Refereed Proceedings

The 12th International Conference on Fluidization - New Horizons in Fluidization Engineering

Engineering Conferences International *Year* 2007

Friction Between Gas-Solid Suspension and Circulating Fluidized Bed Downers

Xiaobo Qi[*] Hui Zhang[†]
Jesse Zhu[‡]

[*] University of Western Ontario, qi1011@hotmail.com
[†] The University of Western Ontario, hzhang1@uwo.ca
[‡] University of Western Ontario, zhu@uwo.ca

FRICTION BETWEEN GAS-SOLID SUSPENSION AND CIRCULATING FLUIDIZED BED DOWNERS

Xiao-Bo Qi, Hui Zhang, Jesse Zhu#
Department of Chemical and Biochemical Engineering,
The University of Western Ontario, London, Ontario, Canada, N6A 5B9
#Tel: 1-519-661-3807; Fax: 1-519-850-2441; Email: jzhu@uwo.ca

ABSTRACT

Friction between co-current downflow gas-solid suspension and the column wall was investigated. A new model to predict pressure drops due to friction between the gas-solid suspension in the fully developed section and the downer wall was developed. The results show that the friction between the gas-solids suspension and the downer wall causes a significant deviation of the apparent solids concentrations from the actual ones, especially for those operating conditions with higher superficial gas velocities and solids circulation rates. When the superficial gas velocity is greater than 8 m/s, the actual solids concentrations in the fully developed region of the downer can be up to 2~3 times of the apparent values. After the frictional pressure drop is considered, the predicted actual solids concentrations by the proposed model agree well with the experimental values.

INTRODUCTION

Differential pressure measurements have usually been used to estimate axial profiles of cross-sectional average solids concentrations in circulating fluidized bed (CFB) risers/downers, assuming that the pressure drops due to gas-solids suspension to wall friction and particle acceleration are negligible. This method has been accepted by many researchers, since it is non-intrusive, inexpensive and simple. However, many experimental results showed that the contributions of friction and acceleration to the total pressure drop can not be neglected under certain operating conditions (1-5). Comparing the actual solids concentration directly measured by a series of quick-closing valves with the apparent values inferred from pressure gradient, Arena et al (1) found that even in the fully developed zone of the riser, the friction between gas-solid suspension and the riser wall can still lead to significant deviation between the apparent and actual solids concentrations. Van Swaaij et al (2) found the frictional pressure drop to be 20~40% of the total pressure drop in dilute flows. Wirth et al (3) found the deviation of the apparent solids concentrations from the actual ones to be about 20%. Hartge et al (4) found good agreement between the apparent solids concentrations and the actual values, but particle-wall friction is significant at high gas velocities. Under high-density operating conditions, the maximum contribution of friction pressure loss to the total pressure drop was less than 20% (5).

Numerous particle-wall friction factor correlations are available in the literature for predicting pressure drops in dilute phase vertical upward gas-solid flow (6-14). Most of them mainly concentrated with dilute phase vertical upward pneumatic conveying in relatively small pipes. However, up to now few work has been conducted to investigate the friction between co-current downflow gas-solid suspension and CFB downer wall. Due to a significant distinction between CFB risers and downers (15) and the fact that all the correlations are merely empirical regression of experimental data, the correlations obtained in the CFB risers cannot be safely extrapolated outside the range of the experimental data.

In this study, systematic experimental tests on the deviation of the apparent solids concentrations from the actual ones in a long downer were carried out to characterize the friction between the gas-solid suspension and the downer wall. At the meantime, a new model that predicts the pressure drops due to friction has been developed for the fully developed region of the downer. Experimental data from the literature are also used to validate the model.

GAS-SOLID SUSPENSION TO WALL FRICITION MODEL

Apparent and Actual Solids Concentration

For a steady co-current downward gas-solid two-phase flow and on the basis of the momentum equation, the pressure drop is expressed as follows:

$$-\left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_{total} = \frac{\mathrm{d}}{\mathrm{d}z}[\rho_{\mathrm{g}}\overline{(1-\varepsilon_{\mathrm{s}})V_{\mathrm{g}}^2} + \rho_{\mathrm{p}}\overline{\varepsilon_{\mathrm{s}}V_{\mathrm{p}}^2}] + [\rho_{\mathrm{g}}(1-\bar{\varepsilon}_{\mathrm{s}}) + \rho_{\mathrm{p}}\bar{\varepsilon}_{\mathrm{s}}]g - \left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_{\mathrm{f}} \tag{1}$$

When the gas-solid flow reaches fully developed state, the acceleration term

$$\frac{\mathrm{d}}{\mathrm{d}z}[\rho_{\mathrm{g}}\overline{(1-\varepsilon_{\mathrm{s}})V_{\mathrm{g}}^2} + \rho_{\mathrm{p}}\overline{\varepsilon_{\mathrm{s}}V_{\mathrm{p}}^2}] \tag{2}$$

should be zero. So, the total pressure drop in the fully developed zone consists of only two parts: the static head of the gas-solid suspension and the pressure loss due to the friction between the gas-solid suspension and the downer wall.

If taking the friction pressure loss into account, the actual solids concentration, $\bar{\varepsilon}_{\mathrm{s\,act}}$, can be evaluated by

$$\bar{\varepsilon}_{\mathrm{s\,act}} = \frac{1}{(\rho_{\mathrm{p}}-\rho_{\mathrm{g}})g}\left[-\left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_{total} - \rho_{\mathrm{g}}g + \left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_{\mathrm{f}}\right] \tag{3}$$

However, if the frictional pressure loss is neglected, one obtains the apparent solids concentration, $\bar{\varepsilon}_{\mathrm{s\,app}}$, by inferring from the measured total pressure gradient.

$$\bar{\varepsilon}_{\mathrm{s\,app}} = \frac{1}{(\rho_{\mathrm{p}}-\rho_{\mathrm{g}})g}\left(-\left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_{total} - \rho_{\mathrm{g}}g\right) \tag{4}$$

Comparing Eq (3) with Eq (4), it can be noted that for co-current downward gas-solid flow, the actual solids concentration must be underestimated by the apparent one, since the friction stress exerted on the downer internal wall is contrary to the direction of the gas-solid flow.

Pressure Drop due to Friction between Gas-solid and Bed Wall

Different form the common approach to separately evaluate the gas-wall and particle-wall frictional pressure drops, this study treats the gas-solid two-phase flow in CFB downer as a one-dimensional pseudo-homogeneous flow, due to the experimental fact that existence of particles has significant influences on the gas flow field of gas-solid flow. As with most investigators, , in this study, the Fanning friction equation for single fluid flow in a pipe was used to define a combined friction factor between gas-solid suspension and CFB downer wall, f_{g+s}, as

$$\left(\frac{\Delta P}{\Delta z}\right)_{\mathrm{f}} = \frac{2 f_{\mathrm{g+s}}\,\rho_{\mathrm{m}}\,u_{\mathrm{m}}^{2}}{D} \tag{5}$$

where ρ_m and u_m are the cross-sectional average gas-solid suspension density and its velocity, respectively. The cross-sectional average gas-solid suspension density ρ_m is known as:

$$\rho_{\mathrm{m}} = \rho_{\mathrm{g}}\left(1-\bar{\varepsilon}_{\mathrm{s}}\right) + \rho_{\mathrm{p}}\bar{\varepsilon}_{\mathrm{s}} = \rho_{\mathrm{g}} + (\rho_{\mathrm{p}}-\rho_{\mathrm{g}})\bar{\varepsilon}_{\mathrm{s}} \tag{6}$$

whereas the suspension velocity u_m can be defined differently depending on different purposes. a definition of u_m according to mass conservation is proposed in this study, that is

$$u_{\mathrm{m}} = \frac{G_{\mathrm{m}}}{\rho_{\mathrm{m}}} = \frac{(1-\bar{\varepsilon}_{\mathrm{s}})\rho_{\mathrm{g}}U_{\mathrm{g}} + G_{\mathrm{s}}}{\rho_{\mathrm{g}} + (\rho_{\mathrm{p}}-\rho_{\mathrm{g}})\bar{\varepsilon}_{\mathrm{s}}} \tag{7}$$

The friction factor, f_{g+s}, can also be defined following the Blasius correlation as

$$f_{\mathrm{g+s}} = 0.079 / Re_{\mathrm{m}}^{0.25} \tag{8}$$

where

$$Re_{\mathrm{m}} = \frac{D\rho_{\mathrm{m}}u_{\mathrm{m}}}{\mu_{\mathrm{g}}} = \frac{D\,((1-\bar{\varepsilon}_{\mathrm{s}})\rho_{\mathrm{g}}U_{\mathrm{g}} + G_{\mathrm{s}})}{\mu_{\mathrm{g}}} \tag{9}$$

Substituting Eqs (6) and (7) into Eq (5), one can obtain the frictional pressure drop between the gas-solid suspension and column wall in the fully developed zone of downers

$$\left(\frac{\Delta P}{\Delta z}\right)_{\mathrm{f}} = \frac{0.1582\,\mu_{\mathrm{g}}^{0.25}\left((1-\bar{\varepsilon}_{\mathrm{s}})\rho_{\mathrm{g}}U_{\mathrm{g}} + G_{s}\right)^{1.75}}{D^{1.25}\left(\rho_{\mathrm{g}} + (\rho_{\mathrm{p}}-\rho_{\mathrm{g}})\,\bar{\varepsilon}_{\mathrm{s}}\right)} \tag{10}$$

Obviously, if there is no particle in the downer (G_s=0), Eq (10) reduces to the Fanning equation for predicting friction pressure drop in a pipe with gas alone.

Consequently, combining Eqs (3) and (10), one can predict the actual solids concentration in the fully developed zone of CFB downers based on the measured axial total pressure gradient, with given downer diameter, gas and solids properties and operating conditions.

EXPERIMENTAL APPARATUS

The experiments were carried out in a cold model CFB downer. The experimental setup is illustrated schematically in Figure 1. The acrylic downer is 9.3 m long and 100 mm i.d. In order to minimize the electrostatics found in the downer column, a small stream of steam was introduced into the main air pipeline to humidify the de-oiled fluidization air to a relative humidity of 70-80%. This has been shown to be very effective.

The fluidization air supplied by a blower is at 20 °C. An orifice plate was employed to measure the superficial gas velocities. The particulate materials were spent FCC (Sauter mean diameter d_p=67 μm,

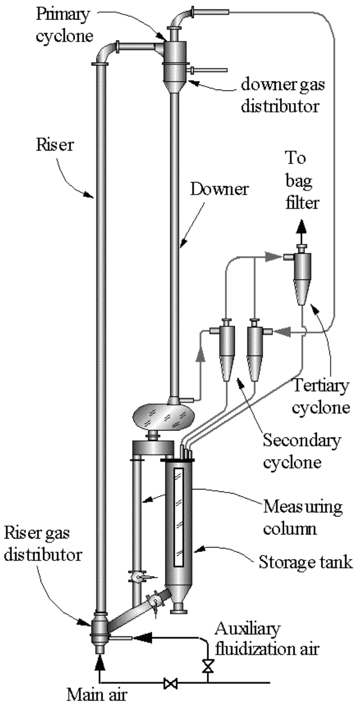


Figure 1. Schematic diagrams of CFB downer setup

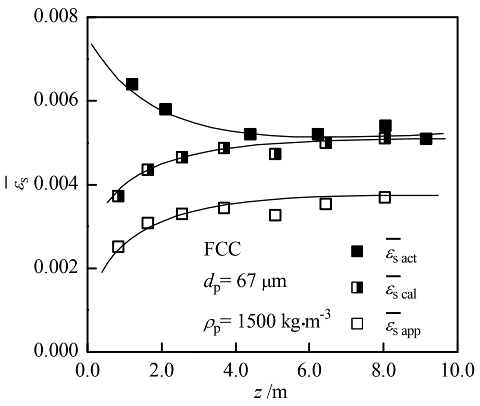
particle density ρ_p=1500 kg/m^3) particles. Solids circulation rates were regulated by a butterfly valve and were measured by a measuring pipe (16).

A series of differential pressure transducers were utilized to measure pressure drops along the downer column. Apparent solids holdups were inferred from the measured pressure gradients. A multi-fiber optical probe was chosen to measure the actual solids concentration in the CFB downer. The precise calibration procedure of the solids concentration probe and other details of the probe can be found in Zhang et al (17). Actual solids concentrations were obtained by integrating the local values at different radial positions.

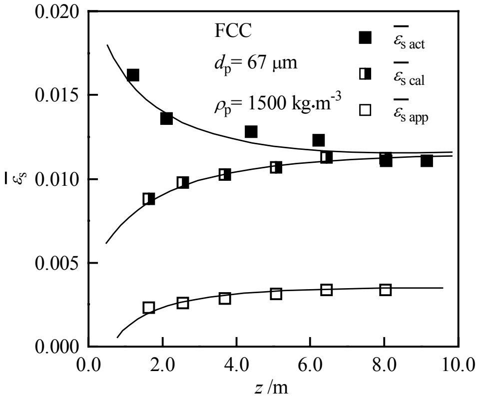
RESULTS AND DISCUSSION

Pressure Drop due to Friction

Figure 2 compares the cross-sectionally averaged apparent solids concentrations measured by the fiber optical probe with the apparent ones in the downer under typical operating conditions. From Figure 2, one can find that the apparent solids concentrations in the downer are far lower than the actual ones not only in the acceleration zone but also in the fully developed region. In the acceleration zone of the downer, the closer to gas distributor, the greater the deviation. This could be explained as: since the acceleration direction of gas-solid suspension is the same as gravity, the particles in the acceleration zone of the downer are not fully suspended by the gas and therefore the measured pressure gradient in the acceleration zone is only a small part of the static head of the gas-solid suspension. Consequently, the measured pressure gradient in the acceleration zone of the downer can not be totally used to estimate the actual solids concentration. Moreover, as shown in Figure 2(b), even in the fully developed zone of the downer, the actual solids concentrations are still more than twice of the apparent values. When the differential pressure measurements method is utilized to estimate the solids concentration in the downer, neglecting the frictional pressure loss in the downer would lead to substantial deviation of the actual solids concentration from the apparent value since the deviation in the fully developed zone of the downer mainly comes from the friction between the gas-solid suspension and the downer wall This is in line with the deduction of Zhu et al (18). That is, it should be very careful to use the differential pressure measurements to estimate the actual solids concentration in a dilute downer given the lower pressure gradient and the relatively high suspension-to-wall friction in the downer.



(a) U_g=3.7 m/s, G_s=49 kg/m^2·s



(b) U_g=10.2 m/s, G_s=205 kg/m^2·s

Figure 2. A comparison of apparent, actual and predicted solids holdups in the downer

To further investigate the effects of the solids concentrations on the friction, Figure 3 compares the apparent solids concentrations and the actual values in the fully developed zone of a high-density downer under different superficial gas velocities (data from Liu et al (19)). When U_g=5.44m/s, the actual solids concentrations can be up to 3 times of the apparent values, indicating that the friction pressure loss is a more important part of the pressure balance in the high-density downer than that in the low-density downer. Extensively examining Figure 3, one can find that, for a given superficial gas velocity, the absolute deviation of the actual solids concentration from the apparent ones increases linearly with the solids concentration in the downer. This suggests that the friction between the gas-solid suspension and downer wall is not only a function of the particle velocity but also the solids concentration. As such, most correlations in the literatures are less accurate since they are only a function of solids velocity.

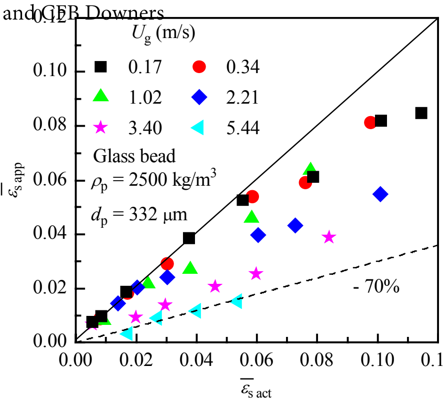


Figure 3. A comparison of apparent and actual solids holdups in the fully developed zone of a high-density downer (data from Liu et al (19))

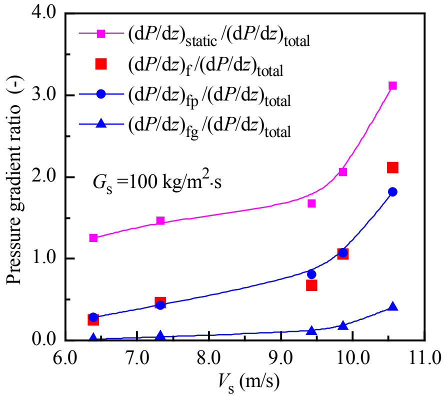


Figure 4. Variation of pressure drop ratios with actual solids velocity in the downer

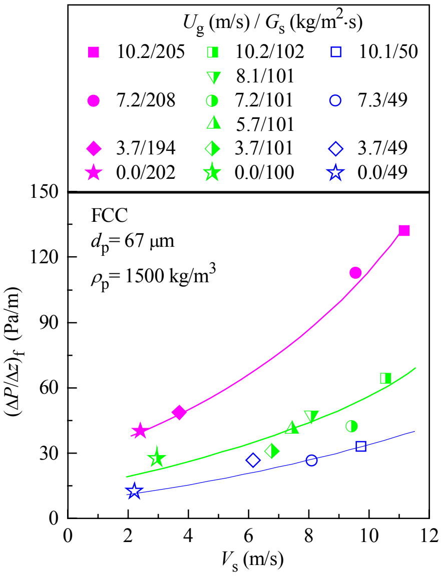


Figure 5. Effects of operating conditions on the frictional pressure drop in the downer

To quantitatively examine the extent of the pressure drops coming from gas-wall and particle-wall friction, Figure 4 shows the relative contribution of the four pressure drops in the downer. Since the frictional pressure drop mainly changes with actual solids velocity, V_s, Figure 4 gives the variation of the four pressure drops with the actual solids velocities in the downer. The particle-wall frictional pressure losses are much greater than those due to gas-wall friction, consistent with the results of Rautiainen and Sarkomaa (14). Most frictional pressure drop comes from the particle-wall friction. Consequently, when high density operation is present in a downer, the particle-wall friction would lead to a more significant deviation of the apparent solids holdup from the actual value, as indicated by Figure 4. It's also seen from Figure 4 that the pressure drop due to particle-wall friction is relatively low and only slightly increases with the actual solids velocities for V_s< 10 m/s. When V_s is greater than 10 m/s, however the pressure drop increases sharply with V_s. Because the actual solids velocities under most operating conditions in lab and pilot gas-solid CFB systems are less than 10 m/s, the frictional pressure losses may be less significant. On the other hand, for the operating conditions under which the actual solids velocities are greater than 10 m/s, the deviation between the actual and apparent solids concentrations due to frictional pressure drop can be significant in industrial FCC riser reactors. Since the axial pressure gradients in the downer are lower than those in the riser (15), the frictional pressure drop in the downer is relatively higher than that in the riser. Therefore, a much more significant error may occur if the apparent solids concentrations inferred from the pressure gradient are used to design, scale up and operate downer reactors.

Effects of Operating Conditions

Figure 5 further shows the effects of operating conditions on the frictional pressure drop in the fully developed zone of the downer. Obviously, the operating conditions have significant influence on the frictional pressure drop. It is expected that when solids circulation rate remains constant, the frictional pressure drop increases with superficial gas velocity. At a given superficial gas velocity, the frictional pressure drops increase with solids circulation rates. And, with increasing superficial gas velocity, the effect of solids circulation rate on the friction pressure drop gradually becomes more significant. Thus, the effects of superficial gas velocities on the frictional pressure loss are different than that of solids circulation rates. But, for the same solids velocity, there would be many sets of superficial gas velocities and solids circulation rates. Consequently, it is not enough to correlate the solids friction factor with the only one parameter of solids velocity, and thus operating condition parameters (i. e. superficial gas velocity and solids circulation rate) should be included in the correlations of friction factor.

Figure 3 also compares the apparent solids concentrations with the actual solids concentrations in the fully developed section of the high-density downer under different superficial gas velocities. The operating conditions have great influences on the difference between the apparent and actual solids concentration. For the same actual solids concentration, the difference between the apparent and actual solids concentration increases with superficial gas velocity. And, with increasing solids concentration, the effect of superficial gas velocity on the difference between the apparent and actual solids concentration becomes more noticeable. At a given superficial gas velocity, the deviation linearly increases with the solids concentration. As a consequence, the frictional pressure loss is a function of both the solids velocity and the solids concentration.

Influences of Particle Properties

Figure 6 presents the effect of particle diameter on the frictional pressure drop in the fully developed section of the high-density downer. Under the same operating conditions in the downer, the frictional pressure loss with smaller particles is greater than that with coarser particles. This trend can also be inferred from the correlation of Klinzing and Mathur (13). However, this conclusion needs further verification with more experimental results.

Validation of the Model

Figure 2 also compares the measured actual solids concentration and the predicted values under typical operating conditions. As shown in Figure 2, after the frictional pressure drop is added to the tested total pressure drop, the predicted actual solids concentration in the fully developed zone of the downer fits well with the tested one integrated from the local solids holdups. In fact, this is generally the case for all experimental results obtained in this work. Figure 7 compares the predicted solids concentrations with the actual ones obtained in this work and the literature (19). Obviously, the measured actual solids concentrations agree well with the predicted values. Given the experiment of Liu et al (19) in a wide range of operating conditions, the excellent fit of the experimental data with the predicted value further shows the reliability of the new model.

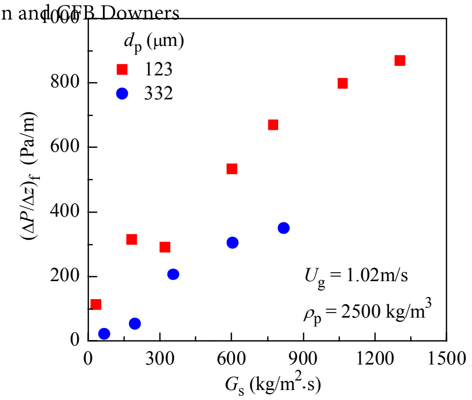


Figure 6. Effects of particle diameter on the friction pressure drops for glass bead (data from Liu et al, (19))

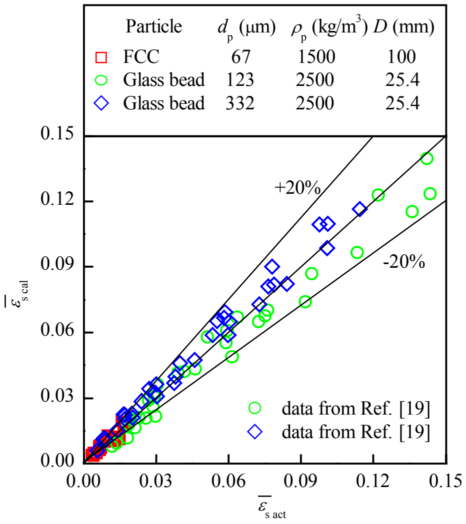


Figure 7. A comparison of tested actual solids holdup with predicted values in the fully developed section of the downers

CONCLUSIONS

The study on the friction between co-current downflow gas-solid suspension in the fully developed zone and the downer wall has led to a new model that can successfully predict the pressure drop due to friction between gas-solid suspension and the downer wall in the fully developed zone. By comparing the apparent solids concentration with the actual values, it is found that the friction between gas-solid suspension and the wall causes a significant deviation of the actual solids concentration from the apparent one so that it cannot be neglected under certain operating conditions, especially for the downward gas-solid flow with higher superficial gas velocities and/or solids circulation rates. For the downward gas-solid flow in the downers, the actual solids concentration can be up to 2~3 times of the apparent value under certain operating conditions. The friction pressure loss decreases with increasing particle diameter. The predicted actual solids concentrations by the proposed model agree well with the experimental values. In general, the friction between the gas-solid suspension and the downer wall is an important factor that must be taken into account in the modeling, design and operation of the CFB downer reactors.

ACKNOWLEDGMENT

The authors are grateful to the National Natural Science Foundation of China and the Natural Science and Engineering Research Council of Canada for financial support.

REFERENCES

[1]. Arena U., Cammarota A., and Pistone L., High Velocity Fluidization Behavior of Solids in a Laboratory Scale CFB, Circulating Fluidized Bed Technology, (ed. P. Basu), Pergamon Press, Toronto, 1986, pp.119-125.

[2]. van Swaaij W. P. M., Buurman C. and Van Breugel J. W., Shear Stresses on the Wall of a Dense-Solids Riser, Chem. Eng. Sci., 1970, 25, 1818-1820.

[3]. Wirth K. E., Seiter M. and Molerus Q., Concentration and Velocities of Solids in Areas Close to the Walls in Circulating Fluidized Bed Systems, Chem. Eng. and Technol., 1991, 14, 82828.

[4]. Hartge E. U., Li Y., and Werther J., Analysis of the Local Structure of the Two Phase Flow in a Fast Fluidized Bed, Circulating Fluidized Bed Technology, (ed. P. Basu), Pergamon, Toronto, 1986, pp.153-160.

[5]. Issangya A. S., 1998, Flow Dynamics in High Density Circulating Fluidized Beds, Ph.D. Thesis, University of British Columbia, Vancouver, Canada.

[6]. Reddy K.V.S. and Pei D.C.T., 1969, Particle Dynamics in Solids-Gas Flow in a Vertical Pipe, I & EC Fund., 8: 491-497.

[7]. Stemerding S., 1962, The pneumatic transport of cracking catalyst in vertical risers, Chem. Eng. Sci., 17(8): 599-608.

[8]. Konno H. and Satio S., 1969, Pneumatic Conveying of Solids through Straight Pipes, J. Chem. Eng. Jpn., 2(2): 211-217.

[9]. Yousfi Y. and Gau G., 1974, Aerodynamique de l'ecoulement vertical de suspensions concentrees gaz-solide—II. Chute de pression et vitesse relative gaz-solide, Chem. Eng. Sci., 29(9): 1947-1953.

[10]. Capes C.E. and Nakamura K., 1973, Vertical Pneumatic Conveying: A Theoretical Study of Uniform and Annular Particle Flow Models, Can. J. Chem. Eng., 5: 31-38.

[11]. Kemic A., Mielczarski S. and Pajakowsku J., 1978, An experimental study on hydrodynamics of a system in a pneumatic flash dryer, Powder Technol., 20(1): 67-74.

[12]. Yang W.C., 1978, A correlation for solid friction factor in vertical pneumatic conveying lines, AIChE J., 24(3): 548-552.

[13]. Klinzing G.E. and Mathur M., 1981, Can. J. Chem. Eng., 59: 590-594.

[14]. Rautiainen A. and Sarkomaa P., 1998, Solids friction factors in upward, lean gas-solids flows, Powder Technol., 95(1): 25-35.

[15]. Zhang H., Huang W. X. and Zhu J-X., 2001, Gas-solids flow behavior: CFB riser vs. downer. AIChE J., 47(9): 2000-2011.

[16]. Zhang H, Zhu J-X and Bergougnou MA., 1999, Hydrodynamics in Downflow Fluidized Beds (1): Solids Concentration Profiles and Pressure Gradient Distributions, Chem. Eng. Sci., 54(22), 5461-5470.

[17]. Zhang H, Johnston PJ, Zhu J-X, de Lasa HI and Bergougnou MA, 1998, A Novel Calibration Procedure for a Fiber Optic Concentration Probe, Powder Technol., 100(2-3), 260-272.

[18]. Zhu J-X, Yu Z-Q, Jin Y, Grace J R and Issangya A, 1995, Cocurrent Downflow Circulating Fluidized Bed (Downer) Reactors - A State of the Art Review, Can. J. Chem. Eng., 73(5), 662-677.

[19]. Liu W-D, Luo K-B, Zhu J-X and Beeckmans JM, 2001, Characterization of High Density Gas-Solids Downflow Fluidized Beds, Powder Technol., 115(1), 27-35.