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Solid Circulation and Gas Bypassing in an Internally Circulating Fluidized Bed with an Orifice-Type Draft Tube

Hong-Sik Ahn, Woon-Jae Lee, Sang-Done Kim† and Byung-Ho Song*

Department of Chemical Engineering, Korea Advanced Institute of Science and Technology, Taejon 305-701, Korea
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Abstract–The effects of orifice diameter in the draft tube, particle size, gas velocities and bed height on the circulation rate of solids and gas bypassing between the draft tube and annulus have been determined in an internally circulating fluidized bed (i.d., 0.3 m ; height, 2.5 m) with an orifice-type draft tube. A conical shape gas separator has been employed above the draft tube to facilitate the separation of gases from the two beds. The circulation rate of solids and the quantity of gas bypass from the annulus to draft tube show their minimums when the static bed height is around the bottom of the separator. The circulation rate of solids increases with an increase in orifice diameter in the draft tube. At fixed aeration to the annulus, gas bypassing from the draft tube to annulus sections decreases, whereas reverse gas bypassing from the annulus to the draft tube increases with increasing the inlet gas velocity to the draft tube. The obtained solids circulation rate has been correlated by a relationship developed for the cocurrent flow of gas and solid through the orifice.

Key words : Circulating Fluidized Bed, Draft Tube, Orifice, Gas Bypass, Solids Circulation Rate

INTRODUCTION

Several types of circulating fluidized beds, using a draft tube to divide the bed for internal circulation of solids in a single vessel, have been developed for gas-solid reactors [Ahn, 1995; Song, 1993; Berruti et al., 1988; Riley and Judd, 1987; Kuramoto et al., 1986; Yang and Keairns, 1978] as for three-phase reactors [Park et al., 1990; Lee et al., 1989]. These internally circulating fluidized beds, with separate aeration of the annulus section, may provide more flexible operation as a gas-solid reactor. A schematic diagram of the system is given in Fig. 1. The particles are always transported upwards in the draft tube and moved downwards in the annulus section. The gas velocities in the draft tube and annulus section are different from the gas velocities given through different gas distributor due to gas bypassing between the draft tube and annulus section. Adjusting the gas velocities to the draft tube and annulus section independently can easily control the circulation rate of solids in the bed. In addition, it has been reported that particle entrainment from the reactor can be greatly reduced by the addition of a draft tube to the fluidized bed [Kim et al., 1997; Kinoshita et al., 1987]. Thus, a consequent increase in the conversion level can be expected when applied to a coal gasifier, compared to conventional fluidized beds. In the coal gasification reactor, gas streams can be fed into the draft tube and annulus section, so that the draft tube zone can be operated as a slugging/turbulent fluidized bed and the annulus zone as a moving bed at the incipient fluidizing condition. Thus, the circulating solids can act as the heat transfer medium between the combustion and gasification zone.

†To whom correspondence should be addressed.
E-mail : kimsd@cais.kaist.ac.kr
*Present address : Department of Chemical Engineering, Kunsan National University, Kunsan, Korea

The circulation rate of solids determines the reactor load and greatly affects the reactor performance: solid residence time, gas-solid contact, and the heat and mass transfer rates. Bypassed air from the draft tube to annulus section may consume

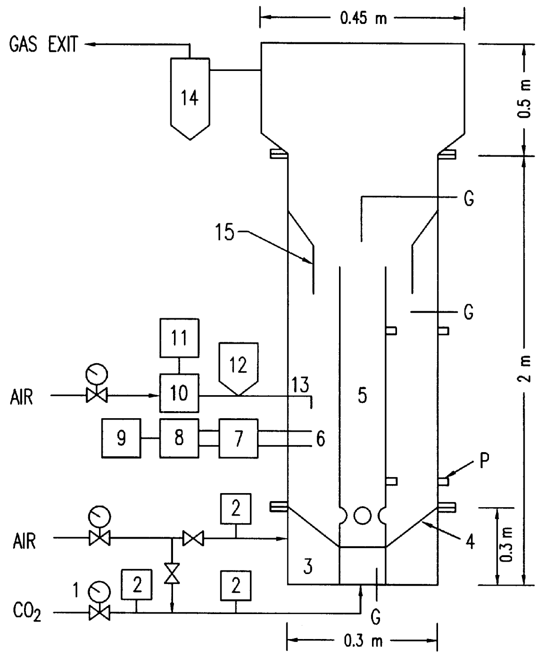

Fig. 1. Schematic diagram of the experimental apparatus.

1. Pressure regulator	10. Solenoid valve
2. Flow meter	11. Timer
3. Air box	12. Solid tracer
4. Gas distributor	13. Tracer injection tube
5. Draft tube	14. Cyclone
6. Thermistor probe	15. The gas separator
7. Bridge circuit	G. Gas sampling tube
8. Data acquisition system	P. To manometer
9. Personal computer	

the carbon source in the gasification zone too much, and can even combust the product gas away. Although the gas bypassing between the two beds can be controlled to an extent by the inlet geometry of the draft tube, the systems with a usual draft tube revealed relatively high bypass quantity [Song et al., 1997; Lee, 1991; Yang and Keairns, 1978]. To reduce gas bypassing, the present study employed several orifices in the wall of the draft tube and extended the bottom of the draft tube to the plate of the gas distributor. The effects of orifice diameter, solids particle size, bed height, and gas velocities on the circulation rate of solids and gas bypass quantity have been determined in an orifice-type draft tube system. The relationship between the solids circulation rate and gas bypass quantity has been also discussed.

EXPERIMENTAL DETAILS

Experiments were carried out in a Plexiglas column (internal diameter (i.d.), 0.3 m; height, 2.5 m) with a centrally located draft tube (i.d., 0.1 m; height, 0.9 m) as shown in Fig. 1. The freeboard region was expanded (i.d., 0.45 m; height, 0.5 m) to reduce particle entrainment. A draft tube with four orifices was mounted on the gas distributor, and several orifice diameters (15, 20, 25, and 30 mm) were tested. The bed was loaded with a known weight of sand particles (d_p=0.3 mm, ρ_s=2,620 kg m^{-3}, U_{mf}=0.1 m s^{-1}, ε_{mf}=0.48) and fluidized by compressor air through a pressure regulator, a filter and a gas flow meter. The air box consisted of two sections to supply gas into the draft tube and annulus section independently. A bubble cap distributor was used for gas supply to the draft tube, and a conical plate with an inclined angle of 60° having 18 tuyeres (4 holes×1.5 mm i.d. in each tuyere) was mounted on the air box for the annulus aeration. This type of gas distribution is known to reduce the stagnant region at the bottom of the bed. Pressure taps were mounted flush to the wall of both the main column and draft tube at 0.3 m height intervals from the gas distributor, which measured the pressure drops across the fluidized bed, the moving bed and the orifice. Gas sampling probes were mounted in the draft tube and annulus at 0.7 m above the distributor to measure gas bypass quantity. A conically shaped gas separator was installed at 0.88 m above the distributor to make the separation of gases from the draft tube and annulus section easy.

The circulation rate of solids was determined from the particle downward velocity in the moving annulus bed, which was measured by the two thermistors and by using the heated bed material as a tracer. A tracer gas of carbon dioxide was continuously fed into the inlet gas stream to the draft tube, and gas samples were taken at the inlet of the draft tube and at the outlets of both the draft tube and annulus bed. The tracer concentration of the samples was analyzed by a gas chromatograph. If the four gas concentrations and the two inlet gas flow rates are known, the splitting of the two inlet gases flowing into the other zone can be determined by a material balance. The details of the above measurements are given by Song et al. [1997]. The bypass fraction of the inlet gas (f) is defined as volume % of the inlet gas bypassed to the other region. The bypass fraction of the inlet gas of the draft tube to the annulus region will be denoted by f_{DA}, where the subscript DA means the bypassed direction from the draft tube to the annulus. The experimental variables and their ranges are summarized in Table 1.

Table 1. The ranges of experimental variables

Variable	Range
Number of orifices	4
Orifice diameter (mm)	15, 20, 25, 30
Gas velocity, U_d/U_{mf}	7-10
Gas velocity, U_a/U_{mf}	0.9-1.5
Static bed height (m)	0.8-0.95
Avg. diameter of sand particles (μm)	300, 390, 460, 610

RESULTS AND DISCUSSION

The effect of static bed height on the circulation rate of solids (W_S) and the bypass fractions of the inlet gases to the draft tube and annulus (f_{AD} and f_{DA}) has been investigated because we employed the gas separator just above the draft tube in the present circulation system. The variation of W_S with static bed height represents a minimum value as shown in Fig. 2. The minimum value occurs when static bed height is just around the height of the separator bottom. When the static bed height increases up to the separator bottom, it is observed that the separator acts like a baffle and hinders the slug motion of particles at the top of the draft tube. Thus the momentum caused by the slug motion of particles is reduced and the circulation rate of solids decreases because of the separator. When the static bed height is above the separator bottom, the space between the draft tube and the separator is filled with solids, and the baffle effect of the separator diminishes and the slug motion increases with an increase in the bed inventory. The change of gas bypass fraction with the static bed height is shown in Fig. 3, in which f_{AD} also represents a minimum value with increasing the static bed height as in the behavior of W_S. It has been shown that the behavior of W_S is very similar to that of f_{AD} in the circulating

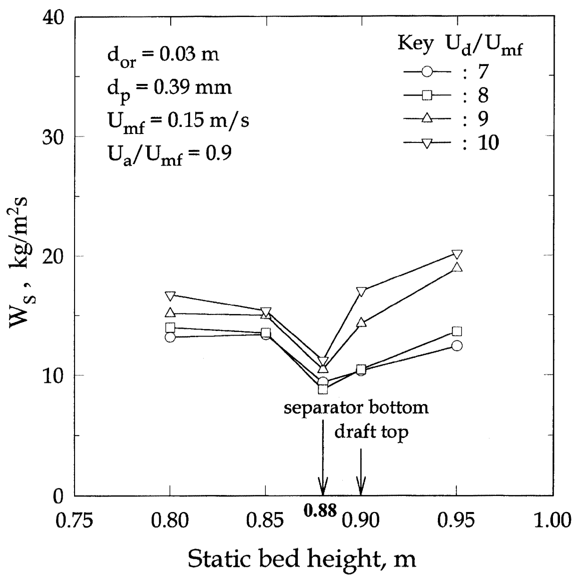

Fig. 2. Effect of static bed height on W_S with variation of U_d.

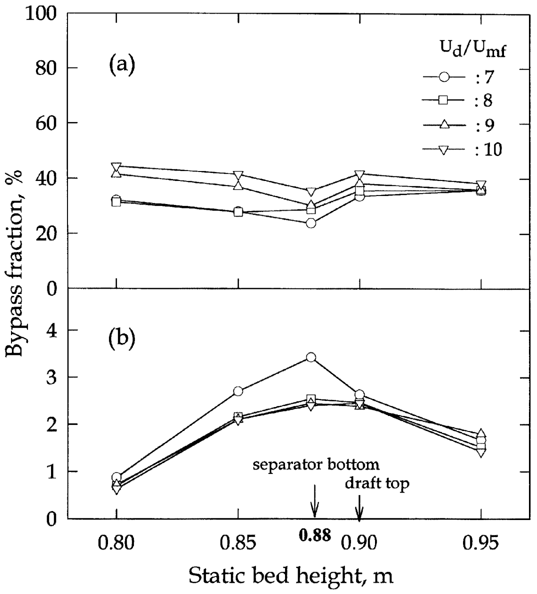

Fig. 3. Effect of static bed height on the gas bypass fraction with different U_d.
(a) f_{AD}; (b) f_{DA} (conditions are same in Fig. 2)

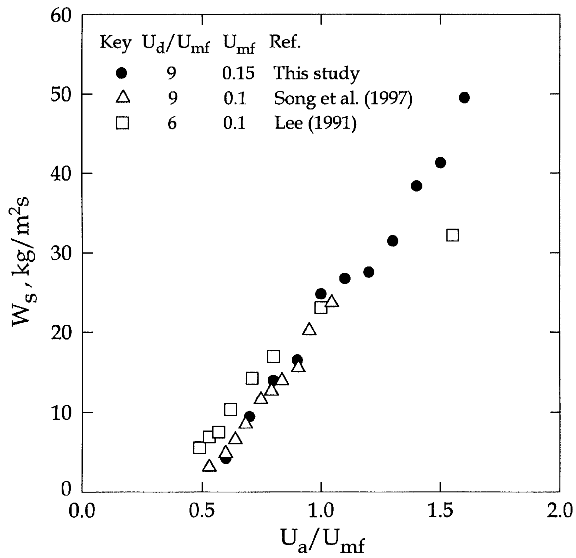

Fig. 4. Effect of U_a on W_S.

fluidized bed with a draft tube [Song et al., 1997]. On the other hand, f_{DA} shows opposite trends to that of the circulation rate of solids. While f_{AD} is between 35 and 40%, f_{DA} is between 1 and 3.5%. Based on the above results, in the rest of the experiments, the fluidized bed was operated with a static bed height of 0.8 m to avoid the effect of separator on W_S and gas bypassing.

The effect of the annulus aeration on W_S is shown in Fig. 4. The circulation rate of solids increases with increasing the annulus aeration because the annulus aeration makes the pressure difference larger between the draft tube and annulus section, which is the driving force for solids circulation. The experimental results of Lee [1991] and Song et al. [1997] are compared with the present result. Their fluidized beds and draft tubes were equal in diameters to the present system, but Lee [1991] used a flat plate distributor instead of the conical type distributor for annulus aeration, and only this study employed orifices in the draft tube. While the changes of W_S with U_a are almost the same in the two systems with the conical shape distributor, that of Lee [1991] seems to tend to level off at high gas velocities. The type of gas distributor for annulus aeration seems to affect the behavior of W_S, even if the experimental conditions of Lee [1991] are a little bit different from those of others.

The effect of the inlet gas velocity to the draft tube (U_d) on W_S at different U_a/U_{mf} is shown in Fig. 5. The circulation rate of solids increases with U_d due to the increase in the driving force for solids circulation with an increase in bed voidage in the draft tube. W_S increases significantly with increasing the gap height between the gas distributor plate and the bottom of the draft tube [Song et al., 1997; Lee, 1991]. With larger gap height, the resistance to the flow of solids from the annulus to draft tube will be smaller, and a steady increase in W_S can be expected. The experimental result of Lee [1991] showed the largest W_S due to the relatively high gap (0.14 m). The experimental result of Song et al. [1997] showed the slowest W_S because both the employed U_a/U_{mf} and gap height (0.08 m) are relatively small compared to the others. The present system with orifice type draft tube seems to provide a reasonable circulation rate of solids.

Since the pressure at the bottom of the draft tube is lower than that at the bottom of the annulus, some of inlet gas to the annulus tends to bypass to the draft tube side. Reverse gas bypassing from the draft tube to annulus is also possible. In a circulating fluidized bed with a draft tube for coal gasification reactor, steam is introduced into the annulus section (moving bed) and the combustion agent (air) is fed to the draft tube (fluidized bed). However, if a large amount of air bypasses into the gasification zone, coal combustion will dominate in both of the two reaction zones. Therefore, the cross flow of the reactant gases should be minimized between the two reaction zones to

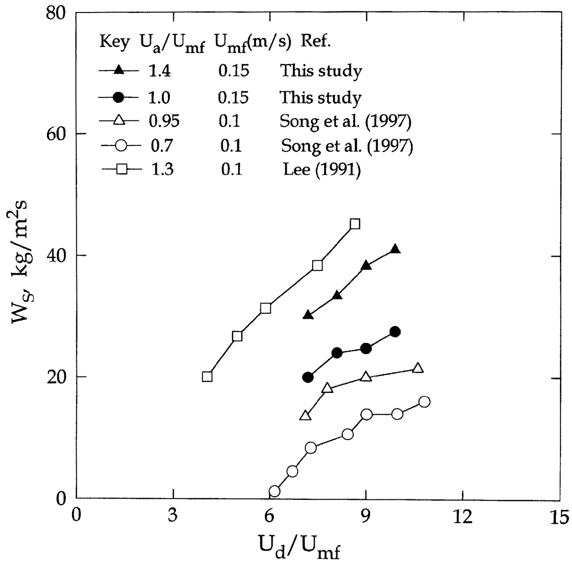

Fig. 5. Effect of U_d on W_S.

obtain the desired product gas quality. The effect of the inlet gas velocity to the draft tube on f_{DA} and f_{AD} is shown for the three systems in Fig. 6. The gas bypassing from the annulus to the draft tube will increase the diameter of the gas jet from the distributor to the draft tube. Thus W_S should increase with f_{AD} even at low U_d. From Figs. 5 and 6, it can be readily seen that the differences of the W_S curves are similar to that of the f_{AD} curves among the three systems. As stated above, f_{DA} is more important than f_{AD} in the application of coal gasifier. In Fig. 6 f_{DA} are over 3% in the previous two systems having a gap which can be relatively large to operate a coal gasifier, and so the attainable circulation rate of solids should be limited. However, the present system with an orifice-type draft tube provides greatly lower values of f_{DA}, lower than 1%. Therefore an orifice-type draft tube will be the most suitable configuration for an internally circulating fluidized bed coal gasifier.

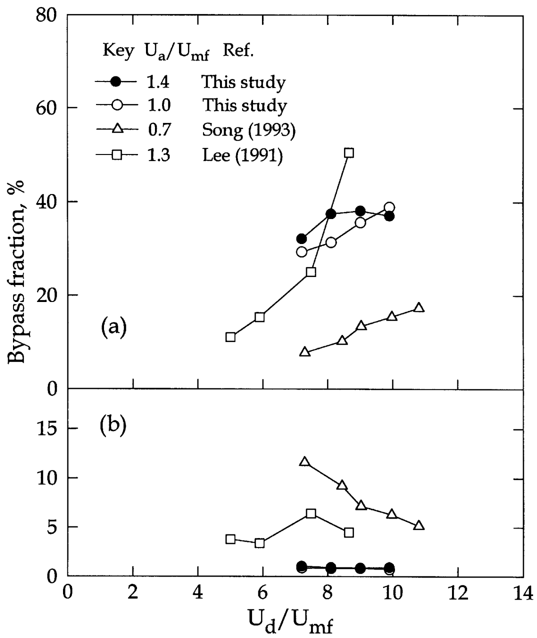

Fig. 6. Effect of U_d on the gas bypass fraction.
(a) f_{AD}, (b) f_{DA}.

The effect of orifice diameter (d_{or}) on W_S is shown in Fig. 7. As can be seen, W_S increases with d_{or} due to the increase of the area for particle passage and the resultant decrease of the resistance of particle flow. Also, the measured pressure drop through the orifice increases with d_{or}. The effect of orifice diameter on the gas bypass fraction is represented in Fig. 8. With increasing d_{or}, it becomes easier for the inlet gas to the annulus to bypass to the draft tube, so f_{AD} increases and f_{DA} decreases. Milne et al. [1992] have also investigated gas bypassing in their orifice-type draft tube system and reported that there was little effect of orifice diameter on the gas bypassing. This may be due to their smaller sizes of orifice compared to the present study.

To examine the dominant gas bypassing direction as a function of U_d for the various particle sizes, the flow ratio was defined as the volumetric gas flow rate in the draft tube over that in the annulus. The flow ratio at the inlet ($FR_{in}=Q_{D1}/Q_{A1}$) and outlet ($FR_{out}=Q_{D2}/Q_{A2}$) of the bed is plotted in Fig. 9, where $FR_{out}>FR_{in}$ indicates the dominant gas bypass from the annulus to the draft tube. As can be seen in Fig. 9, gas bypassing from the annulus to the draft tube dominates at the given gas velocities. $FR_{out}=FR_{in}$ does not mean that there is no gas bypassing at all. Most of the gas flow through the orifices was from the annulus to the draft tube in the present system. In other words, the inlet gas to the draft tube was almost confined to the draft tube zone, confirming the main design objective of the internally circulating fluidized bed coal gasifier.

A simple comparison may be made between the behavior of the annulus bed of solids and that of a continuously fed hopper of aerated solids. Many correlations can be found in the literature describing the gravity discharge of particulate materials from aerated and non-areated hoppers. De Jong and Hoelen

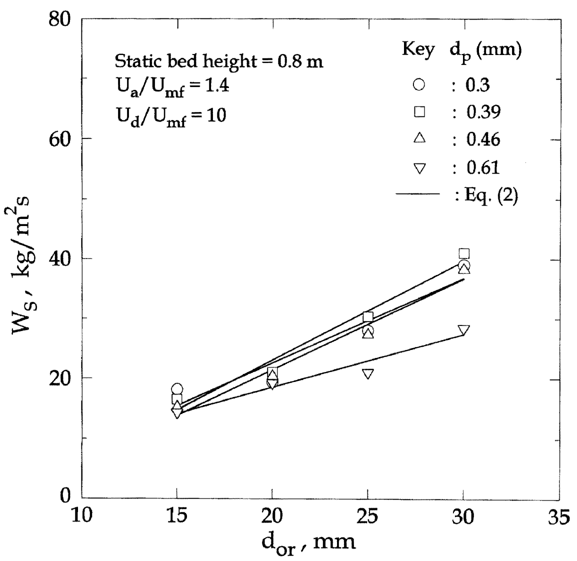

Fig. 7. Effect of orifice diameter on W_S with different particle size.

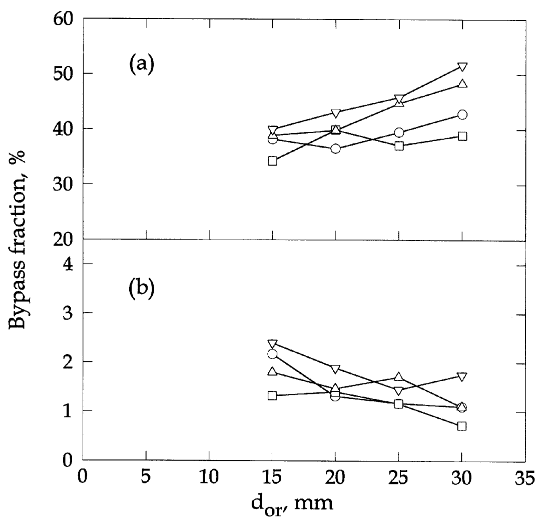

Fig. 8. Effect of orifice diameter on the gas bypass fraction with different particle size.
(a) f_{AD}; (b) f_{DA} (symbols and conditions are same in Fig. 7)

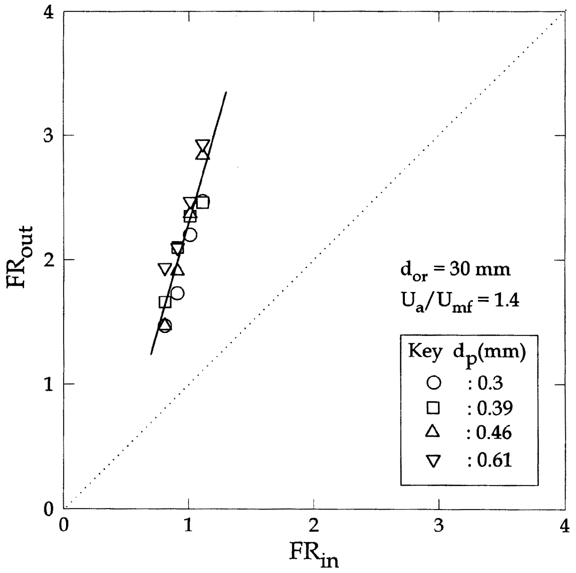

Fig. 9. The outlet to inlet flow ratio with various particle size.

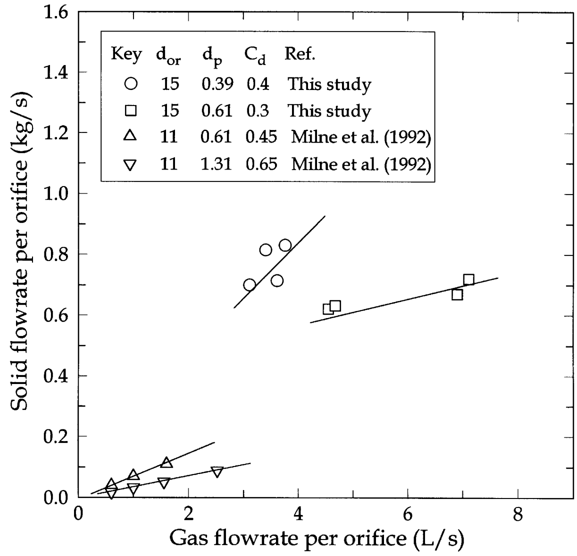

Fig. 10. Comparison of gas flow rate and solids flow rate through the orifice.

[1975] have derived a relationship between the flow rate of solids and the pressure drop through a single orifice given as follows

$$W_S=0.25C_d\pi(d_{or}-kd_p)^2\sqrt{2\rho_s\Delta P_{or}} \tag{1}$$

They evaluated the pressure drop by help of the Ergun equation, between a point an infinite distance away from the orifice and a point one-orifice radius away. The solids within this region were assumed to be at their minimum fluidization state. The gas flow was assumed to be radial with no angular variation. The manipulation of Eq. (1) gives the following relationship for the flow rate of solids in the orifice system:

$$W_S=\frac{-\rho_s(1-\varepsilon_{mf})C_d^2(b+2aF_{or}/\varepsilon_{mf})+\rho_sC_d\sqrt{4a(F_{or}/\varepsilon_{mf})^2+4bF_{or}/\varepsilon_{mf}+C_d^2b^2}}{2(1-aC_d^2)} \tag{2}$$

where $a=\dfrac{1.75\rho_g d_{or}(1-kd_p/d_{or})^4}{12\rho_s\phi_s d_p\varepsilon_{mf}}$

$b=\dfrac{150\pi\mu d_{or}^3(1-\varepsilon_{mf})(1-kd_p/d_{or})^4}{8\rho_s(\phi_s d_p\varepsilon_{mf})^2}$

We used Eq. (2) to correlate the flow rates of gas and solids through the orifices in the present internally circulating fluidized bed. The orifice correction factor, k, was taken to be 2.9 for sand particles as suggested by Beverloo et al. [1961]. The bed voidage at minimum fluidization (ε_{mf}) was taken to be 0.48 and the sphericity of round sand (ϕ_s) was assumed to be 0.89. The orifice discharge coefficient (C_d) was evaluated for each operating condition by a nonlinear regression.

The experimental relationship between the flow rate of gas and that of solids through the orifice is shown in Fig. 10 with the variations of d_{or} and d_p. The discharge coefficients evaluated from Eq. (2) are listed in the plot. This plot shows that the flow rate of solids through the orifice increases with the flow rate of gas through the orifice, in which the flow rate of gas was directly calculated from the measured amount of gas bypass through the orifices (f_{AD}). Thus, as already mentioned before, it can be concluded that the bypassed quantity from the annulus to the draft tube, f_{AD}, enhances the circulation of solids. The data in this plot also shows that both f_{AD} and the solid flow rate through the orifice increase with the diameter of orifice. Much more gas should be fed into the reactor to obtain appropriate solids circulation for a system of large particles with high U_{mf}. The evaluated discharge coefficient was correlated as a function of d_{or} and d_p, and the obtained result shows that C_d increases with d_{or} and decreases with particle size as:

$$C_d=0.23\left(\frac{d_{or}^{0.73}}{d_p^{0.44}}\right) \tag{3}$$

On the other hand, the circulation rate of solids in the fluidized bed with an orifice-type draft tube has been correlated with the pertinent dimensionless groups as:

$$\frac{W_S}{\rho_s(1-\varepsilon_{mf})U_{mf}}=2.63\times10^{-5}\left(\frac{U_aU_d}{U_{mf}^2}\right)^{1.19}\left(\frac{d_{or}}{d_p}\right)^{1.29}\left(\frac{H_d}{H_s}\right)^{0.87} \tag{4}$$

with a correlation coefficient of 0.95, where the range of variables are $5<(U_aU_d/U_{mf}^2)<14$, $24.6<d_{or}/d_p<100$, $0.95<H/H_s<1.13$.

CONCLUSIONS

In a circulating fluidized bed with an orifice-type draft tube and a gas separator, it has been found that W_S exhibits a minimum value when the employed static bed height is around the separator bottom. A reasonable rate of solids circulation could be obtained with the orifice-type draft tube for operation of a coal gasifier. The gas bypassing from the annulus to draft tube increases and reverse bypassing from the draft tube to annulus decreases with increasing U_d. The orifice diameter greatly affects both W_S and f_{AD}, and the particle size effect is insignificant on W_S. The orifice-type draft tube was found to be good enough to eliminate the unwanted gas bypass between the draft tube and annulus bed. On the basis of the gas bypassing and the circulation rate of solids with the present operating variables, the orifice-type draft tube was found to be most suitable for an internally circulating fluidized bed coal gasifier.

NOMENCLATURE

C_d : orifice discharge coefficient [-]
d_{or} : orifice diameter of draft tube [m]
d_p : mean diameter of particles [m]
f : gas bypass fraction, vol% of inlet gas bypasses to the other region [%]
f_{AD} : gas bypass fraction from the annulus to the draft tube [%]
f_{DA} : gas bypass fraction from the draft tube to the annulus [%]
F_{or} : volumetric flow rate of gas in the orifice [m^3/s]
H_d : height of draft tube [m]
H_s : static bed height [m]
k : the orifice correction factor [-]
ΔP_{or} : pressure drop through the orifice [kPa]
Q_{A1} : gas flow rate at the annulus inlet [m^3/s]
Q_{A2} : gas flow rate at the annulus outlet [m^3/s]
Q_{D1} : gas flow rate at the draft tube inlet [m^3/s]
Q_{D2} : gas flow rate at the draft tube outlet [m^3/s]
U_a : gas velocity in annulus [m/s]
U_d : gas velocity in draft tube [m/s]
V_s : particle velocity [m/s]
W_S : solids circulation rate per unit area of annulus [kg/m^2s]

Greek Letters

ε_{mf} : voidage at minimum fluidization condition [-]
μ : gas viscosity [kg/(m·sec)]
ρ_g : air density at 25 °C [kg/m^3]
ρ_s : density of particles [kg/m^3]
τ : time-lag of signals detected by thermistor probe [sec]
ϕ_s : sphericity of particle [-]

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