Observation of Flow Regime Transition in a CFB Riser Using an LDV

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OBSERVATION OF FLOW REGIME TRANSITION IN A CFB RISER USING AN LDV

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Abstract

The solids flow in a circulating fluidized bed (CFB) riser is often described to have a core-annular structure. For a given superficial gas velocity, at the initial introduction of solids into a riser a flow structure of dilute upflow regime exists. Continuing to increase the solids flow in the riser transitions the flow structure to the core-annular flow regime. However, with further increase of solids flow a condition is reached, depending on the superficial gas velocity, where all the solids across the riser cross section flow upwards, even those at the wall. When the solids flux, solids fraction and gas velocity are relatively high, such a condition is described as the dense phase suspension upflow (DSU) regime.

In this paper we report our observations of these flow regime transitions by using a laser Doppler velocimeter (LDV) to monitor the upward and downward particle flow velocities at and near the riser wall of the National Energy Technology Laboratory’s 30.4 centimeters diameter CFB cold flow model. The particles were high density polyethylene (PPE) spheres with a Sauter mean diameter of 861 micron and a density of 800 kg/m³. Three superficial gas velocities of 6.55 m/s, 10.67 m/s and 13.72 m/s were used in this study. For the case of superficial gas velocity 6.55 m/s, the experimental data show that the transition from dilute upflow to core-annular flow occurred when the solids flux was about 7 kg/m²-s and the transition from core-annular flow to dense suspension upflow was about 147 kg/m²-s. As the superficial gas velocity was increased to 10.67 m/s the corresponding flow regime transitions were at 34 kg/m²-s and 205 kg/m²-s, respectively. For the case of superficial gas velocity of 13.72 m/s the data showed no distinct transition of flow regimes. The particles were all upflow for the range of solids fluxes from 10 kg/m²-s to 286 kg/m²-s.

INTRODUCTION

The fluidization condition in a circulating fluidized bed (CFB) is classified as lean-phase fluidization. Within this lean-phase fluidization, two flow regimes exist, the dilute phase upflow regime and the fast fluidization regime (1). The dilute phase upflow regime is characterized by a homogeneous flow structure. The fast fluidization regime is characterized by a heterogeneous flow structure and has higher slip velocity between the gas and solids than that in the dilute phase transport...
regime. In a typical fast fluidized bed, there often exists particle agglomerates or clusters moving up and down especially along the riser wall. This leads to a core-annulus flow structure. The formation of clusters is an important and necessary feature, but by itself is not an adequate condition for a fast fluidized bed (2). In a core-annulus flow structure, the center or core region consists of a mostly dilute phase of upward-flowing gas and particles surrounded by an annular region of descending particles (3). This flow structure is the basis of various CFB models [1]. However, there exists a third flow regime, the dense suspension upflow (DSU), first pointed out by Grace (4). The solids hold-up in his flow regime is typically in the 10% to 20% range and the superficial gas velocities on the order of 6-10 m/s with very high solids net circulation rates, 300-1000 kg/m²-s. Another feature in DSU is the relative lack of particle downflow. Hence, measuring particle velocities at the wall over different solids fluxes should provide the necessary information to identify and discriminate the transitions between these three flow regimes.

We have observed that during the introduction of solids into the riser at the initial stage of operation of a CFB, the solids flow at the upper section of the riser is homogeneous, i.e. in the dilute upflow regime. Upon increasing the solids flux, clusters begin to appear and the flow structure eventually transitions into the fast fluidization regime. Monazam and Shadle (5) have developed a transient method to identify the transition velocities to identify when riser operations are in slugging, fast fluidized or core-annular regimes making the case that many of the riser’s dynamic responses are dependent only upon the gas velocities and solid properties, but independent of the solids flux. Note that this analysis does not distinguish between risers operating with different solids holdups, such as being above and below the saturated carrying capacity (6). Thus, it is of interest to explore the behavior of particles near the wall at an axial location that is normally in the fully developed region of the riser. Basu (2) has stated that there is a lack of a clear picture of the transition to and from fast fluidization. This is interpreted to include transitions due to both the gas velocity and solids flux.

Figure 1. Schematic of National Energy Technology Laboratory's cold flow circulating fluidized bed.
We conducted particle velocity measurements with a laser Doppler velocimeter (LDV) system. By using the axial down-flow velocity component (one can also use the upflow component), we were able to identify the flow regime transitions from the velocity counts. The solids hold up in these flow transitions were compared with the apparent solids fraction profiles based on the differential pressure measurements along the vertical axis of the riser.

FLOW REGIME TRANSITION MEASUREMENTS

The measurements were conducted at the National Energy Technology Laboratory’s cold flow CFB model illustrated in Figure 1. The riser has a height of 15 meters and a diameter of 30.4 centimeters. It has been described in detail elsewhere (5-8). The particles were high density polyethylene (PPE) spheres with a Sauter mean diameter of 861 micron and a density of 800 kg/m³. Three superficial gas velocities of 6.55 m/s, 10.67 m/s and 13.72 m/s were used in this study. The classical or lower transport velocity was 4.3 m/s for this material while the upper transport velocity was found to be 6.3 m/s (5). Thus, all of these tests were conducted in dilute, core annular, or dense suspension upflow conditions.

The LDV was used to monitor the particle flow in the axial direction. The probe volume of the LDV was positioned at 9.3 meters above the centerline of the solids entry port. This location is the upper part of the middle region of the riser (9). The riser wall in this section is of optical quality acrylic material. The approach was to obtain the upflow and downflow velocity counts rather than velocities in the space close to the inside wall of the riser. We set the transceiver of the LDV on a manually operated translation platform. A digital meter with a resolution of 0.01 mm is attached to the driving screw. In order to ensure the LDV probe volume is at the riser wall, we initially positioned it inside the acrylic wall of the riser. With the CFB running on air only, the vibrations induced on the structure by the air flow was sufficient to generate detectible velocity signals on the LDV, shown in Figure 2. Monitoring these signals while advancing the probe volume of the LDV through the wall, the "at wall" position was determined accurately when these noise velocity signals disappeared. Figure 3 is an example when such a condition was reached. The few particles detected over
the 30 second period were probably particles entrained from the CFB wall.

RESULTS AND DISCUSSIONS

Since the condition of a flow regime is defined by the axial component of the particle velocity we used the downflow velocity counts in our analysis. It would be equally valid to use the upflow velocity counts. 

Flow Regimes Transition at Superficial Gas Velocity $U_g = 6.55 \text{ m/s}$

This superficial gas velocity was chosen to be consistent with previous CFB operation conditions to provide experimental data for model validation study. Figure 4 shows that a typical velocity distribution containing broadly two to three velocity groups. The flow direction convention used by the instrument is such that positive velocities indicate downflow direction and negative for upflow direction. Hence, in Figure 4 the negative velocities are particle upflow velocities in the CFB riser and the positive velocities are downflow particle velocities.

With reference to the velocity histogram, notice that the high velocity group has velocities more than twice the superficial gas velocity used. It has been reported that some particles in a riser may have velocities much higher than the gas velocity [10]. However, because of their relatively low count, most of the data sets showed that they comprised less than 10% of the total velocity counts; we have not included them in our analyses. We expressed the down flow velocity counts, respectively, as a percentage of the total velocity count, excluding the high velocity group. In Figure 5 we plotted the downflow velocity count in percentage of the total velocity count (both upflow and downflow) against particle flux derived from mass flow rate measured by a spiral device (6). However, for particle
flux greater than 100 kg/m²-s we observed that the downflow velocity count percentage decreased as the particle mass flux increased. This indicates a shift in the particle flow direction towards the dense suspension upflow condition.

We compared this observation based on the velocity count analyses with the solids fraction profiles for two flow conditions, one in the dilute upflow and one in dense suspension upflow as shown in Figure 6. For low solids flux condition (the red curve) the apparent solids fraction at the 9 to 10 meter level shows a value of much less than 10% indicating the bed is in the dilute transport regime which is also indicated in Figure 5, showing low downflow velocity count percentage. On the other hand, for the high flux case the solids fraction profile (the blue curve in Figure 6) indicates a solids fraction of higher than 10% exists at the 9 to 10 meters level agreeing with that indicated in Figure 5.

**Flow Regime Transition at superficial velocities of 10.67 m/s and 13.72 m/s**

Similar measurements were made at higher superficial gas velocities. The purpose is to see how, if any, the superficial gas velocities would affect the flow regimes transition. It is obvious that at higher superficial gas velocity, because of the dilution effect, one would expect the transition would require higher solids flux.

For the case of superficial gas velocity of 10.67 m/s the downflow velocity counts are plotted in Figure 7 as in Figure 5. However, it seems that the transition from dilute transport regime to core-annular flow regime was not clearly observed. The overall downflow velocity count
percentage is low throughout this solids flux range indicating that high percentage of the particles were being carried upwards by the higher carrier gas velocity. The decrease in downflow as solids flux is increased suggests that the flow structure is approaching the dense suspension upflow (DSU) regime. The data show that at high gas velocities (for both low and high solids fluxes) there can be no net downflow at the wall. These data also suggest that dilute phase flow may transition to DSU regime without going through the core annular flow regime. However, more experimental data will be needed to verify this trend. Figure 8 show the apparent solids fraction profiles. As the data suggested, at riser gas velocity of 10.67 m/s and at solids flux of 205 kg/m2-s, the average solids fraction was still less than 10%.

The corresponding downflow velocity count percentage plot and the apparent solids fraction profile plot for the superficial gas velocity of 13.72 m/s are shown in Figures 9 and 10, respectively. Figure 9 shows that there is no apparent flow regime transition detected. The apparent solids fraction profile, Figure 10, also indicates low solids hold-up in the riser at the sample location showing the diluting effect. Indeed, at these high gas velocities it may require much higher solids flux to the riser to achieve dense suspension upflow.

CONCLUSIONS

We have shown that it Herman Yue <hermanyue76@gmail.com> is possible by monitoring either the downflow or upflow velocity counts measured by an LDV system at the riser wall to demarcate the transitions of flow regimes. These transition measurements were supported by apparent solids fractions obtained from differential pressure measurements at the corresponding sampling region of the riser. At higher riser gas velocity, the flow regime transition from dilute phase flow may directly transit to DSU flow regime without going through the core annular flow regime. This solids flow behavior may be attributed to the higher percentage of particles are being transported out of the riser through the high gas velocity. However, more experimental data will be needed to verify this trend.
NOTATION

\( M_a \quad \text{Mass circulation rate, kg/hr} \)
\( U_g \quad \text{superficial gas velocity, m/s} \)

REFERENCES