Detailed measurements of flow dynamics inside a dense gas-solids fluidized bed

Haiyan Zhu and Jesse Zhu
Departments of Chemical and Biochemical Engineering,
University of Western Ontario, London, Ontario, N6A 5B9

Turbulent fluidization is commonly utilized in industrial processes, (e.g. FCC regeneration, Fischer-Tropsch synthesis, acrylonitrile production, silicon chloridization and particle drying) due to its vigorous gas-solid contacting, good mixing, high heat and mass transfer rates, high solids hold-ups (typically 25-35% by volume) and relatively low axial mixing of the gas. Despite its practical importance, turbulent fluidization has received much less attention than other flow regimes and many important aspects of hydrodynamics of fluidized systems are still poorly understood, probably due to the significant complex dynamic flow behavior. This study provides a comprehensive experimental work about flow structure characteristics in both bubbling and turbulent fluidization and the regime transition, and then establishes a good description of flow patterns for the turbulent fluidized bed.

Experiments were carried out in a large diameter air-fluidized bed (0.267m i.d. × 2.5m high) using FCC particles (d_p = 62 µm, ρ_p =1780 kg/m^3). The flow dynamics were investigated based on local solids concentration and velocity data, as well as differential pressure signals, under various superficial gas velocities of 0.02~1.4 m/s (covering both bubbling and turbulent fluidization regimes). Differential pressure transducers are used to measure the pressure drops with a frequency of 1000 Hz and the total acquisition time is 30s. A newly developed optical fiber probe system capable of simultaneously measuring instantaneous solids concentration and velocity at two different locations or just measuring solids concentration at four different locations were used to determine the radial solids concentration and velocity profiles at several axial levels. The diameter of the probes is 3 mm, each of the probe contains two sub-probes with diameters of 0.3 mm and the physical center-to-center separation distance is 0.3 mm; the sub-probes consist both light-emitting and receiving quartz fibers, arranged in an alternating array, corresponding to emitting and receiving layers of fibers, the diameter of fibers is 25 um. In order to prevent particles from occupying the blind zone, a glass cover was placed over the probe tip. The received light reflected by the particles is multiplied by the photo-multiplier and converted into voltage signals. The voltage signals are further amplified and fed into a PC. In order to map the entire cross-section of the fluidized bed, three entry ports are installed around the periphery of the column to measure the solids concentration and velocity. To ensure the validity and repeatability of sampled signals, for each run the sampling time is 30s with a frequency of 50 kHz. Because the relationship between the output signals of the optical fiber probe and the solids concentrations is nonlinear, a reliable calibration is required to ensure that the output correctly represents the measurement. The calibration was carried out in a stable gas-solid downcomer system with a small enough diameter (1/2 inch) so that a local measurement could yield a cross-sectionally averaged value. The solids volume concentration values range from 0 to 0.56 which corresponding to the solids concentration in a loosely packed bed.

Longitudinal differential pressure profiles (H_0 = 1.3 m): 1) with increasing superficial gas velocity U_g, two clearly identifiable transition velocity U_g = 0.6 ~ 1.0 m/s and U_g = 1.1 ~ 1.4 m/s are revealed in the pressure gradient profiles; 2) at the same U_g, the pressure gradient decreases with increasing bed height; it may be contributed to the bubble growth with the height and large mount of entrainment of particles; 3) the corresponding standard deviations profile of differential pressure fluctuations shows the same two transition velocities; here we define the lower transition velocity as U_c; 4) it is interesting to note that with increasing the bed height the critical points shrift to lower gas velocities (from U_c = 0.6 m/s at H = 1.1 m to U_c = 1.0 m/s at H = 0.4 m), indicating that the bubbles breakup start first in the upper section of the bed and the fluctuations caused by the movements of bubbles reach a maximum first.

Instantaneous solids concentration in bubbling and turbulent flow regime (H_0 = 1.3 m, H = 1.1 m, r/R = 0.3): 1) in bubbling flow regime ($U_g < U_c$), the magnitude and intensity of the fluctuations of instantaneous solids concentration increasing with gas velocity, but there are still clear two phases: dense phase and bubble phase. However, with further increasing gas velocity beyond U_c, the stable dense phase disappears and the bubbles' frequency becomes more intense, resulting in the disappearance of stable two-phase flow structure and an stronger turbulent gas-solids flow, which is the typical feature of turbulent flow regime; 2) the corresponding possibility density distribution (PDD) curves give more information about the changes in flow structures: with increasing gas velocity the distinction between the bubble and dense phase disappears gradually (almost no signals for $0.15 < \varepsilon_s < 0.35$), and for the high gas velocity ($U_g > U_c$), it is very difficult to identify the two phases; 3) in bubbling flow regime, the solids concentration (about 0.45) in the dense phase changes a little with increasing gas velocities, however in the turbulent regime, the solids concentration in the dense phase or the clusters decreases obviously (from 0.45 to 0.41) with increasing U_g.

Radial solids distribution and fluctuation (H_0 = 1.3m, H = 1.1m): 1) the results taken by three probes from three different radial directions show that under all gas velocities the radial solids concentration distribution is not symmetric, and the degree of asymmetry increases with the gas velocity until reaching U_c (~ 0.6 m/s), further increasing the gas velocity, the asymmetric phenomenon becomes not obvious; 2) for local flow regime, the transition from bubbling to turbulent fluidization is a gradual process instead of a sudden change; 3) at low gas velocities (< U_c), the average solids concentration is remain stable along the radial direction, at higher gas velocities, there is a relatively uniform and dilute region (ε_s ~ 0.2) in the central region and a dense annular region (ε_s = 0.25 ~ 0.4) near the wall , however, there was no clear boundary between the dilute and dense zones; 4) at the region from r/R = 0.4 to 0.85, the solids concentration distributions are extremely non-radial symmetric, especially when operating conditions belong to bubbling regime. One reason is that the bubbles move in a zigzag pattern instead of straightforward route, so the radial bubble distribution is not symmetric. Second, at the wall region, because of the wall effect or the wall friction, solids hold-up is relatively high, so there are few bubbles appearing or generated, and in the central region the bubble sizes are smaller than that in the middle region, due to the high gas velocity in the center region and stronger gas turbulent eddies; 5) the corresponding radial profiles of standard deviation clearly shows a non-symmetric flow structure under lower gas velocities (< U_c), and confirms again that for local flow the transition from bubbling to turbulent fluidization is a gradual process, the high standard deviation values suggest a vigorous gas-solids interaction; 6) the solids concentration and its corresponding standard deviation profiles as a function of U_g at different radial positions also gives two identifiable transition velocities: U_g = 0.5 ~ 0.7m/s and 1.0 ~ 1.2m/s; with increasing gas velocity, the solids concentration in the central region decreases much faster than that in the wall region, and this decreasing rate decreases by moving outwards towards the wall region, and at very near wall region (r/R = 0.98), the solids concentration almost maintains constant (around 0.48) at all operating conditions.

Axial solids distribution and fluctuation (H_0 = 1.3 m): in order to obtain more accurate and detailed information about the axial solids concentration profiles, four optical fiber probes are used to take the measurement simultaneously at four different axial levels (H = 0.4, 0.6, 0.8, 1.1m), the results show that: 1) the axial solids concentration distributions are not uniform under all operating condition, in the upper region, the solids concentrations are always lower than that in the bottom region, especially under the lower gas velocities (< U_c); 2) with increasing gas velocity, the solids concentrations at upper region decreases much faster than that in the lower region; 3) the similar two transition velocities (U_g = 0.6~0.7 and 1.0~1.2m/s) are also found, at lower height, the transition velocities tend to shift to higher values.

Particle velocity profiles (H_0 = 1.3 m, H = 1.1 m): In the study, cross-correlation of the signals method was used to calculate the particle velocities. The direction of the particle movement was calculated based on the maximum cross-correlation coefficient from the positive and negative correlation of the signals. The results indicate that: 1) under all operating conditions, both positive (particle up-flowing) and negative (particle descending) velocities exist at all measuring locations, the velocity distributions are not uniform in both radial and axial directions; 2) with increasing superficial gas velocity, the positive particle velocity in the central region increases much faster than that in the wall region; 3) in the central region the negative particle velocity changes a little with superficial gas velocity, however it increases much faster in the wall region with increasing superficial gas velocity; 4) the effect of superficial gas velocity on the positive particle velocity is much larger than that on the negative particle velocity, especially within turbulent flow regime; 5) the effects of axial position on the positive particle velocity: for all the conditions studied, the velocity at the top level (H = 1.1m) is always the highest, and the lowest velocity appears at middle region (H = 0.6 and 0.8m), it is reasonable result due to the effect of the gas distributor and solids entrainments; 6) the negative particle velocity change a little with axial positions, especially in the central region; in the wall region, with increasing superficial gas velocity, the negative particle velocity at lower axial level increases faster than that in the upper region.

Effects of static bed height on local flow structure (from H_0 = 0.9 to H_0 = 1.3 m): the results reveal: 1) the static bed height does not exhibit considerable effluence on the transition velocity U_c from bubbling to turbulent regime for the same axial position; 2) with increasing the static bed height, the solids concentration increases at all measurement locations, the increase is larger in the central region than that in the wall region; the rate of increase is proportional to the superficial gas velocity until reaching U_c, then the rate is reduced with further increasing gas velocity; 3) increasing static bed height reduces the degree of the non-uniformity of radial solids concentration distributions, especially for the bottom region, however, the radial asymmetry phenomenon becomes more serious.

Conclusion:

1) Results show that in the turbulent fluidized bed the two-phase flow structure breaks down and the solids concentration distribution is not at all uniform in both radial and axial directions;
2) By analyzing the differential pressure drops and the transient behavior of the solids concentration, two transition velocities has been found;
3) Although the curves of standard deviation for the differential pressure signals and local solids concentration all peak at the transition velocity U_c from the bubbling to turbulent regimes, the statistical analysis of the radial solids concentration distribution indicates that the local flow regime transition from bubbling to turbulent fluidization is a gradual process instead of a sudden change;
4) According to the measurements of three probes from different radial directions at the same axial level, the across-sectional non-uniform flow structure has been identified: in the bubbling regime, this non-uniformity increases with increasing gas velocity; however in the turbulent regime, the flow structure becomes more radial symmetric with increasing gas velocity, and generate a relatively uniform central region and a high-density annulus region;
5) Under all operating conditions, both up-flowing and descending particles exist at all measuring locations; the positive particle velocities are greatly increased with increasing superficial gas velocity and static bed height, especially within turbulent flow regime, and the variations in negative particle velocities are relatively slow;
6) Although increasing static bed height has no significant influence on the transition velocity U_c at a given axial position, it generates a denser fluidized bed, and the local flow structure becomes more uniform.