Particle Velocity Measurements in a Circulating Fluidized Bed

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In recent years, circulating fluidized beds (CFBs) have been extensively employed in a variety of industrial applications related to coal combustion and gasification, solid waste incineration, catalytic cracking of oil, and so on. To accomplish successful and reliable operation of CFBs, a number of investigations pertaining to different hydrodynamic aspects have been undertaken. Many of these are referenced in the monograph of Basu and Fraser (1991), review of Horio (1991), and the article of Mahalingam and Kolar (1991). The gross hydrodynamic features of CFBs are generally understood, but the detailed structure is established only to a limited extent. Some advancements in this direction have been made in recent years by Yang et al. (1991), Horio et al. (1988), and others. Detailed researches in this direction will considerably help in the optimum and economic designs of CFB boilers. To aid in this direction, we have measured the three-dimensional particle velocities in a square-section CFB cold model under certain operating conditions at ambient temperature and pressure. Particle turbulent intensities and bed cross-sectional averaged voidage along its height are also measured. A majority of the investigations have been conducted in circular cross-section CFBs, but industrial preference is for a square cross-section boiler, and hence we have adopted this configuration in our present work. Our measurements, while confirming the core-annulus flow structure for CFBs, also provide a more comprehensive microscopic detail of particle velocities in the two regions, in addition to providing a basis for particle aggregation.

Experimental Apparatus and Results

The schematic of the CFB employed in the present work is shown in Figure 1. The riser section is 3 m long and has a square cross-section, 222 mm by 222 mm. Seventeen pressure taps (13) are installed along the metal bed wall starting from a height of 250 mm above the air distributor plate (3) and up to the height of 2.5 m. Most of these taps are 0.1 m apart. The air distributor plate has 25 bubble caps, each having 18 orifices of 6 mm in diameter. The open area is 25.8%. The bed is drained through an opening (4). The horizontal section (7) connecting the bed with the gas-solid cyclone separator (8) is 240 mm long and has a rectangular section, 140 mm by 360 mm. This cyclone has a novel design (Chen et al., 1991) with downward movement of gas and is specially appropriate for "PI" type of boilers. A Y-type valve (9) connects the cyclone to the bed. Air to the CFB riser section is supplied from a concentric blower (1) through the air box (2). Solids are fed to the bed through a hopper (5). Air controlled by a butterfly valve (10) enters into the Y-type valve through a perforated gas-plate distributor (11) to return the solids from the cyclone into the bed. By adjusting this air-flow rate that is relatively small compared to the main air flow, the particle recycle rate is controlled. A sand bed of average surface-volume particle, 530 μm in diameter, is used in the present investigations. The sand particle density is 2,300 kg/m^3, and the slumped bed height is kept at about 0.3 m in all the experiments described below.

A particle dynamic analyser (PDA), supplied by Dantec Electronics Ltd. of Denmark, is used to measure the three components of a particle velocity. Its major components are shown in Figure 2. PDA is based on the principle of Phase/Doppler for simultaneous noncontact and real-time measurements utilizing the knowledge of phase differences between Doppler signals received by three detectors at different positions. The PDA measuring system (Figure 2) comprises an argon optical laser (1), injector (2), one-dimensional optical distribution box (3), two-dimensional optical distribution box (4), green filter and photomultiplier (5), violet filter and photomultiplier (6), receiving fiber-optic system (7), blue filters and photomultipliers (8–10), one-dimensional fiber-optic probe (11), two-dimensional fiber optic probe (12), test section (13), 386 computer (14), and signal processor (15). At a given height, the test section is a horizontal plane through the bed riser as shown in Figure 3. The particle velocities in this horizontal plane are designated as V_x and W_y along the X and Y axes, respectively. In the vertical direction (Z-axis) perpendicular to this horizontal XY plane, the velocities are designated by U_Z.

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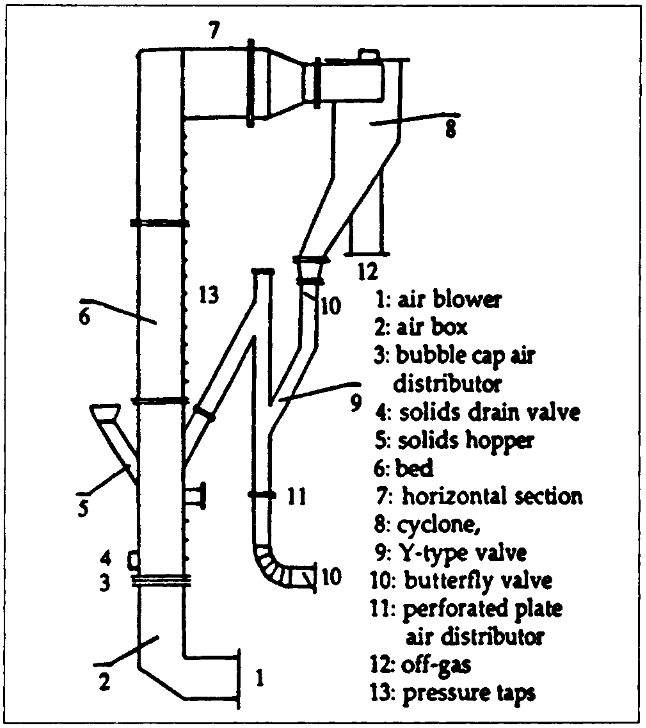

Figure 1. Circulating fluidized bed.

Positive and negative U_Z values indicate vertical velocities in the upward and downward directions, respectively. Positive directions for V_x and W_y along the X and Y axes, respectively, are as indicated in Figure 3.

The pressure drop ΔP across two probes on the bed wall section separated by a distance L are related to bed voidage, ϵ, by the following relation for a fully developed flow when the wall friction and local particle acceleration are negligibly small:

$$\Delta P = (\rho_s - \rho_g)(1-\epsilon)gL$$

Here ρ_s and ρ_g are the solid particle and gas densities, respectively, and g is the acceleration due to gravity. Pressure gradient, $\Delta P/L$, along the bed height is therefore directly proportional to $(1-\epsilon)$ or solids concentration. In Figure 4,

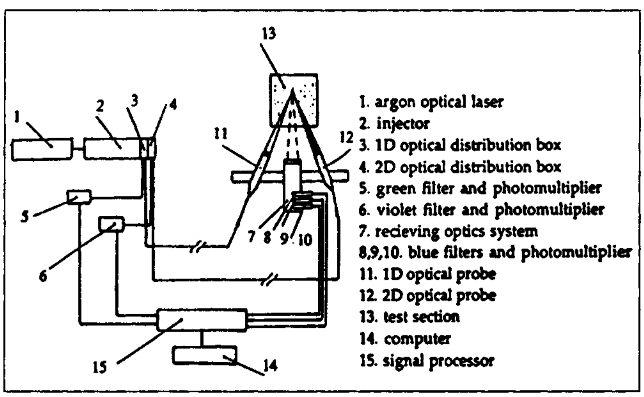

Figure 2. Particle dynamic measuring system.

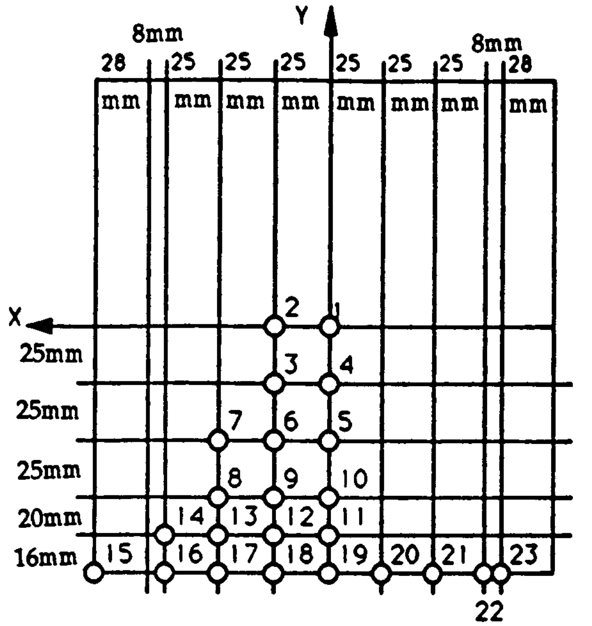

Figure 3. Distribution of 23 measurement points in a horizontal plane.

such data are presented for four different values of superficial air velocities (Ug) in the range 4.20 to 6.80 m/s. The corresponding values of solids circulating rates (G_s) are also listed which are in the range 13.0 to 27.8 kg/m^2•s. This variation of $(1-\epsilon)$ with H, the height above the gas distributor plate, is similar to that obtained by other workers: see, for example, Schnitzlein and Weinstein (1988) and Takeuchi and Hirama (1991). At the lowest gas velocity (4.2 m/s), the solids concentration is the largest and is constant in the lower bed section, while it is the smallest and is constant in the upper bed section. These are typical characteristics of fast fluidization in a CFB, that is, a dense bed in the lower section and a dilute suspension in the upper section of the bed. At the highest gas velocity of 6.8 m/s, the solids concentration is uniform all along the bed height. The latter condition is usually referred to as the dilute transport regime. All our data are in the fast fluidization re-

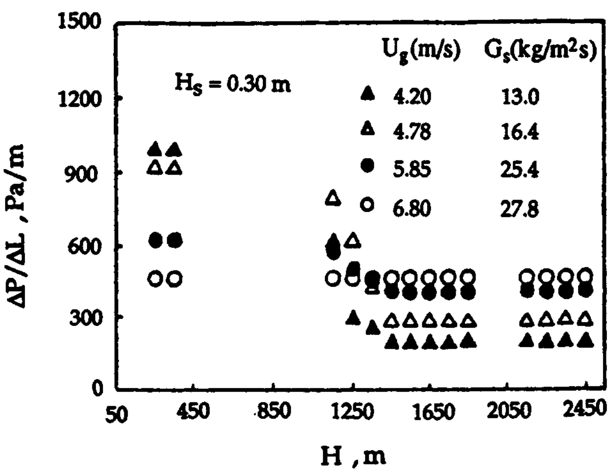

Figure 4. Variation of solids concentration along the bed height for constant U_g and G_s values.

gime, and Bi and Fan (1992) have discussed these turbulent and transport regimes.

The 23 measurement points in the XY-plane are shown in Figure 3 which are uniformly distributed on the grid with a pitch of 25 mm except for the two outer horizontal row and vertical column spacings that are 16 and 20 mm and 28 and 8 mm, respectively. The variations of the vertical components of particle velocities (U_Z) along the Y-axis at positions designated at 1, 4, 5, 10, 11, and 19 (Figure 3) are shown in Figure 5 for eight different heights above the gas distributor plate: 1.19, 1.34, 1.49, 1.64, 1.79, 1.94, 2.09 and 2.24 m. The corresponding values of U_g and G_s are 5.85 m/s and 25.4 kg/m^2·s, respectively.

At the upper four cross-section elevations (1.79, 1.94, 2.09 and 2.24 m), the upward particle velocity is maximum at the bed axis and the same decreases as the measurement point moves away from the bed axis toward the bed wall in a horizontal plane. The particle velocity at each elevation eventually becomes zero at some position, and thereafter the particle moves downward with increasing negative velocity as its location moves toward the wall. At a certain position, the downward particle velocity assumes a maximum value; thereafter, as the particle position moves closer to the wall, it moves relatively slower though still in the downward direction. At the lower elevations, H values being in the range 1.19 to 1.64 m, the important difference to notice here is that the particle velocities (U_Z) in the lower section of the bed do not always approach zero and then to negative values as in the higher bed section. In certain cases, the particles maintain their upward velocity and approach to a minimum positive value close to the bed wall, and then the upward velocity increases for particles in the region close to the bed wall. See, for example, curve 3 for $H = 1.49$ m. Thus, the nature of particle movement in the microscopic scale in the region close to the bed wall is more complicated than conjectured so far, and its qualitative nature has some dependence on bed height, particularly in the lower dense section of the riser.

Similar measurements at nine grid positions, 15 through 23 (Figure 3), located within 1 mm of the bed wall are shown in Figure 6. These velocity profiles are in qualitative agreement with one another and exhibit the fact that particle downward velocities are increasing at locations toward the wall, generally supporting the observed structure of the bed annulus region. For all the eight values of H in the range 1.19 to 2.24 m, the qualitative variation is about the same and variation in U_z values with changes in H values does not exhibit any systematic trend.

Particle velocities (W_y) measured in a horizontal plane at eight different positions above the gas distributor plate (H) in the range 1.19 to 2.24 m and for a maximum of six positions (1, 4, 5, 10, 11 and 19 indicated in Figure 3) are presented in Figure 7. Particle velocities (V_x) measured in the same eight horizontal planes and for the same six positions as in Figure 7 are shown in Figure 8. A characteristic trend to note is that the V_x component of particle velocities are always positive, while W_y particle component velocities fluctuate between positive and negative values. This may be caused by solids circulation and point to a general trend: particles in the core region are moving in the direction of the wall and particles in the wall region are moving toward the core, but at a lower velocity.

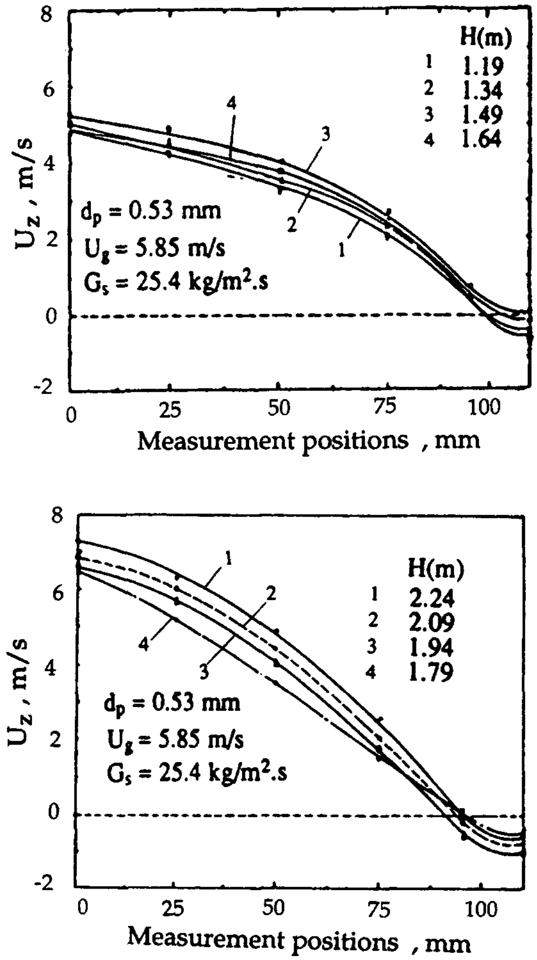

Figure 5. Variations of vertical component of particle velocities at different positions 1, 4, 5, 10, 11, and 19 (Figure 3).

Discussion of Results

Yang et al. (1991) reported the local particle velocity measurements at ambient conditions of a FCC catalyst particle bed of 59 μm in average diameter and having a solids density of 1,474 kg/m^3. The riser section of the CFB was 11 m tall and had an internal diameter of 140 mm. The measurements were taken for the superficial gas velocity of 4.33 m/s at a height

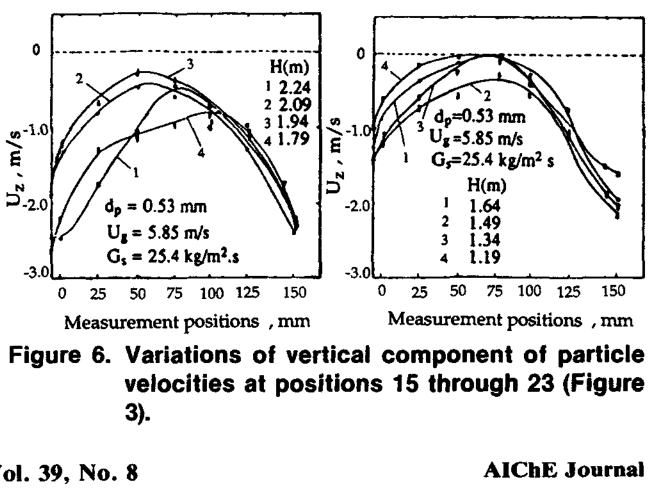

Figure 6. Variations of vertical component of particle velocities at positions 15 through 23 (Figure 3).

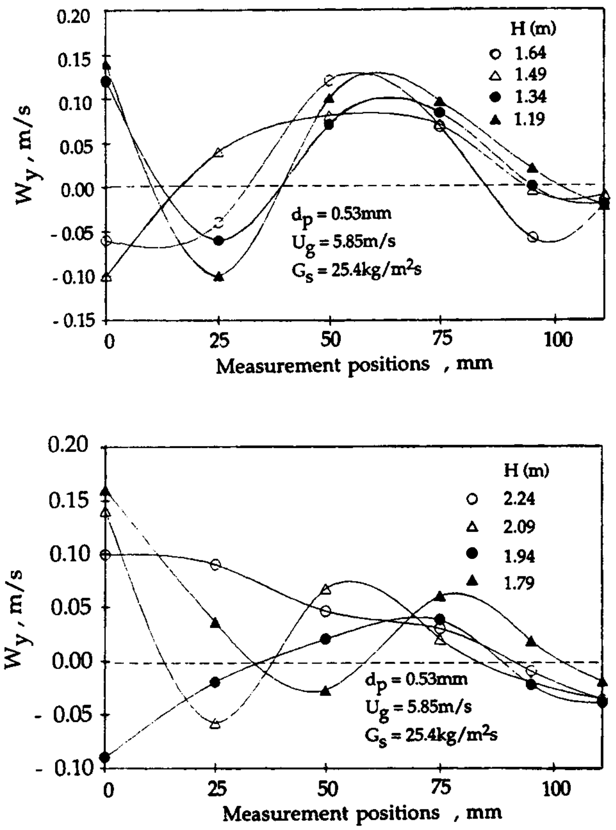

Figure 7. Variations of horizontal velocity W_y for a sand bed (d_p = 0.53 mm) at different gas velocities and bed heights for positions 1, 4, 5, 10, 11, and 19 (Figure 3).

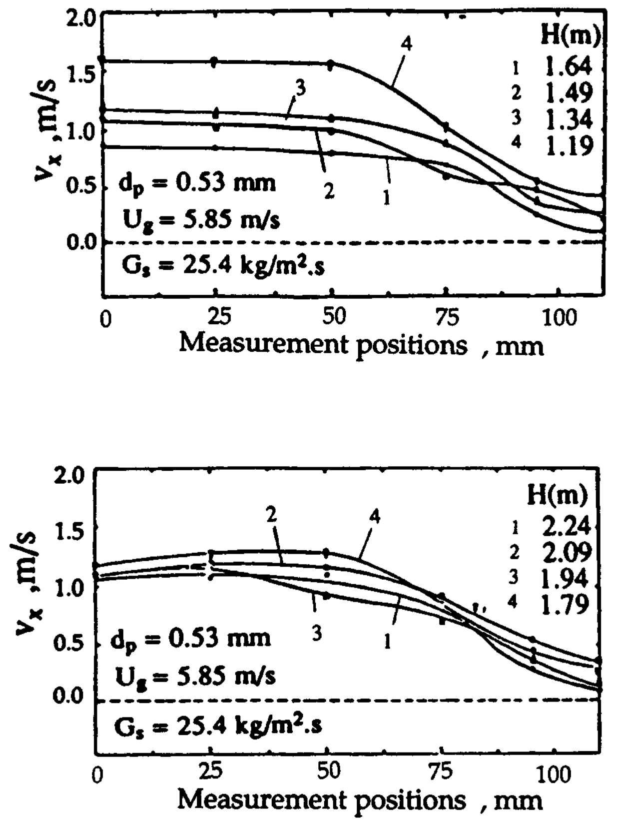

Figure 8. Variations of horizontal velocity V_x for a sand bed (d_p = 0.53 mm) at different gas velocities and bed heights for positions 1, 4, 5, 10, 11, and 19 (Figure 3).

of 3.3 m above the gas distributor plate and for the solids circulating rate of 7.6 and 31.9 kg/m^2·s. In both cases, they found the particle velocity to decrease monotonically and approach the small negative values in the region close to the bed wall. This qualitative variation is in slight disagreement to that found here in the present work. On the other hand, these present velocity profiles are in good agreement with those established by Li et al. (1991) on the basis of their theoretical calculations employing the energy minimization principle. They found the upward particle velocity to decrease initially in the increasing radial direction toward the wall, achieve a negative minimum value, and then increase to a small positive value in a region close to the bed wall.

Turbulent energy of the particles defined as $U_Z V_x$, $V_x W_y$, and $U_Z W_y$ (Hinze, 1975) are presented in Figure 9 for a superficial gas velocity of 4.78 m/s and for four values of H. The solids circulating rate in each case is 16.4 kg/m^2·s. These refer to six grid positions, 1, 4, 5, 10, 11, and 19, as specified in Figure 3. In all cases, it is seen that the turbulent particle energy is maximum in the central core region of the riser and the same decreases in the annulus region toward the wall where it is minimum. No systematic differences are observed with H. In the riser core region, the particle turbulent energy is large, and hence the particle aggregation tendency is smaller as compared to the annulus region where the particle turbulent energy is small which will promote particle aggregation. The present measurements thus support the observed enhanced formation of particle clusters and strands in the annulus region better than in the core region of the riser.

Conclusions

Based on the experimental results described above, the following conclusions may be drawn:

- In the square-section riser of a circulating fluidized bed, a variation of the solids concentration along the bed height is obtained for a range of superficial gas velocities. Above a certain gas velocity, the CFB transforms into a transport regime operation when the solids concentration is almost constant along the bed height.
- The measurement of the vertical component of particle velocities in a sand bed for different gas velocities at different elevations and locations supports the commonly believed core-annulus flow structure of the CFBs. Recently, Rhodes et al. (1991) have concluded the same from their measurements of solids residence time distributions.
- The measured particle turbulent energies support the preferential formation of particle aggregates (cluster and strands) in the annulus region relative to the core region of the CFB riser. This, of course, is in accord with visual observations of many investigators.

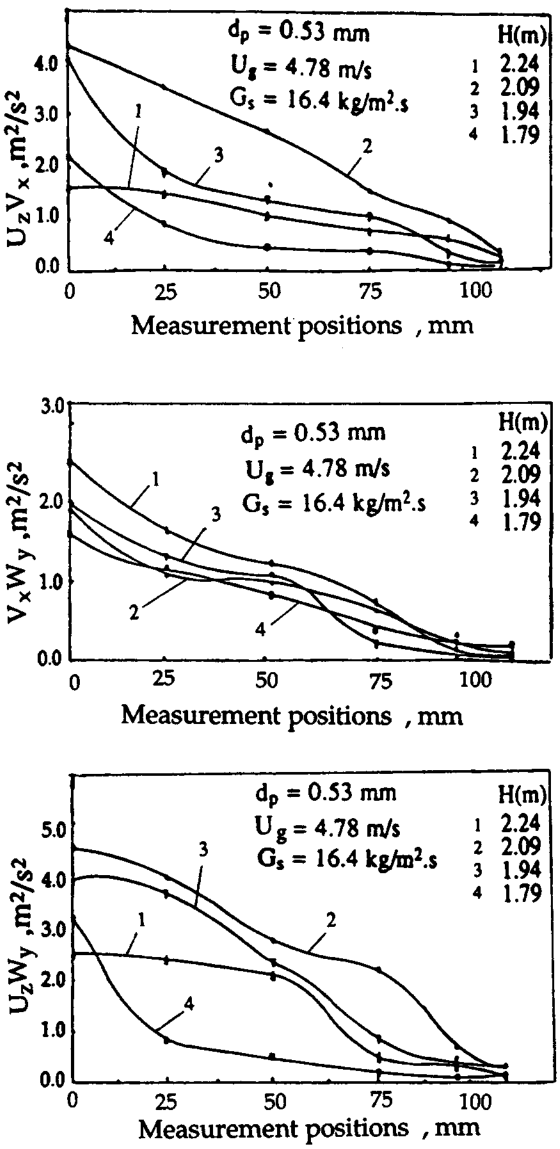

Figure 9. Variations of particle turbulent energies at positions 1, 4, 5, 10, 11, and 19 (Figure 3).

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Notation

d_p = average bed particle diameter, mm
g = acceleration due to gravity, m/s^2
G_s = solids circulating rate, kg/m^{2}s
H = height above the gas distributor plate in the riser section of the bed, m
H_s = slumped bed height, m
L = length of a bed section, m
U_g = superficial gas velocity, m/s
U_Z = vertical component of a particle velocity in the Z-direction, m/s
V_x = horizontal component of a particle velocity in the X-direction, m/s
W_y = horizontal component of a particle velocity in the Y-direction, m/s
X, Y, Z = axes of three-dimensional coordinate system

Greek letters

ΔP = pressure drop across a bed section, Pa
ρg = gas density, kg/m^3
ρ_s = solids density, kg/m^3
ϵ = average voidage of a bed section

Abbreviations

CFB = circulating fluidized bed
FCC = fluid catalytic cracking
PDA = particle dynamic analyzer

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