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Continuous Measurement of Solids Flow in a Circulating Fluidized Bed

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Abstract−A modified impact probe for continuous measurement of solids circulation rate in a circulating fluidized bed has been developed based on a principle similar to a momentum probe. The response curves of solid flow from the probe have been characterized and calibrated in a test column (0.05 m-I.D.×0.80 m-high). The probe was validated in situ in the downcomer of a circulating fluidized bed (0.10 m-I.D.×4.80 m-high). The solid circulation rates obtained by the modified impact probe well agree with the measured solids circulation rate by the descent time method.

Key words: Circulating Fluidized Beds, Solid Circulation Rate, Solid Flow Measurement, Impact Probe

INTRODUCTION

There are many techniques for measuring gas and liquid flow rates, but relatively few for measuring particulate solid flow rates. To study the hydrodynamics of circulating fluidized beds (CFB), the reliable measuring technique of solids circulation rate (G_s) is needed, and this reliable method would find many other industrial applications [Harris et al., 1997]. Existing techniques for measuring G_s are limited for various reasons, including lack of sensitivity, on-line, and reliability etc. Burkell et al. [1988] defined eight criteria that constitute ideal measuring techniques: on-line, sensitivity, non-interfering, capable of operation at elevated temperatures, possibility of scale-up, reliable, broad range of operation, unnecessary to calibrate. However, no single method satisfies the above eight criteria. Among the proposed methods in the literature, butterfly valve and flow diversion methods are most commonly used [Patience and Chaouki, 1991]. This technique may be called the "bucket-and-stop watch," e.g. measuring the rate of particle accumulation over a porous butterfly valve [Harris et al., 1997] or in a secondary bed [Kim et al., 1999]. These methods may be accurate without calibration, but they are not an on-line technique and intrusive [Harris et al., 1997]. Whereas, the impact meter and a modified orifice meter are suitable as on-line modes. However, they may interfere with solid flow in a CFB loop or be inadequate to employ in the downcomer of a CFB, respectively [Burkell et al., 1988].

In this study, a method for continuous measurement of solid flow rate by a modified impact probe is proposed. The response curves from the probe have been characterized and the probe is validated in situ in a CFB.

EXPERIMENTAL

1. Modified Impact Probe

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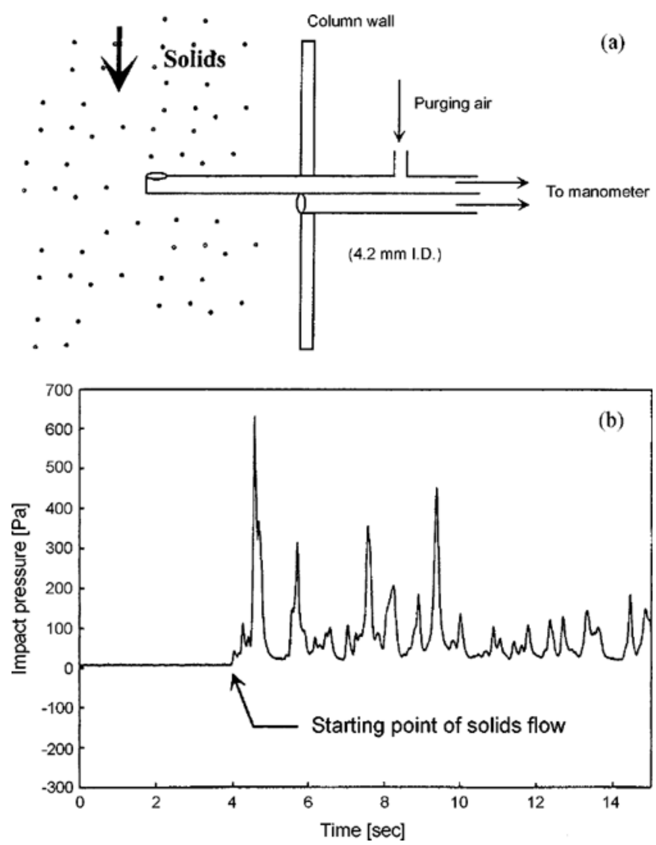

Fig. 1. Schematic diagram of (a) the modified impact probe and (b) typical signals.

A schematic diagram and the principle of the modified impact probe are shown in Fig. 1. The principle of the probe is that the impact of gas-solid suspension on the probe results in a momentum transfer between the gas and particulate phases inside the nozzle. The momentum was measured by dynamic pressure signal, and mass flux was obtained from the signals. This probe is similar to the momentum probe of Zhang et al. [1997]. However, the momentum probe consists of two tips that direct upward and downward, and it was used to predict not G_s but the core-annulus structure by measuring differential pressure between two tips in the riser of a CFB. The modified impact probe was used in the downcomer of a CFB where solid particles have only downflow motion by gravity, and G_s could be obtained by averaging the local values of the radial position like a pitot tube. The modified impact probe has several advantages as follows: a) the probe is simple in design and easy to manufacture and operate, b) on-line measurement is possibe, c) size of sensing head is small so that the probe does not affect solid flow pattern in a CFB loop, and d) the probe may be applicable to high temperature and/or pressure system due to simple pneumatic operation. As can be seen in Fig. 1, the modified impact probe in this study consisted of two stainless steel tubes (4.2 mm-I.D.). One was to measure impact pressure, and the other one was to correct static pressure at the measuring location. The end of the tube for impact pressure measurement was bent in a right angle to direct upstream. The tube was allowed to move horizontally so that measurements could be made at the different radial positions. Air-purging was introduced into the tube to prevent entrained particles from blocking the tube hole. The probe was connected to a pressure transducer (Validyne, P306D, USA) and a data acquisition system was used to record the instantaneous pressure signals.

2. Test Column and CFB Apparatus

A test column to determine the response characteristics and calibration of the probe is shown in Fig. 2. In the column, solid flows downward by gravity as in the downcomer of a CFB. It consisted of a main Plexiglas column (0.05 m I.D.×0.8 m high), a hopper and a top-loading balance. A perforated plate distributor was located between the hopper and the main column for uniform downward flow of solids in the column. The probe was located at 0.6 m below the distributor where solid particles are free falling at terminal velocity. Solid mass flux was varied by using a ball valve below the hopper and measured by an electronic-balance. Impact pressure (ΔP_m) was measured with the probe after ΔP_m was observed to be constant along the radial direction.

The circulating fluidized bed (CFB) unit in the present study with the modified impact probe is shown in Fig. 3. It consists of a riser (0.1 m-I.D.×7.6 m-high), two cyclones, a downcomer (0.1 m-I.D.), a loop-seal (0.1 m-I.D.) and a fluid bed heat exchanger. The details of the experimental facilities can be found elsewhere [Kim et al., 1999; Namkung and Kim, 1999]. The entrained particles from the riser (U_g=4.5 m/s) were collected by the primary and secondary cyclones and flowed down through the downcomer. They were fed to the riser through a loop-seal that regulated solid circulation rate (G_s) by aeration [Kim et al., 1999]. At steady state, the entire solid flow was from cyclones into the measuring column to determine G_s through the CFB by the descent time method. In the transparent measuring column, descending time of particles along the known

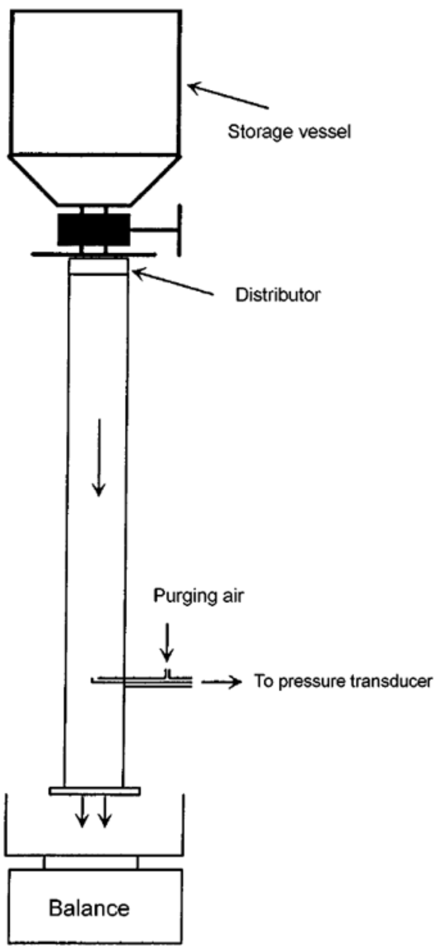

Fig. 2. Schematic diagram of a test column.

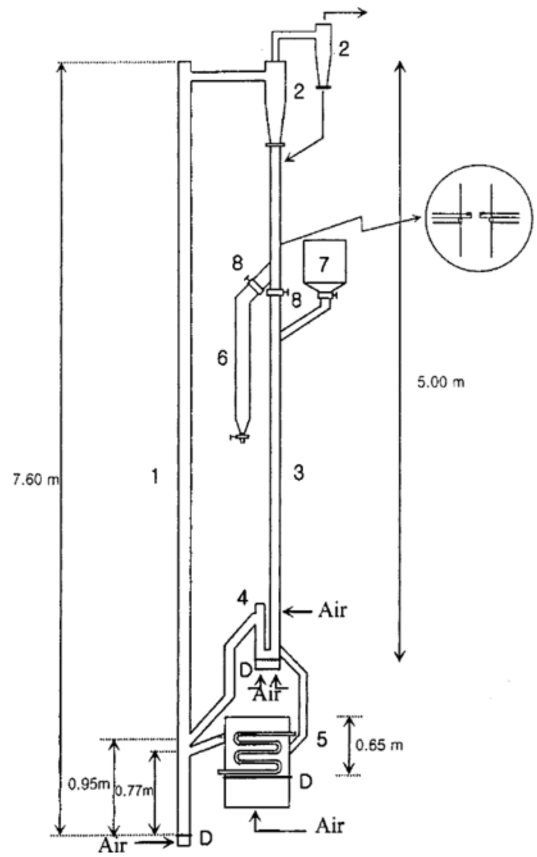

Fig. 3. Schematic diagram of a circulating fluidized bed.

1. Riser 5. Fluidized bed heat exchanger (FBHE)
2. Cyclone 6. Sampling bottle
3. Downcomer 7. Storage hopper
4. Loop-seal 8. Disk valve
D. Distributor

Table 1. Physical properties of silica sand particles

Properties	Silica sand I	Silica sand II
d_p (μm)	101	240
ρ_s (kg/m^3)	3120	2582
U_{mf}(m/s)	0.0108	0.0474
U_t (m/s)	0.66	2.06

distance was measured [Choi et al., 1995; Namkung and Kim, 1999] to compare G_s obtained by the modified impact probe. With knowledge of bulk density and the measured time, G_s can be determined. The solid particles used in this study were two silica sand particles with different mean size and density, and their properties are shown in Table 1.

RESULTS AND DISCUSSION

Typical response signals of the measured impact pressure (ΔP_m) at each solid mass flux (G_s) are shown in Fig. 4. As can be seen, ΔP_m increases with increasing G_s at a purging air velocity (U_{pa}) to the probe tube of 6.0 m/s. From the signals from the probe, they are similar with those from the momentum probe used in the core region of riser in circulating fluidized beds in previous studies [Bai et al., 1995; Zhang et al., 1997]. Since a force probe such as impact or momentum probe is directional, the downward solid movement produces a positive response from the probe, and the magitude of response is an indication of the magnitude of solid mass flux [Yang et al., 1986].

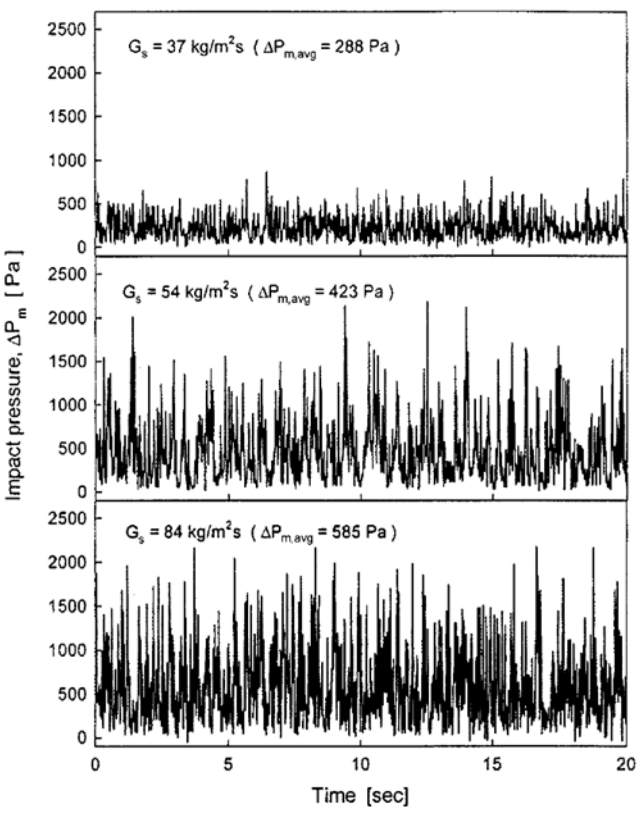

Fig. 4. Typical response signals of the measured impact pressure (U_{pa}=6.0 m/s).

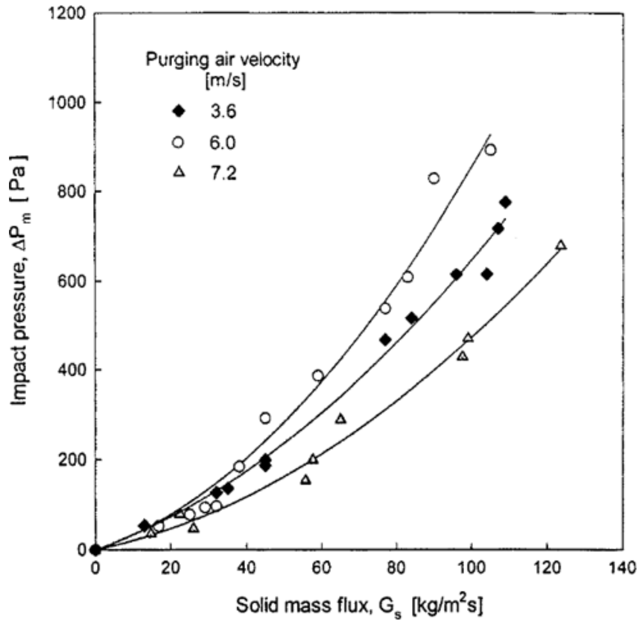

Fig. 5. Effect of solid mass flux on the impact pressure with purging air velocity in the test column.

The effect of solid mass flux on the impact pressure by solid momentum is shown in Fig. 5. Purging air velocities into the probe were varied 3.6, 6.0 and 7.2 m/s, respectively. As can be seen, the impact pressure on the probe increases with an increase in solid mass flux. However, the rate of increase is different with the purging air velocity. The pressure drop by solid momentum should correspond to the kinetic energy of gas-solid suspension flow as [Bai et al., 1995]

$$\Delta P_m=\alpha(\rho_g\varepsilon U_g|U_g|+\rho_s\varepsilon_s U_s|U_s|) \quad (1)$$

where α is the momentum transfer coefficient. Noting that the solids density is usually over a thousand times the gas density, a magnitude analysis indicates that the gas kinetic energy corresponding to the first term of the right-hand side in Eq. (1) can reasonably be ignored with a relative error of less than 5% [Bai et al., 1995]. Thus, Eq. (1) can be expressed as Eq. (2).

$$\Delta P_m=\alpha\rho_s\varepsilon_s U_s|U_s|=\alpha G_s U_s \quad (2)$$

In Eq. (2), α is 0.5 in incompressible fluid. However, α should be determined experimentally in gas-solid flows [Zhang et al., 1997], and it is affected largely by purging air velocity in the probe [Rhodes et al., 1998]. From Eq. (2), ΔP_m is dependent upon α and solids mass flux since particle velocity (U_s) is constant when it becomes terminal velocity. Therefore, information on the effect of purging air velocity to the probe is important for improving the sensitivity of the probe at a constant mass flux.

The effect of purging air velocity to the probe on the impact pressure of solid particle is shown in Fig. 6. As can be seen, the impact pressure exhibits a maximum value with purging air velocity (U_{pa}) at a constant mass flux. The maximum value exhibits at U_{pa}=4.8 m/s with different mass fluxes. In the probe, the fixed quantity of purging air flow passes through the tube and entrains the incoming particles backwards. However, particles have different behavior with U_{pa}. Too small purging air flow results in a longer deceleration length

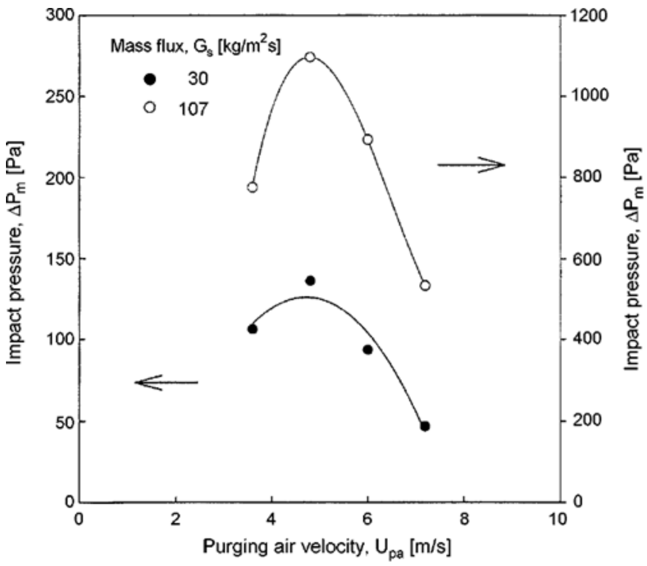

Fig. 6. Effect of purging air velocity to the probe on the impact pressure.

which could exceed length of the probe inlet tip (4.2 mm) in this study. Then, particles hit the horizontal wall of the tube with either loss or change of particle momentum flux due to the force exerted on the tube wall. Both effects lead to a lower impact pressure and inaccurate measurement. Too high purging air velocity, on the other hand, results in release of kinetic energy of incoming particle flow at the probe inlet tip. The optimum purging air velocity is therefore obtained as the velocity at which the particle deceleration length matches length of the probe tip.

When pitot-tube type impact probes are used in gas-solid systems, attention should be given to the momentum transfer coefficient (α). According to Eq. (2), the momentum transfer coefficient (α) can be determined experimentally. The particle velocity can be assumed to be equal to the single particle terminal velocity (U_t). Thus, the impact pressure varies in proportion to the solid mass flux. This relationship gives the calibration line as shown in Fig. 7 from which a value yields 2.98 at U_{pa}=4.8 m/s for 240 μm silica sand.

The effect of purging air velocity to the probe on the momentum transfer coefficient is shown in Fig. 8. As can be seen, α exhibits a maximum value with variation of purging air velocity (U_{pa}) for each particle size. The maximum value exhibits at 4.8 m/s irrespective of particle size, but it shows higher value for 101 μm sand. From the theoretical analysis, α is inversely proportional to particle velocity [Zhang et al., 1997]. The particle velocity increases with increasing particle size and density due to the increase of terminal velocity. Therefore, α for coarser particles have lower value than that of fine particles at the corresponding U_{pa}. Since ΔP_m and α may be affected by the purging air velocity (Figs. 6 and 8), further re-

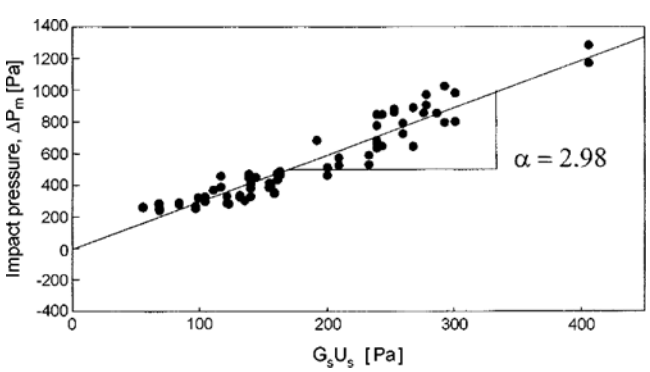

Fig. 7. Calibration of the developed impact probe (U_{pa}=4.8 m/s, d_p= 240 μm).

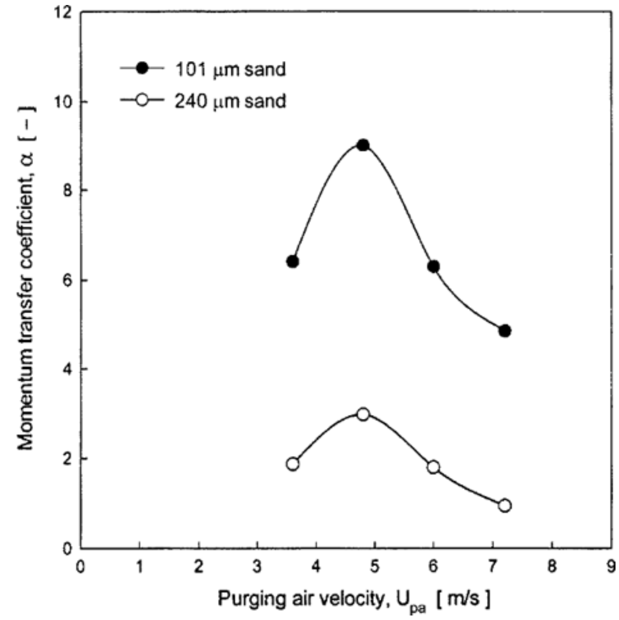

Fig. 8. Variation of the momentum transfer coefficient with purging air velocity to the probe tube.

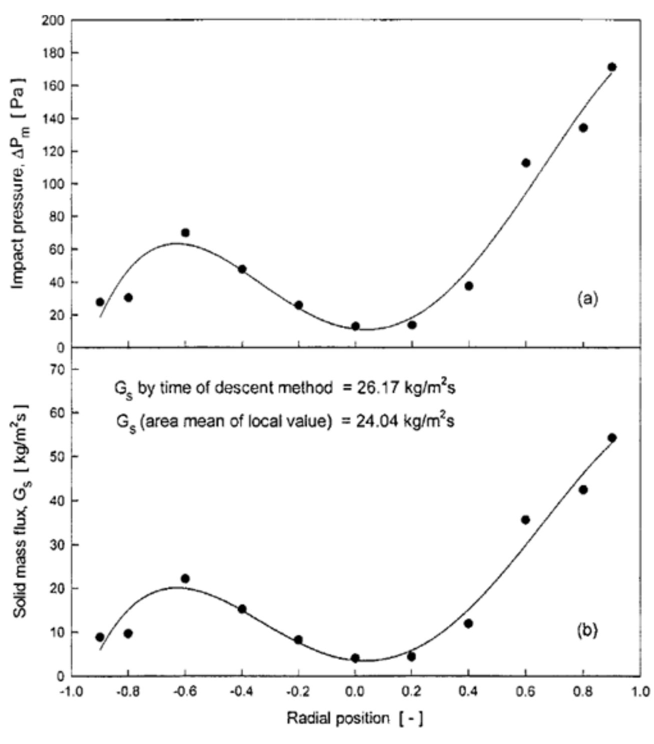

Fig. 9. Variation of (a) the impact pressure on the probe and (b) local solids mass flux along the radial direction.

search work is needed for wide applications of the probe.

Experimental evaluation of the probe was carried out in a circulating fluidized bed (Fig. 3). The probe was installed at the upper part of the downcomer where solid particles flow downward from cyclones to the bed surface in the lower part of the downcomer with dilute phase flow. The probe was located at 1.0 m below the feeding point from the secondary cyclone to maintain particle terminal velocity by gravitivity.

Variation of the impact pressure and local solid mass flux along the radial direction are shown in Fig. 9. As can be seen, the impact pressure exhibits non-symmetry in the radial direction. Neglecting solids loss from the cyclones, the solid mass flux is generally inferred from the solid flow rate traversing the downcomer based on the assumption of the homogeneous one dimensional flow [Louge, 1997]. However, non-symmetric flow in the radial direction is observed due to solid feeding from the secondary cyclone. Also, pressure signals from the probe describe well the solid flow pattern in the downomer. The obtained impact pressure can be converted into local mass flux by Eq. (2) with α=2.98. As can be seen in Fig. 9(b), local flux values show large variation in the radial direction. Overall mass flux is obtained by integrating the local mass flux for the net downcomer area. In comparison with the descent time method, the inferred G_s from the impact probe shows a good agreement. As mentioned by Burkell et al. [1988], the most commonly used methods for measuring G_s are the butterfly valve and the descent time methods in laboratory or commercial scale of CFBs. Although they are good in non-interfering or breadth of range for the measurement, the methods are very poor from the viewpoint of on-line measurement. Therefore, reliable on-line measurement is required for monitoring and diagnosis of CFB systems.

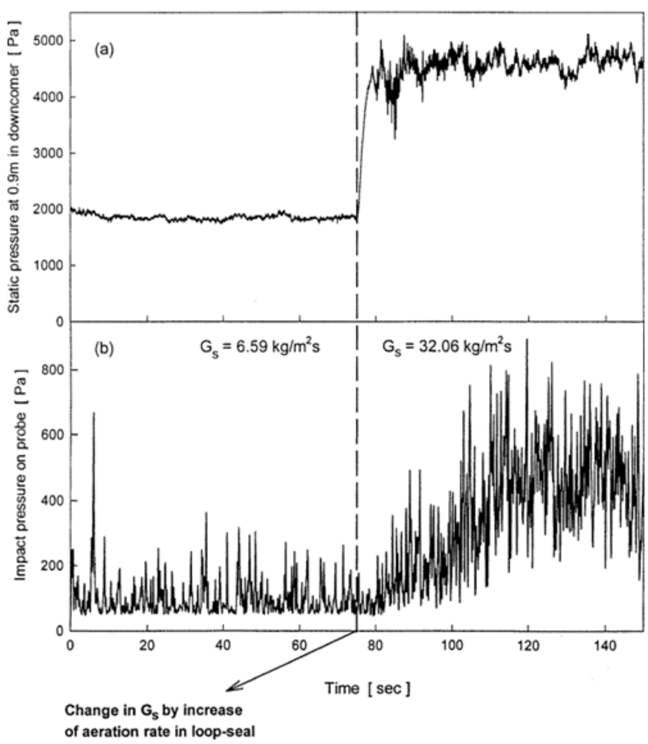

Fig. 10. Time-varying (a) signals of static pressure in the downcomer and (b) response signals of the impact probe with change in solids mass flux.

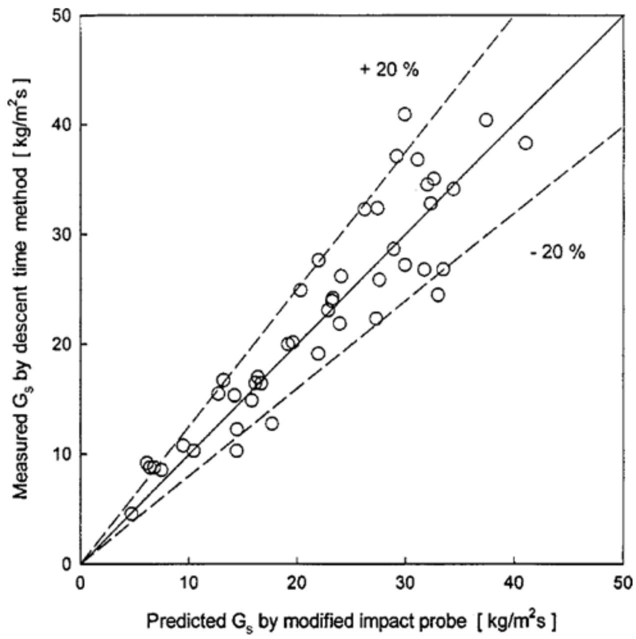

Fig. 11. Comparison of solids mass fluxes obtained by the developed impact probe and the descent time methods.

The time-varying response signals from the probe with solid mass flux (G_s) are shown in Fig. 10. With increasing aeration rate in a loop-seal of CFB [Kim et al., 1999], G_s was varied from 6.59 to 32.06 kg/m^{2}s. The static pressure in a downcomer increases with increasing aeration rate in a loop-seal due to the increase of frictional drag on particles in the beds and consequent increase in G_s is shown as in Fig. 10(a). The amplitude of probe signals increases significantly with increasing G_s. As a result, the response from the impact probe well represents the variation of G_s in a sensitive manner and is adequate for on-line measurement.

The obtained G_s by the developed impact probe is compared with the measured G_s by the descent time method as shown in Fig. 11 where the good agreement between two methods can be observed in a wide range of operating variables.

CONCLUSION

A modified impact probe for continuous measurement of solids circulation rate (G_s) in circulating fluidized beds has been developed based on the principle of momentum probe. The response curves from the probe to determine solid flow rate have been characterized with calibration in a test column. The impact pressure and momentum transfer coefficient exhibit maximum values at U_{pa}=4.8 m/s for different solid mass fluxes and particle sizes. The probe is validated in situ in the downcomer of a circulating fluidized bed. The obtained G_s values from the modified impact probe are well in accord with the values obtained from the descent time method.

ACKNOWLEDGEMENT

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NOMENCLATURE

d_p : mean diameter of particle [μm]
G_s : solids mass flux or solid circulation rate in CFB [kg/m^{2}s]
P : pressure [Pa]
ΔP_m : impact pressure [Pa]
$\Delta P_{m,avg}$: average impact pressure [Pa]
U_g : gas velocity in riser [m/s]
U_{pa} : purging air velocity [m/s]
U_{mf} : minimum fluidization velocity [m/s]
U_s : solid particle velocity [m/s]
U_t : terminal velocity of particle [m/s]

Greek Letters

α : momentum transfer coefficient [-]
ε : voidage [-]
ε_s : solids holdup [-]
ρ_g : gas density [kg/m^3]
ρ_s : apparent density of particle [kg/m^3]

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