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Modeling the hydrodynamics of cocurrent gas–solid downers according to energy-minimization multi-scale theory

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ABSTRACT

Cocurrent gas–solid downer reactors have many applications in industry because they possess the technological advantages of a lower pressure drop, shorter residence time, and less solid backmixing when compared with traditional circulating fluidized bed risers. By introducing the concept of particle clusters explicitly, a one-dimensional model with consideration of the interphase interactions between the fluid and particles at both microscale and mesoscale is formulated for concurrent downward gas–solid flow according to energy-minimization multi-scale (EMMS) theory. A unified stability condition is proposed for the differently developed sections of gas–solid flow according to the principle of the compromise in competition between dominant mechanisms. By optimizing the number density of particle clusters with respect to the stability condition, the formulated model can be numerically solved without introducing cluster-specific empirical correlations. The EMMS-based model predicts well the axial hydrodynamics of cocurrent gas–solid downers and is expected to have a wider range of applications than the existing cluster-based models.

Introduction

Cocurrent gas–solid downers feature the flow of both gas and solids in the same direction as gravity, which makes it possible to prepare a gas–solid flow with a low pressure drop, short residence time, and little solid backmixing, and thus to perform ultra-rapid reactions such as the fast catalytic conversion of heavy oil and the pyrolysis of solid fuel (Cheng, Wu, Zhu, Wei, & Jin, 2008; Guan et al., 2011; Li, Nakhla, & Zhu, 2012; Yun et al., 2013; Zenklusen & Reh, 2000; Zhu, Herbert, Jin, Grace, & Issangya, 1995).

Many experiments have been carried out to investigate heterogeneities in cocurrent gas–solid downers (Cao & Weinstein, 2000; Chen & Li, 2004; Herbert, Gauthier, Briens, & Bergougnou, 1998; Li, Wu, Wei, & Jin, 2004; Wang, Barghi, & Zhu, 2014; Wang, Zhu, Barghi, & Li, 2014; Zhang, Zhu, & Bergougnou, 1999a; Zhang, Zhu, & Bergougnou, 1999b; Zhang & Zhu, 2000;) and their differences from those in circulating fluidized bed (CFB) risers (Li, Ray, Ray, & Zhu, 2013; Zhang, Huang, & Zhu, 2001). A variety of mathematical models have also been developed to clarify the underlying mechanisms in concurrent downward gas–solid flow (Bolkan-Kenny, Pugsley, & Berruti, 1994; Chen, Yang, Li, & Tan, 2006; Wu, Cheng, & Jin, 2008). It is generally acceptable that the axial flow structure of a sufficiently high cocurrent downer can be successively divided into first and second acceleration as well as full development sections from the top to bottom according to the variations in gas and particle velocities (Wang, Bai, & Jin, 1992). As in CFB risers, there is also a particle clustering phenomenon in gas–solid downer reactors (Krol, Pekediz, & de Lasa, 2000; Lanza, Islam, & de Lasa, 2012; Lu et al., 2005; Nova, Krol, & Lasa, 2004; Tuzla et al., 1988; Zhang, Chu, Wei, & Yu, 2008). A cluster-based model for cocurrent downer reactors was thus developed with an over-simplified assumption that all particles exist in the form of aggregation (Karimipour, Mostoufi, & Sotudeh-Gharebagh, 2006). This type of mathematical model generally calls for the accurate determination of the effective cluster diameter, yet it is necessary to resort to empirical correlations for such determination at present (Arsenijević, Radoičić, Garić-Grulović, Đuriš, & Grbavčić, 2014).

Energy-minimization multi-scale (EMMS) theory, as originally proposed to capture the particle clustering phenomenon and the resultant effect on gas–solid two-phase flow (Li, 1987; Li, Tung, & Kwauk, 1988; Li & Kwauk, 1994), has been successfully extended to perform the steady-state modeling of heterogeneities in CFB risers (Hu, Liu, & Li, 2013) and the overall hydrodynamics of gas–solid bubbling fluidization (Liu, Jiang, Liu, Wang, & Li, 2014).

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Nomenclature

$\bar{N}_{gs0}$	average N_{gs0} for the whole downer unit
a_f, a_c, a_p	dilute, dense, and average particle accelerations, m/s^2
C_{Dc}, C_{Df}, C_{Di}	effective drag coefficients in dense, dilute, and interphases
d_{cl}	cluster diameter, m
d_p	particle diameter, m
dp/dz	pressure drop gradient, Pa/m
D_t	downer diameter, m
f	volume fraction of dense phase
f_p	particle–wall fraction coefficient
g	gravity acceleration, m/s^2
G_s	solids flux, $kg/(m^2\,s)$
m_p	particle mass, kg
n_{cl}	volume-average number density of particle clusters, m^{-3}
n_{cl0}	normalized n_{cl}
N_{gs}	energy dissipation rate for the gas, m^2/s^3
N_{gs0}	normalized N_{gs}
N_T	total energy associated with gas–solid suspension, m^2/s^3
P	pressure, Pa
P_{inlet}	pressure at the downer entrance, Pa
U_f, U_c	dilute and dense superficial gas velocities, m/s
u_g, u_p	actual gas and particle velocities, m/s
U_g, U_p	superficial gas and particle velocities, m/s
U_{pf}, U_{pc}	dilute and dense superficial particle velocities, m/s
U_{sc}, U_{sf}, U_{si}	superficial slip velocities in the dense, dilute, and interphases, m/s
W_{gs}	energy dissipation for the gas, $kg/(m\,s^3)$
z	distance from the downer entrance, m
Z_t	downer height, m
ΔH	cross-section height, m

GreekLetters

ε	cross-sectional average voidage
ε_f, ε_c	dilute and dense voidage
ε_{max}	maximum dilute voidage for clustering
ε_{mf}	minimum fluidization voidage
ε_z	cross-sectional average voidage
ρ_g, ρ_p	gas and particle density, kg/m^3
τ_{wg}, τ_{wp}	gas–wall and particle–wall friction, N/m^3
τ_{wpf}, τ_{wpc}	dilute and dense particle–wall friction, N/m^3

An EMMS-based radial model was also developed to describe radial heterogeneity in the fully developed region of a downer reactor (Li, Lin, & Yao, 2004). All these studies show the potential of the EMMS approach to be further extended to model concurrent downward gas–solid flow in order to explicitly account for the hydrodynamic effect of particle clustering behavior. Although computational fluid dynamics (CFD) simulation is more and more often conducted to troubleshoot the operational problems of downer reactors (Cheng et al., 2014; Gisdapow, 1994; Kongkitisupchai & Gidaspow, 2013; Liu, Wei, Zheng, & Jin, 2006; Zhao, Dong, Wu, & Chen, 2010;), the accurate mathematical modeling of concurrent downward gas–solid flow is still necessary to provide a quantitative reference for the design of a downer reactor and to generate an initial flow field for accelerating CFD simulation (Ge et al., 2011; Liu et al., 2012).

According to EMMS theory, interphase interactions between the fluid and particles at both microscale and mesoscale are explicitly considered to develop a general axial model for concurrent downward gas–solid flow in this article. This will lay a solid basis for the description of both the axial and radial heterogeneities in cocurrent gas–solid downers by coupling with the radial EMMS model (Liu, Hu, Jiang, & Li, 2014), since the so-called core–annulus structure was found to exist in gas–solid downer reactors (Chalermsinsuwan, Chanchuey, Buakhao, Gidaspow, & Piumsomboon, 2012; Deng, Wei, Liu, & Jin, 2002; Liu et al., 2006; Ropelato, Meier, & Cremasco, 2005). As mentioned above, concurrent downward gas–solid flow may fall into three different development stages and be dominated by mechanisms different from those in concurrent upward gas–solid flow, and the emphasis of this article is thus placed on the analyses of the stability condition and numerical solution of the one-dimensional model. The prediction of the formulated model is validated by comparing it with experimental data obtained by various research groups.

Mathematical formulation and numerical solution

If the gas–solid flow in a downer is assumed to be fully developed, as shown in Fig. 1, the particles begin to be accelerated by both the gas and gravity at the top entrance of the downer until u_g decreases to equal u_p at the end of the first acceleration section. The particles are then accelerated further by the gravitational force only until the sum of the drag force and particle–wall friction (τ_{wp}) is in balance with the gravitational force at the end of the second acceleration section. Finally, both u_g and u_p remain constant downstream and a_p approaches zero in the fully developed region of the downer.

Following the method of system resolution with respect to both dominant mechanisms and scales in CFB risers, a cocurrent gas–solid downer can also be resolved into three sub-systems of a dilute phase, a dense phase, and an interphase in between. Consequently, the momentum and mass conservation equations should be built with respect to the dilute and dense phases separately.

Momentum and mass conservation equations

Particle–wall friction (τ_{wp}) has been reported to affect the hydrodynamics of gas–solid downer reactors, especially at high U_g and/or high G_s (Qi, Zhang, & Zhu, 2008). Thereby, this effect should be taken into account in the model formulation. Following the Fanning equation, τ_{wp} can be expressed as

$$\tau_{wp} = f_p \frac{1}{2D_t} \rho_p (1-\varepsilon) \left(\frac{U_p}{1-\varepsilon} \right)^2, \tag{1}$$

where f_p is generally assumed to be a constant but is taken in this article as a function of operating parameters (Bolkan, Berruti, Zhu, & Milne, 2003):

$$f_p = 0.003 \left(\frac{U_p}{1-\varepsilon} \right)^{0.426}. \tag{2}$$

The particle–wall friction force is assumed to uniformly exert on each particle, and the particle–wall friction in the dilute and dense phases can thus be estimated respectively as

$$\tau_{wpf} = \frac{(1-f)(1-\varepsilon_f)}{1-\varepsilon} \tau_{wp}, \tag{3}$$

$$\tau_{wpc} = \frac{f(1-\varepsilon_c)}{1-\varepsilon} \tau_{wp}. \tag{4}$$

Altogether, 10 structural parameters (ε_f, ε_c, a_f, a_c, f, U_f, U_c, U_{pf}, U_{pc}, and d_{cl}) are used to describe gas–solid flow at the specified cross-section, among which ε_c, a_c, f, U_c, U_{pc}, and d_{cl} refer to the

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