EFFECT OF PARTICLE SIZE ON HYDRODYNAMICS OF AN INTERNALLY CIRCULATING FLUIDIZED BED WITH A DRAFT TUBE

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Abstract – The main objective of the present research is an experimental investigation of effect of particle size on hydrodynamics of an internally circulating fluidized bed (ICFB) with a draft tube. An ICFB (0.3 mx3.0 m) with a draft tube (0.1 mx0.6 m) is adopted to investigate the hydrodynamic characteristic of sand particles having wide range size distributions at cold bed test conditions. The particles with a moderately wide size distribution in the range of Geldart group B and Geldart group B-D nature are used in the experiments. U-tube manometer probes used to investigate the evolution of pressure drop across in the draft tube and the annular pressure drop. A complete pressure drop flow curves are established for wide range of static bed heights, draft tube gap height and gas superficial velocities. High speed camera was utilized to measure particle downward velocity in the annular moving bed region, which is useful to estimate solids recirculation rate in the ICFB. The pressure drop in ICFB's draft tube found increases with an increase with bed height and also increases with gap height between the draft tube bottom and air distributor. The pressure drop found sharply decreases with superficial gas velocity after the minimum spouting fluidization, and then a cross-over is observed in the pressure drop of annular bed compared to the draft tube. Solid Recirculation rate, Gs, slowly increases with the superficial velocity initially and then rapidly increases to larger values as the annular bed descents. Gs increases with bed height due to increased bed mass that causes the higher bed pressure drop. Geldart-B particles are having more pressure drop than the Geldart B-D particles due to the maximum possible packing and high frictional resistance of the fine particles for the gas flow. Gas bypassing fraction increases with increased gap height and decreases with increased bed height. Gas bypassing fraction increases with increased mean particle size.

INTRODUCTION

Compared with the conventional fluidized bed reactor, the ICFB has the advantages of less heat loss, higher solid holdup, longer residence time of particles and lower construction cost. It is widely applied in coal gasification (Y.J.Kim et al., 1997). Internally circulating bubbling fluidized bed (ICBFB) consists of two concentric cylinders of different diameters. The inner cylinder also called the draft tube operates as a bubbling fluidized bed combustor. Whilst between the inner and outer cylinder is the annulus zone that operates as aerated bed gasifier. The two regions are connected through two separate air distributors at the bottom. This configuration is compact and has relatively low heat loss from the reactor compared to the DFB since the draft tube is located inside the annulus. However, conventional circulating fluidized beds required very long column as a solids raiser and also a tall cyclone is required for an external circulation of solids. The internally circulating fluidized bed (ICFB), solves the problems of CFB and make possible high efficiency, low pollution combustion with wide range of fuels and also reduce the height of conventional CFB and its construction cost. This ICFB reactor has many advantages such as its compact size and act as heat sink because riser is located inside the vessel so annular section acts as a heat sink (Jin et al., 2010). ICFB used in our work was divided radially by a central draft tube into a reaction zone inside the draft tube and a heating zone in the annulus (Li et all., 2015). In the ICFB, the draft tube (or riser) was fixed directly to the distributor of the riser section. A draft tube is provided to divide the bed for internal circulation of solids in a single vessel (Kim et al., 2000). The use of a fluidized bed with a draft tube for internal circulation of solids, with separate aeration of the annulus region, may provide more flexible operation, due to which there are several advantages of using a draft tube in a conventional spouted bed (Ishikura, T.Nagashima., 2003). However, hydrodynamic conditions in the ICFB reactor strongly depend on the design parameters and reaction conditions. Stable and homogeneous circulation of solids was observed only over a narrow range of gas velocities and strongly depended on the design of the draft tube (Mleczko, L., & Marschall., 1997). In this paper solid circulation flow patterns studied with the effect of geometric on solids hold-up in annular and in the draft tube were studied.

BED MATERIAL

To study the effects of particle size on solid circulation and bed pressure drop profiles, two fractions of solids particles with a wide range of distribution have been used. The powder size was determined using laser diffraction particle analyzer (S3500 Microtrac). The particle sizes of fraction are 75-995 µm and 150-1600 µm as shown in the fig. 1.

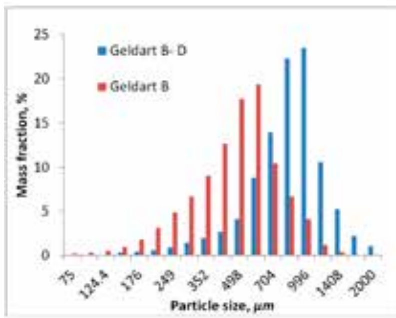


Fig. 1 Particle size distribution of silica particles.

EXPERIMENTAL SET-UP & PROCEDURE

In the schematic diagram of an internally circulating fluidized bed, a cylindrical draft tube was installed in the center position of an ICFB reactor. An experimental bed material properties mentioned in the table 1. Experiments were carried out in an ICFB rig of dimension (0.3 m X 3.0 m) with a draft tube of dimension (0.1 m X 0.9 m), gap height between draft tube bottom & above distributor is 0.07 m. The detailed description of the experimental rig shown in the Fig.2. A high end compressor was used to supply air as fluidizing gas. Initially air was directly supplied to the draft tube and no air supplied to the annular section. Flow meter is used to measure air flow rate and controlled by a gate valve. A pressure regulator was used to avoid pressure fluctuations in the air flow rate. Sudden closing and opening valves was used to for the cut down flow to the ICFB system(Gujjula.R & Mangadoddy.N, 2015). Superficial gas flow rates were measured by a turbine flow meter. Bed pressure drop was sampled with a U-tube manometer. Solids circulation rate was determine by using a high speed camera. Silica particles used as bed materials with range of diameter of 75 to 1600 µm. ICFB consist of an acrylic cylindrical pipe with an inside diameter of 300 mm with a conical acrylic air distributor at the bottom to supply air to annulus shown in the Fig. 3. Two U- tube manometers with water were used to measure the pressure difference within the draft tube and in the annular section shown in the Fig.2.

Table 1: Properties of particles

Item	Units	Values
Mean diameter of particles(d_p)	µm	75-925 & 450-1600
Bulk density of a particle (ρ_b)	kg/m^3	1275
Particle density (ρ_p)	kg/m^3	2500
Particle bulk voidage (ε)	-	0.44

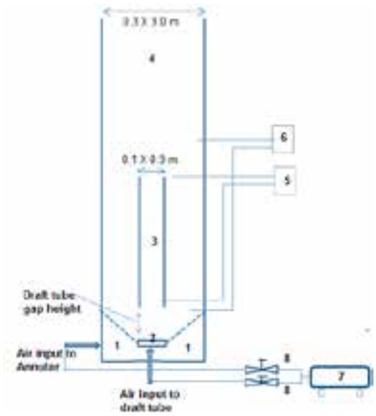


Fig 2. Schematic diagram of ICFB section. (1) annular air box (2) draft tube distributor (3) draft tube (4) ICFB (5) draft tube pressure measuring ports (6) annular bed pressure measuring ports (7) compressor (8) Air control value

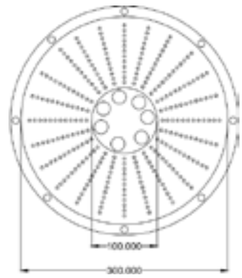


Fig. 3 Draft tube and annular distributor's dimensions in mm

A number of experiments were performed with various bed heights 40cm to 60cm. The effect of static bed height in three levels as shown in the Fig 4, the bed particle mean diameter in two levels, the gas superficial velocity in the range of 0-1.2 m/s (including 4 levels after minimum fluidization) and the draft tube gap height in two levels are varied for this ICFB in order to study the hydrodynamic behavior of gas-solid system.

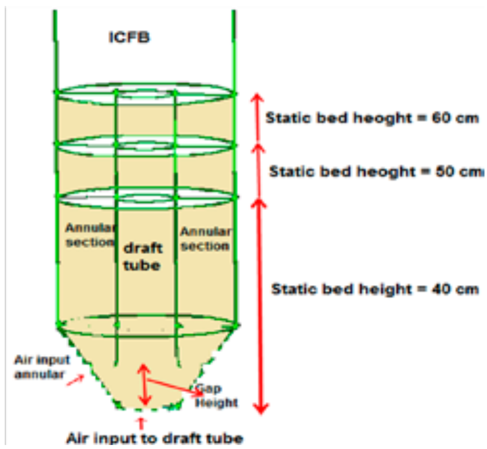
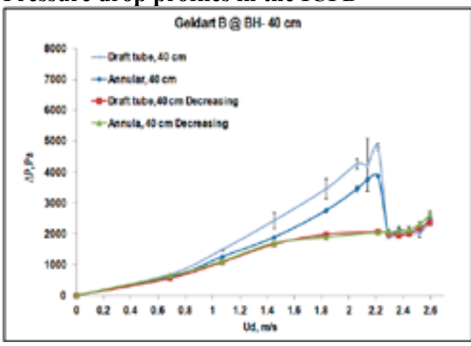
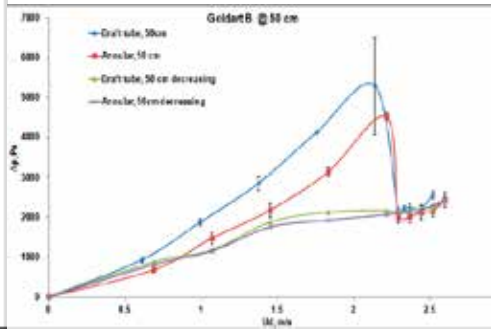


Fig. 4 ICFB experimental configuration schematic view

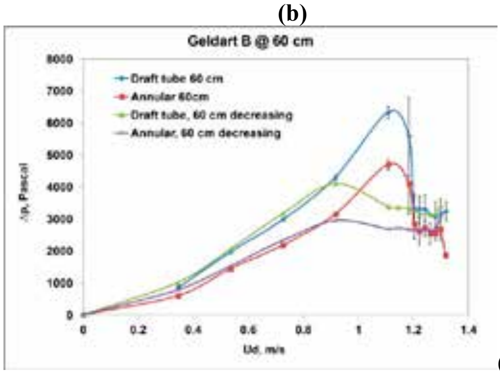
RESULTS & DISCUSSIONS

Pressure drop profiles in the ICFB





(a) (b)



(c)

Figure 5 Pressure drop v_s superficial flow curve for (a) Bed height 40 cm (b) Bed height 50 cm and (c) Bed height 60 cm beds consisting of Geldart group B particles.

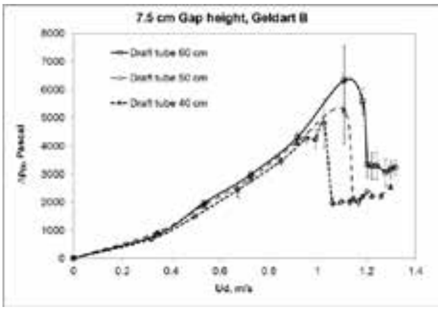
In every experimental run the measurement of bed pressure drop in the draft tube as well as in the annular section with superficial air velocity was carefully monitored from fixed bed to fluidizing bed conditions. Once the ΔP -Uo full curve is measured, the superficial velocity values are reversed to observe the hysteresis of the pressure drop. The same experiment is repeated thrice and the average data tabulated and also error bar are presented in the Fig. 5.

Typical bed pressure drop versus gas superficial velocity (U0) for Geldart B particles was shown in Fig. 5. (a) (b) & (c). It is observed that for a given initial bed height condition, the pressure drop increases with superficial velocity in both draft tube and annular bed similar to any packed bed condition. Then it reaches a maximum value near the minimum fluidized bed condition followed by sudden drop with superficial velocity. Unlike conventional CFB riser, in which the ΔP is fairly constant after the minimum fluidization, the draft tube's ΔP slightly increases with U0 after the minimum fluidization and remains constant at higher fluidization velocities.

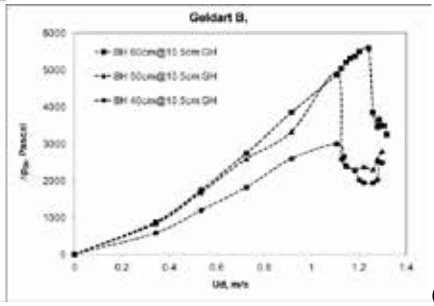
Similarly, in the annulus region, ΔP increases with U0 till the minimum fluidization condition prevails in the draft tube. Once the minimum fluidized bed condition is achieved, the fluidized bed solids blow out from the draft tube and a fountain is created above the draft tube, which then experience neutrally buoyancy condition and will fall into the annulus region. As the maximum portion of solids falls into the annular zone, the bed of solids start descend due to effect momentum induced by annulus air-inflow and gas-bypassing flow from the draft to annular region near the gap area of draft tube bottom section. This phenomenon may lead to sudden drop in ΔP across the annulus bed particles

Influence of the static bed height

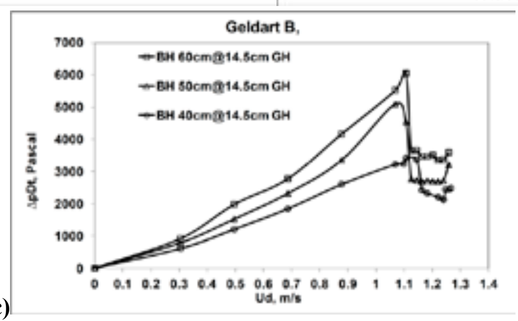
Pressure drop profiles for 40, 50 and 60 cm static bed heights consisting Geldart B particles ICFB in the draft tube and the annular bed region are shown in Fig. 6.(a)(b)(c). It is observed that as the static bed height increases the pressure drop across the draft tube and annular region increases due to its resultant increase in mass and bulk density of the bed. As the bed length increases, the bulk density and the effective mass loadings increases. The bed pressure drop increases with increasing bed height because more pressure forces is needed to fluidized more bed mass in the constant diameter bed, which is similar to Su et al., 2014 As reported in the general pressure flow curves in prior section, the maximum pressure fluctuations were found at peak pressure drop position, at which the minimum fluidization starts. This pressure drop certainly is influencing the solids recirculation rate in the annular bed zone.



(a)



(b)



(c)

Fig 6. Pressure profiles for 40, 50 and 60 cm bed heights consisting Geldart B particles ICFB in the (a) draft tube (b) gap height of 10.5 cm and draft tube pressure (c) gap height of 14.5 cm and draft tube pressure

Solid recirculation rate (SRR)

Solid recirculation rare (SRR) was quantified by using equation (1), in which silica particle velocity v_{SA} was determined by measurement of the averaged time for a particles moving downward through a fixed distance of 50 mm in the annular. This is measured with the help of high speed camera. Same procedure was adopted at different location along the circumference of annular section and was averaged out minimize errors. In the annular section volume fraction ε_s assumed to be equal to the dense bed volume fraction, annular region not fluidized in our current study.

$$G_s = v_{sA}(1-\varepsilon_s)\rho_s \quad (1)$$

Actually equation (1) is correct if the velocity of solid and volume fraction measured simultaneously, because the downward particle velocity in the annular section has a radial distribution of particles in the case of a conventional spouted bed without draft tube (He, Qin, Lim, & Grace, 1994; Olazar, San Jose, & Izquierdo, 2001). According to Hadzismajlovic et al. (1992) the particle velocity in the annuls section uniform except conical section at the bottom. It was assumed that the flow of solid particles in the annular section was treated as plug flow except in the conical section (Mukadi et al. 1999). Since the flow of solid particles in the annular section not fluidized in our experiments. So that SRR could be calculated approximately by using above equation (1).

From Fig. 7(a) & (b), an increasing trend in the solids circulation rate is observed for the gap height for ICFB. The increase in circulation rate is possibly due to an increased cross-sectional area and the availability of a higher pressure head across the gap area. Moreover, increased gap height will enhance gas bypassing through the clearance to the annular region, similar to Yang and Keairn's work [20]. This will lead to an increase in resistance across the clearance for the flow of solids. Possibly due to the bypassing of gas, the velocity of the gas in the draft tube will reduce, thereby increasing the concentration of solids in the draft tube and leading to increased pressure at the draft tubes gap edge position. Finally, the profile of solids circulation rate with gap height will depend on the pressure head available, the resistance across the clearance, the extent of gas bypassing through the gap, and the solid static bed height (the mass of the bed) which determines the pressure at the annular region near the draft tube gap. Further it is observed that the use of higher static bed height increases the pressure in the annular region near the gap height and thus reducing the bypassing of gas to the annular zone. That result an increase in solids circulation rate and use of higher superficial gas velocity increases the gas penetrating power making stable operation possible even at higher gap height.

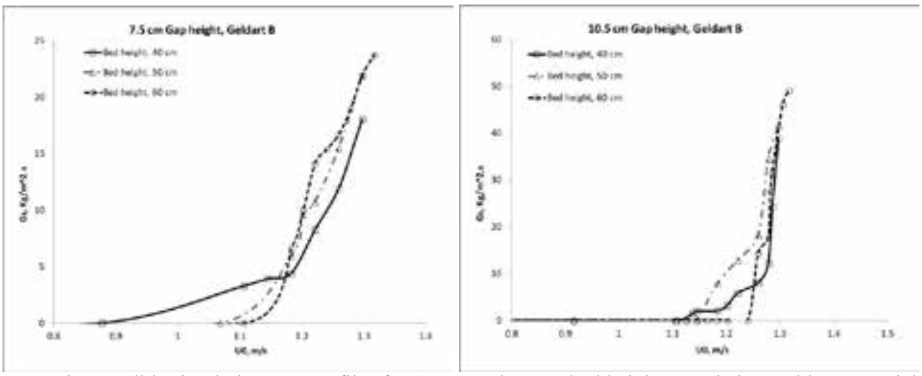


Fig 7. Solids circulation rate profiles for 40, 50 and 60 cm bed heights consisting Geldart B particles ICFB at different gap heights 7.5 cm and 10.5 cm

CONCLUSIONS

Hydrodynamics characteristics of internally circulating fluid bed (ICFB) with a draft tube were investigated in a cylindrical bed with 30 cm diameter at a cold bed condition. Sand particles with wide particle size distribution were used as bed materials. The pressure drop profile studies were made by both experiments and computational simulations at different initial static bed heights and two different particle size distributions. SRR at higher static bed height requires more input superficial gas velocity to initiate solid circulation rate. Whereas low static bed heights requires less superficial velocity required to start solids recirculation from annular region to draft tube region.

NOTATION

dp Particle diameter (m)
g Acceleration due to gravity (m/s2)
Gs Solid recirculation rate (kg/m2s)
P Pressure (N/m2)
R Radius of ICFB (m)
r Draft tube radius (m)
Ua Superficial velocity in the annulus (m/s)
Ud Superficial velocity in the draft tube (m/s)

vs_A Solid Velocity in annular (m/s)

Greek Symbols

εg Air volume fraction
εs Solid volume fraction
ρg Air density (kg/m3)
ρs Solid density (kg/m3)
SRR-Solids recirculation's rate

REFERENCES

Epstein, N. Grace, J. 1997. Spouting of particulate solids, Handbook Powder Sci.

Technol. 532–567.

Geldart, D. 1973. Types of Gas fluidization. Powder Technology, 7,285–292.

Gujjula.R, Narasimha.M 2-15Experimental Investigation of Hydrodynamics of gas-solid flow in an internally circulating fluidized bed. Canadian journal of Chemical Engineering. 93 (8). 1380 - 1391.Hadzismajlovic, Dz., Grbavcic, Z., Povrenovic, D. S., Vukovic, D. V., Garic, R. V., & Littman, H. 1992

The hydrodynamic behavior of a 0.95 m diameter spout-fluid bed with a draft tube. In Proceedings of the 7th engineering foundation conference on fluidization, Brisbane, Australia, pp.337–344.

He, Y. L., Qin, S. Z., Lim, C. J., & Grace, J. R. 1994. Particle velocity profiles and solid flow patterns in

spouted. Can. J. Chem. Eng., 72 , 561-568.

Ishikura, T.Nagashima, H. Ide. 2003. Hydrodynamics of a Spouted Bed with a Porous Draft Tube Containing a Small Amount of Finer Particles.Powder Technol. 131, 56-65.

Jin, H. J. Kim, S.D. 2010. Hydrodynamic Characteristics of Binary Solids Mixtures in a Square Internally Circulating Fluidized Bed. J. Chemical Engineering of Japan 43(2), 126-131.

Kim, Y. J., Lee, J.M. and Kim, S.D. 2000. Modeling of Coal Gasification in an Internally Circulating

Fluidized Bed Reactor with Draught Tube, Fuel 79, 69.

Kim. Y.J, Lee. J.M. Kim. S.D.1997. Coal gasification characteristics in an internally circulating fluidized bed with draught tube, Fuel 76, 1067-1073.

Li. P.L, Yu X.Y. , Liu. F., Wang T.F. 2015 Hydrodynamic behaviors of an internally circulating fluidized bed with wide-size-distribution particles for preparing polysilicon granules, Powder Technol. 281 112-120.

Mleczko, L. Marschall, K.J. 1997. Performance of an internally circulating fluidized bed reactor for the catalytic oxidative coupling of methane. Can. J. Chem. Engg, 75, 610-619. Mukadi, L., Guy, C. and Legros, R. (1999). Can. J. Chem. Eng.. 77, 420.

Patankar, S. V. 1980. Numerical Heat Transfer and Fluid Flow: Hemisphere Publishing Corporation.

Su.G, Huang.G, Ming.L, Liu.L. 2014 Study on the flow behavior in spout-fluid bed with a draft tube of sub-millimeter grade silicon particles. Chemical Engineering Journal, 277.

Yang, W. and D. Keairns. 1974Recirculating fluidized bed reactor data utilizing a two-dimensional cold model. in AIChE Symp. Ser.

Zhong, W. Chen, X. Zhang,M. 2006 Hydrodynamic characteristics of spout-fluid bed:pressure drop and minimum spouting/spout-fluidizing velocity, Chem. Eng. J.118 37–46.

Li. P.L, Yu X.Y. , Liu. F., Wang T.F. 2015 Hydrodynamic behaviors of an internally circulating fluidized bed with wide-size-distribution particles for preparing polysilicon granules, Powder Technol. 281 112-120.

Mleczko, L. Marschall, K.J. 1997. Performance of an internally circulating fluidized bed reactor for the catalytic oxidative coupling of methane. Can. J. Chem. Engg, 75, 610-619.

Mukadi, L., Guy, C. and Legros, R. (1999). Can. J. Chem. Eng.. 77, 420.

Patankar, S. V. 1980. Numerical Heat Transfer and Fluid Flow: Hemisphere Publishing Corporation.

Su.G, Huang.G, Ming.L, Liu.L. 2014 Study on the flow behavior in spout-fluid bed with a draft tube of sub-millimeter grade silicon particles. Chemical Engineering Journal, 277.

Yang, W. and D. Keairns. 1974Recirculating fluidized bed reactor data utilizing a two-dimensional cold model. in AIChE Symp. Ser.

Zhong, W. Chen, X. Zhang,M. 2006 Hydrodynamic characteristics of spout-fluid bed:pressure drop and minimum spouting/spout-fluidizing velocity, Chem. Eng. J.118 37–46.