Numerical simulation of polydisperse gas-particle flow in a vertical riser using a size-velocity quadrature-based moment method

Bo Kong[1,2] and Rodney O. Fox[1,2]

[1]Department of Chemical and Biological Engineering
Iowa State University, Ames, IA, USA

[2]Ames Laboratory – U.S. DOE, Ames, IA, USA

2015 Crosscutting Technology Research Review Meeting

Completed Tasks in FY15

MFIX-QBMM

Created collection of gas-particle solvers using quadrature-based moment methods

- Migrated from MFIX-2013 to current MFIX version, using MFIX git development repository
- Developed comprehensive post-processing capabilities using Python and VTK package
- Prepared documentation and tutorials for code
- Enabled code to run in both DMP and SMP mode
- Developed capability of handling non-uniform grid
- Provided users with a full range of drag models
- Developed realistic wall boundary condition
- Validated code against Euler-Lagrangian simulations

Outline

Motivation

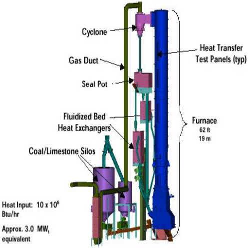
Problem :

In many commonly encountered engineering applications

1. polydispersity (e.g., size, density, shape) is present
2. “size” and velocity of disperse phase are closely coupled

Power plant

Fluidized bed



Coal particles

Proposed solution:

Joint number density function of “size” and velocity of disperse phase can be solved using quadrature-based moment methods (QBMM)

Existing models for polydisperse gas-particle flows

Euler-Lagrange Models

- Discrete Element Method (DEM)

  Limitation: Computationally expensive for industrial applications

Euler-Euler Models

- Population Balance Equation (PBE) carried by fluid velocity

  Limitation: Spatial fluxes do not depend on size
- Class method with separate class velocities

  Limitation: Computationally expensive for continuous size distribution
- Direct Quadrature Method of Moments (DQMOM) with a multi-fluid model

  Limitation: Weights and abscissas are not conserved quantities

Objective

Develop a robust and accurate moment-based polydisperse flow solver that incorporates microscale physics at reasonable computation cost

Governing equations for polydisperse gas-particle flow

Gas phase: Continuity and momentum transport equations

$$\frac{\partial}{\partial t}\rho_{\mathrm{g}}\varepsilon_{\mathrm{g}} + \nabla \cdot \rho_{\mathrm{g}}\varepsilon_{\mathrm{g}}\mathbf{U}_{\mathrm{g}} = 0$$

$$\frac{\partial}{\partial t}\rho_{\mathrm{g}}\varepsilon_{\mathrm{g}}\mathbf{U}_{\mathrm{g}} + \nabla \cdot \rho_{\mathrm{g}}\varepsilon_{\mathrm{g}}\mathbf{U}_{\mathrm{g}} \otimes \mathbf{U}_{\mathrm{g}} = \nabla \cdot \varepsilon_{\mathrm{g}}\boldsymbol{\tau}_{\mathrm{g}} - \nabla p + \rho_{\mathrm{g}}\varepsilon_{\mathrm{g}}\mathbf{g} + \mathbf{M}_{\mathrm{lb}}$$

Particle phase: Kinetic equation for joint size-velocity NDF $f(\xi, \mathbf{v})$

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} + \frac{\partial}{\partial \mathbf{v}} \cdot f\mathbf{A} = \mathbb{S}$$

where $\mathbf{A}$ represents acceleration due to forces acting on each particle, $\mathbb{S}$ represents other possible source terms (e.g., collisions, aggregation, break up, and chemical reaction in particles)

Moments method for solving Kinetic Equation

Moments for joint size-velocity NDF

$$m_{p,i,j,k} = \int \xi^p v_x^i v_y^j v_y^k f(\xi, \mathbf{v})\, d\xi d\mathbf{v}$$

Lower-order moments have particular physical significance:

$m_{1,0,0,0} = \rho_{\mathrm{p}}\varepsilon_{\mathrm{p}}$, $m_{1,1,0,0} = \rho_{\mathrm{p}}\varepsilon_{\mathrm{p}} U_{\mathrm{bx}}$, $m_{1,0,1,0} = \rho_{\mathrm{p}}\varepsilon_{\mathrm{p}} U_{\mathrm{by}}$, $m_{1,0,0,1} = \rho_{\mathrm{p}}\varepsilon_{\mathrm{p}} U_{\mathrm{bz}}$

Moments transport equation:

$$\frac{\partial m_{p,i,j,k}}{\partial t} + \frac{\partial m_{p,i+1,j,k}}{\partial x} + \frac{\partial m_{p,i,j+1,k}}{\partial y} + \frac{\partial m_{p,i,j,k+1}}{\partial z} = F_{p,i,j,k}$$

$$F_{p,i,j,k} = \int \xi^p v_x^i v_y^j v_z^k \left[i v_x^{-1}(A_x) + j v_y^{-1}(A_y) + k v_z^{-1}(A_z) \right] f(\xi, \mathbf{v})\, d\xi d\mathbf{v}$$

Quadrature-Based Moment Methods (QBMM) are introduced to attain closure of higher-order moments (spatial fluxes) and $F_{p,i,j,k}$

Representation of joint size-velocity NDF

Joint size-velocity NDF

$$n(\xi, \mathbf{v}) = f(\xi) \; g(\mathbf{v}|\xi)$$

Comparison with traditional particle size population transport method

Kinetic equation for particle size number density (with $\mathbb{S} = 0$) can be rewritten

$$\frac{\partial n}{\partial t} + \nabla \cdot \mathbf{U} n = 0$$

$$\frac{\partial n \mathbf{U}}{\partial t} + \nabla \cdot \mathbf{U} \otimes \mathbf{U} n = n\mathbf{g} + \mathbf{A}(\mathbf{U}) n$$

$\mathbf{U}$ is often assumed to be independent of size ξ, however, a model with a continuous particle velocity conditioned on size $\mathbf{U}(\xi)$ needed for polydisperse particles

Particle size distribution $f(\xi)$: Extended quadrature method of moments (EQMOM)

Reconstructed size NDF

$$n(\xi) = \sum_{\alpha=1}^{N} w_\alpha \delta_\sigma(\xi, \xi_\alpha)$$

with parameters found from size moments:

- Gamma ($0 < \xi < \infty$)

$$\delta_\sigma(\xi, \xi_\alpha) \equiv \frac{\xi^{\lambda_\alpha - 1} e^{-\xi/\sigma}}{\Gamma(\lambda_\alpha)\, \sigma^{\lambda_\alpha}}$$

  with $\lambda_\alpha = \xi_\alpha / \sigma$

- Beta ($0 < \xi < 1$)

$$\delta_\sigma(\xi, \xi_\alpha) \equiv \frac{\xi^{\lambda_\alpha - 1} (1 - \xi)^{\mu_\alpha - 1}}{B(\lambda_\alpha, \mu_\alpha)}$$

  with $\lambda_\alpha = \xi_\alpha / \sigma$ and $\mu_\alpha = (1 - \xi_\alpha)/\sigma$

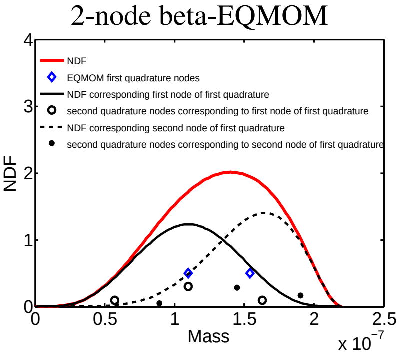
First $2N$ moments always exact

Converges to exact NDF as $N \to \infty$

Dual-quadrature form

$$\delta_\sigma(\xi, \xi_\alpha) \approx \sum_{\beta=1}^{M} w_{\alpha\beta} \delta(\xi - \xi_{\alpha\beta})$$

with known weights $w_{\alpha\beta}$ and abscissas $\xi_{\alpha\beta}$



Size-conditioned particle velocity distribution $g(\mathbf{v}|\xi)$

Anisotropic Gaussian velocity distribution

$$g(\mathbf{u}-\mu(\xi),\sigma^2(\xi)\underline{R}) = \frac{1}{(2\pi)^{3/2}\sqrt{|\sigma^2(\xi)\underline{R}|}} \exp\left[-\frac{1}{2\sigma^2(\xi)}\left(\mathbf{u}-\mathbf{U}(\xi)\right)^T \underline{R}^{-1}\left(\mathbf{u}-\mathbf{U}(\xi)\right)\right]$$

Approximation method

$\mathbf{U}(\xi)$ and $\sigma^2(\xi)$ can be approximated as

$$\mathbf{U}(\xi) = \sum_{n=0}^{2N_s} \mathbf{u}_n g_n(\xi) \qquad \sigma^2(\xi) = \sum_{n=0}^{2N_s} \sigma_n g_n(\xi)$$

where $\mathbf{u}_n(\xi)$ and σ_n are constant coefficients, and $g_n(\xi)$ are basis functions, which can be defined using various kinds of **orthogonal polynomial functions** and **piecewise functions**

Conditional mean velocity

Vector function $\mathbf{U}(\xi)$ is defined to have following properties, which can be used to solve for $\mathbf{u}_n(\xi)$

$$\sum_{\alpha=1}^{N_s} \rho_\alpha \int_\Omega \xi^s \mathbf{U}(\xi) K(\xi;\xi_\alpha,\sigma_s) d\xi = \begin{bmatrix} M_{s,1,0,0} \\ M_{s,0,1,0} \\ M_{s,0,0,1} \end{bmatrix} \qquad M_{s,i,j,k} = \int_\Omega \int_{\Re^3} \xi^s u^i v^j w^k \, n(\xi,\mathbf{u})\, d\xi d\mathbf{u}$$

for $s = 0, ..., d_s$ with $d_s \leq 2N_s$

Solving size-conditioned velocity

Conditional granular temperature

Similarly, the conditional granular temperature $\sigma^2(\xi)$ has the following properties, which are used to solve for σ_n:

$$\sum_{\alpha=1}^{N_s} \rho_\alpha \int_\Omega \xi^s \left(\mathbf{U}(\xi) \cdot \mathbf{U}(\xi) + 3\sigma^2(\xi)\right) K(\xi; \xi_\alpha, \sigma_s) d\xi = M_{s,2,0,0} + M_{s,0,2,0} + M_{s,0,0,2}$$

$$\text{for } s = 0, ..., d_s \text{ with } d_s \leq 2N_s$$

Normalized velocity covariance tensor

Finally, normalized velocity covariance tensor (size-independent) is found using its definition:

$$\sum_{\alpha=1}^{N_s} \rho_\alpha \int_\Omega \xi^s \left[\mathbf{U}(\xi) \otimes \mathbf{U}(\xi) + \sigma^2(\xi) \underline{\boldsymbol{R}}\right] K(\xi; \xi_\alpha, \sigma_s) d\xi = \begin{bmatrix} M_{s,2,0,0} & M_{s,1,1,0} & M_{s,1,0,1} \\ M_{s,1,1,0} & M_{s,0,2,0} & M_{s,0,1,1} \\ M_{s,1,0,1} & M_{s,0,1,1} & M_{s,0,0,2} \end{bmatrix}$$

Sample size and sample velocity

Sample size: Jacobi quadrature for Beta kernel function

$$K(\xi;\xi_\alpha,\sigma_s) = \sum_{\beta=1}^{N_{jq}} \tilde{\rho}_{\alpha\beta}\delta(\xi,\tilde{\xi}_{\alpha,\beta})$$

Sample velocity: 3-D Hermite quadrature for anisotropic Gaussian kernel function

$$g(\mathbf{u}-\mathbf{U}(\xi),\sigma^2(\xi)\underline{R}) = \sum_{\gamma=1}^{N_{hq}} \tilde{\rho}_\gamma \delta(\mathbf{u},\tilde{\mathbf{u}}_\gamma) = \sum_{\gamma=1}^{N_{hq}} \tilde{\rho}_\gamma \delta\left(\mathbf{u},\begin{bmatrix}\tilde{u}_\gamma\\ \tilde{v}_\gamma\\ \tilde{w}_\gamma\end{bmatrix}\right)$$

Using spectral decomposition scheme with triple 1-D Hermite quadratures

Moments calculation using sample size and velocity

Now moments can be calculated as

$$\begin{aligned} M_{s,i,j,k} &= \sum_{\alpha=1}^{N_s} \rho_\alpha\ \xi_\alpha^s u^i v^j w^k\ K(\xi;\xi_\alpha,\sigma_s)\ g(\mathbf{u}-\mathbf{U}(\xi),\sigma^2(\xi)\underline{R}) \\ &= \sum_{\alpha=1}^{N_s} \rho_\alpha \sum_{\beta=1}^{N_{jq}} \tilde{\rho}_{\alpha\beta}\tilde{\xi}_{\alpha\beta}{}^s \sum_{\gamma=1}^{N_{hq}} \tilde{\rho}_{\alpha\beta\gamma}\ \tilde{u}_{\alpha\beta\gamma}{}^i \tilde{v}_{\alpha\beta\gamma}{}^j \tilde{w}_{\alpha\beta\gamma}{}^k \end{aligned}$$

Kinetics-based finite-volume method: spatial fluxes

Spatial moment fluxes are decomposed into two contributions corresponding to positive and negative velocity in each spatial direction:

$$F^{x}_{s,i,j,k} = Q^{x,+}_{s,i,j,k} + Q^{x,-}_{s,i,j,k}$$

$$\begin{aligned}
Q^{x,+}_{s,i,j,k} &= \int_{\mathbb{R}} \left(\int_0^{\infty} \xi^i u^{i+1} v^j w^k f_{sv}(\xi, \mathbf{u})\, d\mathbf{u} \right) d\xi \\
&= \sum_{\alpha=1}^{N_s} \sum_{\beta=1}^{N_{jq}} \sum_{\gamma=1}^{N_{hq}} \mathbf{max}(\tilde{u}_{\alpha\beta\gamma}, 0) \rho_\alpha \tilde{\rho}_{\alpha\beta} \tilde{\rho}_{\alpha\beta\gamma} \tilde{\xi}^s_{\alpha\beta} \tilde{u}^i_{\alpha\beta\gamma} \tilde{v}^j_{\alpha\beta\gamma} \tilde{w}^k_{\alpha\beta\gamma} \\
Q^{x,-}_{s,i,j,k} &= \int_{\mathbb{R}} \left(\int_{-\infty}^{0} \xi^i u^{i+1} v^j w^k f_{sv}(\xi, \mathbf{u})\, d\mathbf{u} \right) d\xi \\
&= \sum_{\alpha=1}^{N_s} \sum_{\beta=1}^{N_{jq}} \sum_{\gamma=1}^{N_{hq}} \mathbf{min}(\tilde{u}_{\alpha\beta\gamma}, 0) \rho_\alpha \tilde{\rho}_{\alpha\beta} \tilde{\rho}_{\alpha\beta\gamma} \tilde{\xi}^s_{\alpha\beta} \tilde{u}^i_{\alpha\beta\gamma} \tilde{v}^j_{\alpha\beta\gamma} \tilde{w}^k_{\alpha\beta\gamma}
\end{aligned}$$

Realizablity condition:

$$\Delta t = CFL \min_{\alpha\beta\gamma} \left(\frac{\Delta x}{|\tilde{u}_{\alpha\beta\gamma}|}, \frac{\Delta y}{|\tilde{v}_{\alpha\beta\gamma}|}, \frac{\Delta z}{|\tilde{w}_{\alpha\beta\gamma}|} \right)$$

Forces: drag and gravity

Contributions to evolution of moments due to drag force acting on each particle are directly computed, operating on sample velocities $\tilde{\mathbf{u}}$ from quadrature approximation by solving an ODE:

$$\frac{d\tilde{\mathbf{u}}}{dt} = \mathbf{A}_d + \mathbf{g} = K_D \left(\mathbf{u}_g - \tilde{\mathbf{u}}\right) + \mathbf{g}$$

The sample velocity at next time step is

$$\tilde{\mathbf{u}}^* = \tilde{\mathbf{u}} e^{-K_D \Delta t} + \left(1 - e^{-K_D \Delta t}\right) \left(\mathbf{u}_g + \frac{\mathbf{g}}{K_D}\right)$$

And overall drag force received by entire particle phase is

$$\mathbf{F}_{D,pg} = \sum m_p \cdot A_d = \frac{\rho_p \pi}{6} \sum_{\alpha=1}^{N_s} \sum_{\beta=1}^{N_{jq}} \rho_\alpha \tilde{\rho}_{\alpha\beta} \tilde{\xi}^3_{\alpha\beta} \sum_{\gamma=1}^{N_{hq}} \tilde{\rho}_{\alpha\beta\gamma} K_{D,\alpha\beta\gamma} \left(\mathbf{u}_g - \tilde{\mathbf{u}}_{\alpha\beta\gamma}\right)$$

So using Newton's first law, drag force received by gas phase is

$$\mathbf{F}_{D,gp} = -\mathbf{F}_{D,pg}$$

Polydisperse collision model

Moment transport equation

$$\frac{\partial M_{s,i,j,k}}{\partial t} + \frac{\partial M_{s,i+1,j,k}}{\partial x} + \frac{\partial M_{s,i,j+1,k}}{\partial y} + \frac{\partial M_{s,i,j,k+1}}{\partial z} = \mathbb{A}_{s,i,j,k} + \boxed{\mathbb{C}_{s,i,j,k}}$$

Using operator splitting, collision term can be conveniently updated by solving

$$\frac{\partial M_{s,i,j,k}}{\partial t} = \boxed{\mathbb{C}_{s,i,j,k}}$$

$$M_{s,i,j,k} = \sum_{\alpha=1}^{N_s} \sum_{\beta=1}^{N_{jq}} \rho_\alpha \, \tilde{\rho}_{\alpha\beta} \tilde{\xi}^s_{\alpha\beta} \sum_{\gamma=1}^{N_{hq}} \tilde{\rho}_{\alpha\beta\gamma} \, \tilde{u}^i_{\alpha\beta\gamma} \tilde{v}^j_{\alpha\beta\gamma} \tilde{w}^k_{\alpha\beta\gamma} = \sum_{a=1}^{N_t} w_a \xi^s_a G_{ijk}(\xi_a)$$

Since we can assume that size does not change due to collisions, and also that collisions are binary

$$\boxed{\mathbb{C}_{s,i,j,k}} = \frac{\partial}{\partial t} \sum_{a=1}^{N_t} w_a \xi^s_a G_{ijk}(\xi_a) = \sum_{a=1}^{N_t} w_a \xi^s_a \frac{\partial G_{ijk}(\xi_a)}{\partial t} = \sum_{a=1}^{N_t} w_a \xi^s_a \sum_{b=1}^{N_t} \mathbb{C}_{i,j,k}(\xi_a, \xi_b)$$

$$\mathbb{C}_{i,j,k}(\xi_a, \xi_b) = C_{i,j,k}(\xi_a, \xi_b) + \nabla \cdot \mathbf{G}_{i,j,k}(\xi_a, \xi_b)$$

Collision source term

BGK model (valid to second order)

$$C_{ijk}(\xi_a, \xi_b) = \kappa_{ab}\left(G^*_{ijk,ab} - G_{ijk,a}\right) = \frac{24 g_{0,ab}\alpha_b \chi^3_{ab}\sqrt{\sigma^2_{ab}}}{\sqrt{\pi} d_{ab}}\left(G^*_{ijk,ab} - G_{ijk,a}\right)$$

Zero-order moments $\quad C_{i+j+k=0}(\xi_a, \xi_b) = 0$

First-order moments $\quad C_{i+j+k=1}(\xi_a, \xi_b) = \kappa_{ab}\left(\mathbf{U}_{ab} - \mathbf{U}_a\right)$

Second-order moments $\quad C_{i+j+k=2}(\xi_a, \xi_b) = \kappa_{ab}\left(\mathbf{U}_{ab}\otimes\mathbf{U}_{ab} + \underline{\underline{\Sigma}}_{ab} - \mathbf{U}_a\otimes\mathbf{U}_a - \underline{\underline{\Sigma}}_a\right)$

For equilibrium Gaussian distribution

Mean velocity

$$\mathbf{U}_{ab} = \mathbf{U}_a + \tfrac{1}{4}(1+e_{ab})\,\mu_{ab}\left(\mathbf{U}_b - \mathbf{U}_a\right)$$

Covariance tensor

$$\underline{\underline{\Sigma}}_{ab} = \underline{\underline{\Sigma}}_a + \tfrac{1}{2}(1+e_{ab})\,\mu_{ab}\left[\tfrac{1}{4}(1+e_{ab})\,\mu_{ab}\underline{\underline{\boldsymbol{S}}}_{ab} - \underline{\underline{\Sigma}}_a\right]$$

where $\underline{\underline{\boldsymbol{S}}}_{ab} = 1/2(\underline{\underline{\Sigma}}_a + \underline{\underline{\Sigma}}_b + \sigma^2_{ab}\boldsymbol{I})$, $\quad \underline{\underline{\Sigma}}_a = \sigma^2_a\underline{\underline{\boldsymbol{R}}}$, $\quad \underline{\underline{\Sigma}}_b = \sigma^2_b\underline{\underline{\boldsymbol{R}}}$

Collisional flux term

m^{th} component of collisional-flux term caused by collisions between particles of size ξ_a and ξ_b can be calculated as

$$\mathbf{G}_{m,ijk}(\xi_a, \xi_b) = \mathbf{G}^{(0)}_{m,ijk}(\xi_a, \xi_b) + \cancel{\mathbf{G}^{(1)}_{m,ijk}(\xi_a, \xi_b)}$$

$$\mathbf{G}^{(0)}_{m,ijk}(\xi_a, \xi_b) = \frac{3\chi_{ab}^2 \xi_a g_{0,ab}}{\xi_b} \int_{\mathbb{R}^6} I^{(m)}_{ijk} \left(\omega_{ab}, \mathbf{v}_a, \mathbf{v}_a - \mathbf{v}_b\right) f(\mathbf{v}_a) f(\mathbf{v}_b) d\mathbf{v}_a d\mathbf{v}_b$$

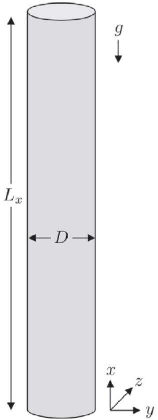
If let $\underline{M}_{s,1} = [M_{s,1,0,0}, M_{s,0,1,0}, M_{s,0,0,1}]^T$, the collisional fluxes for this vector can thus be written as a tensor

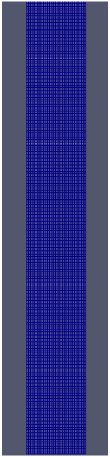
$$\underline{\underline{\mathbf{P}}}_{s,1} = \sum_{a=1}^{N_t} w_a \xi_a^s \left\{ \rho_p \alpha_a \underline{\underline{\Sigma}}_a + \right.$$
$$\left. \rho_p \alpha_a \sum_{b=1}^{N_t} \alpha_b \frac{2\chi_{ab}^3 \mu_{ab} (1 + e_{ab}) g_{0,ab}}{5\chi_{ba}} \left[\frac{1}{2} E_{ab} \underline{\underline{\mathbf{I}}} + \underline{\underline{\Sigma}}_a + \underline{\underline{\Sigma}}_b + (\underline{U}_a - \underline{U}_b) \otimes (\underline{U}_a - \underline{U}_b) \right] \right\}$$

where $E_{ab} = 3\sigma_a^2 + 3\sigma_b^2 + |\underline{U}_a - \underline{U}_b|^2$, which is defined as the energy scaling factor.

Test case: Wall-bounded vertical riser

Geometry and mesh (2D)

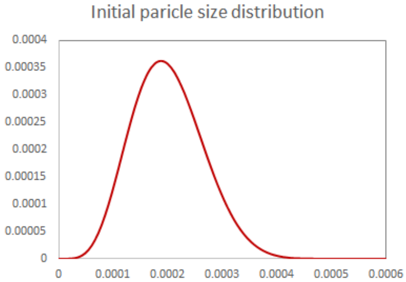




Periodic in X-direction

Gas phase is statistically stationary with zero volume flow rate

gas density (ρ_p)	1 kg/m^3
gas viscosity (ν_g)	1.84e-5 m^2/s
particle density (ρ_g)	2000 kg/m^3
mean diameter (d_p)	0.0002 m
restitution coeff (e)	0.9



Animation: velocity fields, 2–5 second

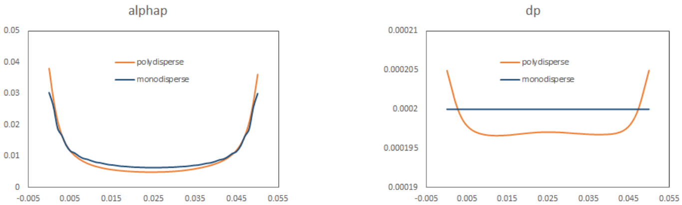
Particle-phase velocity, gas-phase velocity, and granular temperature

Animation, scalar fields, 2–5 second

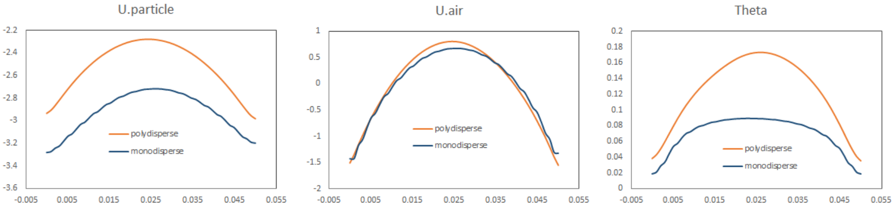
Volume fraction, mean particle diameter, and standard deviation

Statistical results (time averaged)

Particle volume fraction and mean diameter



Particle velocity, gas-phase velocity, and granular temperature



Cluster-Induced Turbulence: Comparison with DPM Simulation

Influence of domain size on CIT statistics

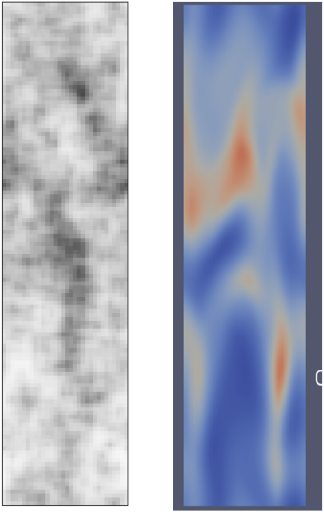
In gravity-driven gas solids flows, slip velocity between clusters and gas drive turbulence, referred to as cluster-induced turbulence (CIT)

$$\mathcal{L} = \tau_p^2 g$$

Domain size	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
$L_1/\mathcal{L}$	4.03	8.06	16.13	32.26	64.51	129.01
$L_2/\mathcal{L}$	1.01	2.02	4.03	8.06	16.13	32.25
$L_3/\mathcal{L}$	1.01	2.02	4.03	8.06	16.13	32.25
N_1	64	128	256	512	1024	2048
N_2	16	32	64	128	256	512
N_3	16	32	64	128	256	512
N_p	1,678	13,417	107,329	858,629	6,869,032	54,952,240

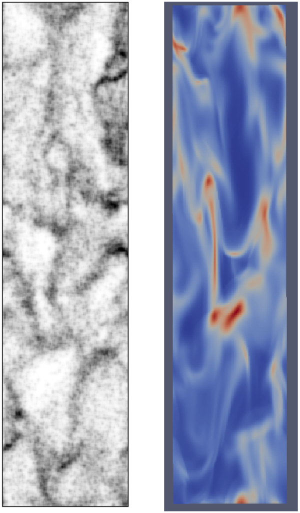
Instantaneous particle volume fraction field

DPM EE-AG



Case2 : $32 \times 32 \times 128$

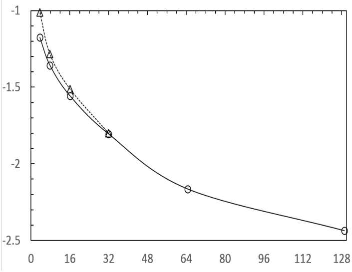
DPM EE-AG



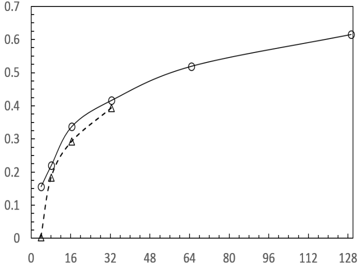
Case 4 : $128 \times 128 \times 512$

Comparison between DPM and EE-AG simulation results

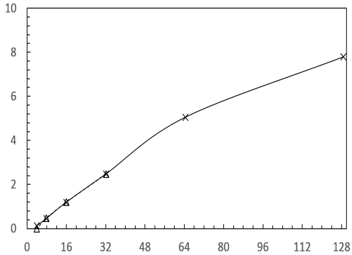
Particle average settling velocity, $\langle u_{p,1} \rangle_p / \mathcal{V}$



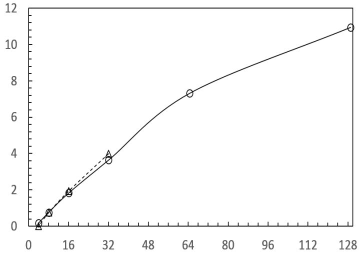
Deviation of volume fraction fluctuations



Particle total fluctuation energy, $K_p / \mathcal{V}^2$



Fluid total fluctuation energy, $K_f / \mathcal{V}^2$



Summary

Conclusions

- Novel approach to model polydisperse gas-particle flows with quadrature-based moment methods using kinetic equation for joint size-velocity number density function
- Quasi-2D wall-bounded vertical riser simulated with continuous particle size distribution initial condition
- Solver includes explicit representation of joint NDF using EQMOM that directly incorporates effects of polydispersity
- Size segregation is captured in simulations, and results demonstrate our approach is effective way to model complicated polydisperse gas-particle flows
- Comparison between CIT simulations using anisotropic Gaussian model and DPM method has demonstrated assumption for particle velocity is valid and this novel method can be used to perform mesoscale DNS for gas-particle flows

Summary

Plans for future work

- Detailed validation with high resolution Euler-Lagrange simulation data for polydisperse gas-particle flows
- Implement realizable high-order numerical schemes for moment transport equations in MFIX
- Replace and update all previous implemented QBMM methods in MFIX, and implement newly developed QBMM methods in MFIX
- **Extend QBMM models to dense regime**
- Perform mesoscale DNS of CIT and wall-bounded channel flow to study gas-particle turbulence, such as effect of size distribution on cluster size
- Implement a new multiphase turbulence model, and validate against Euler-Lagrange simulations

Acknowledgment

Financial support from DOE - National Energy Technology Laboratory (Contract Number: DE-AC02-07CH11358)

Tasks completed in FY15

- Migrated from MFIX-2013 to current MFIX version, using MFIX git development repository
- Developed comprehensive post-processing capabilities using Python and VTK package
- Prepared documentation and tutorials for the code
- Enabled code to run in both DMP and SMP mode
- Developed the capability of handling non-uniform grid
- Provided a range of drag models
- Developed more realistic wall boundary condition
- Validated code against Lagrangian particle simulations