MODELING THE AXIAL HYDRODYNAMICS OF COUNTER-CURRENT GAS-SOLID DOWNERS

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Abstract – Counter-current gas-solid downer reactors can be used to prepare necessary high solids concentrations for high heat and/or mass transfer processes. However, the downward particle movement is much likely to be prevented by an upward gas flow, which can be named as so-called "flooding" phenomenon. The energy-minimization multiscale (EMMS) theory has been shown to be capable of capturing multiscale heterogeneous structures in gas-solid systems, and hence is further utilized to simulate counter-current gas-solid downward flow in this article. The formulated model characterizes well the axial hydrodynamics and its parametric effects in counter-current gas-solid downers. Flooding gas velocity can be further determined from the calculation results, which is consistent with the empirical correlation qualitatively.

1. INTRODUCTION

Gas-solid fluidized bed reactors can be classified into different types (e.g., fast beds, cocurrent and counter-current downers) according to the variations of the movement directions of the gas and particles with respect to gravity (Kwauk, 1963). Counter-current downers are characterized by the downward movement of particles due to the gravity in an upward gas flow, which are usually used to prepare high solids concentrations for high heat and/or mass transfer processes such as biomass gasification and coal pyrolysis with solid heat carrier (Luo et al., 2001; Schmid et al., 2012; Dong et al., 2012). Many experiments and numerical simulations were performed to investigate the fluid dynamics of counter-current gas-solid downers (Luo et al., 2001; Zhang & Zhu, 2006; Peng et al., 2013; Jia et al., 2014). As in fast fluidized beds, particle clustering phenomena also occur in counter-current downers. It is generally accepted that the increase of gas velocity or solids flux leads to increasing solids concentration and interphase slip in the downer reactors.

The downward particle movement in a counter-current downer is much likely to be prevented by the upward gas flow, which can be named as a "flooding" phenomenon (Bi et al., 2004) and thus calls for accurate prediction in process design and scaling-up. Kwauk (1963) defined the flooding gas velocity at the specified solids flux as

$$\left[\partial U_{\mathrm{g}}/\partial \varepsilon\right]_{G_{\mathrm{s}}}=0 \tag{1}$$

and proposed an empirical method to calculate it based on the Richardson-Zaki correlation. Bi et al. (2004) calculated the flooding gas velocity in a gas-solid stripper with complex internals. Garic-Grulovic et al. (2014) found that at the flooding point the particles move to the peripheral location while the gas transfers into the rest part of the circular tube to form a channel. However, the underlying mechanism involved in the flooding phenomenon is still far from being understood completely.

The energy-minimization multiscale (EMMS) theory has been shown to be capable of capturing multiscale heterogeneous structures reasonably in gas-solid systems (Hu et al., 2013; Liu et al., 2014; Liu et al., 2015; Hu et al., 2016), and can be extended to model the so-called first and second acceleration as well as fully developed sections in cocurrent gas-solid downers (Wang et al., 1992; Zhang et al., 2016). Since the essence of gas-solid interactions in counter-current downers is similar to those in the latter two regions of cocurrent downers according to the force analyses of the gas and particles, the EMMS theory may be similarly applied to the simulation of counter-current gas-solid downers.

In this article, an EMMS-based one-dimensional model is established for counter-current gas-solid downward flow. Because of taking into consideration the mesoscale heterogeneous interaction, the formulated model characterizes well the axial hydrodynamics as well as the effects of operating conditions in counter-current gas-solid downers. Especially, the flooding gas velocity can be determined further, so as to explore the underlying mechanism involved in the flooding phenomenon.

2. MATHEMATICAL MODELING AND NUMERICAL SOLUTION

In counter-current gas-solid downers, as shown in Fig. 1, the particles begin to be accelerated by the gravity once they enter the tube, and then move downward in a uniform motion due to the increasing drag force if the tube is long enough. During this process, the gas tends to choose a path with minimal resistance to agglomerate particles together, while the particles prefer to continue in the existing state through inertia. Considering the upward direction as positive, the minimal resistance for gas flow results in minimal negative energy dissipation at a specified cross-section ($-W_{gs,z}\rightarrow$min), while the inertia of particles leads to maximal particle acceleration ($a_{p,z}\rightarrow$max) because the mean drag force exerted by the gas on each particle in a homogeneous state is always greater than the interphase drag force under aggregation. As a result, the energy dissipation per unit mass of particles tend to be minimal at the cross-section,

$$\left|N_{gs0,z}\right|=\frac{\left|N_{gs,z}\right|}{\left|N_{T,z}\right|}=\frac{-W_{gs,z}/[\rho_p(1-\varepsilon)]}{U_g(g+a_{p,z})(\rho_p-\rho_g)/\rho_p}\propto\frac{-W_{gs,z}}{a_{p,z}}\rightarrow\min. \tag{2}$$

This equation can be set as the mesoscale constraint for a stable radial distribution. Besides this, a stable axial flow structure throughout the downer calls for minimal energy dissipation in the whole downer unit,

$$\bar{N}_{gs0,z}=\int_0^Z(1-\varepsilon_z)N_{gs0,z}dz\Big/\int_0^Z(1-\varepsilon_z)dz\rightarrow\min. \tag{3}$$

Therefore, according to the momentum conservation for the dilute, dense and inter phases as well as the mass constitution for the gas and particles, an EMMS-based mathematical model for counter-current gas-solid downward flow can be summarized in Table 1.

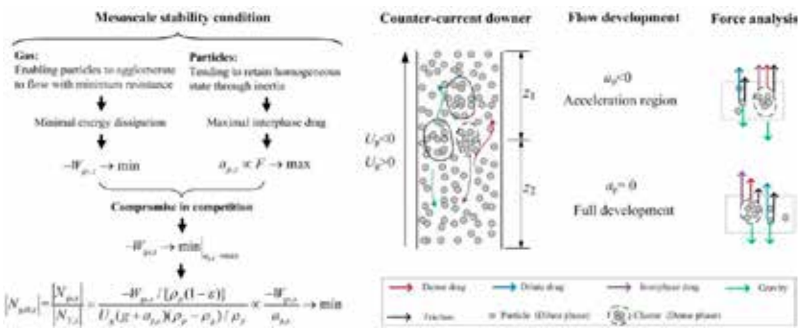


Fig. 1 Physical basis of the EMMS-based model for counter-current gas-solid downward flow

Table 1 Main equations of the EMMS-based counter-current gas-solid downer model

Equation	Mathematical expression	
Force balance		
for dilute phase	$\frac{3}{4}C_{Df,z}\frac{(1-f_z)(1-\varepsilon_{f,z})}{d_p}\rho_g U_{sf,z}^2-(1-f_z)(1-\varepsilon_{f,z})(\rho_p-\rho_g)(a_{f,z}+g)+\tau_{wpf,z}=0$	(T1)
for dense phase	$\frac{3}{4}C_{Dc,z}\frac{f_z(1-\varepsilon_{c,z})}{d_p}\rho_g U_{sc,z}^2+\frac{3}{4}C_{Di,z}\frac{f_z}{d_{cl,z}}\rho_g U_{si,z}^2-f_z(1-\varepsilon_{c,z})(\rho_p-\rho_g)(a_{c,z}+g)+\tau_{wpc,z}=0$	(T2)
Pressure balance	$C_{Df,z}\frac{1-\varepsilon_{f,z}}{d_p}\rho_g U_{sf,z}^2+\frac{f_z}{1-f_z}C_{Di,z}\frac{1}{d_{cl,z}}\rho_g U_{si,z}^2-C_{Dc,z}\frac{1-\varepsilon_{c,z}}{d_p}\rho_g U_{sc,z}^2=0$	(T3)
Mass balance		
for the gas	$U_g-f_zU_{c,z}-(1-f_z)U_{f,z}=0$	(T4)
for the particles	$U_p-f_zU_{pc,z}-(1-f_z)U_{pf,z}=0$	(T5)
Height calculation	$\Delta S_z=\left(\frac{1}{1-\varepsilon_z}+\frac{1}{1-\varepsilon_{z-1}}\right)\left(\frac{U_{pc,z}}{1-\varepsilon_{c,z}}-\frac{U_{pc,z-1}}{1-\varepsilon_{c,z-1}}\right)\frac{U_p}{a_{c,z}+a_{c,z-1}}$	(T6)

A numerical scheme shown in Fig. 2 is proposed to compute the axial profiles of the hydrodynamic parameters in a counter-current downer at the specified U_g and G_s. We need to solve Eqs. (T1)-(T5) under the constraint of Eq. (2) one cross-section by one cross-section from the top to bottom and then repeat this process to traverse all possible axial profiles of the structural parameters, in order to determine the stable axial profile according to the global stability condition expressed as Eq. (3). More details on the formulated model can refer to our previous publication (Zhang et al., 2016).

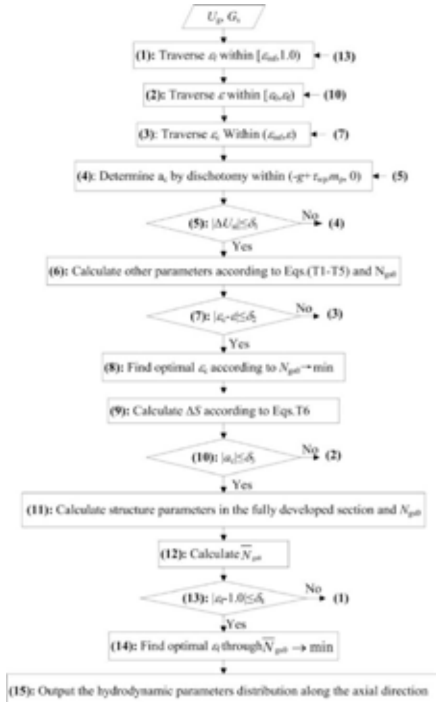
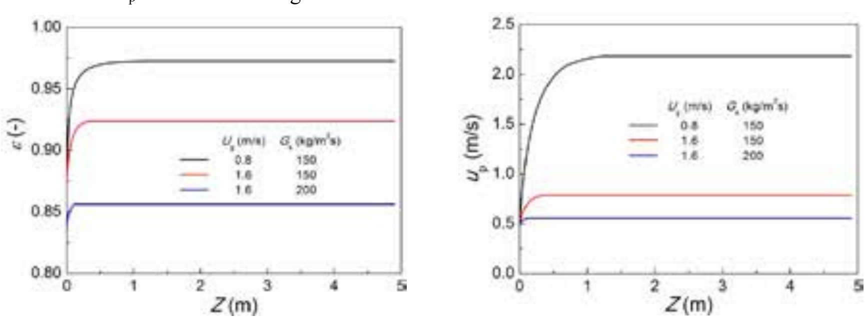


Fig. 2 Numerical scheme for solving the EMMS-based counter-current gas-solid downer model

3. PARAMETRIC EFFECTS ON THE AXIAL HYDRODYNAMICS

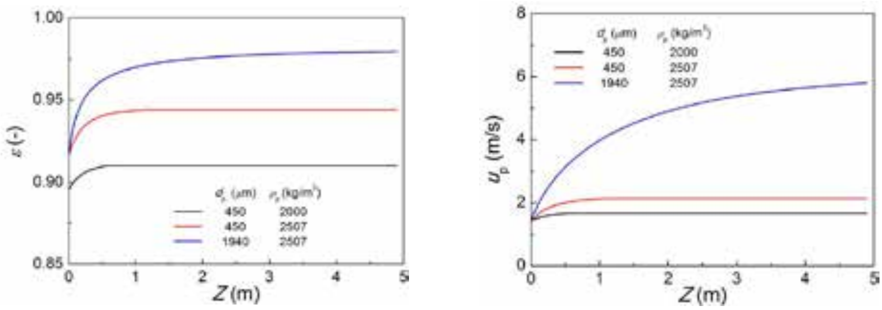
Figure 3 reveals the effects of operating conditions on the axial profiles of voidage (ε) and particle velocity (u_p) in a counter-current downer of D_t = 0.05 m and H_t = 5.0 m. Particle diameter and density are d_p = 450 μm and ρ_p =2507 kg/m^3, respectively. It can be shown that both ε and u_p firstly increase along the downer tube and finally level off in the fully developed region. Increasing U_g and/or G_s result in the decreases in ε and u_p as well as the length of the acceleration section in the downer tube.



(a) ε (b) u_p

Fig. 3 Effects of operation conditions on the axial profiles of ε and u_p

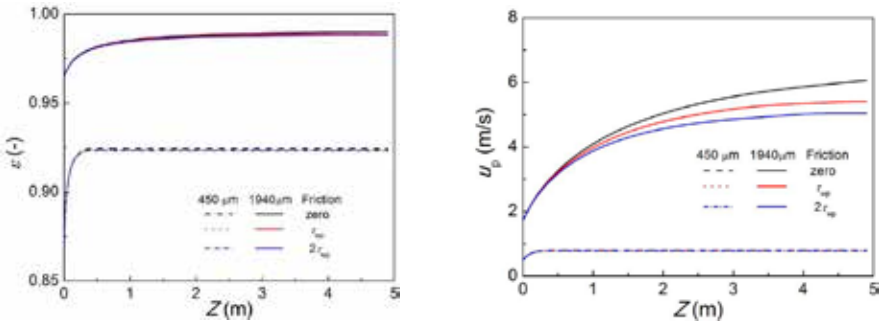
[Figure 4](#) shows the effects of particle properties on the axial profiles of ε and u_p in the downer reactor. Three types of particles are adopted in the simulation. It can be found that increasing either d_p or ρ_p under the given operating conditions is equivalent to decreasing U_g for the specified fluidized material, and leads to the increases in ε and u_p as well as the length of the acceleration section in the downer tube at U_g = 0.8 m/s and G_s = 300 kg/m^{2}s.



(a) ε (b) u_p

Fig. 4 Effects of particle properties on the axial profiles of ε and u_p

The effects of wall friction on the axial flow structures of counter-current gas-solid downers are also investigated numerically in this study. Particle density is 2507 kg/m^3. As shown in Fig. 5, at U_g = 1.6 m/s and G_s = 150 kg/m^{2}s, both ε and u_p decrease clearly with the increase of wall friction (τ_{wp}) for 1940 μm particles, while change little for 450 μm particles, indicating that the wall friction should be taken into account in counter-current gas-solid downers of coarse (e.g., Geldart D) particles.



(a) ε (b) u_p

Fig. 5 Effect of wall friction on the axial profiles of ε and u_p

4. PREDICTION OF FLOODING GAS VELOCITY

According to the proposed definition of flooding gas velocity (U_g^*) by Kwauk (1963), the onset of flooding is characterized by the zero derivative of U_g with respect to ε, that is, the voidage inside the downer reactor varies significantly with gas velocity once U_g increases to be greater than U_g^*. In this article, the voidage (ε^*) in the fully developed region instead of that in the whole downer reactor is calculated as the reference for the determination of U_g^*, because the voidage in the acceleration region can be significantly affected by the boundary condition of the downer reactor. As shown in Fig. 6, with increasing U_g from point A, the decrease trend of ε^* is not clear initially; but then becomes to be significant after point B; finally remains invariable after point C until point D, beyond which the model cannot be numerically solved again. Since the flooding phenomenon is not an abrupt but a gradual process in actual counter-current gas-solid downers, the gas velocity corresponding to the intersection point of the two tangents to the curves BC and CD is defined as the flooding gas velocity for the specified particles at the fixed solid fluxes.

As indicated by Fig. 7, the predicted U_g^* clearly increases with increasing particle sizes under the different operating conditions. For three types of particles of the same density (ρ_p = 2507 kg/m^3) but different diameters, increasing G_s always results in the onset of flooding phenomenon at a lower gas velocity. Under the tested operating conditions, the predicted U_g^* agrees with Kwauk's correlation qualitatively, though the absolute disparity between them seems to increase with increasing particle sizes.

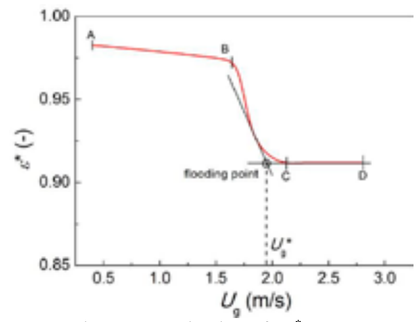


Fig. 6 Determination of U_g^*

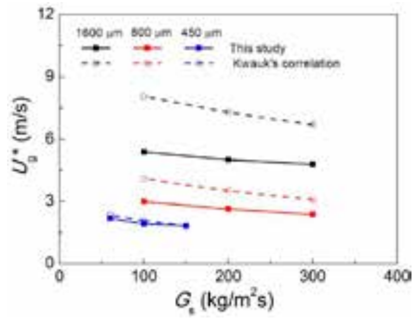


Fig.7 Comparison between predicted and empirical U_g^*

5. CONCLUSION

The energy-minimization multiscale (EMMS) theory is utilized to model counter-current gas-solid downward flow by incorporating the multiscale stability conditions according to the principle of competition in compromise. The EMMS-based model quantifies the axial flow structures in counter-current gas-solid downers and facilitates the prediction of so-called flooding gas velocity, which lay the basis for exploring the underlying mechanism involved in the flooding phenomenon in counter-current gas-solid downers.

NOTATION

$N_{gs0,z}$	normalized energy dissipation
$\bar{N}_{gs0,z}$	normalized global energy dissipation
a_c	dense phase particle acceleration, m/s^2
a_f	dilute phase particle acceleration, m/s^2
C_{Dc}	dense phase drag coefficient
C_{Df}	dilute phase drag coefficient
C_{Di}	interphase drag coefficient
d_{cl}	cluster diameter, m
d_p	particle diameter, 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)
H_t	downer height, m
N_{gs}	energy dissipation rate for gas, m^2/s^3
N_t	total energy dissipation for system, m^2/s^3
U_c	dense phase superficial gas velocity, m/s
U_f	dilute phase superficial gas velocity, m/s
u_g	gas velocity, m/s
U_g	superficial gas velocity, m/s
U_g^*	flooding gas velocity, m/s
u_p	particle velocity, m/s
U_p	superficial particle velocity, m/s
U_{pc}	dense phase particle velocity, m/s
U_{pf}	dilute phase particle velocity, m/s
U_{sc}	dense phases slip velocity, m/s
U_{sf}	dilute phases slip velocity, m/s
U_{si}	interphase slip velocity, m/s
W_{gs}	energy dissipation for the gas, J/(m^{3}s)
ΔS	cross-section height, m

Greek Letters

ε^*	voidage in the fully developed region
ε_f	voidage in the dilute phase
ε_c	voidage in the dense phase
ε_{max}	cluster maximum voidage
ρ_g	gas density, kg/m^3
ρ_p	particle density, kg/m^3
τ_{wpf}	dilute phase particle-wall friction, N/m^3
τ_{wpc}	dense phase particle-wall friction, N/m^3

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