Hydrodynamic Similarity of Riser Flow in a Dense Transport Bed

Kai ZHAO [1,2,3], Shaojun YANG [2,3], Xiang XU [2,3] and Yunhan XIAO [2,3]

[1] University of Chinese Academy of Sciences, Beijing 100049, China
[2] Key Laboratory of Advanced Energy and Power, Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China
[3] Research Center for Clean Energy and Power, Chinese Academy of Sciences, Lianyungang, Jiangsu 222069, China

Abstract—**Pressurized dense transport bed is a new coal gasification technology under development. It is necessary to carry out study of hydrodynamic similarity of the gas solids flow to provide basis and reference for reactor design and scale-up. Literature research on hydrodynamic similarity have been mostly directed to bubbling fluidization and fast fluidization, while gas solids flow in dense transport bed riser correspond to dense suspension upflow, which has significant differences from fast fluidization in characteristics of distribution of solids concentration and solids velocity. In this study, we analyzed characteristics of hydrodynamic similarity of dense suspension upflow, and obtained corresponding dimensionless parameters.**

Keywords-dense transport bed, hydrodynamic similarity, dense suspension upflow

I. INTRODUCTION

Pressurized dense transport bed coal gasification technology is an important technology for the development of IGCC, which is characterized by high solids flux and high solids concentration in the riser.[1] It is necessary to carry out study of hydrodynamic similarity of the gas solids flow to provide basis and reference for reactor design and scale-up.

Glicksman[2] proposed full-set of hydrodynamic dimensionless parameters based on dimensionless momentum equations of gas solids flow. Further, Glicksman *et al*.[3] and Glicksman *et al*.[4] advanced simplified-set and viscous-limit set of hydrodynamic dimensionless parameters respectively. Horio *et al*.[5] proposed hydrodynamic dimensionless parameters for bubbling fluidization based on emperical correlation and Horio *et al*.[6] used hydrodynamic model to develop dimensionless parameters for fast fluidization. Patience *et al*.[7] and Qi *et al*.[8] investigated hydrodynamic similarities of gas solids flow in fully development region in risers. However, literature research on hydrodynamic similarity have been mostly directed to bubbling fluidization and fast fluidization, while gas solids flow in dense transport bed riser correspond to dense suspension upflow, which is characterized by net upward solids flux at each radial position of the riser. There are significant differences between dense suspension upflow and fast fluidization in characteristics of distribution of solids concentration and solids velocity[9]. In this study, we analyze characteristics of hydrodynamic similarity of dense suspension upflow, and obtain corresponding dimensionless parameters.

II. DIMENSIONLESS ANALYSIS

Reference concerned on hydrodynamic similarity of gas solids flow in risers are listed in Table I., in which U_{mf} is the minimum fluidization velocity, U_t is single particle terminal velocity, and BG represents bed geometry.

Glicksman[2] proposed full-set of hydrodynamic dimensionless parameters based on dimensionless momentum equations of gas solids flow, which can be applied to all flow regimes theoretically. If we make two hydrodynamic dimensionless parameters equivalent, their combinations should also be consistent in value, such as the combination of Renolds number and Froude number can be obtained:

$$\frac{\rho_g U_g D_r}{\mu_g} \Bigg/ \frac{U_g}{\sqrt{g D_r}} = \frac{D_r^{3/2}\sqrt{g}}{\nu_g} \qquad (1)$$

whrer ν_g is dynamic viscosity of fluid. It is to say that the unit size of scale model is uniquely determined by the dynamic viscosity of fluid, when the fluidization medium is selected, the size of scale model unit will be uniquely determined, which will bring difficulties in practical applications. We will not be able to carry out scale model experiments under this circumstances without changing fludization medium.

To avoid this difficulty, Glicksman *et al*.[3] make approximations for the interphase momentum transfer coefficient β between gas and solids phase in momentum equations, forming simplified-set of hydrodynamic dimensionless parameters. In addition, Glicksman *et al*.[4] show that for gas solids flow in the visous control region, such as bubbling fluidization and slugging fluidization, it is just required to meet the viscous-limit set of dimensionless parameters, which are listed in Table I, hydrodynamic similarity can be achieved. Horio *et al*.[5] obtained hydrodynamic dimensionless parameters for bubbling fluidization based on empirical relationship used for calculating bubble rise velocity. Horio *et al*.[6] proposed hydrodynamic similarity parameters for fast fluidization from their core-annular model. Glicksman *et al*.[11] show that, viscous-limit set of hydrodynamic dimensionless parameters is equivalent to Horio *et al*.[5], and simplified set of hydrodynamic dimensionless parameters is equivalent to Horio *et al*.[6]. Patience *et al*.[7] show that slip factor in fully development region of fast fluidization is a function of $\frac{U_g}{\sqrt{gD_r}}$ and $\frac{U_g}{U_t}$. In addition, Qi *et al*.[8] proposed that the apparent solids concentration and the radial distribution of local solid concentration show similariry as dimensionless parameter $\frac{G_s}{\rho_s U_g}\left(\frac{U_g}{\sqrt{gD_r}}\right)^{-0.6}$ remains unchanged in fully development region of fast fluidization.

TABLE I. DIMENSIONLESS PARAMETERS IN REFERENCES

Reference	Dimensionless parameters
Glicksman[2]	$G_s/(\rho_s U_g)$, d_s/D_r, $U_g^2/(gD_r)$, ρ_s/ρ_g, $\rho_g U_g d_s/\mu_g$, Φ, BG
Glicksman *et al*.[3]	$G_s/(\rho_s U_g)$, U_g/U_{mf}, $U_g^2/(gD_r)$, ρ_s/ρ_g, Φ, BG
Chang and Louge[10]	$G_s/(\rho_s U_g)$, $\Phi d_s/D_r$, $U_g^2/(gD_r)$, ρ_s/ρ_g, $\rho_g U_g \Phi d_s/\mu_g$, BG
Horio *et al*.[5]	$(U_g-U_{mf})^2/(gD_r)$, $U_{mf}^2/(gD_r)$, Φ, BG
Glicksman[4]	U_g/U_{mf}, $U_g^2/(gD_r)$, Φ, BG
Horio *et al*.[6]	$G_s/(\rho_s U_g)$, U_g/U_t, $U_g^2/(gD_r)$, ρ_s/ρ_g, Φ, BG
Patience *et al*.[7]	U_g/U_t, $U_g^2/(gD_r)$
Qi *et al*.[8]	$U_g^{-0.6}(gD_r)^{0.3}G_s/(\rho_s U_g)$

As discussed above, literature mainly investigated hydrodynamic similarity of bubbling fluidization and fast fluidization, while lack of analysis of hydrodynamic dimensionless parameters of dense suspension upflow.

On the other hand, according to van der Meer *et al*.[12] and Liu *et al*.[13], there are eight independent parameters without considerration of stresses of solids phase:

$$\rho_s, \rho_g, U_s, U_g, D_r, d_s, \mu_g, g \quad (2)$$

which has three demensions as time (T), length (L) and mass (M). According to Buckingham π theory，it should be five qualitative dimensionless parameters. As a dependent variable, solids concentration can be expressed as a function of this dimensionless parameters. Dimensions of eight independent parameters are $\frac{\mathrm{M}}{\mathrm{L}^3}, \frac{\mathrm{M}}{\mathrm{L}^3}, \frac{\mathrm{L}}{\mathrm{T}}, \frac{\mathrm{L}}{\mathrm{T}}, \mathrm{L}, \mathrm{L}, \frac{\mathrm{M}}{\mathrm{LT}}, \frac{\mathrm{L}}{\mathrm{T}^2}$. There are three independent parameters which are in same demension, results in three qualitative dimensionless parameters $\frac{\rho_s}{\rho_g}, \frac{U_s}{U_g}, \frac{D_r}{d_s}$. Another two qualitative dimensionless parameters can be obtained by means of undetermined coefficients. According to demension equation as below:

$$\mathrm{M}^0\mathrm{L}^0\mathrm{T}^0 = \left(\frac{\mathrm{L}}{\mathrm{T}}\right)^a \left(\frac{\mathrm{M}}{\mathrm{L}^3}\right)^b (\mathrm{L})^c \left(\frac{\mathrm{M}}{\mathrm{LT}}\right)^d \left(\frac{\mathrm{L}}{\mathrm{T}^2}\right)^e \quad (3)$$

make three demensions all equal to zero, we can obtain:

$$\begin{cases} c = \frac{3b - a}{2} \\ d = -b \\ e = \frac{b - a}{2} \end{cases} \quad (4)$$

by rearranging (3) and (4), two qualitative dimensionless parameters can be expressed as:

$$\mathrm{M}^0\mathrm{L}^0\mathrm{T}^0 = \left(\frac{\frac{\mathrm{L}}{\mathrm{T}}}{\sqrt{\frac{\mathrm{L}}{\mathrm{T}^2}\mathrm{L}}}\right)^{a-b} \left(\frac{\frac{\mathrm{M}}{\mathrm{L}^3}\frac{\mathrm{L}}{\mathrm{T}}\mathrm{L}}{\frac{\mathrm{M}}{\mathrm{LT}}}\right)^b \quad (5)$$

which are forms of Froude number and Renolds number. Archimedes number can be obtained by combinations of Froude number, Renolds number and density ratio of solids and gas, as:

$$\varepsilon = f\left[\frac{\rho_g U_g d_s}{\mu_g}, \frac{G_s}{\rho_s U_g}, \frac{D_r}{d_s}, \frac{U_g^2}{gD_r}, \frac{(\rho_s - \rho_g)\rho_g g d_s^3}{\mu_g^2}\right] \quad (6)$$

In addition, hydrodynamiv similarity should be based on similarity of bed geometry (BG). So hydrodynamic similarity may be achieved by making dimensionless parameters equivalent in value:

$$\frac{\rho_g U_g d_s}{\mu_g}, \frac{G_s}{\rho_s U_g}, \frac{D_r}{d_s}, \frac{U_g^2}{gD_r}, \frac{(\rho_s - \rho_g)\rho_g g d_s^3}{\mu_g^2}, \phi_s, \mathrm{BG} \quad (7)$$

To achieve hydrodynamic similarity of gas solids flow in risers, it should also ensure that the initial and boundary conditions of momentum equations are in similar.

Achieving hydrodynamic similarity completely is very difficult in practice, and even impossible under many circumstances. In applications, it is more concerned with characteristics of gas solids flow in fully development region, for which similarity of bed geometry just require same cross-sectional shape (CSS). In addition, it is difficult to ensure the scale model and actual device has same diameter ratio (D_r/d_s). This is because under many circumstances it is difficult to obtain particles which meet the diameter ratio with riser columns. On the other hand, if holding the same diameter ratio D_r/d_s, it is likely to cause changes in fludization characteristics of particles (such as requiring Geldart B particles in actual device, whereas Geldart A particles using in scale model)[14, 15]. To overcome these difficulties, researchers generally use a simplified form of hydrodynamic dimensionless parameters, with ignoring diameter ratio D_r/d_s and using U_g/U_{mf} or U_g/U_t or replace Archimedes number or Renolds number. In addition, it may result in different flow regimes between actual device and scale model by keeping the same Froude number (such as gas solids flow correspond to fast fluidization in actual device, while under turbulent fluidization in scale model).

According to Qi *et al*.[8], apparent solids concentration and the radial distribution of local solid concentration show

DOI 10.5013/IJSSST.a.17.38.07

ISSN: 1473-804x online, 1473-8031 print

similariry as dimensionless parameter $\frac{G_s}{\rho_s U_g}\left(\frac{U_g}{\sqrt{gD_r}}\right)^{-0.6}$ remains unchanged in fully development region of fast fluidization. Patience and Bockrath[16, 17] show that $\frac{G_s}{\rho_s U_g}\left(\frac{U_g}{\sqrt{gD_r}}\right)^{-0.5}$ is a critical parameter in determining apparent solids concerntration under high solids ciuculation rate conditions. The experimental results of Yan and Zhu[18] and Knowlton *et al*.[14] show that, for oprating conditions of which superficial gas velocity is greater than 4.0 m/s and solids circulation rate is greater than 50 kg/(m^2·s), small diameter risers do not exhibit wall effect due to the shear stress resulting in increases of solids concentration, while largeer diameter risers have greater solids concentration since the radial diatributions of gas velocity are more nonuniform. It is reasoned that some dimensionless parameter combinated by superficial velocity ratio of gas and solids $V = \frac{U_s}{U_g}$ with Froude number can be a hydrodynamic similarity parameter for dense suspension upflow.

As discussed above, hydrodynamic similarity of dense suspension upflow may be determined by dimensionless parameters as:

$$\mathrm{Ar}, V \cdot \mathrm{Fr}^{f}, \phi_s \tag{9}$$

Wherein, f is a coefficient obtained from experiments.

III. RESULTS AND DISCUSSION

A. Experimental method

Riser of experimental apparatus is 0.1 m in diameter and 18.0 m in height. Sand particles are used as experimental material, and particle properties are as shown in Table II, which are Geldart B particles. Apparent solids concentration was calculated by pressure drop measurement, while an optic fiber probe was used to measure local solids velocity. Details of experimental apparatus and experimental procedure are discribed in [19].

TABLE II. PARTICLE PROPERTIES

	ρ_s, kg/m^3	**d_s, mm**	**ρ_b, kg/m^3**
Sand I	3092	0.106	1740
Sand II	2584	0.190	1557
Sand III	2620	0.154	1588

B. Axial profile of apparent solids concerntration

Axial profiles of apparent solids concentration of Sand I and Sand II are plotted in Fig. 1 and Fig. 2 respectively. Superficial gas velocity and solids circulation rate under corresponding operating conditions of Sand I and Sand II are all different, but when dimensionless parameter V·Fr$^{-1.0}$ meet similar values, axial profiles of apparent solids concentration (i.e. dimensionless pressure drop) are consistent with each other, which means gas solids flow achieve hydrodynamic similarity.

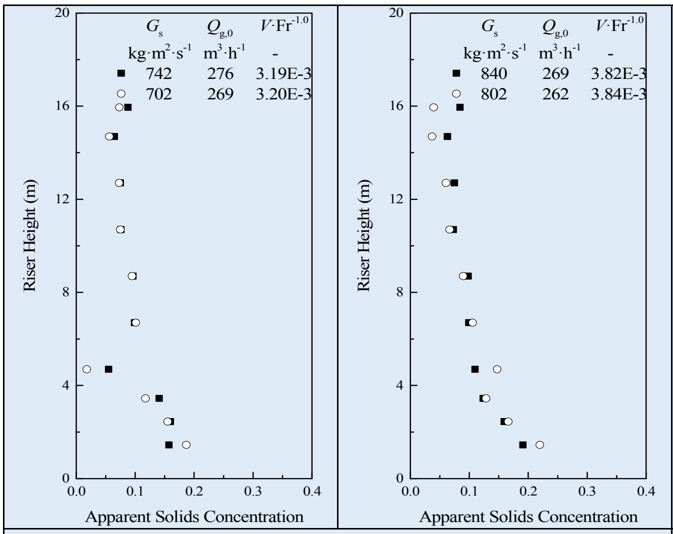

Figure 1. Axial profile of apparent solids concerntration of Sand I

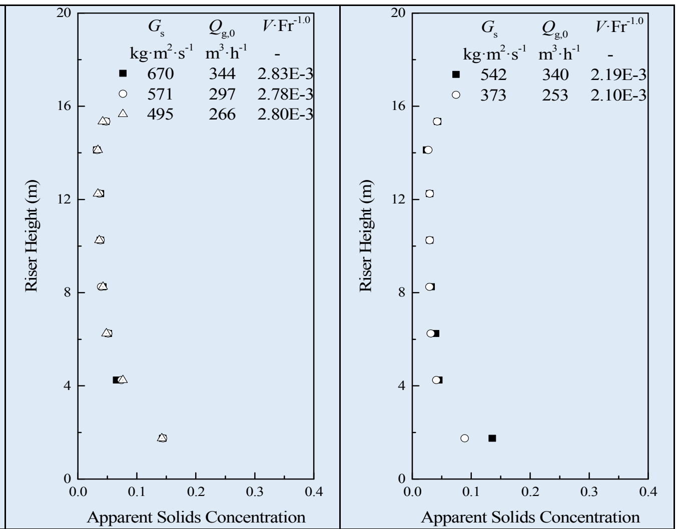

Figure 2. Axial profile of apparent solids concerntration of Sand II

Table III lists two oprating conditions of Sand I and Sand III under different temperature and pressure, wherein dimensionless particle diameter d_s^* is equivalent to 1/3 power of Archimedes number.

Fig. 3 shows axial profiles of apparent solids concentration of Sand I and Sand III under above operating conditions. As seen in Fig.3, although properties of gas and solids, superficial gas velocity and solids circulation rate varies for two oprating conditions of Sand I and Sand III, they have similar values of dimensionless particle diameter and V·Fr$^{-1.0}$. Axial profiles of apparent solids concentration (i.e. dimensionless pressure drop) are also consistent with each other, which means gas solids flow achieve hydrodynamic similarity.

TABLE III. OPERATING CONDITIONS UNDER DIFFERENT TEMPERATURE AND PRESSURE

	T_r, K	P_r, MPa	d_s, mm	ρ_s, kg/m^3	G_s, kg/(m^2·s)	d_s^*	V	Fr
Sand I	300	0.03	0.105	3092	519	5.37	0.016	10.67
Sand III	600	0.15	0.154	2620	450	5.31	0.016	10.66

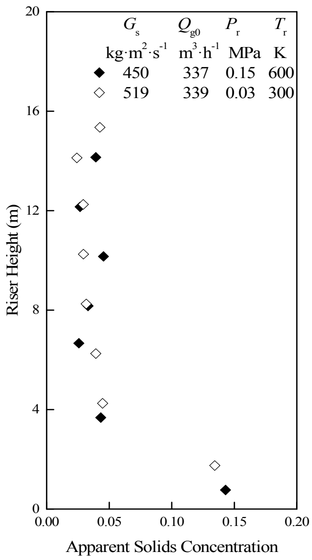

Figure 3. Axial profile of apparent solids concerntration of different particles under different temperature and pressure.

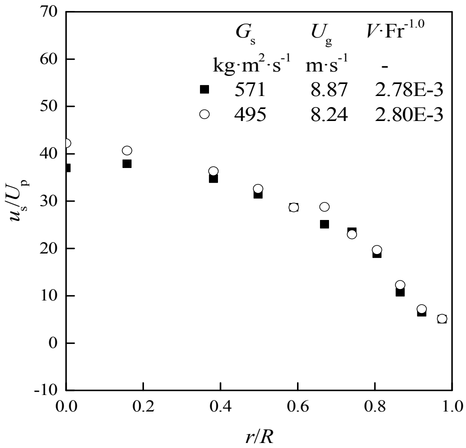

Figure 4. Radial profile of dimensionless solids velocity of Sand II.

C. Raidial profile of dimensionless solids velocity

Local solids velocity can be dimensionlessed by superficial solids velocity. Fig. 4 shows radial profiles of dimensionless solids of Sand II in fully development region. While superficial gas velocity and solids circulation rate are different, values of dimensionless parameter $V{\cdot}\mathrm{Fr}^{-1.0}$ are similar under two oprating conditions. Raidial profile of dimensionless solids velocity express similar form, suggesting gas solids flow achieve hydrodynamic similarity.

IV. CONCLUSION

Pressurized dense transport bed is a new coal gasification technology under development. It is necessary to carry out study of hydrodynamic similarity of the gas solids flow to provide basis and reference for reactor design and scale-up. Literature research on hydrodynamic similarity have been mostly directed to bubbling fluidization and fast fluidization, while gas solids flow in dense transport bed riser correspond to dense suspension upflow, which has significant differences from fast fluidization in characteristics of distribution of solids concentration and solids velocity.

Based on Buckingham π theory and emperical correlations in literatures, we obtained hydrodynamic dimensionless parameters applied for dense suspension upflow. Experimental results show that, when dimensionless particle diameter and dimensionless parameter $V{\cdot}\mathrm{Fr}^{-1.0}$ are in same or similar values, axial profile of apparent solids concerntration and raidial profile of dimensionless solids velocity of different particles show consistent with each other, which suggest gas solids flow achieve hydrodynamic similarity.

ACKNOWLEDGEMENT

Supported by Strategic Priority Research Program of Chinese Academy of Sciences (XDA07050500).

REFERENCES

[1] Bi, X.T. and X. Liu, High density and high solids flux CFB risers for steam gasification of solids fuels. Fuel Processing Technology, 2010. 91(8): p. 915-920.

[2] Glicksman, L.R., Scaling relationships for fluidized beds. Chemical Engineering Science, 1984. 39(9): p. 1373-1379.

[3] Glicksman, L.R., M. Hyre and K. Woloshun, Simplified scaling relationships for fluidized beds. Powder Technology, 1993. 77(2): p. 177-199.

[4] Glicksman, L.R., Scaling relationships for fluidized beds. Chemical engineering Science, 1988. 43(6): p. 1419-1421.

[5] Horio, M., A. Nonaka, Y. Sawa, and I. Muchi, A New Similarity Rule for Fluidized-Bed Scale-up. AIChE Journal, 1986. 32(9): p. 1466-1482.

[6] Horio, M., H. Ishii, Y. Kobukai, and N. Yamanishi, A Scaling Law for Circulating Fluidized Beds. Journal of Chemical Engineering of Japan,

1989. 22(6): p. 587-592.

[7] Patience, G.S., J. Chaouki, F. Berruti, and R. Wong, Scaling considerations for circulating fluidized bed risers. Powder Technology, 1992. 72: p. 31-37.

[8] Qi, X., J. Zhu and W. Huang, Hydrodynamic similarity in circulating fluidized bed risers. Chemical Engineering Science, 2008. 63(23): p. 5613-5625.

[9] Grace, J.R., A.S. Issangya, D. Bai, H. Bi, and J. Zhu, Situating the high-density circulating fluidized bed. AIChE Journal, 1999. 45(10): p. 2108-2116.

[10] Chang, H. and M. Louge, Fluid dynamic similarity of circulating fluidized beds. Powder Technology, 1992. 70: p. 259-270.

[11] Glicksman, L.R., M.R. Hyre and P.A. Farrell, Dynamic similarity in fluidization. International Journal of Multiphase Flow, 1994. 20(Supplement 1): p. 331-386.

[12] van der Meer, E.H., R.B. Thorpe and J.F. Davidson, Dimensionless groups for practicable similarity of circulating fluidised beds. Chemical Engineering Science, 1999. 54(22): p. 5369-5376.

[13] Liu, H., B. Chen and C. Li, Identification of hydrodynamic similarity in risers of circulating fluidized beds. Chemical Engineering Science, 2000. 55: p. 2741-2744.

[14] Knowlton, T.M., S.B.R. Karri and A. Issangya, Scale-up of fluidized-bed hydrodynamics. Powder Technology, 2005. 150(2): p. 72-77.

[15] Knowlton, T.M., Simulating hydrodynamics of hot and large Group A particle systems at cold conditions to obtain data for scale-up. Particuology, 2010. 8: p. 501-502.

[16] Patience, G.S. and R.E. Bockrath, Drift flux modelling of CFB risers. The Canadian Journal of Chemical Engineering, 2008. 86(3): p. 458-469.

[17] Patience, G.S. and R.E. Bockrath, Drift flux modelling of entrained gas–solids suspensions. Powder Technology, 2009. 190: p. 415-425.

[18] Yan, A. and J.J. Zhu, Scale-Up Effect of Riser Reactors (1): Axial and Radial Solids Concentration Distribution and Flow Development. Industrial & Engineering Chemistry Research, 2004. 43(18): p. 5810-5819.

[19] Xiao, Y., S. Wang, S. Yang, K. Zhao, X. Zeng, and X. Xu, Solids acceleration length in a cold dense transport bed. Journal of Thermal Science, 2012. 21(6): p. 533-538.