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Flow Behavior of Geldart A and Geldart C Particles in a Co-current Downflow Circulating Fluidized Bed Reactor

Parinya Khongprom [a,b*], Piyanat Soontarose [a,b], Sirilux Manchandrarat [a,b], Sunun Limtrakul [c], and Terdthai Vatanatham [c]

[a] *Department of Industrial Chemistry Faculty of Applied Science, King Mongkut's University of Technology North Bangkok, THAILAND*
[b] *Integrated Nanoscience Research Center, Science and Technology Research Institute, King Mongkut's University of Technology North Bangkok, THAILAND*
[c] *Department of Chemical Engineering, Faculty of Engineer, Kasetsart University, THAILAND*

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ABSTRACT

The purpose of this research is to study the effect of Geldart A and C particles on the hydrodynamics behavior in a 9.3 m height, 0.1 m diameter co-current downflow circulating fluidized bed (downer reactor) using CFD simulation. Two-fluid model with kinetic theory of granular flow was adopted to predict flow behavior in the system. The simulation results show that hydrodynamics behavior in the downer strongly depends on the type of the particle. Geldart C particle exhibits a more uniform distribution along the lateral direction as compared with Geldart A particle. In addition, the effects of operating conditions were also studied. The uniformity of lateral direction of solids fraction increases with decreasing of solids circulation rate (Gs) or increasing of inlet superficial gas velocity (Ug). However, the radial distributions of gas and solids velocity are more uniform when Ug decreases especially for Geldart C particle.

*Corresponding author (P. Khongprom). Tel/Fax: +66-2-5552000 Ext.4811. E-mail addresses: parinyak@kmutnb.ac.th

1. Introduction

A co-current downflow circulating fluidized bed (downer reactor) has been developed to overcome the drawback of a co-current upflow circulating fluidized bed or riser reactor. In the downer, both gas and solids particles are fed to the reactor at the top section. The suspension of gas and particle mixture co-currently downward flows along the gravitational direction. According to this feed setup, flow behavior in the downer is much more uniform as compared with that in the riser (Zhang *et al.,* 2001). Moreover, the particle residence time is lower and the particle residence time distribution (RTD) is narrower due to less back mixing (Khongprom *et al.,* 2012; Wei and Zhu, 1996).

Hydrodynamics behavior in the fluidized bed reactor strongly depends on the physical properties of particle (Khongprom, 2011; Khongprom *et al.,* 2012; Limtrakul *et al.,* 2008; Ye *et al.,* 2005). Small or fine particles are desired to apply in the chemical processes due to low mass and heat transfer resistances. Geldart A particles are normally applied due to its small particle size and can be easily fluidized at ambient conditions (Geldart, 1973). Geldart C particles are defined as an extremely fine particle. However, this particle type is rarely used in the conventional fluidized bed because these particles are very difficult to fluidize. According to feeding system and the assistant of gravitational force in the dower, Geldart C particles might be able to use in the downer reactor. Therefore, the objective of this research is to study the effect of Geldart A and C particles on the hydrodynamics behavior in the downer reactor.

2. Methodology

2.1 Reactor Geometry

The typical circulating fluidized bed (CFB) system is shown in Figure 1(a). This system mainly consists of downer section, gas-solids separator, riser section and gas and solids distributors. This work focuses on the hydrodynamics behavior in the 0.1 m inner diameter and 9.3 m height downer reactor (Figure 1(b)). Gas and solids particle are fed into the reactor at the top section and the exit locates at the bottom. To simplify the system, 2-D simulation was considered (see Figure 1(c). Physical properties of particle used are shown in Table 1. Air at ambient condition was used as a fluidizing gas. The operating conditions used in this work are shown in Table 2.

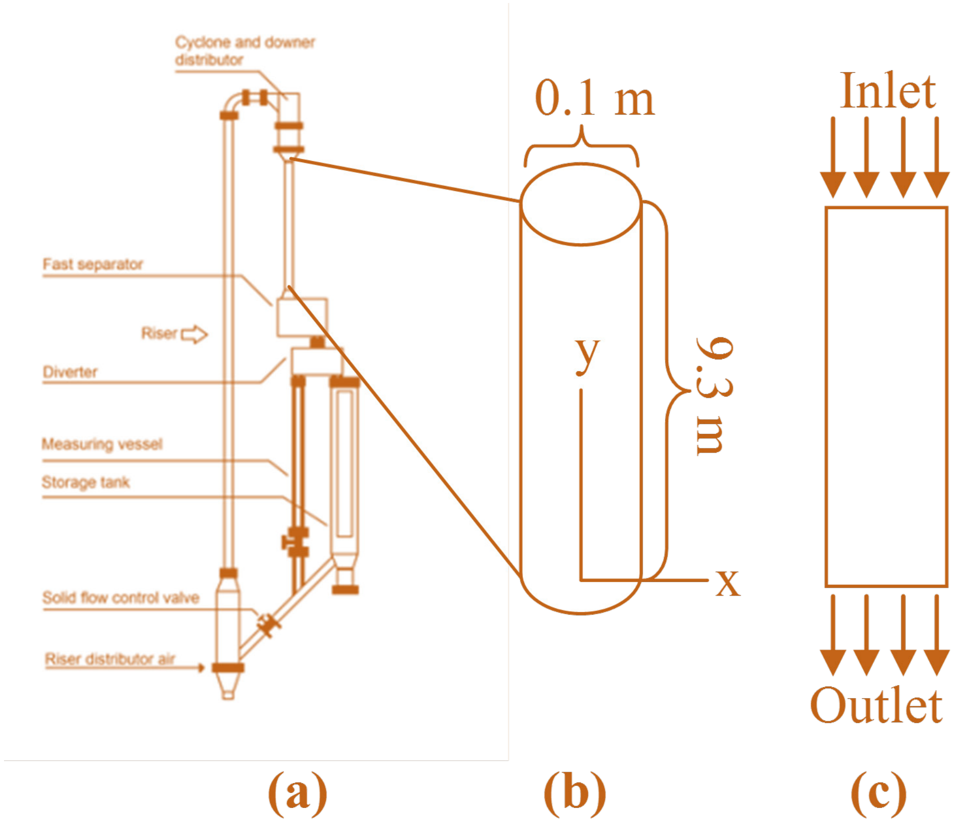

Figure 1: Typical CFB system (a); downer section (b); 2-D downer section (c).

Table 1: Physical properties of particle used in this study.

Particle type	D_p (μm)	ρ_p (kg/m^3)
Geldart A	80	1,500
Geldart C	20	1,500

Table 2: Operating conditions used in this study.

Case	U_g (m/s)	Gs (kg/m^{2}s)
Effect of Gs	3.5	150 200 250
Effect of Ug	2.5 5.0 7.0	101

2.2 Mathematical Modeling

Two-fluid model was adopted to predict flow behavior in the reactor. This model treats each phase as an interpenetrating continuum. Flow behavior of each phase was characterized by its own governing equations. The conservation equations are as follow,

*Corresponding author (P. Khongprom). Tel/Fax: +66-2-5552000 Ext.4811. E-mail addresses: parinyak@kmutnb.ac.th

The continuity equation for phase q is expressed as:

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{u}_q\right) = 0 \tag{1}$$

where t stands for time (s), α_q the volume fraction, ρ_q the density (kg/m^3), and $\vec{u}_q$ the velocity vector (m/s).

Momentum conservation equation for gas phase is

$$\frac{\partial}{\partial t}\left(\alpha_g \rho_g \vec{u}_g\right) + \nabla \cdot \left(\alpha_g \rho_g \vec{u}_g \vec{u}_g\right) = -\alpha_g \nabla p + \alpha_g \rho_g \vec{g} + \nabla \cdot \overline{\overline{\tau}}_g + \nabla \cdot \overline{\overline{\tau}}_{tu,g} + \beta_{gp}(\vec{u}_p - \vec{u}_g) \tag{2}$$

where p is gas pressure (Pa), $\vec{g}$ gravitational acceleration (m/s^2), $\overline{\overline{\tau}}_g$ and $\overline{\overline{\tau}}_{tu,g}$ the viscous stress tensor and the Reynolds stress tensor, respectively (Pa), β_{gp} the interphase momentum transfer coefficient (kg/m^{3}s).

Momentum conservation equation for solids phase (p) is

$$\frac{\partial}{\partial t}\left(\alpha_p \rho_p \vec{u}_p\right) + \nabla \cdot \left(\alpha_p \rho_p \vec{u}_p \vec{u}_p\right) = -\alpha_p \nabla p - \nabla p_p + \nabla \cdot \overline{\overline{\tau}}_p + \nabla \cdot \overline{\overline{\tau}}_{tu,p} + \alpha_p \rho_p \vec{g} + \beta_{pg}(\vec{u}_g - \vec{u}_p) \tag{3}$$

Interphase momentum transfer coefficient (Gidaspow's drag model) is defined as

For $\alpha_g \le 0.80$: $$\beta_{gp} = 150\frac{\left(1-\alpha_g\right)^2 \mu_g}{\alpha_g d_p^2} + 1.75\frac{(1-\alpha_g)\rho_g\left|\vec{u}_g - \vec{u}_p\right|}{d_p} \tag{4}$$

For $\alpha_g > 0.80$: $$\beta_{gp} = \frac{3}{4}\frac{\left(1-\alpha_g\right)\alpha_g}{d_p}\rho_g\left|\vec{u}_g - \vec{u}_p\right| C_D \alpha_g^{-2.65} \tag{5}$$

where $$\mathrm{Re} = \frac{\rho_g \alpha_g \left|\vec{u}_g - \vec{u}_p\right| d_p}{\mu_g} \tag{6}$$

where μ is gas viscosity (kg/m.s), d_p particle diameter (m), C_D drag coefficient (-).

Granular temperature conservation can be expressed in the form

$$\frac{3}{2}\left[\frac{\partial}{\partial t}\left(\rho_p\alpha_p\Theta_p\right)+\nabla\cdot\left(\rho_p\alpha_p\vec{u}_p\Theta_p\right)\right]=\left(-p_p\overline{\overline{I}}+\overline{\overline{\tau}}_p\right):\nabla\vec{u}_p+\nabla\cdot\left(k_{\Theta p}\nabla\Theta_p\right)-\gamma_{\Theta p}+\phi_p \tag{7}$$

where Θ_p is granular temperature (m^2/s^2), $\overline{\overline{I}}$ unit tensor (-), $k_{\Theta p}$ diffusion coefficient of granular temperature (kg/m.s), γ_Θ collisional dissipation of solid fluctuating energy (kg/ms^3), ϕ_p energy exchange between phases (kg/ms^3).

The detail of this model has been discussed in previous works (Khongprom, 2011; Khongprom *et al.,* 2012).

k-ε turbulent model was used to explain the turbulent in the system. k equation for *q* phase is defined as

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q k_q\right)+\nabla\cdot\left(\alpha_q\rho_q\vec{u}_q k_q\right)=\nabla\cdot\left(\alpha_q\frac{\mu_{tu,q}}{\sigma_k}\nabla k_q\right)+\left(\alpha_q G_{k,q}-\alpha_q\rho_q\varepsilon_q\right)+K_{pq}(C_{pq}k_p-C_{qp}k_q- \\ K_{pq}(\vec{u}_p-\vec{u}_q).\frac{\mu_{tu,p}}{\alpha_p\sigma_p}\nabla\alpha_p+K_{pq}(\vec{u}_p-\vec{u}_q).\frac{\mu_{tu,q}}{\alpha_q\sigma_q}\nabla\alpha_q \tag{8}$$

where k_q is the turbulent kinetic energy (m^2/s^2), G_k production of turbulent kinetic energy (kg/ms^3), ε_q turbulent dissipation rate (m^2/s^3), K_{pq} turbulent momentum transfer coefficient (kg/m^3s), σ_p turbulent Prandtl number.

Turbulent dissipation rate (ε) is expressed in the form

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\varepsilon_q\right)+\nabla\cdot\left(\alpha_q\rho_q\vec{u}_q\varepsilon_q\right)=\nabla\cdot\left(\alpha_q\frac{\mu_{tu,q}}{\sigma_\varepsilon}\nabla\varepsilon_q\right)+\frac{\varepsilon_q}{k_q}\left[C_{1\varepsilon}\alpha_q G_{k,q}-C_{2\varepsilon}\alpha_q\rho_q\varepsilon_q+ \\ C_{3\varepsilon}\left[K_{pq}(C_{pq}k_p-C_{qp}k_q)-K_{pq}(\vec{u}_p-\vec{u}_q)\frac{\mu_{tu,p}}{\alpha_q\rho_q}\nabla\alpha_q+K_{pq}(\vec{u}_p-\vec{u}_q).\frac{\mu_{tu,q}}{\alpha_q\sigma_q}\nabla\alpha_q\right]\right. \tag{9}$$

where ε_q is turbulent dissipation rate (m^2/s^3), $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ turbulent constants.

The kinetic theory of granular flow was used to predict the fluid properties of solids phase such as solids viscosity and solids pressure. The detail of this model was described somewhere else (Gidaspow, 1994).

2.3 Numerical Method

The governing equations were discritized using finite volume method. The first order upwind was applied for convection term. The SIMPLE scheme was used for solving the pressure and velocity in the system (Patankar, 1980). The 49 grid numbers in the radial direction and 140 grid numbers in the axial direction were employed. This grid system was obtained from grid independency study. A time step of 10^{-5} s was adopted. A convergence criterion of 10^{-4} for each scale was used.

3. Result and Discussion

3.1 Effect of Solids Circulation Rate (Gs)

Figure 2 shows the effect of Gs on the radial distribution of solids fraction at various heights. Both Geldart A and C particles exhibit core-annulus flow structure which uniform solids fraction in the center and high density peak near the wall region. This flow structure has been reported by several researchers (Cheng *et al.,* 1999; Khongprom, 2011; Khongprom *et al.,* 2012; Lehner and Wirth, 1999; Limtrakul *et al.,* 2008). However, Geldart C shows a much more uniform profile with smaller density peak near the wall. In addition, solids fraction increases with Gs.

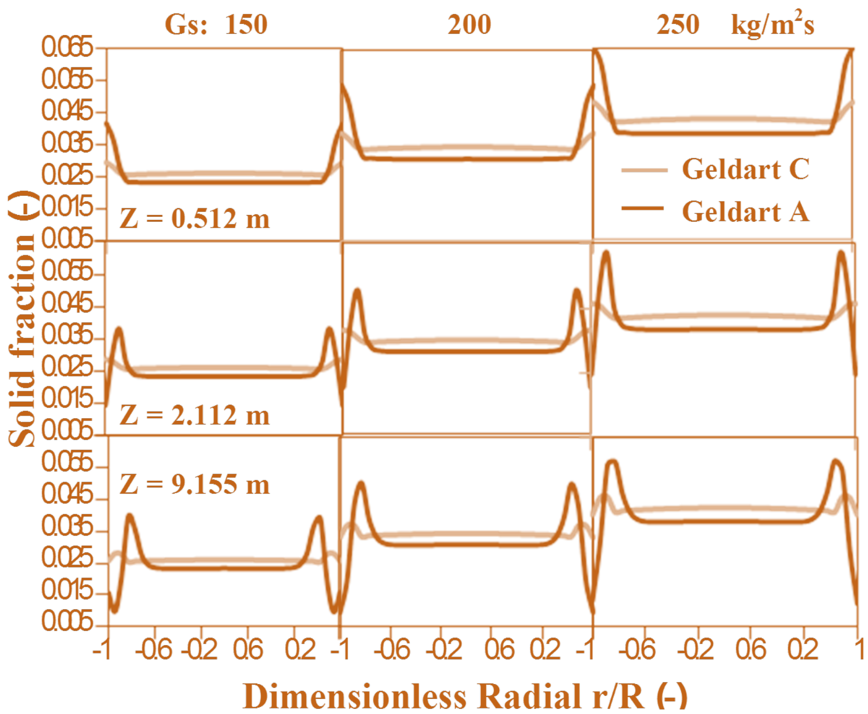

Figure 2: Effect of Gs on the radial distribution of time-averaged solids fraction.

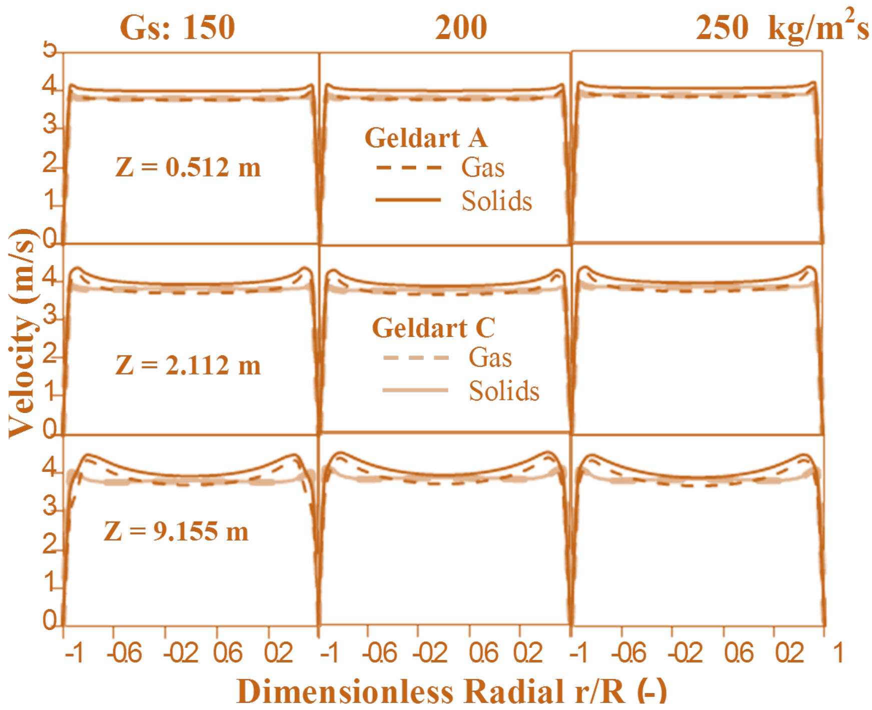

Figure 3: Effect of Gs on the radial distribution of time-averaged gas and solids velocities.

Figure 3 shows the effect of Gs on the radial distribution of gas and solids velocities. Near the inlet section (Z = 0.512 m), both gas and solids velocities are almost constant along the radial direction due to the uniform feed profile. Further down the column, Geldart C particle exhibits an almost uniform gas and solids velocities in the center region with a small velocity peak near the wall. Geldart A particle, both gas and solids velocities slightly increase from the center to the wall and the high velocity peak near the wall was form. This high velocity peak near the wall is the results of the particle cluster formation in this region (see Figure 2). These phenomena can also be observed by several experimental studies (Grassler and Wirth, 1999; Lehner and Wirth, 1999). In addition, the no slip velocity between gas and particles can be observed for Geldart C particle operation. This indicated that gas and Geldart C particle form a homogenous suspension mixture.

3.2 Effect of inlet Superficial Gas Velocity (Ug)

The effect of Ug on the lateral distribution of the solids fraction is shown in Figure 4. It was found that Ug exhibits less effect on the shape of the radial distribution profile of solids fraction. At z = 0.512 m, both Geldart A and C particles show a uniform profile in the center region with high solids fraction at the wall. Further down the column, the radial profiles

*Corresponding author (P. Khongprom). Tel/Fax: +66-2-5552000 Ext.4811. E-mail addresses: parinyak@kmutnb.ac.th ©2014. International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies. Volume 5 No.1 ISSN 2228-9860 eISSN 1906-9642. Online available at http://tuengr.com/V05/0057.pdf .

developed to form a core-annulus structure. However, solids fraction decreases with increasing of Ug. The density peak near the wall region decreases when Ug increases leading to more uniform in the radial direction especially for Geldart C particle.

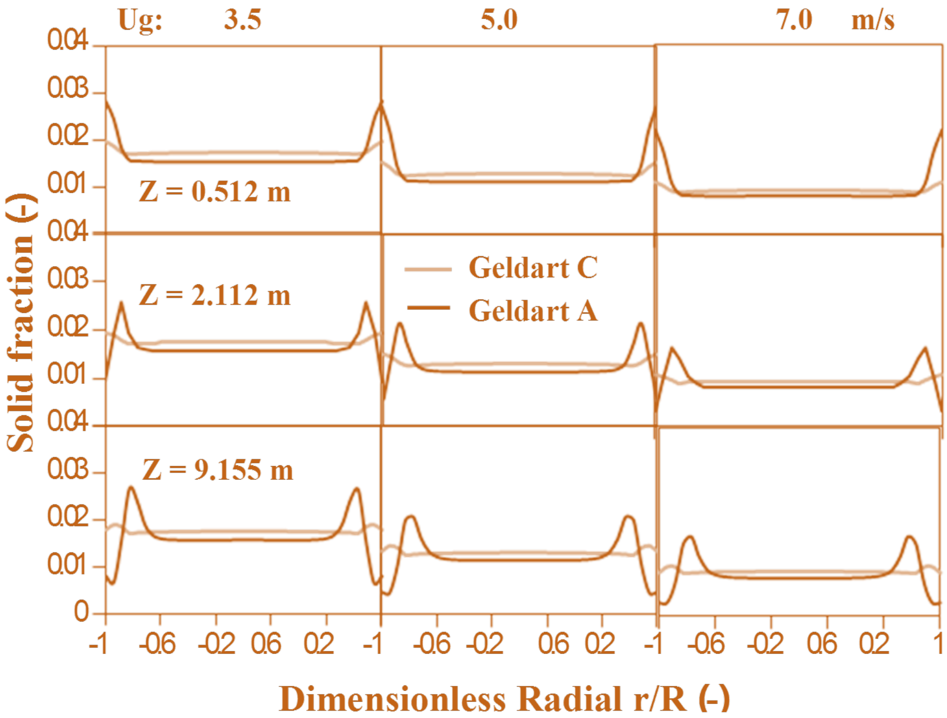

Figure 4: Effect of Ug on the radial distribution of time-averaged solids fraction.

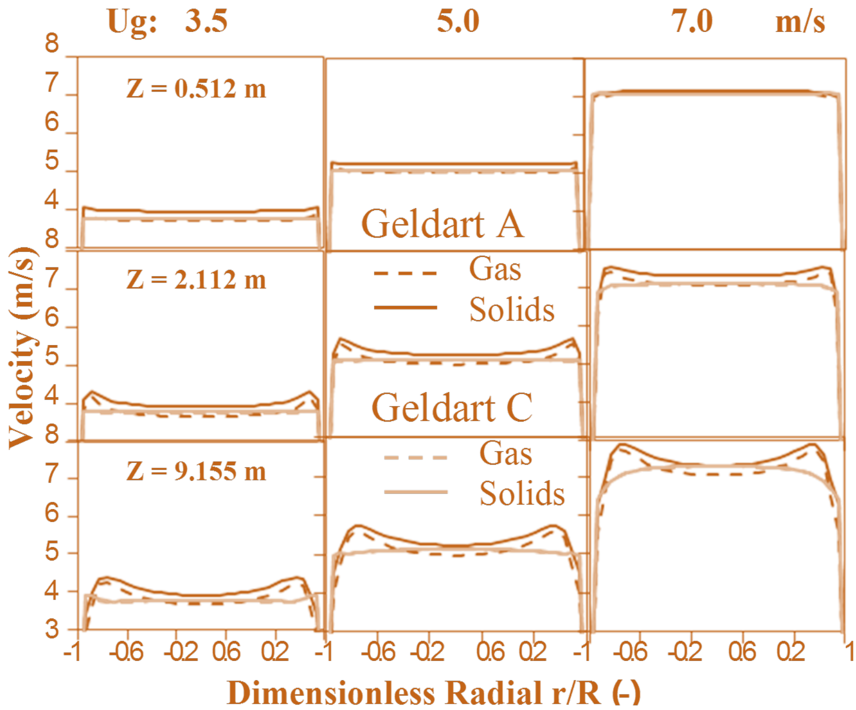

Figure 5: Effect of Ug on the radial distribution of time-averaged gas and solids velocities.

Figure 5 exhibits the effect of Ug on the radial profile of gas and solids velocities. As expected, gas and solids velocities increase with Ug. In case of Geldart C, gas and solids velocity profile in the fully developed region (Z = 9.155 m) can be classified into 2 types. At low Ug (Ug = 3 m/s), gas and solids velocities shows a uniform profile in the center with a small peak near the wall. At high Ug (Ug = 7.0 m/s), gas and solids velocities profiles shows a parabolic shape with consistency with gas velocity profile when operate with no solids particle feeding (did not show here). In this low solids fraction operating regime, gas phase governs the overall flow behavior in the system.

4. Conclusion

Two-fluid model with kinetic theory of granular flow was successfully developed to predict the hydrodynamics behavior in a downer reactor. The simulation results show that Geldart C particle exhibits a more uniform distribution along the lateral direction as compared with Geldart A particle. Geldart C particle exhibits a no-slip velocity between gas and solids particle phases. Moreover, high density peak near the wall region can be observed when operate with Geldart A particle. In addition, the effects of operating conditions were also studied. The uniformity of lateral distribution of solids fraction increases with decreasing of Gs or increasing of Ug. However, the radial distributions of gas and solids velocity are more uniform when Ug decreases especially for Geldart C particle.

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6. References

Cheng, Y., Guo, Y., Wei, F., Jin, Y., Lin, W. (1999). Modeling the Hydrodynamics of Downer Reactors Based on Kinetic Theory. *Chemical Engineering Science Journal,* 54, 2019-2027.

Geldart, D. (1973). Type of Gas Fluidization. *Powder Technology*, 7, 285-292.

Gidaspow, D. (1994). Multiphase Flow and Fluidization: Continuum and Kinetic Theory Discription. Academic Press, Boston.

Grassler, T. and K.E. Wirth. (1999). X-ray Computer Tomography—Potential and Limitation for the Measurement of Local Solids Distribution in Circulating Fluidized Bed. In: T. York, T. Dyakowski, T. Peyton, A. Hurt (Eds.), Proceedings of the 1st World Congress on Industrial Process Tomography: Buxton, 402-409.

Lehner, P. and K.E. Wirth. (1999). Characterization of the Flow Pattern in a Downer Reactor. *Chemical Engineering Science Journal,* 54, 5471-5483.

Limtrakul, S., N. Thanomboon, T. Vatanatham, and P. Khongprom. (2008). DEM Modeling and Simulation of a Down-Flow Circulating Fluidized Bed. *Chemical Engineering Communications Journal,* 195, 1328-1344.

Khongprom, P. (2011). Modeling and Simulation of Hydrodynamics, and Heat and Mass Transfer in a Down-Flow Circulating Fluidized Bed Reactor. PhD. Thesis, Kasetsart University, Bangkok, Thailand.

Khongprom, P., A. Aimdilokwong, S. Limtrakul, T. Vatanatham, P.A. Ramachandran. (2012). Axial Gas and Solids Mixing in a Down Flow Circulating Fluidized Bed Reactor Based on CFD Simulation. *Chemical Engineering Science Journal,* 73, 8-19.

Patankar, S.V. (1980). Numerical Heat Transfer and Fluid Flow. Hemisphere, New York.

Wei, F., and J.-X. Zhu. (1996). Effect of Flow Direction on Axial Solids Dispersion in Gas-Solid Concurrent Upflow and Downflow System. *Chemical Engineering Journal and Biochemical Engineering Journal,* 64, 345-352.

Ye, M., M.A. vander Hoef, and J. A.M. Kuipers. (2005). The Effect of Particle and Gas Properties on the Fluidization of Geldart A Particles. *Chemical Engineering Science Journal,* 60, 4567-4580.

Zhang, H., W-X. Huang, and J-X. Zhu. (2001). Gas-Solid Flow Behavior: CFB Riser vs Downer. *AIChE Journal,* 47, 2000-2011.

Dr. P. Khongprom is a lecturer a Department of Industrial Chemistry, Faculty of Applied, King Mongkut's University of Technology Northy Bangkok. He received his B.Eng. of Chemical Engineering from Prince of Songkla University with Honors in 2001. He obtained his PhD also in Chemical Engineering from Kasetsart University in 2011. Dr. Khongprom current interests in modeling and simulation of hydrodynamics heat and mass transfer in a multiphase flow reactor.

Dr.Sunun Limtrakul is an Associate Professor of Department of Chemical Engineering at Kasetsart University. She holds a B.Sc. in Industrial Chemistry from Chiengmai University, MS in Chemical Engineering from Chulalongkorn University and Ph.D. degrees in Chemical Engineering from Washington University. Dr. Sunun is interested in reaction engineering, modeling and simulation, transport phenomena, and polymer electrolyte membrane (PEM) fuel cell.

Dr. Terdthai Vatanatham earned his bachelor degree from Chulalongkorn University Thailand, Master degree in Structural Engineering from Pennsylvania State University and Ph.D. in Chemical Engineering from University of Akron. He is an Associate Professor at Kasetsart University, Thailand. Dr. Terdthai is interested in reaction engineering, equipment design, and PEM fuel cell.

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