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memphis multiphase

AMCG

A novel finite element framework for numerical simulation of fluidization processes & multiphase granular flow

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DEPARTMENT OF
EARTH SCIENCE AND ENGINEERING

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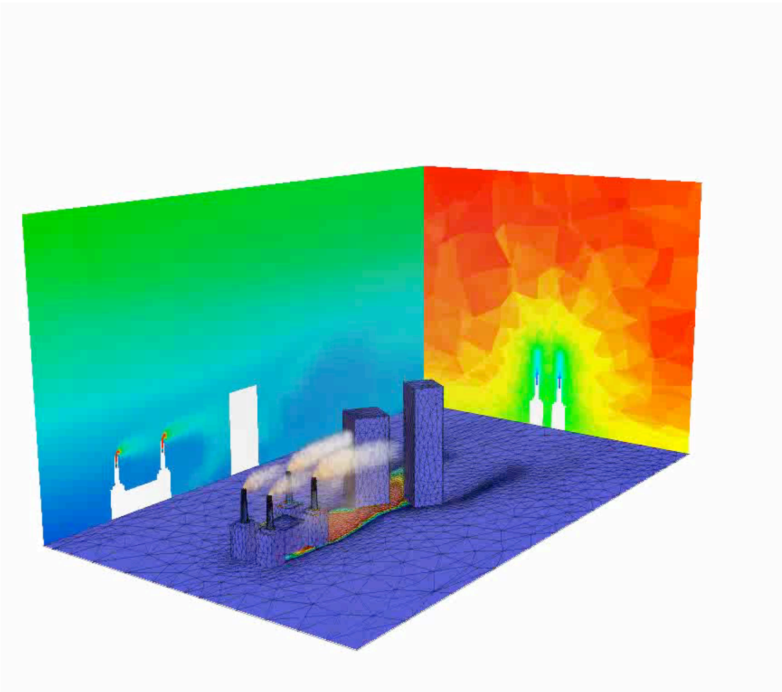
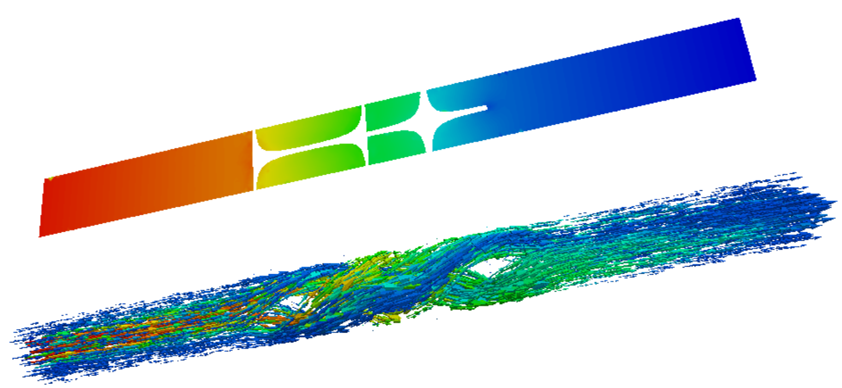
FLUIDITY

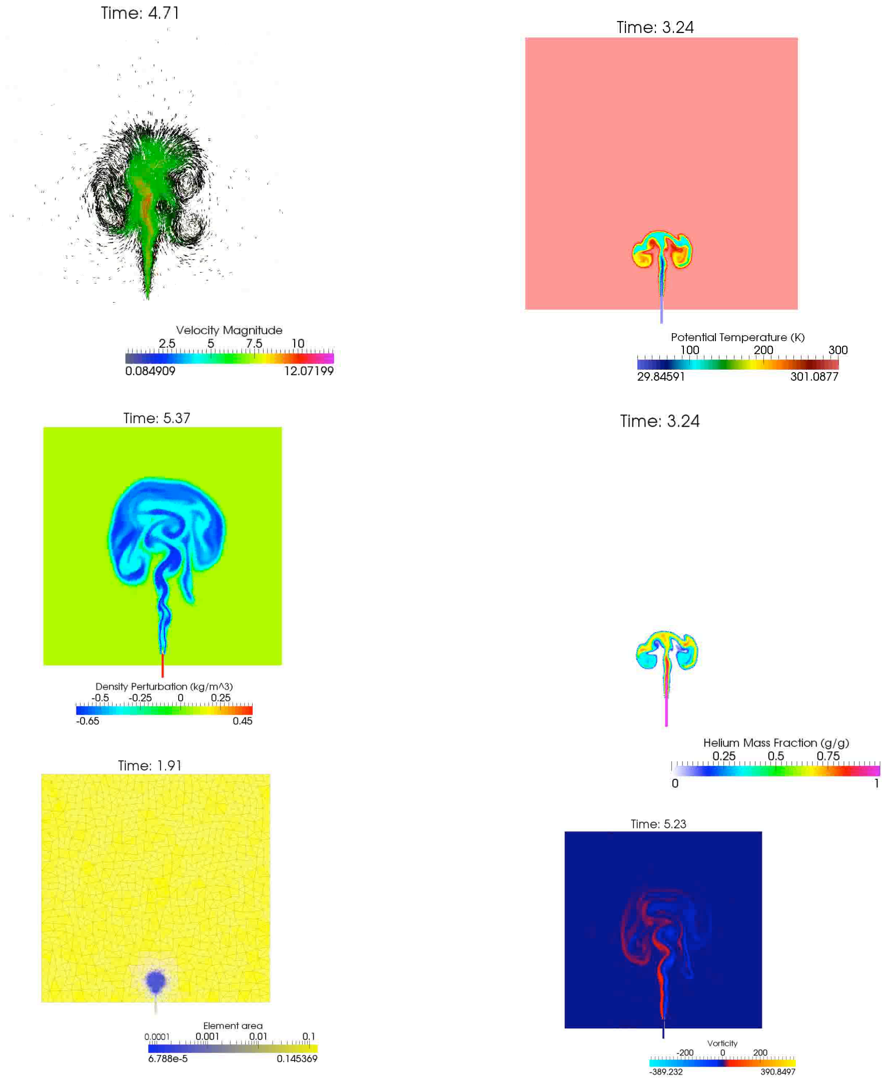
- (CV)FEM based Navier Stokes/Darcy flow solver framework
- Mesh adaptivity capability
- Multimaterial & multiphase formulations (and both together)





Mesh adaptivity

- Hessian approach optimizes estimate of linear interpolation error in chosen variables for given number of DOFs



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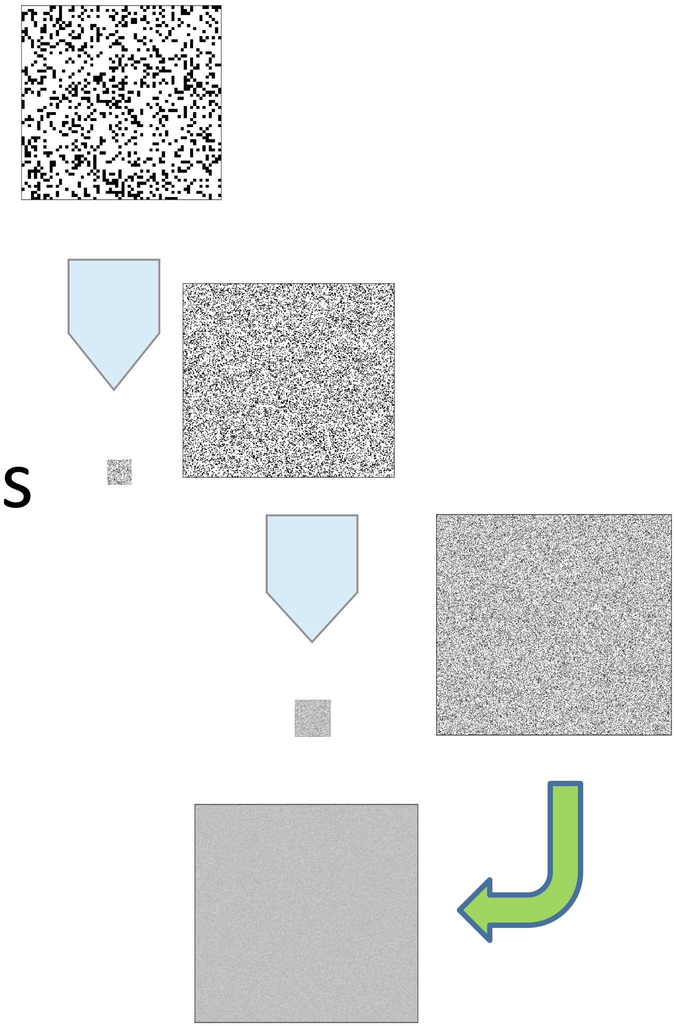
Eulerian-Eulerian modeling

Numerical modeling implies existence minimum resolvable length scale



Droplets/bubbles/solid particles may be far below this scale.

Filter equations to homogenize into "two-fluid" model.

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Eulerian-Eulerian modeling

General equations:

momentum:

$$\frac{\partial}{\partial t}(\rho_i \alpha_i \boldsymbol{u_i}) + \nabla \cdot (\rho_i \alpha_i \boldsymbol{u_i} \boldsymbol{u_i}) = -\alpha_i \nabla p_i - \rho_i \alpha_i g \hat{\boldsymbol{z}} + \boldsymbol{F_i}$$

continuity:

$$\frac{\partial}{\partial t}(\rho_i \alpha_i) + \nabla \cdot (\rho_i \alpha_i \boldsymbol{u_i}) = S_i$$

internal energy:

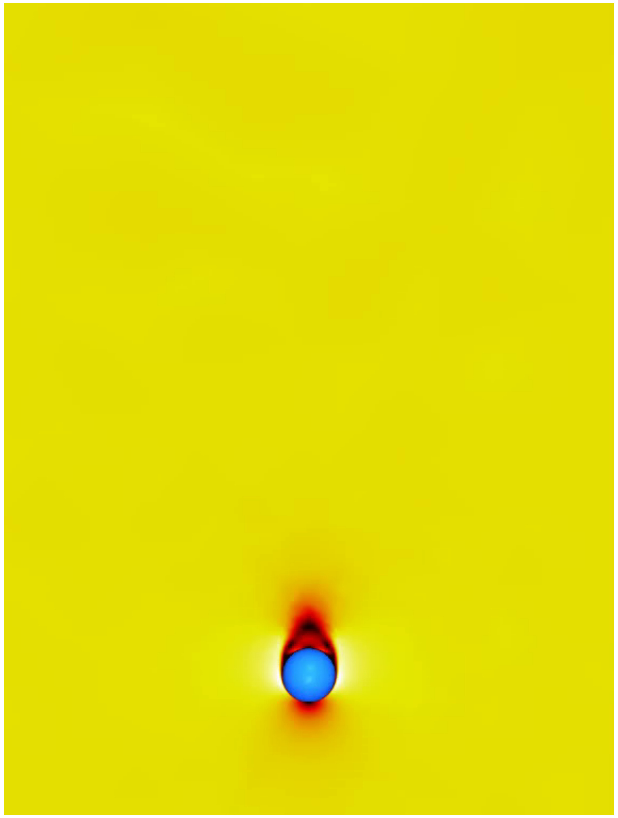
$$\frac{\partial}{\partial t}(\rho_i \alpha_i c_{p,i} T_i) + \nabla \cdot (\rho_i \alpha_i c_{p,i} T_i \boldsymbol{u_i}) + p_i \nabla \cdot \boldsymbol{\alpha_i u_i} = S_i$$

Interphase forces: drag

- Drag term: momentum exchange between phases

$$K_{\text{drag}} = \frac{\partial \boldsymbol{F}}{\partial \Delta \boldsymbol{u}} (\boldsymbol{u}_1 - \boldsymbol{u}_2)$$

- In limit of few, small particles: Stokes law
- Behaviour at higher concentrations less well determined.



$$v_{\text{terminal}} = \frac{2}{9} \frac{(\rho_d - \rho_c)}{\mu_c} g {d_p}^2$$

Interphase forces: drag

Many drag closure models exist:

- Schiller and Naumann (1935)
- Ergun (1952)
- Wen & Yu (1966)
- Symlaml & O'Brien (1987)
- Gidaspow(1990)
- Hill Koch & Ladd (2006)

Variously from theory, numerical modelling or matching experiments.

Interphase forces: drag

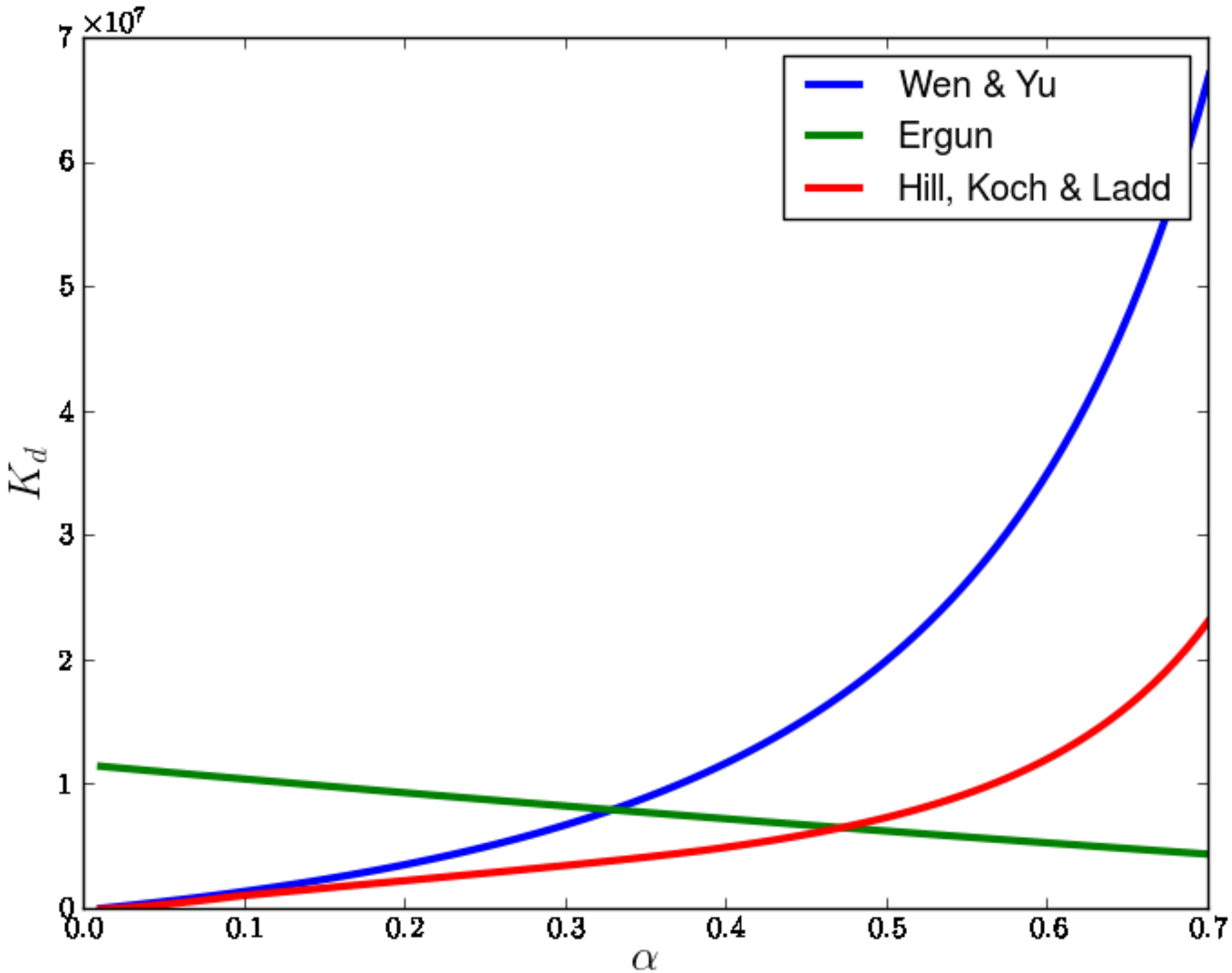
- Different closures appropriate for different systems
- Don't just implement a few, implement a framework

$$K_{\mathrm{drag}} = \frac{\partial \boldsymbol{F}}{\partial \Delta \boldsymbol{u}} (\boldsymbol{u}_1 - \boldsymbol{u}_2)$$

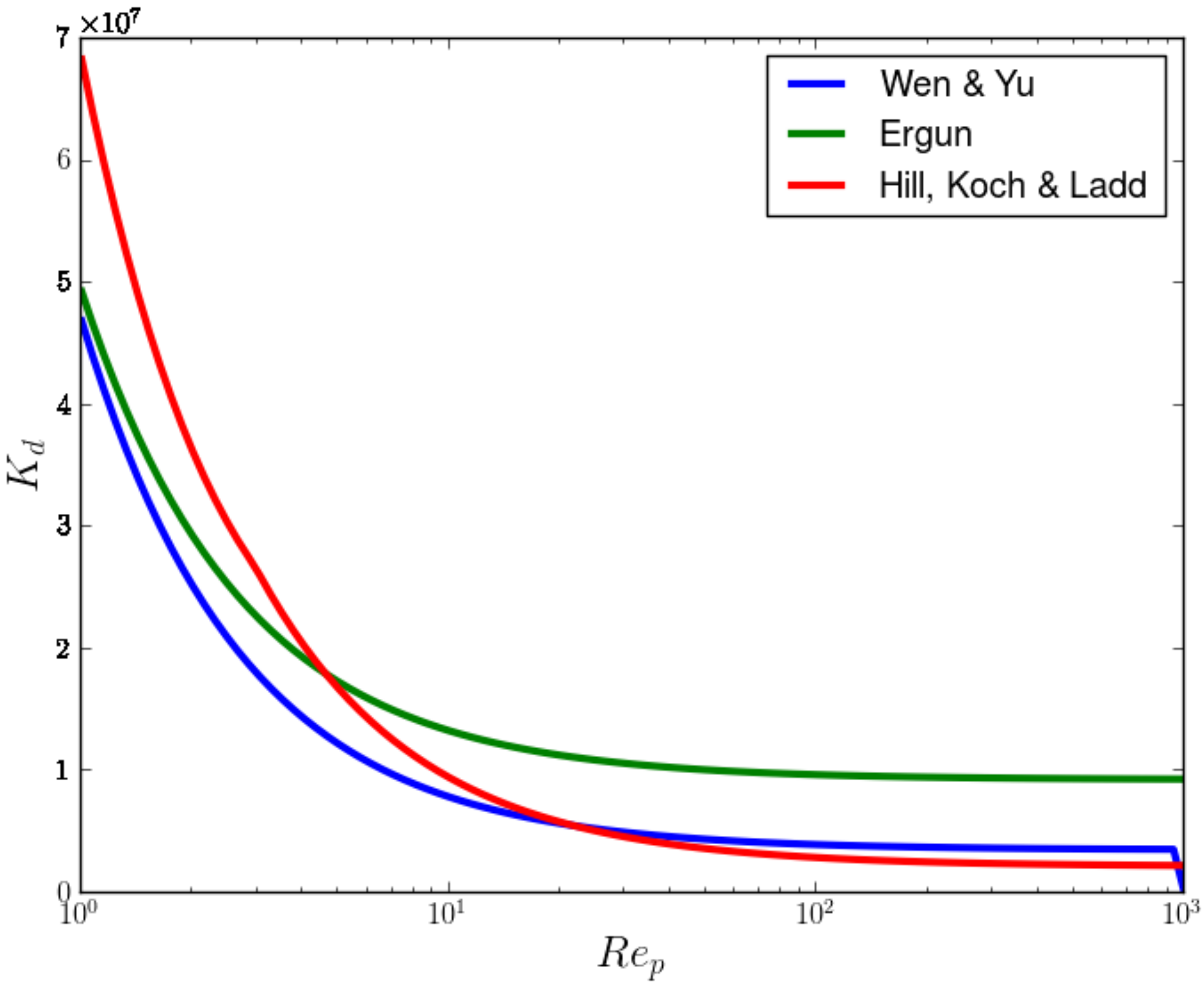
$$\frac{\partial \boldsymbol{F}}{\partial \Delta \boldsymbol{u}} = f(\alpha_i, \boldsymbol{u}_i, \rho_i)$$

- Specify through scripting code

Interphase forces: drag



Interphase forces: drag



Interphase forces: drag

Example: Wen & Yu drag correlation

```
def val(x,t,a_1,a_2,rho_1,rho_2,u_1,u_2):
   mu=1.0e-5
   d_s=150e-6
   Re_s=a_1*rho_1*abs(u_1-u_2)*d_s/mu
   if Re_s>1000:
       C_D=0.44
   else:
       C_D=24/Re_s*(1.0+0.15*(Re_s**0.687))
   return 3*C_D/4.0*a_1*a_2*rho_1*abs(u_1-u_2)/d_s*a_1**-2.65
```

Interphase forces: granular temperature

- Specialize to dense fluid-solid systems
- Solid has
  - Max packing density
  - Quasi-elastic collisions
  - Additional kinetic energy in fluctuations
- Kinetic theory closure
- qv. Gidaspow(1994)

$$\boldsymbol{F}_{\text{solid}} = \nabla p_s + K_{\text{drag}} + \boldsymbol{F}_{\text{friction}}$$

$$\Theta_s = \frac{1}{3}\left\langle \left|\boldsymbol{u} - \boldsymbol{v}\right|^2 \right\rangle$$

$$p_s = \rho_s \alpha_s \left(1 + 2\left(1 + e\right)\alpha_s g_0\right)\Theta_s$$

$$g_0 = \left(1 - \left(\frac{\alpha_s}{\alpha_{s,\max}}\right)^{\frac{1}{3}}\right)^{-1}$$

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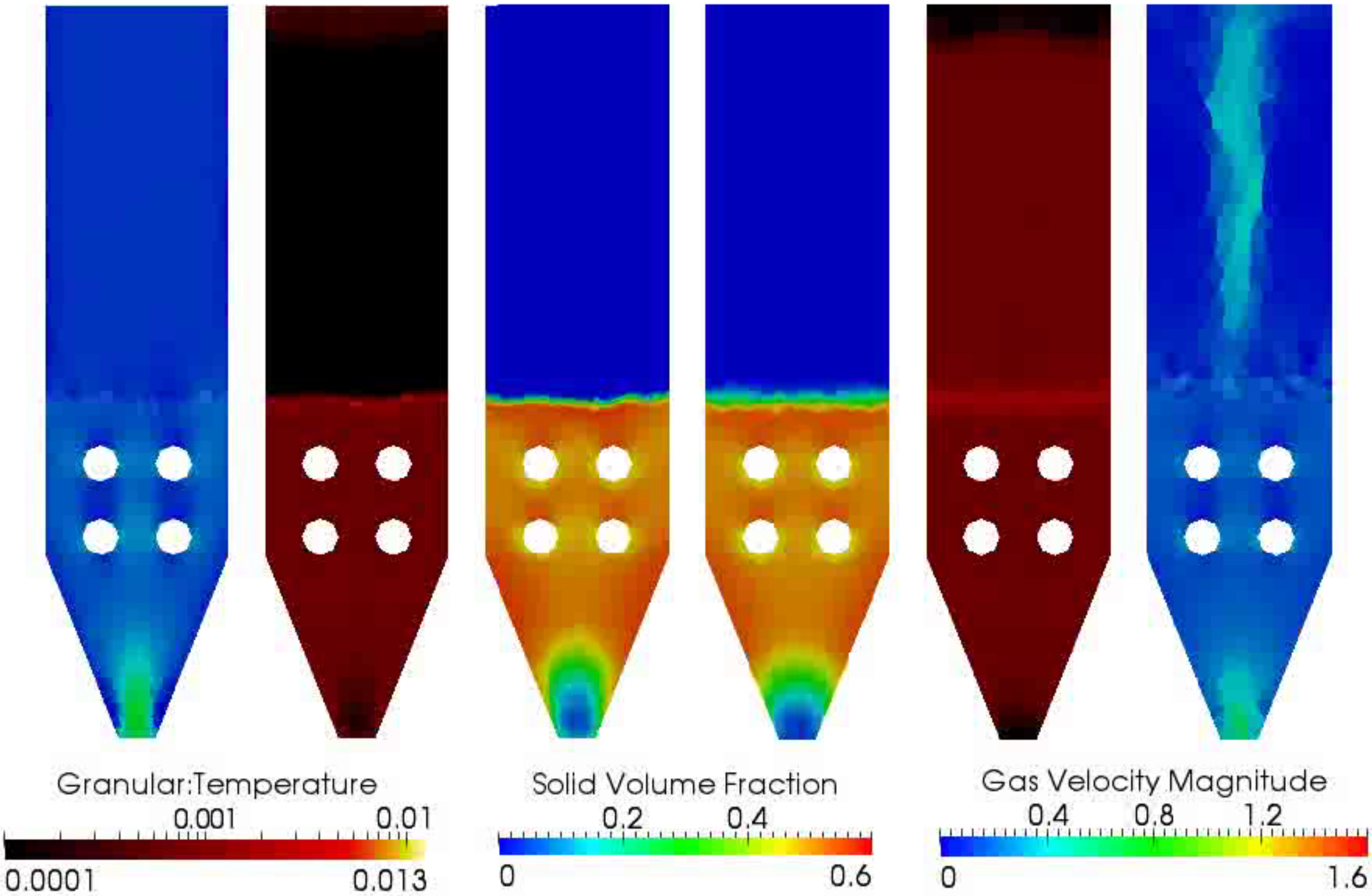
Interphase forces: granular temperature

$$\boldsymbol{F}_{\text{friction}} = \alpha_s \nabla \cdot \left(\mu_s \left(\nabla \boldsymbol{u}_s + \nabla \boldsymbol{u}_s \right) + \left(\lambda_s - \frac{2\mu_s}{3} \nabla \cdot \boldsymbol{u}_s \right) \boldsymbol{I} \right)$$

$$\mu_s = \frac{4}{5} \alpha_s d_s g_0 \left(1 + e\right) \left(\frac{\Theta_s}{\pi} \right)^{\frac{1}{2}}$$

$$\lambda_s = \frac{4}{3} \alpha_s d_s g_0 \left(1 + e\right) \left(\frac{\Theta_s}{\pi} \right)^{\frac{1}{2}}$$

$$\frac{\partial}{\partial t} \left(\rho_s \alpha_s \Theta \right) + \nabla \cdot \left(\rho_s \alpha_s \Theta \boldsymbol{u}_s \right) = \nabla \boldsymbol{u}_s \cdot \tau_s - \gamma \Theta - \frac{\partial \boldsymbol{F}}{\partial \Delta \boldsymbol{u}} \Theta$$


Granular:Temperature
0.001
0.01
0.0001
0.013
Solid Volume Fraction
0.2
0.4
0
0.6
Gas Velocity Magnitude
0.4
0.8
1.2
0
1.6

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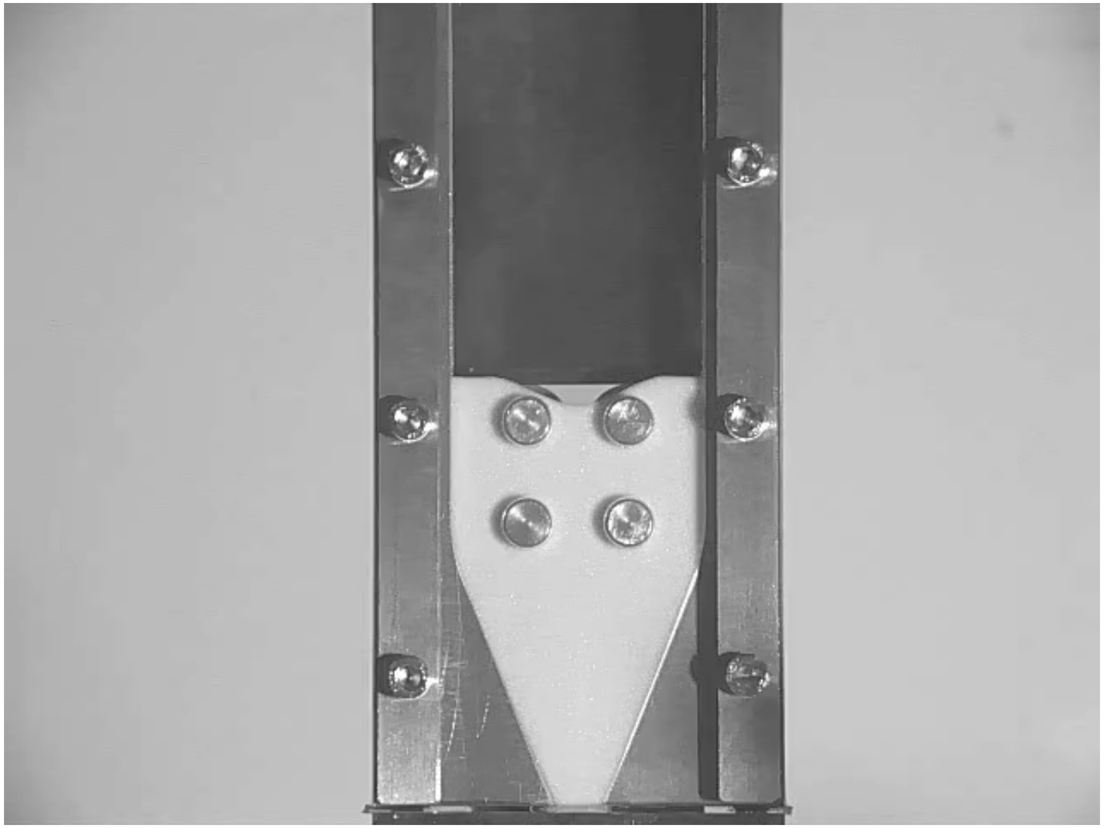
Fluidized bed verification

Experimental reactor in Lab Mikio Sakai Univ. Tokyo



Polydispersion

Multiple sizes/shapes of dispersed material

- Drag terms:
    - technology already there!
- Particle-particle interactions
- Size parameterization:
    - Binning approach

Polydispersion

Little consensus in literature:

- Single or multiple granular temperatures?
- Modification of maximum packing fraction for mixtures?
- Existing gas-solid drag term, or additional terms?
- Which solid-solid interactions to consider?
  - Solid-solid interphase drag
  - Which phases contribute to solid viscosity?

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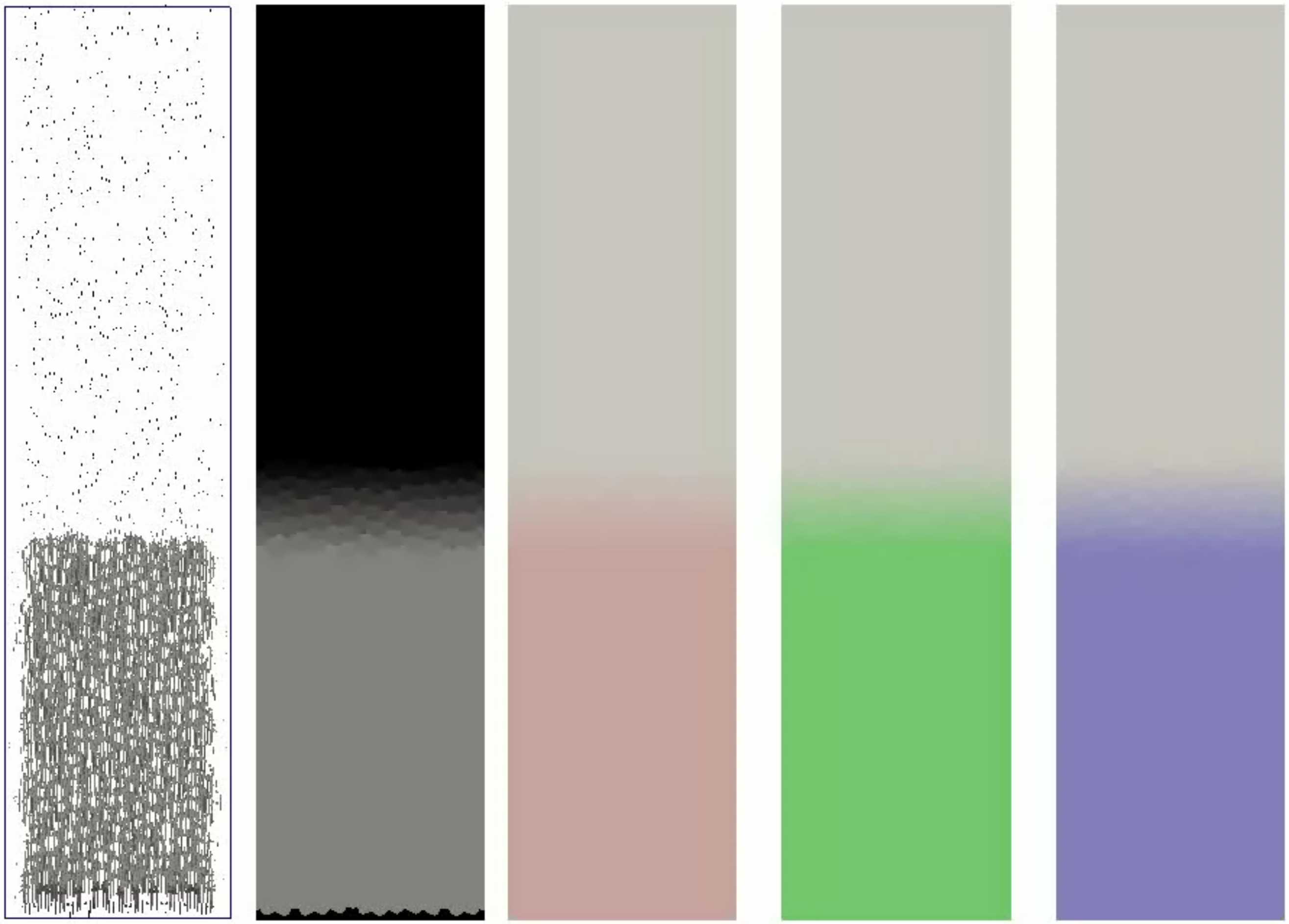
Polydispersed Granular Mixtures: Single temperature



Future work

- Extensions to non-spherical and to deformable media
- Coupling with source/rate models
    - Chemistry
    - Combustion
- Coupled phase & species models

Thank you for your attention

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