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EMMS mixture model with size distribution for two-fluid simulation of riser flows

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ABSTRACT

Further development of an energy-minimization multiscale modeling approach to simulating two-phase flow under turbulent conditions that considers the size distribution of mesoscale structures, i.e. bubbles and clusters, is presented. User-defined values of minimum and maximum cluster or bubble diameters were specified. A uniform size distribution was first considered as a test case, in which the drag force comprised contributions from each size group. The mathematical form of the objective function describing the energy for suspension and transport was not altered. The heterogeneity index of this new drag modification was then used to simulate pilot-scale circulating fluidized-bed risers involving Geldart group A particles. The results were validated against available experimental data. The model is capable of capturing both axial and radial profiles of flow-field variables.

Introduction

Gas–solid flows, such as in fluidized beds, show a wide range of spatial and temporal mesoscale structures, which results in heterogeneous flow. Depending on the operating regime of the fluidized bed, these mesoscale structures may appear in the form of gas bubbles or particle clusters (Avidan & Yerushalmi, 1982; Bai, Issangya, & Grace, 1999; Glasser, Sundaresan, & Kevrekidis, 1998; Grace, 2000; Smolders & Baeyens, 2001; Takeuchi, Hirama, Chiba, Biswas, & Leung, 1986; Yerushalmi & Cankurt, 1979; Zijerveld, Johnsson, Marzocchella, Schouten, & van den Bleek, 1998). In dense fluidization, gas bubbles rising through a suspension of solid particles have been the subject of intensive research. Several experimental and modeling efforts have been undertaken to improve understanding of the gas voids or bubbles that appear in low-velocity fluidized beds (Anderson, Sundaresan, & Jackson, 1995; Horio & Kuroki, 1994; Kunii & Levenspiel, 1968; Rowe, 1971; van Wachem, Schouten, Krishna, & van den Bleek, 1998). For high-velocity fluidization, as observed in fast fluidization, considerable research has been performed to study the origin, effects, and scale of mesoscale clusters (Glasser et al., 1998; Harris, Davidson, & Thorpe, 2002; Horio & Kuroki, 1994; Sharma, Tuzla, Matsen, & Chen, 2000; Zou, Li, Xia, & Ma, 1994).

Gas–solid flow in a circulating fluidized bed (CFB) riser is characterized by a dense bottom zone and dilute top zone, which is characteristic of a fast fluidization regime (Bai & Kato, 1999; Bai, Shibuya, Masuda, Nakagawa, & Kato, 1996; Schlichthaerle & Werther, 1999). It is, therefore, expected that the bottom zone would be dominated by bubbling effects whereas the top region would be dominated by particle clusters. A modeling approach that covers both regimes should therefore be able to predict the hydrodynamics with reasonable accuracy.

Accurate modeling and computation fluid dynamics (CFD) simulations of fluidized beds remains a challenge (Gelderbloom, Gidaspow, & Lyczkowski, 2003; McKeen & Pugsley, 2003; van Wachem et al., 1998). Two major approaches have been used to simulate gas–solid fluidized beds using CFD, i.e., Eulerian–Lagrangian models and Eulerian two-fluid models (TFM) (Chiesa, Mathiesen, Melheim, & Halvorsen, 2005; Tsuji, Kawaguchi, & Tanaka, 1993; Tsuo & Gidaspow, 1990). In the former approach, gas is considered as a continuous phase and the motion of particles is treated in a Lagrangian framework where the equation of motion for each particle is individually solved. Although this is a promising technique, it is, however, limited by its computational cost. Furthermore, accurate interparticle closures are not exactly known. It is therefore not common practice to use Eulerian–Lagrangian

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Nomenclature

a	Inertial term, m/s^2
C_d	Effective drag coefficient for a particle or bubble
C_{d0}	Standard drag coefficient for a particle or bubble
d_b	Bubble diameter, m
d_p	Particle diameter, m
D_t	Column diameter, m
e_s	Particle–particle restitution coefficient
e_w	Particle–wall restitution coefficient
f	Volume fraction of dense phase
F	Drag force, N
g	Gravitational acceleration, m/s^2
g_0	Radial distribution function
H	Column height, m
H_d	Heterogeneity index
l	Ratio of cell size to particle diameter
N_{st}	Mass-specific energy consumption for suspending and transporting particles, W/kg
N_T	Total mass-specific energy, W/kg
p	Pressure, Pa
Re	Reynolds number
$\mathbf{u}$	Actual or real velocity, m/s
U	Superficial velocity, m/s
U_{slip}	Superficial slip velocity, m/s
u_t	Terminal velocity of a single particle, m/s

Greek letters

β	Drag coefficient, kg/(m^3 s)
γ_s	Collisional energy dissipation, J/(m^3 s)
Δt	Time step, s
ε_g	Voidage
ε_{gc}	Voidage of dense phase
ε_{gf}	Voidage of dilute phase
ε_{mf}	Incipient/minimum fluidization voidage
ε_{sc}	Solids' concentration in the dense phase
ε_{sf}	Solids' concentration in the dilute phase
ε_{max}	Maximum voidage for particle aggregation
$\varepsilon_{s,max}$	Maximum close-packing solids' concentration
Θ_s	Granular temperature, m^2/s^2
$\mathbf{I}$	Unit tensor
I_{2D}	Second invariant of the deviatoric stress tensor
κ_s	Diffusion coefficient for granular energy, Pa s
λ	Bulk viscosity, Pa s
μ	Viscosity, Pa s
ρ	Density, kg/m^3
$\boldsymbol{\tau}$	Stress tensor, Pa
φ	Specularity coefficient
Φ	Angle of internal friction (°)

Subscripts

b	Bubble
c	Dense phase
f	Dilute phase
g	Gas phase
gc	Gas in dense phase
gf	Gas in dilute phase
ic	Cluster meso-scale interphase
ib	Bubble meso-scale interphase
mf	Minimum fluidization
min	Minimum value
max	Maximum value
p	Particle
s	Solid phase
sc	Dense-phase solid
sf	Dilute-phase solid

methods for simulation of medium- or large-scale fluidized beds comprising millions of particles. In contrast, Eulerian modeling has emerged as the preferred choice for large systems. In this approach, both the continuous fluid and dispersed particulate phases are considered to be fully interpenetrating continua (Pain, Mansoorzadeh, & de Oliveira, 2001); however, the resulting approximation for the solid phase does not have an equation of state to close variables such as stresses and viscosity (Busciglio, Vella, Micale, & Rizzuti, 2008). To solve this issue, the kinetic theory of granular flow (KTGF) has been used in conjunction with the TFM (Gidaspow, 1994). Eulerian methodology is, however, limited by its requirement for fine grid resolution and a small time step to properly resolve all of the flow fields (Wang, van der Hoef, & Kuipers, 2009). In such a scenario, a Eulerian TFM with a coarser mesh may not accurately resolve mesoscale structures smaller than the grid resolution and, thus, may not be able to reproduce the multi-scale nature of heterogeneous gas–solid flows unless some sub-grid modeling is performed. In recent years, a hybrid Eulerian–Lagrangian approach has evolved, in which the fate of the particles is tracked in a Lagrangian coordinate system and interactions between the particles are modeled by the KTGF. This hybrid methodology is termed the dense discrete-phase model (DDPM). In this approach, the momentum equations for individual particles are not solved; instead, groups of particles (called parcels) are tracked. Each parcel contains several particles that share the same mass, velocity, and position (Adamczyk et al., 2014). The DDPM approach, available in commercial software such as ANSYS Fluent® and Barracuda *VR*®, has successfully been used to simulate both pilot- and industrial-scale CFB boilers (Adamczyk et al., 2014, 2015). A significant advantage of this methodology is that particle size distribution can be easily taken into account, as compared with Euler–Euler modeling; its major limitation is the fact that it requires large computational time to reach pseudo-steady state and it may be very difficult to stabilize the solution (Adamczyk et al., 2015).

Recent years have witnessed significant growth in modeling and simulation of fluidization processes, with specific focus on the resolution of the mesoscale structures discussed above (Agrawal, Loezos, Syamlal, & Sundaresan, 2001; Schneiderbauer, Puttinger, & Pirker, 2013; Wang & Chen, 2015). Apart from particle–particle collisions and particle–wall interactions, interphase momentum transfer between gas and solid phases is one of the dominant forces in the gas- and solid-phase momentum balances (Taghipour, Ellis, & Wong, 2005). It has been shown that drag force is one of the most important factors affecting the dynamics of fluidized beds (Zhang & VanderHeyden, 2002). General correlations used to estimate drag forces for Eulerian CFD analyses are empirically derived for idealized conditions and therefore neglect the effects of mesoscale entities. To accommodate these effects, a practical approach is to use structure-oriented drag for sub-grid corrections, in addition to the resolved parts of two-fluid simulations. Significant improvements have been made in this context in recent years (Schneiderbauer et al., 2013). Some researchers have used empirical correlations or equivalent cluster diameters to modify the homogeneous drag force (Huilin et al., 2005); others have considered heterogeneity by modifying the drag coefficient using a cluster- or bubble-based energy-minimization multiscale (EMMS) approach (Hong, Shi, Ullah, & Wang, 2014; Lu, Wang, & Li, 2011; Nikolopoulos, Atsonios, Nikolopoulos, Grammelis, & Kakaras, 2010;