A Hybrid Lagrangian-Eulerian Approach in Simulating Gas-Solid Flows Consisting of Multiple Solid Phases

Dhanunjay (Jay) Boyalakuntla, Sreekanth Pannala, Stuart Daw
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Sofiane Benyahia, Tom O'Brien, Madhava Syamlal
National Energy Technology Laboratories, DOE
Morgantown, West Virginia

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Motivation

- **Two existing approaches in simulating granular flows**
  - **Continuum Models (CM)**
  - **Discrete Element Simulation (DES)**
- **DES**
  - **Tracks individual particles**
  - **Provides detailed information regarding each individual solid particle**
  - **Captures certain granular flow behaviors better than CM**
  - **Computationally expensive**
- **CM**
  - **Relatively faster than DES**
  - **Less expensive than DES**
  - **Provides averaged solids information**
  - **Generally adequate to understand the overall behavior of granular systems**

Motivation

- **Simulating granular flows with multiple solid phases such as in coal gasification (where there are many small particles but few big particles) using either of the approaches has its own cost/details benefits**
- **Continuum representation of the bigger sparse solids phase would not be as Lagrangian tracking**
- **DES for smaller dense solids phase would be computationally expensive**

Can we get the best out of both worlds?

Objective

- **Here we present a new idea to couple the two approaches**
- **A mixed approach which uses DES as well as CM in simulating granular flows**
- **The use of DES or CM for a particular phase can be specified based on the physics of the problem**
  - **DES for the bigger sparse solids phase and CM for the smaller dense solids phase**

- **Hybrid *Discrete Element – Continuum Model (DECM)***

Discrete Element – Continuum Model (DECM)

- **DECM could efficiently combine the advantages of both CM and DES**
- **Can reduce the cost of DES**
- **Provide more details than CM**
- **More realistic simulation of certain solid phases**

- **DECM – More accuracy; Less computational time**

- **MFIX is used for this development**
  - **CM and DES implemented in MFIX**

Continuum Approach

Continuity Equation

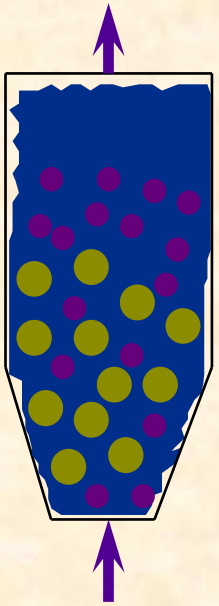
$$\frac{\partial}{\partial t}(\varepsilon_m \rho_m) + \nabla \cdot (\varepsilon_m \rho_m \vec{v}_m) = \sum_{l=1}^{M} R_{ml}$$

Momentum Equation

$$\frac{\partial}{\partial t}(\varepsilon_m \rho_m \vec{v}_m) + \nabla \cdot (\varepsilon_m \rho_m \vec{v}_m \vec{v}_m) = \nabla \cdot \bar{\bar{S}}_m + \sum_{l=1}^{M} \vec{I}_{ml} + \vec{f}_m$$

Stresses

Interaction Term



- **Two Phases**

Fluid

Solids

- **Three phases**

Fluid

Solids - 1

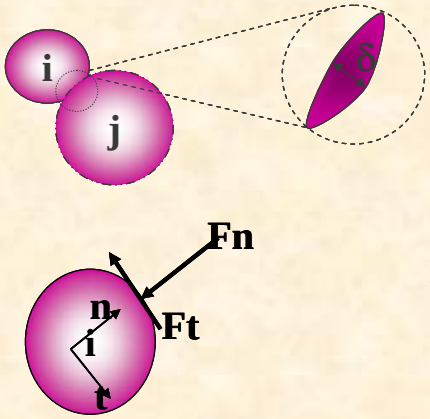
Solids - 2

Size 1

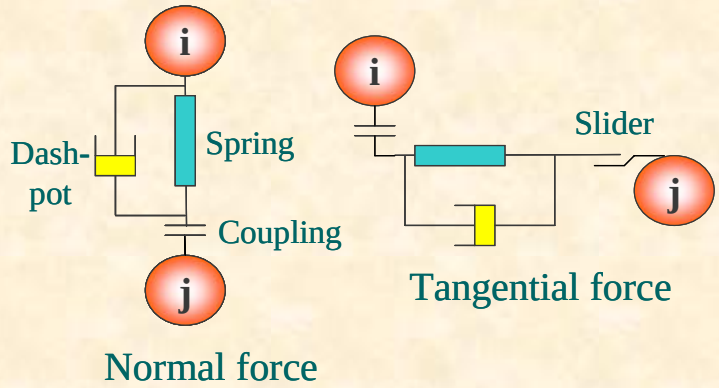
Size 2

- **Each solids phase treated as continuum fluid**
- **Constitutive equations determine phase flows and phase interactions (key inputs to model)**
- **Model posed as a system of PDEs simulating variations in space and time (Eulerian framework)**

Discrete Element Approach



Force Model



- **DES codes can track single particles but computational cost is enormous**
- **More detailed studies of single particle behavior (e.g., particle-particle attrition, particle-wall sticking)**

Governing Equations

$$\dot{\vec{v}}_s = \frac{\vec{F}}{m} + g \qquad \vec{F} = \vec{f}_C + \vec{f}_D \qquad \vec{f}_{Ci} = \sum_j \left(\vec{f}_{Cnij} + \vec{f}_{Ctij}\right)$$

$$\vec{f}_{Cni} = -k\vec{\delta}_{nij} - \eta\vec{v}_{nij} \qquad \vec{f}_{Cti} = -k\vec{\delta}_{tij} - \eta\vec{v}_{tij}$$

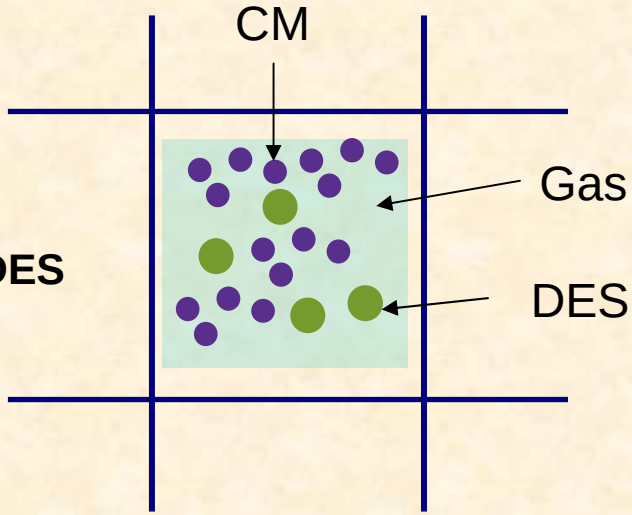
$$\vec{v}_n = (\vec{v}_r \bullet \vec{n})\vec{n} \qquad \vec{v}_t = \vec{v}_r - \vec{v}_n + r(\vec{\omega}_i + \vec{\omega}_j) \times \vec{n}$$

$$\left|\vec{f}_{Ctij}\right| \triangleright \mu_f \left|\vec{f}_{Cnij}\right| \qquad \vec{f}_{Ctij} = -\mu_f \left|\vec{f}_{Cnij}\right| \vec{t}_{ij} \qquad \vec{t}_{ij} = \frac{\vec{v}_{tij}}{\left|\vec{v}_{tij}\right|}$$

$$\dot{\vec{\omega}} = \frac{\vec{T}_C}{I} \qquad \vec{T}_{Ci} = \sum_j \left(r\vec{n}_{ij} \times \vec{f}_{Ctij}\right)$$

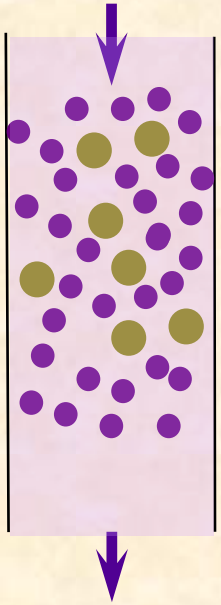
DECM Algorithm

- **In each time step**
  - **Continuum Step**
    - **Calculate the void fractions**
    - **Calculate the gas velocities**
    - **Calculate Continuum solids velocities**
    - **Account for the drag (Gas and solids – DES and CM)**
  - **DES Step**
    - **Track DES solids in each cell**
    - **Calculate the inter-particle collision forces**
    - **Calculate the drag from the gas phase and the continuum solids phase**
    - **Calculate velocities**

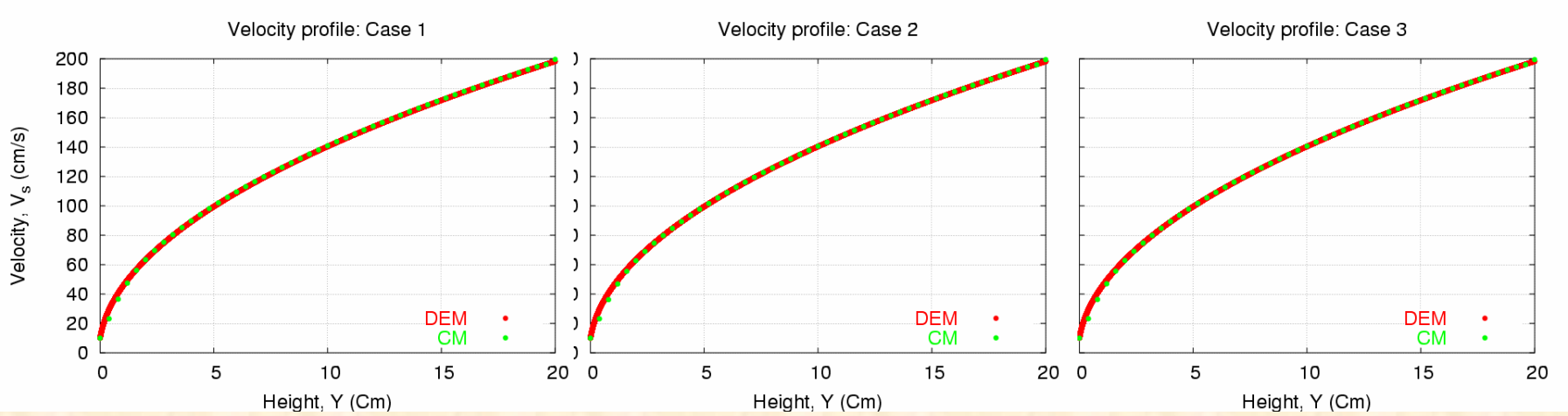


DECM Verification: Free Fall in Vacuum

- **Comparison between DES and CM**
- **2 Solids Phases (1:DES; 2:CM)**
- **Cases**
  - **1: same solids (Particle size and density); no solids interaction**
  - **2: same solids; solids phases interact**
  - **3: Different solids; solids phases interact**

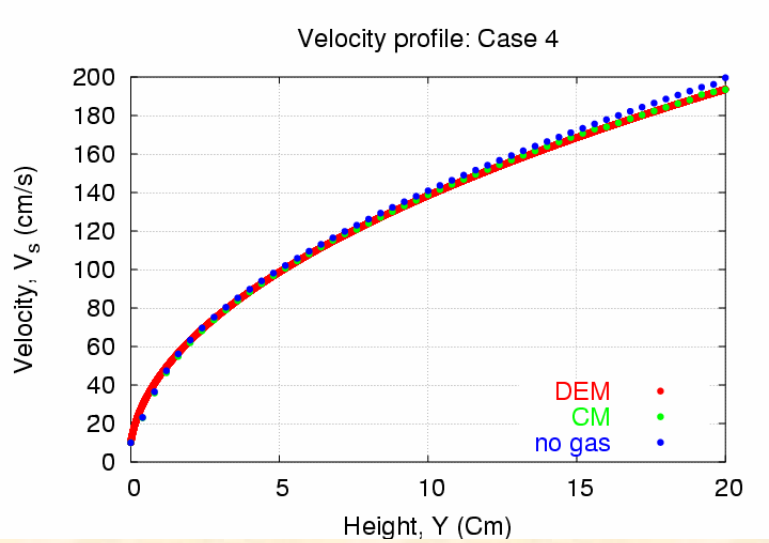


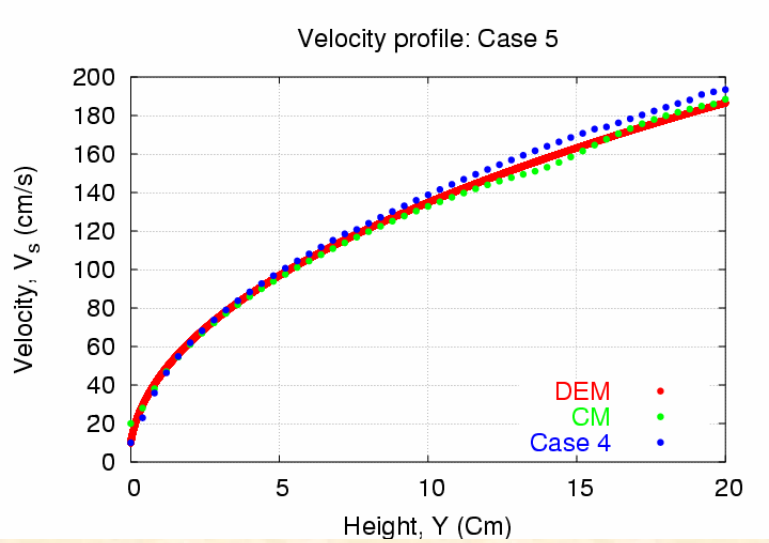
No Gas

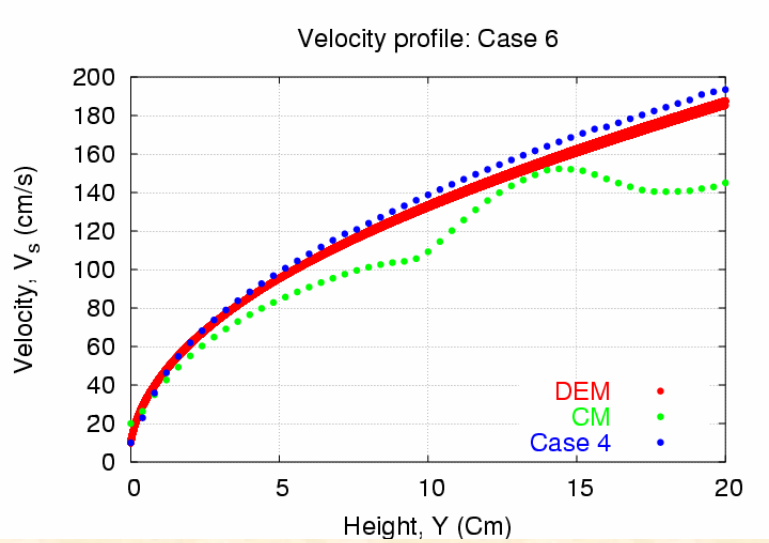


DECM Verification: Free Fall in air

- **Comparison between DES and CM**
  - **Case 4: same solids; no solids interaction**
  - **Case 5: same solids; solids phases interact**
  - **Case 6: Different solids; solids phases interact**

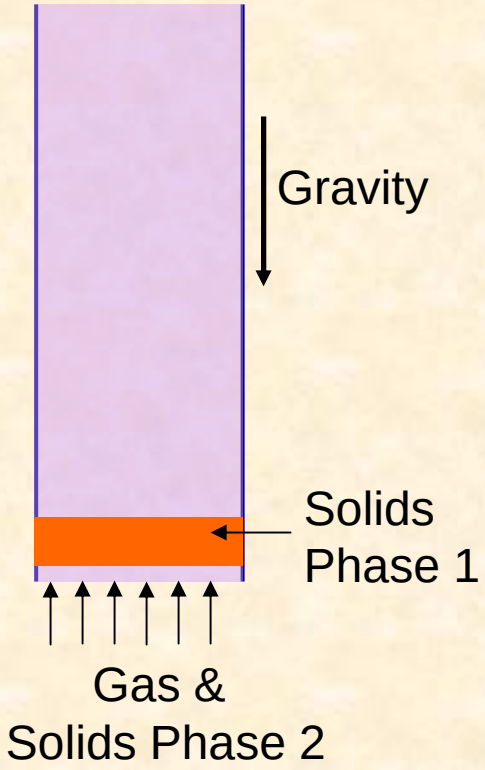




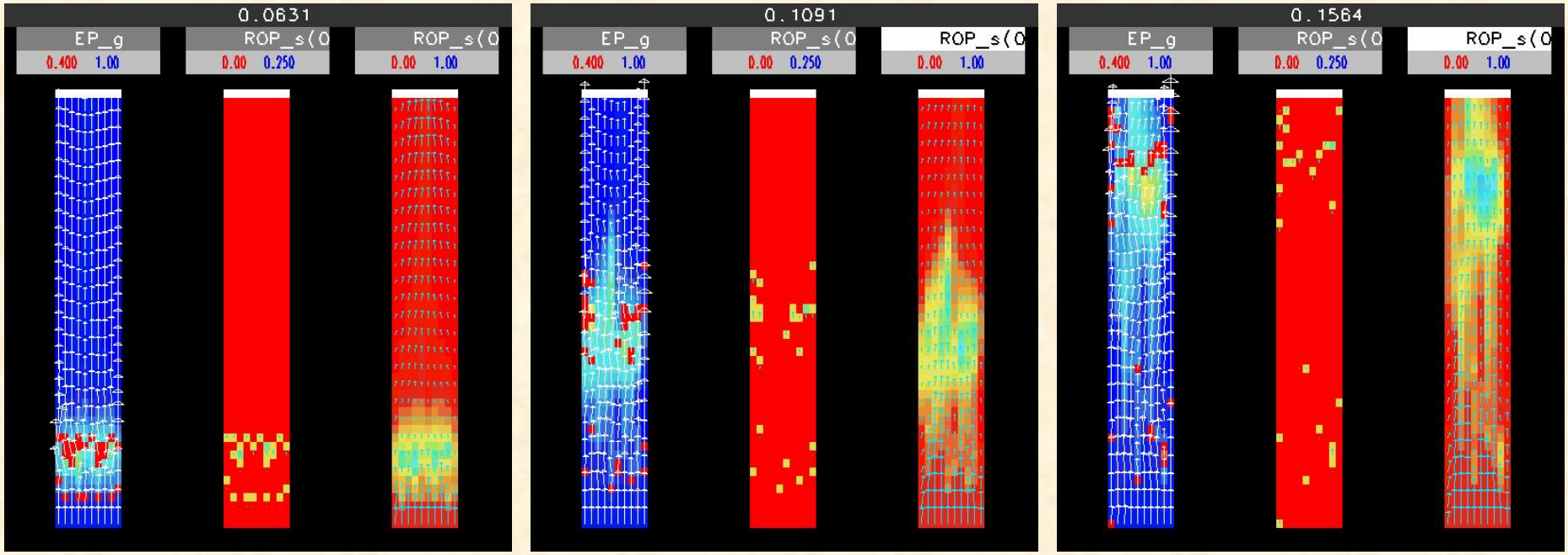


Riser Simulation: Problem Description

- **A Vertical channel**
- **2 solids phases**
  - **bigger solids – phase 1 (sparse phase)**
  - **Smaller solids – phase 2 (dense phase)**
- **Gas and solids injected from the bottom**
- **Phase 1 treated using DES**
- **Phase 2 treated using CM**
- **Gas and Solids enter from the bottom and exit at the top**



Results

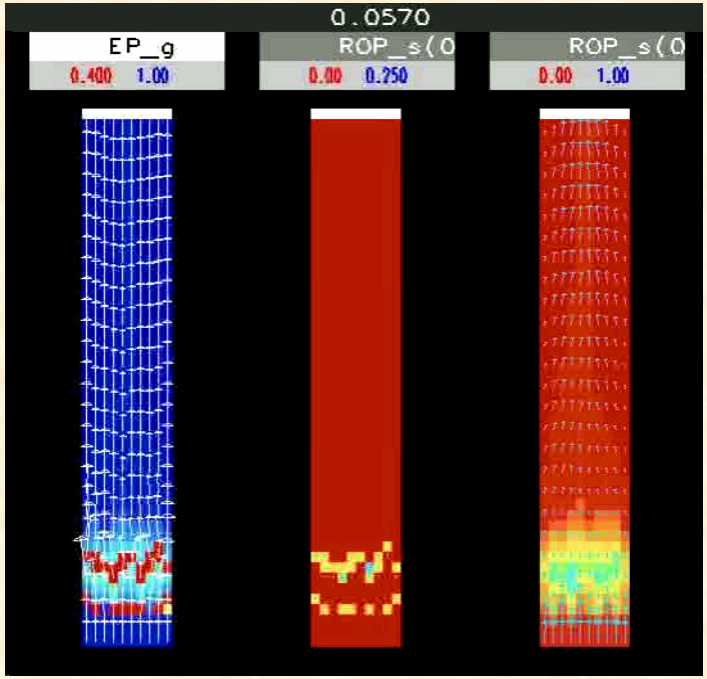


0 1 2
DES CM

0: Void Fraction & Gas Velocity Vectors
1: Solids Phase 1 & Velocity Vectors
2: Solids Phase 2 & Velocity Vectors

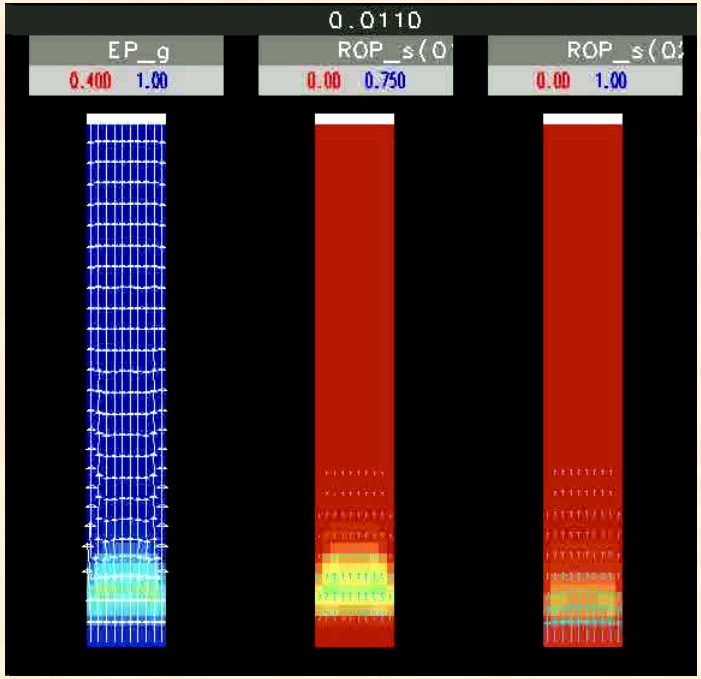
Comparison with Continuum Simulation

DECM



0 1 2
DES CM

CM



0 1 2
CM CM

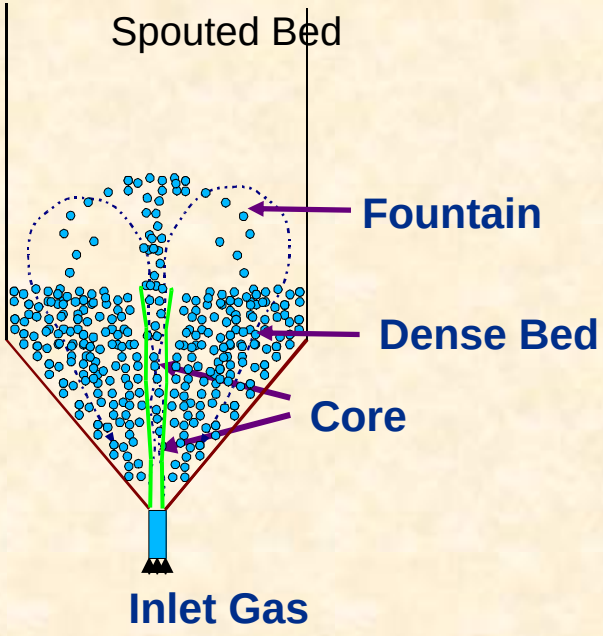
0: Void Fraction & Gas Velocity Vectors
1: Solids Phase 1 & Velocity Vectors
2: Solids Phase 2 & Velocity Vectors

Observations

- **Cell void fraction**
  - **If particle size comparable to cell size DECM could give result in cells with negative void fraction**
- **Gas Solids drag**
  - **Accounting for each solids phase in the cell**
- **Solid-Solid drag**

Future Work

- **DECM for more complex applications**
  - **More solid phases**
  - **Different solid phases *eg.* Elliptical solids and spherical solids**
- **DECM based on the solids location in the domain**
  - **In a spouted bed simulation with DECM**
    - **the core and fountain using DES**
    - **the dense bed using CM**
    - **At interface**
- **Incorporate Heat and Mass Transfer**



Conclusions

- **DECM has been implemented by coupling DES and CM for solid phases for granular flow simulations**
- **Demonstrated on a riser problem**
- **Observations**
  - **Void fraction**
  - **Gas-Solids coupling**
  - **Solids-Solids coupling**

Thank you for your attention!!

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