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Estimate of solid flow rate from pressure measurement in circulating fluidized bed

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ABSTRACT

A method is described to estimate solid mass flow rate based on measurement of pressure drop in horizontal section of circulating fluid bed (CFB). A theoretical model was derived based on momentum balance equation and used to predict the solids flow rate. Several approaches for formulating such models are compared and contrasted. A correlation was developed that predicts the solids flow rate as a function of pressure drop measured in the horizontal section of piping leading from the top of the riser to the cyclone, often referred to as the cross-over. Model validation data was taken from literature data and from steady state, cold flow, CFB tests results of five granular materials with various sizes and densities in which the riser was operated in core-annular and dilute flow regimes. Experimental data were taken from a 0.20 m ID cross-over piping and compared to literature data generated in a 0.10 m ID cross-over pipe. The solids mass flow rate data were taken from statistically designed experiments over a wide range of Froude number $\left(\frac{U_g^2}{gD}, 25\text{–}200\right)$, load ratio $\left(\frac{G_s}{\rho_g U_g}, 0.2\text{–}23\right)$, Euler number $\left(\frac{2\Delta P_{Horiz}}{\rho_g U_g^2}, 2\text{–}50\right)$, density ratio $\left(\frac{\rho_p-\rho_g}{\rho_g}, 60\text{–}2000\right)$, Reynolds number $\left(\frac{\rho_g U_g d_p}{\mu_g}, 60\text{–}1600\right)$, and Archimedes number $\left(\frac{(\rho_s-\rho_g)\rho_g d_p^3}{\mu_g^2}, 29\text{–}9500\right)$. Several correlations were developed and tested to predict the solids mass flux based on measuring pressure drop in the horizontal section of CFB. It was found that load ratio $\left(\frac{G_s}{\rho_g U_g}\right)$ is a linear function of the Euler number $\left(\frac{2\Delta P_{Horiz}}{\rho_g U_g^2}\right)$ and that each of these expressions all worked quite well (R^2>95%) for the data within the range of conditions from which the coefficients were estimated.

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1. Introduction

One of the crucial issues in gas–solid transport by circulating fluidized bed (CFB) is the correct way to measure the mass flow rate of transported materials. An accurate measurement of mass flow rate is needed to improve the economy of operation and maintain operation safety and technological stability of CFB processes [1]. The solid circulation rate is a very fundamental parameter controlling the hydrodynamics and process requirements in CFB research. Thus, it is even more critical to experimental investigations of the flow structure in CFB so that results of various researchers can be compared. As a result, many technological approaches and devices have been proposed to measure the mass flow rate in CFB, such as particle tracking methods and solid accumulation or depletion approaches. However, quantifying the solid mass flux is problematic [2]. Ideally, it should be continuous and readily calibrated. Unfortunately, these techniques usually give an instantaneous, or at best time-averaged, value of solid velocity in a dynamic process constantly experiencing perturbations and fluctuations. In addition, many of these measurements result in process interferences which disturb and, under the worse situations, completely interrupt the operations [3]. Any instrument inserted into the pipe is exposed to abrasion and interferes with the flow. Laser and any nucleonic methods have a limited scope of use and safety requirements must be considered. A method to estimate the mass flow rate based upon routine measurement of pressure drop is needed.

Several authors use the pressure gradient measurement, which can be continuously monitored to estimate the solids mass flux. Dry et al. [4] considered four possible differential-pressure drop measurements in a large scale cold flow CFB and empirically discovered that the riser mid-section or riser top pressure drop were the most useful parameters for on-line solid flux measurement. Patience et al. [5] analyzed the physics of the differential-pressure drop measurements and described a new on-line technique for estimating solids mass flux based upon measuring the pressure drop in the horizontal pipe in the CFB loop connecting the top of the riser to the primary cyclone. Their model represents a combination of theory and empirical data; test

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data were used to estimate the parameters of a model formulated from first principles. This method was shown to be suitable for application of hot and large scale units. They have shown that the pressure drop increases linearly with the mass flow rate and is sensitive to the gas flow rate according to,

$$\Delta P_{\mathrm{Horiz}} = G_s\left(a + bU_g^2\right) + cU_g^2 \qquad (1)$$

where, $a = (U_{s,2} - U_{s,1})$, $bG_s = 2f_s\frac{L}{D}\rho_g$ and $c = 2f_g\frac{L}{D}\rho_g$. Eq. (1) is based on the momentum balance across the cross-over piping for two-phase flow of gas and solids. The unknown gas and solids friction factors, f_g and f_s, respectively, were combined with other physical variables into the parameters b and c. These parameters were estimated along with the acceleration term a using the measured pressure drop $\Delta P_{\mathrm{Horiz}}$, mass flux G_s and superficial gas velocity U_g in the cross-over.

In addition to Eq. (1), correlations for mass flux predictions from pressure drop measurements have also been obtained for a smooth Pyrex test section in [5]:

$$\Delta P_{\mathrm{Horiz}} = G_s\left(a + bU_g^2\right) \qquad (2)$$

where the contribution due to gas friction to the total pressure drop has been omitted.

It is proposed that solids flow rate can be extracted from a measurement of the pressure drop between the riser and the cyclone of CFB, in the horizontal cross-over piping.

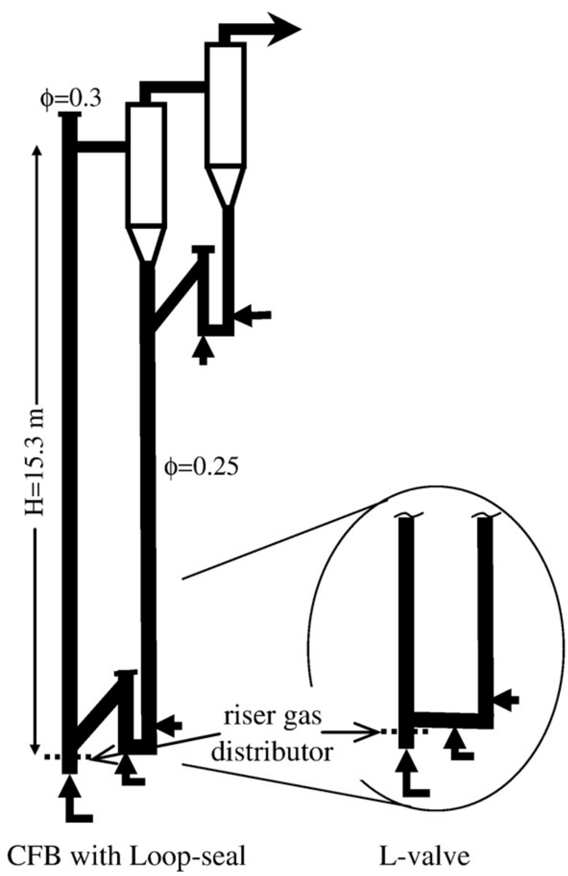

Fig. 1. Schematic of NETL cold flow circulating fluid bed depicting both the loop-seal and L-valve (inset) configurations.

2. Experimental method

The test unit configuration is described by Monazam et al. [6] and shown in Fig. 1. The riser is constructed of flanged steel sections with one 1.22-m acrylic section installed 2.44-m above the solids feed location. Solids exit the riser through a 0.20-m port at 90° and 1.2-m below the top of the riser corresponding to a point 15.3-m above the solids' entry location (centerline to centerline). The solids enter the riser from one of two non-mechanical valves (loop-seal, Fig. 1; and L-valve, Fig. 1 inset). The solids' entry point into the riser for both valves such that the bottom of the inlet piping connects at a point about 0.155 m above the gas distributor. In the loop-seal the solids flow down a 60° slope while in the L-valve the solids flow horizontally into the riser.

The mass circulation rate was continuously recorded by measuring the rotational speed of a twisted spiral vane located in the packed region of the standpipe as described by Ludlow et al [7]. This calibrated volumetric measurement was converted to a mass flux using the measured packed bed density presented in Table 1 and assuming that the packed bed void fraction at the point of measurement was constant (i.e. $\varepsilon_b = 0.45$). This assumption was verified by using the mass balance methods prescribed by Ludlow et al. [7] and the overall mean relative error was estimated to be 8% for these packed bed standpipe operation.

The primary response parameter was the overall cross-over pressure differential and it was calibrated within 0.45 Pa/m. This measurement was taken between ports located in the riser at a location directly opposite from the gas exit on the centerline of the horizontal cross-over piping and a port located 0.965 m from the riser centerline positioned. This port was located on the top of the horizontal cross-over piping to avoid interferences from solids settling in the port. Both impulse lines were maintained clear of particles by using in-line 20 µm porous metal filters with cylindrical dimensions of 25.4 mm long, 6.35 mm outer diameter.

Operating conditions were varied by adjusting the riser flow or solids circulating rate while maintaining constant system outlet pressure at 1 atm. The solid circulation was varied by controlling the aeration flow at the bottom section of the standpipe and by adjusting the total system inventory to increase the standpipe height. Steady state conditions were defined as holding a constant set of flow conditions and achieving a constant response in all the system pressure differentials over a 5-min period. All steady state test results represent an average over that 5-min period.

Superficial riser gas velocities were corrected for temperature and pressure as measured at the base of the riser. The superficial gas velocities in the cross-over was calculated at the pressure and temperature measured in the cross-over piping. The air's relative humidity was maintained between 40 and 60% to minimize effects of static charge building up on the solids.

3. Theory

Taking an approach similar to Patience et al. [5] a data based theoretical model was first considered, though with several notable differences. In Eq. (1) the acceleration was assumed to be constant, $a = (U_{s,2} - U_{s,1})$. This was based upon the fact that their measurement

Table 1
Granular material characteristics.

Bed material	Sauter mean, d_p, µm	Solids density, ρ_s, kg/m^3	Packed bed voidage, ε_b	*Ar*	Geldart type
PPE	1030	0.863	0.45	32641	B
Cork	812	189	0.5	3593	B/A
Coke	230	1250	0.45	608	B/A
Glass beads	60	2500	0.4	29.6	A
Glass beads	180	2500	0.4	749	B