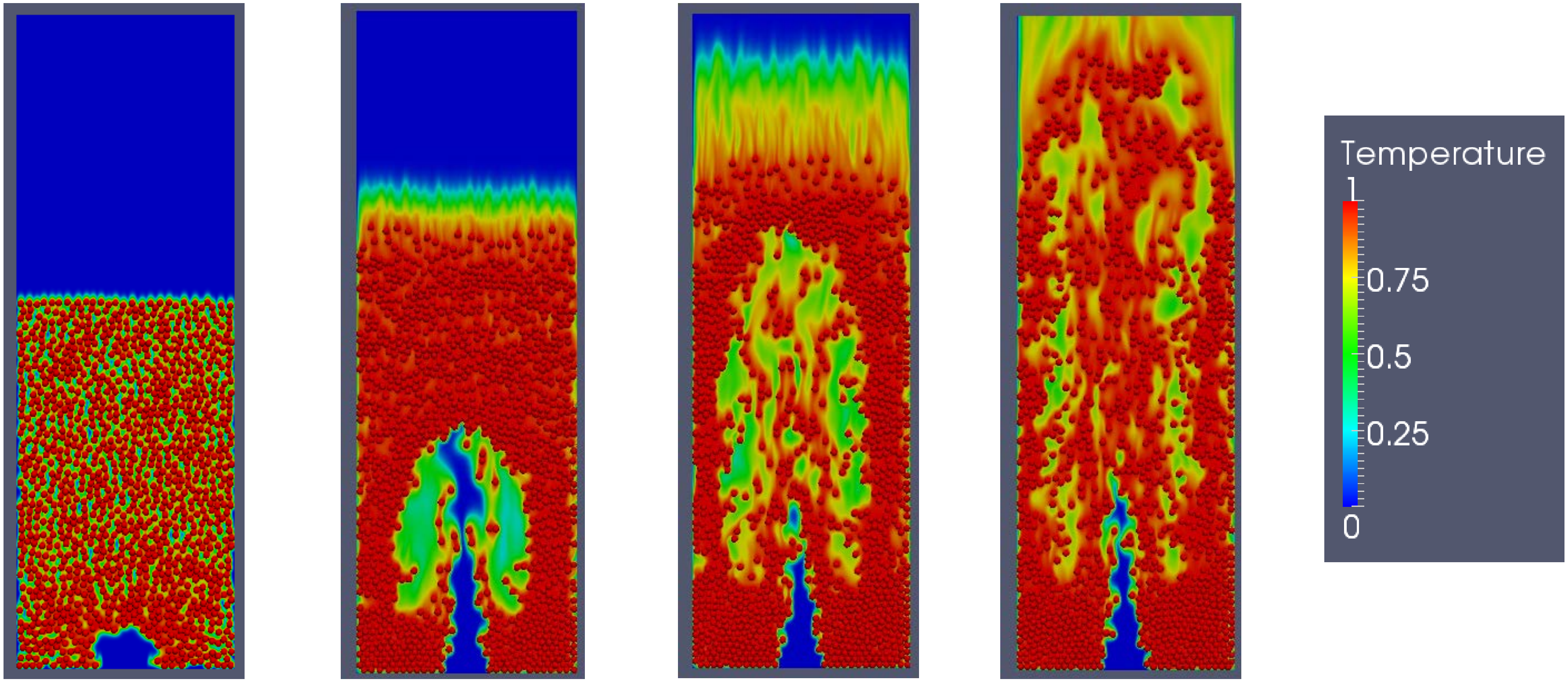


Fluidization of Particles in Narrow Channel-Velocity



t=10s *t=100s* *t=200s* *t=300s*

Fluidization of Particles in Narrow Channel-Temperature



t=10s *t=100s* *t=200s* *t=300s*

Summary

- A DNS combined with IBM is used to solve three-dimensional thermal interaction between particles and fluid. A heat transfer scheme, similar to the momentum force scheme, was developed to determine the temperature field.
- The presence of neighboring particles affects the average Nusselt number. Depending on the separation of the particles, the Nusselt number can increase or decrease.

Summary

- The incident angle is an important factor in a mixed convection process.
  - Incident Angles between 0° – 90°: Nusselt number decreases if the angle increases
  - Incident Angles between 90° – 180°: Nusselt number decreases if the angle increases

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Future Work

- Derive correlation of particle Nusselt number as a function of solid fraction
- Study heat transfer rate of non-spherical particles

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QUESTIONS ?

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