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Cheng Chen

Investigations on Mesoscale Structure in Gas–Solid Fluidization and Heterogeneous Drag Model

Doctoral Thesis accepted by
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Author
Dr. Cheng Chen
Tsinghua University
Beijing
China

Supervisor
Prof. Haiying Qi
Tsinghua University
Beijing
China

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Supervisor's Foreword

The modeling of drag between gas and solid phase has always been a challenging issue in Eulerian simulation of heterogeneous fluidization processes for a long time.

It is generally known that existing drag models such as Wen-Yu and Ergun do not apply to above processes because of their hypothesis of a homogeneous flow. The key of the modeling is whether a drag model can account for effects of the mesoscale structure, namely clusters that characterize the heterogeneous flow state. It has been proved in recent years that the theory of Energy Minimization Multi-scale (EMMS) is effective for developing heterogeneous drag models. However, this theory still needs further improvement in hypothesis, description of the mesoscale structure, definite conditions of conservative equations, and generalization of drag models.

Dr. Cheng Chen devoted herself in last 5 years to drag modeling based on the EMMS and made a series of significant progress. She focused on analysis of flow heterogeneity and found a common feature—the “single peak” profile—in many relationships, including cluster size d_{cl} , cluster density ϵ_{sc} , and local gas–solid slip velocity via local particle volume fraction ϵ_s , as well as overall slip velocity via superficial velocity of circulating fluidized bed. She indicated that cluster size tends to single particle diameter at the dense extreme and clarified the difference between cluster size defined by the EMMS theory and measured in experiments. Compared with the size, cluster density is the major factor that causes qualitative change of drag. In addition, she established a relationship between the local heterogeneity and operation parameters of fluidized bed reactors.

According to the above research, she developed a new drag model named QC-EMMS and verified its prediction ability, accuracy, and universality by simulations and comparison with experiments.

Overall, her work gives us valuable information and methods to deal with drag issue and enlightens us that one should pay major attention to physical judgment and understanding of mesoscale effects in fluidization process. I believe this work will be helpful in simulating large-scale fluidization systems.

Beijing
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Prof. Haiying Qi

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Nomenclature

a_c, a_f	Internal particle acceleration in dense, dilute phase (m/s ²)
a, b, c	Coefficients in drag expressions (-)
Ar	Archimedes number, $Ar = \frac{\rho_g(\rho_p - \rho_g)d_p^3 g}{\mu_g^2}$ (-)
C_1, C_2, C_3	Empirical coefficients (-)
C_{D0}	Single-particle drag coefficient (-)
C_D	Multi-particle drag coefficient (-)
d_{cl}	Cluster size (m)
d_p	Particle size (m)
d_p^*	Dimensionless particle size, $d_p^* = Ar^{1/3} = \left(\frac{\rho_g(\rho_p - \rho_g)d_p^3 g}{\mu_g^2}\right)^{1/3}$ (-)
D	Diameter of fluidized bed riser (m)
d_v	Bubble diameter (m)
e_s	Particle elastic collision coefficient (-)
f	Volumetric fraction of particle dense phase (-)
f_c	Heterogeneity correction factor in O-S model (-)
F_c, F_f, F_i	Single-particle drag in dense phase, dilute phase, and interaction phase (N)
F_D	Grid-average drag force (N)
g	Gravity acceleration (m/s ²)
G_s	Particle circulating mass flux (kg/m ² s)
h	Fluidized bed height (m)
H_0	Initial particle accumulation height in fluidized bed (m)
H_d	Heterogeneous drag correction factor (-)
I_{inv}	Particle inventory in fluidized bed (kg)
n	Empirical coefficient (-)
n_c, n_f, n_i	Numerical density of particles in dense phase, dilute phase and interaction phase (1/m ³)
n_p	Number of single particles in computational parcel (-)
N_p	Number of computational parcels in grid (-)
N_{st}	Suspended transport energy (J/kg)

p_g	Gas pressure (Pa)
p_s	Particle pressure (Pa)
$\Delta p/\Delta h$	Pressure drop per unit bed height (Pa/m)
Re	Local gas–solid slip Reynolds Number, $Re = \frac{\rho_g d_p}{\mu_g} (u_g - u_s)$ (–)
Re^*	Overall gas–solid slip Reynolds number, $Re^* = \frac{\rho_g d_p}{\mu_g} \left(U_g - \frac{\varepsilon_g}{1-\varepsilon_g} \cdot \frac{G_s}{\rho_p} \right)$ (–)
Re_t	Terminal velocity Reynolds number, $Re_t = \frac{\rho_g d_p}{\mu_g} U_t$ (–)
Δt	Time step (s)
U^*	Dimensionless gas velocity, $U^* = \frac{\rho_g d_p}{\mu_g} \left(U_g - \frac{\varepsilon_g}{1-\varepsilon_g} \cdot \frac{G_s}{\rho_p} \right) / Ar^{1/3}$ (–)
U_c	Gas velocity in dense phase (m/s)
U_f	Gas velocity in dilute phase (m/s)
U_{FD}	Critical gas velocity between fast and transport fluidization (m/s)
u_g	Grid-average gas velocity (m/s)
U_g	Cross-sectional average gas velocity (empty-bed gas velocity) (m/s)
U_{mf}	Minimum fluidization gas velocity (m/s)
u_p	Computational parcel velocity (m/s)
U_p	Cross-sectional average particle velocity (m/s)
U_{pc}	Particle velocity in dense phase (m/s)
U_{pf}	Particle velocity in dilute phase (m/s)
U_{PT}	Critical gas velocity between dilute and dense pneumatic transport (m/s)
u_s	Grid-average particle velocity (m/s)
u_{slip}	Local gas–solid slip velocity in grid, $u_{slip} = u_g - u_s$ (m/s)
U_{slip}	Overall gas–solid slip velocity, $U_{slip} = U_g - U_p$ (m/s)
U_t	Single-particle terminal velocity (m/s)
$U_{t,cl}$	Cluster terminal velocity (m/s)
U_{TF}	Critical gas velocity between turbulent and fast fluidization (m/s)
V_m	Grid volume (m ³)
V_p	Particle volume (m ³)
V_r	The ratio of gas–solid slip velocity to terminal velocity in O-S model (–)
x_p	Position coordinate of computational parcel (–)

Greek Character

β	Drag function for heterogeneous flows (Ns/m ⁴)
β_0	Drag function for uniform flows (Ns/m ⁴)
ε_g	Gas volume fraction (Voidage) (–)
ε_{max}	Max voidage where clusters exist, $\varepsilon_{max} = 0.9997$ (–)
ε_{mf}	Minimum fluidization voidage (–)
ε_s	Local time-averaged volume fraction of particle (local solids concentration) (–)

$\varepsilon_{s,av}$	Cross-sectional averaged volume fraction of particle (Cross-sectional averaged solids concentration) (-)
$\varepsilon_{s,cr}$	Critical solids concentration, $\varepsilon_{s,cr} = \varepsilon_s + n \cdot \sigma_s$ (-)
$\varepsilon_{s,in}$	Solids concentration at fluidized bed return inlet (-)
ε_{sc}	Solids concentration in clusters (Cluster density) (-)
ε_{sf}	Solids concentration in dilute phase (-)
ε_{smf}	Solids concentration for minimum fluidization (-)
σ_s	Standard deviation of solids concentration fluctuation (-)
φ	Particle-wall specular reflection coefficient (-)
Φ	Local heterogeneous index (-)
Ψ	The overall system heterogeneous index (-)
γ	Local heterogeneity defined by solids concentration fluctuation (-)
μ_g	Gas kinematic viscosity coefficient (Pa s)
ρ_{cl}	Cluster density, $\rho_{cl} = \varepsilon_{sc} \cdot \rho_p + (1 - \varepsilon_{sc}) \cdot \rho_g$ (kg/m ³)
ρ_g	Gas density (kg/m ³)
ρ_p	Particle density (kg/m ³)
τ_g, τ_s	Gas/solid phase stress tensor (-)

Subscript

c, cl	Particle dense phase (cluster)
f	Particle dilute phase
g	Gas
i	Interaction phase
p, s	Particle/Solid

Abbreviation

DNS	Direct numerical simulation
EMMS	Energy minimization multi-scale
MP-PIC	Multiphase particle-in-cell
UDF	User defined function