DYNAMIC ASPECTS OF SOLIDS FLOW IN A CIRCULATING FLUID BED

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Abstract – The development and use of more efficient non-mechanical valves require an understanding of the dynamics of solids flow. The influences of the L-valve aeration scheme and the riser operating regime were tested. Specific geometric configuration for fluidizing the horizontal leg of the L-valve were found to significantly reduce the day to day variability in flow of solids circulating around the CFB as measured by a continuous solids flow meter. This was accompanied by a reduction in the variability in the riser pressure differentials. The variability in the solids flow was also characterized for a set of tests varying the riser gas velocity using outlet pressures of 1 and 2 atmosphere. The riser gas velocities, pressures, and to a lesser extent the state of the standpipe all affected the second by second fluctuations in the solids circulation rates. Solids flows varied by as much as 80% of the mean flow rate at the lower gas flow conditions of the fast fluidized bed regime. The fluctuations reduced as the gas flows increased and routinely varied by 25 to 50% of the mean value in core annular and homogenous riser flows. Higher pressure reduced the observed variability at a given superficial velocity consistent with its relative progress across each regime.

INTRODUCTION

Commercial CFB combustors are designed with loopseals that ensure the direction of flow; they cost additional backpressure which could be used instead to increase heat transfer rates within the boiler by increasing solids flux. The development and use of more efficient non-mechanical valves, such as an L-valve, require a better understanding of the dynamics of solids flow to develop reliable controllers to overcome these shortcomings. Solids flow is one of the key factors affecting the state of a circulating fluidized bed reactor; however, there is little information on flow dynamics for solids in systems employing non-mechanical valves.

There are few reports in which the flow rate of solids in a CFB is monitored continuously (Sarra et al, 2004; Ludlow et al 2002; Panday et al., 2016). In these reports there is notable lack of discussion of the variability of the solids flow for different granular materials or the influence of operating the CFB in different transport regimes. It was initially reported that the solids flow fluctuates by nearly 50%· from the average flow (Ludlow et al., 2013).

Solids flow in an L-valve is affected by solid-wall frictional forces. Sarra et al. (2005) have quantified the reduction in solids-wall frictional forces as standpipe aeration increases by measuring the downward on a thin plate suspended in the center of the moving bed of solids in a 0.2 m diameter standpipe from a wire attached to a load cell. There was no information on how these forces impact the variability of the dynamic flow and thereby influence the system controllers. These frictional forces can lead to the type of hysteresis observed during testing in minimum fluidization depending on the granular materials. Geldart Group B particles, so prevalent in energy conversion and cleanup applications, are particularly susceptible to overshooting of minimum fluidization velocity when increasing the gas velocity, and when decreasing the velocity past the same incipient fluidization point they exhibit lower bed pressure, presumably because of gas channeling, bypassing, or local defluidization of solids.

In this study the variability of solids flow was evaluated in an industrial scale CFB employing an L-valve for solids circulation. The effects of riser and standpipe operating regimes were evaluated for Geldart Group B materials and compared to behavior for Geldart Group A. For Geldart Group B materials, two slightly different L-valve aeration schemes were tested.

EXPERIMENTAL METHODS

Experiments were conducted using glass beads or polyethylene beads (Table 1) in an industrial scale CFB Pandey et al., 2014). A schematic of the test equipment is shown in Fig. 2 with key dimensions. In addition, there was 1.52 m horizontal distance between the centerline of the riser and that of the standpipe. The experiments were conducted at ambient conditions using compressed air for aeration and as the fluidizing or transport gas. A continuous solids flow device was employed to measure solids flow dynamics (Ludlow et al., 2002). The twisted spiral vane was mounted in the return leg of the CFB (standpipe) in the dense moving bed of solids about 3.5 m above the horizontal leg of the L-valve. These measurements were improved by incorporating a real time standpipe model and using measured flows and incremental pressures to account for the changes in moving bed void fraction (Ludlow et al., 2013). The solids flow was sampled at 1 Hz. Steady state measurements were recorded following a five (5) minute period when the independent parameters remained unchanged within acceptable error limits and dependent parameters demonstrated no perceptible trend or change.

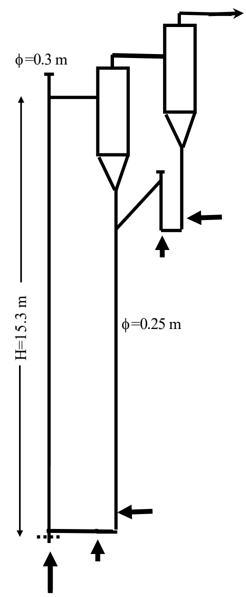

Figure 1. Schematic of NETL cold flow CFB

Table 1. Properties of solids particles.

Material	Polyethylene beads	Glass Beads
Density (kg/m^3)	950	2550
Particle Size (μm)	850	68
Ar	20332	28.5
U_{mf} (cm/s)	8.2	0.15
U_t (m/s)	2.93	0.29
U_{tr} (m/s)	2.62	2.05
Geldart classification	B	A

RESULTS AND DISCUSSION

Effect of Standpipe Aeration

A series of tests were conducted to quantify the uncertainty in solids flow measurements during the testing of a large scale CFB in Challenge Problem III (Panday et al., 2014). For each test condition a wide range of detailed measurements were made on local solids velocities, fluxes, and for dispersion using gas and solids tracers. Thus, each operating condition was repeated many times to enable characterization of the hydrodynamics. Some of the computer modelers responding to the challenge requested information regarding the return leg, specifically the standpipe aeration locations and flows. Since standard procedures were to control the riser flows and use the spiral device in a feedback loop to drive the standpipe aeration without control of the inventory, a new series of tests was needed in which both the inventory and standpipe aeration rates were fixed as well as the riser gas velocity. Contrary to the challenge problem tests, in this test series both the riser pressure profile and the solids flow rate were the dependent parameters.

Initial attempts to achieve reproducible results that matched the Challenge Problem III test condition using the polyethylene beads failed. The variations in the *average* solids flows were as high as 40%. The uncertainty or confidence intervals for the riser pressure drops also increased by an order of magnitude. Initial analysis of the other tracked parameters including barometric pressure, ambient temperature, humidity, and test time or sequence yielded no clear dependence. However, the L-valve in the CFB loop was refitted with a porous metal sparger sized to provide uniform flow distribution along its bottom of the horizontal leg. In the initial configuration, extended only along the horizontal length of the L-valve. It replaced a sparger consisting of a low permeability small diameter (0.0254m OD) plastic tubes feeding off of a plenum that was installed in the standpipe below the horizontal leg of the L-valve. This new sparger had no apparent influence on the lack of control and high day to day variablility observed in the average solids flow rates.

After analysis of this test series, the sparger was extended below the standpipe. The sparger was connected with an elbow at the back wall of the standpipe so that aeration sufficient to fluidize the horizontal leg of the L-valve was introduced under the vertical portion of the L-valve, or standpipe, as well as along the entire length of its horizontal leg. Another series of tests were conducted in which only the aeration flows and total solids inventory were controlled. The solids flows and pressure drops were the dependent parameters. The reproducibility improved dramatically for both the solids flow and the riser pressure when operating in this aeration controlled mode. The uncertainty measured in these dependent parameters was comparable to that uncertainty when operated using a simple feedback controller for solids flow with proportional and integral (PI) gains.

Effect of Pressure

A series of tests were conducted with glass beads to evaluate dynamic aspects of the CFB over a wide range of riser operating conditions. The experiments were conducted with nominally 1 and 2 atmospheres back pressure. Gas velocities and mass flow rates were varied over the range of conditions portrayed in Figure 2. The data sets for different pressures clustered along two distinct lines; the higher pressure tests achieving higher solids flows for a given riser condition. In other words, the 1 atmosphere tests generally achieved lower solids flows than their high pressure counterparts at the same superficial gas velocity. This suggests that solids were easier to move at higher pressure. This can be attributed to higher gas densities and production of smaller more effective bubbles at higher pressures.

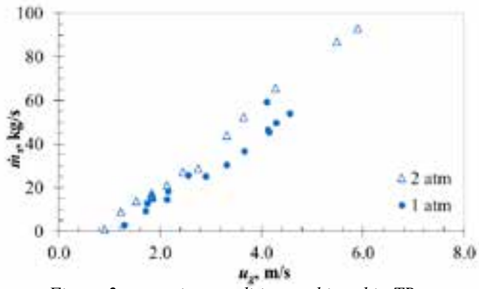

Figure 2. operating conditions achieved in TR tests conducted on glass beads.

However, it can be seen that there are individual tests that crossover these imaginary trend lines based upon pressure. For example, the 1 atmosphere test conducted at about 4.1, and several between 1.9 and 2.3 m/s, achieve high solids flows similar to the higher pressure data. Upon closer inspection of the standpipe conditions it was found that the crossover points produced greater apparent densities in the standpipe than the others that produce their respective lines (Figure 3). Apparent densities in the standpipe were estimated by dividing the pressure gain in the standpipe by the observed standpipe bed level. It should be noted that the overall standpipe pressure gain may include a pressure loss somewhere near the bottom where the relative gas velocity changes direction flowing downward and into the L-valve. Thus, the effect observed could be a change in the relative gas and solids velocities or a change in the transition point where the relative flows change direction. In either case, it was apparent that the conditions in the standpipe were different for these crossover points. It is interesting to note that the 1 atmosphere tests achieved higher solids flows when the apparent standpipe bed densities increased, while the 2 atmosphere tests that were in this higher apparent standpipe density group exhibited the opposite response. The 2 or 3 tests in this same highlighted circle (Figure 3) exhibited marginally lower solids flow below the norm. These differences demonstrate the potential influence of standpipe regime on riser performance. Below we will explore how these same tests stand out in their dynamic solids flow behavior.

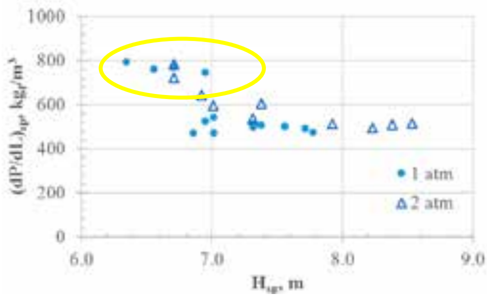

Figure 3. Apparent standpipe bed density for glass bead TR tests and its relationship with standpipe height.

Effect of Riser Gas Velocity

The solids flow in a CFB fluctuates from second to second. Further inspection of the data reported by Ludlow et al. (2013) indicates that over a 2 second sampling interval fluctuations as large as 25% of the average occur frequently (i.e. >25% of the time) while changes as large as 40% of the mean occur occasionally (i.e.> 5% of the time). A more in depth analysis of different granular materials evaluated over different flow regimes demonstrates that this is more typical than may be expected. Data sampled at 1 Hz and with greater resolution in solids flow were analyzed over both particle fluid compromising and fluid dominated riser regimes where the standpipe inventory was tracked using different granular materials. Panday et al. (2016) have demonstrated that the riser dynamics vary significantly in different operating regimes and the processes have different time constants in fluid dominated and particle fluid compromising regimes. A different granular material was chosen here in order to provide further evidence for these observations.

Time series solids flow data for three TR tests having widely different average flows are presented in Figure 4. These represent points in time during a steady state period. A single point is highlighted in the center of each at the mean solids flow condition with error bars representing twice the standard deviation in the total 5 minute steady state period. It is apparent that the 1Hz data was insufficient to capture the structure of the fluctuations including the true peak and shape. Thus, the frequency response could not be accurately analyzed. However, the large relative size of the apparent amplitude of the fluctuations suggests that this is significant to CFB dynamics and strategies designed to control these processes.

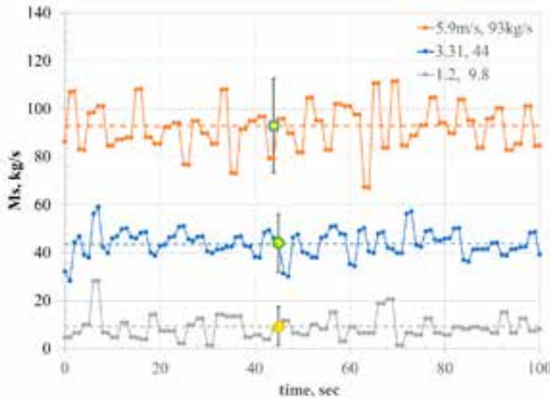

Figure 4. Time series solids flow rates for tests using glass beads TR26, TR32, and TR35 taken at 1.2 m/s in the fast fluidized, and 3.3, and 5.9 m/s in the core annular flow regimes, respectively.

In the highest flow case, a flow swing equal to or greater than twice the standard deviation occurred 11 times in 90 seconds and twice this surge was 4 times this measure. The surges appeared to be fewer over the time period selected for the lower flow cases. Indeed, in the middle test case at 3.3 m/s the surge exceeded 2σ 10 times, but never 4σ. However, in the fast-fluidized case at 1.2 m/s, the amplitude of the fluctuations exceeded 2σ about the same 11 times and 3 times exceeded 4σ. A more thorough comparison is provided by plotting the scaled standard deviation for the complete data set (Figure 5 and 6).

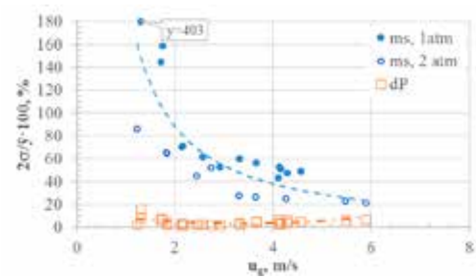

Figure 5. Comparison the scaled standard deviation in $\bar{y}$ - i.e. both solids flow, $\dot{m}_s$, and riser pressure differential, dP_r, for TR tests.

Fluidized beds are well known for their large pressure fluctuations; however, these fluctuations were quite small compared to the fluctuations in solids flows. The fluctuations were characterized by $2\sigma/\bar{y}$, where $\bar{y}$ is the mean value for the dependent parameter, either solids flow, $\dot{m}_s$, or the riser pressure differential, dP_r. Fluctuations in dP_r was analyzed for comparative purposes and to evaluate any correlation between the two. In Figure 5 it is at least qualititatively shown that the fluctuations in the solids flow were dependent upon both the gas velocity, u_g, and pressure, P. The values for $2\sigma/dP_{r,\,avg}$ never exceeded 20% of the mean, while those for solids flow $2\sigma/\dot{m}_{s,\,avg}$ never dropped below 20%. The fluctuations for solids flow were as high as 400% for one case approaching the choking limit, and exponential dropped as the superficial gas velocity increased. In the fast-fluidized regime with gas velocities below 2 m/s the fluctuations were between 160 and 60% of the mean flow. Above this velocity fluctuations varied widely but generally continued to drop as riser gas velocity increased.

The effect of pressure qualitatively described above are evident by comparing the two pressure sets in Figure 5. Fluctuations in solids flow rates at higher pressures were generally smaller than those for the atmospheric cases. A reduction of about one-half of the value for $2\sigma/\dot{m}_{s,\,avg}$ can be attributed to the increased system pressure. The 3 atmospheric cases discussed above which had high apparent standpipe bed densities can be readily identified as having lower values of $2\sigma/\dot{m}_{s,\,avg}$ and fell much closer to the trend line than other atmospheric cases. Likewise, the most apparent high pressure case described above is more readily identified as having an higher $2\sigma/\dot{m}_{s,\,avg}$ value and is nearer the trend line than the other high pressure cases.

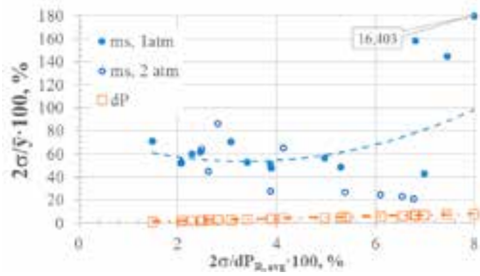

Figure 6. Relationship between scaled standard deviation in solids flow, $\dot{m}_s$, with that in the riser pressure differential, dP_r, for TR tests.

In Figure 6 the magnitude of the solids flow fluctuations are compared directly to the pressure fluctuations. The simple 1:1 correlation between $2\sigma/dP_{r,\,avg}$ and itself is retained for scale. The correlation is not a strong one. There appears to be a general decrease in the magnitude of the solids flow fluctuations with increase pressure fluctuations. However, the trend line for all of the solids flow cases captures the fact that fluctuations in solids flow increased when the pressure fluctuations increased, at least for the very low velocity atmospheric cases. However, in the 2 atmosphere cases, the magnitude of the solids flow fluctuations appeared to decrease with increasing pressure fluctuations. This is consistent with the higher pressure producing a more dense gas that is more effective transporting solids.

CONCLUSION

Test data have been analyzed using Geldart Group A glass beads. Solids circulation in a CFB exhibited large second to second variations which were dependent on both the riser and standpipe operating regimes. These effects have been quantitively characterized using a scaled standard deviation. The solids flow fluctuations were found to greatly exceed those observed in the pressure differentials. Perhaps this was a result of utilizing the overall pressure drop in the riser for comparison; however, this emphasizes the magnitude of the potential impact of solids flow on CFB process dynamics. Operations at elevated pressure and in the homogeneous regime at high gas velocities reduced these fluctuations. Likewise, operations utilizing lower standpipe heights nearer fluidization also decreased the magnitude of solids flow fluctuations. Variability in solids flow and CFB performance using an L-valve was found to be enhanced dramatically by ensuing that any fluidization of the horizontal leg be extended below the vertical standpipe.

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