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Radial Distribution of Local Concentration Weighted Particle Velocities in High Density Circulating Fluidized Beds

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RADIAL DISTRIBUTION OF LOCAL CONCENTRATION-WEIGHTED PARTICLE VELOCITIES IN HIGH-DENSITY CIRCULATING FLUIDIZED BEDS

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ABSTRACT

An extensive experimental investigation of radial profiles of concentration-weighted particle velocities was carried out by simultaneously measuring local transient particle velocity, solids concentration and solids flux using a three-fibre optical probe at five axial levels and seven radial locations in a 0.2 m diameter riser operating over a wide range of solids circulation fluxes (198 to 350 kg/m^{2}s) and superficial gas velocities (6 to 8 m/s). Particle velocities averaged over time and concentration-weighted particle velocities were compared and found to differ from each other, the latter being smaller than the former at most radial locations. The difference, which results from the correlation between velocity and voidage fluctuations, was more pronounced for high-density conditions.

INTRODUCTION

Understanding flow behavior is essential for successful design and scale-up of circulating fluidized bed (CFB) systems. Particle velocity is an important parameter due to its effect on mixing, heat and mass transfer and erosion in fluidized bed systems. For these measurements, many researchers have preferred optical fibre probes because of their simplicity, high accuracy and relatively low cost. In addition, given their compact size, optical probe measurements are localized, with minimum disturbance to the flow dynamics (1). Although these measurement systems are used widely, few of these techniques offer the possibility of determining local instantaneous particle velocities and solids concentrations simultaneously. In comparison to low-density CFB riser studies, few investigations have been conducted on the radial distribution of particle velocity in the dense section of CFB risers or in high-density CFB units operated at solids circulation fluxes (G_s) beyond 200 kg/m^{2}s due to the limitations of experimental facilities and measurement systems.

Among the researchers who have worked on high-density systems, van Zoonen (2) was the first to determine net particle velocity profiles. He employed a Pitot tube in a 0.05 m diameter, 10 m high riser. He reported the particle velocities at the wall to be always positive. On the other hand, using a backward scattering optical fibre laser Doppler velocimeter (LDV) system, Wei et al. (3) detected downward net particle velocities near the wall of a 0.186 m diameter riser operating in superficial gas velocities (U_g) from 2.3 to 6.2 m/s and net solids fluxes (G_s) ranging from 18 to 200 kg/m^{2}s. They also reported that profiles of particle velocity are influenced by the operating regime of the riser. After reviewing various reported methods for measuring local particle velocities in gas-solid suspensions, Zhu et al. (4) suggested a compact five-fibre optical probe system due to its ability to measure particle velocities from 0.3 to 24 m/s, for particles with mean sizes in the range of 50 μm to 5 mm, and for solids hold-up between 0.1% and 25%. With the same probe, Parssinen and Zhu (5) measured radial profiles of particle velocities in a 76 mm diameter riser over a wide range of U_g (up to 10 m/s) and G_s (up to 550 kg/m^{2}s). They characterized the radial profiles of particle velocities as S-shaped and found that they were significantly less uniform at high fluxes (>300 kg/m^{2}s) than at low fluxes (<200 kg/m^{2}s). The superficial gas velocity was found to have more influence on the radial velocity profiles than the solids flux at high solids circulation fluxes. They also observed the disappearance of negative particle velocities with increasing solids circulation flux. Liu et al. (6) drew attention to the need to investigate the effect of suspension density on particle velocities. Using a 3-fibre optical probe, they were able to simultaneously measure particle velocities, solids concentrations and solids fluxes in a riser of 0.076 m diameter, a component of a dual-loop HDCFB unit, at superficial gas velocities of 4 to 8 m/s and solid circulation fluxes up to 550 kg/m^{2}s. They found that the time-mean particle velocities can be downward or upward near the wall, with dense suspension upflow more likely at high superficial gas velocities and high net solids circulation fluxes.

In all of the aforementioned studies, the local time-mean particle velocities were calculated by directly averaging the transient particle velocity, V_p, over time based on:

$$\overline{V_p} = \frac{1}{T}\int_0^T (V_p(t))dt \tag{1}$$

However, as also noted by Qian and Li (7), since particle velocity is dependent on particle concentration, it should be weighted with respect to particle concentration. The concentration-weighted particle velocity, $\overline{V_{p,w}}$, can be calculated from:

$$\overline{V_{p,w}} = \frac{\overline{G_s}}{\rho_p\,\bar{\varepsilon}_s} = \frac{\frac{1}{T}\int_0^T [G_s(t)]\,dt}{\rho_p\,\frac{1}{T}\int_0^T [\varepsilon_s(t)]\,dt} = \frac{\frac{\rho_p}{T}\int_0^T V_p(t)\,\varepsilon_s(t)\,dt}{\rho_p\,\overline{\varepsilon_s}} \neq \overline{V_p} \tag{2}$$

In order to obtain concentration-weighted time-mean particle velocities, the instantaneous solids hold-up and particle velocity must be measured simultaneously, using the same measurement system. Qian and Li (7) measured the instantaneous particle velocity and solids hold-up simultaneously, employing an optical fibre probe and compared the time-average and concentration-weighted particle velocities measured at z/H = 0.65 in a CFB riser operating at U_g = 2.5 m/s and G_s = 62 kg/m^{2}s. They concluded that concentration-weighted time-mean particle velocities were smaller than particle velocities averaged over time at most radial locations. Nieuwland et al. (8) measured local solids hold-up and particle velocity simultaneously using an optical fibre probe at one axial location in a CFB riser operating at high U_g (7.5 m/s to 15 m/s) and high G_s (100 kg/m^{2}s to 400 kg/m^{2}s). They measured parabolic radial profiles of local concentration-weighted particle velocities and positive particle velocities at the walls of the CFB riser and suggested that the shape of the radial concentration-weighted particle velocity profiles is weakly dependant on both U_g and G_s.

To provide an overall picture of the flow, a thorough experimental investigation of radial profiles of concentration-weighted particle velocities needs to cover a wide range of solids fluxes, gas velocities and levels. To the authors' knowledge, no such extensive study is available to date. The objective of this study was to perform such an investigation by measuring local transient particle velocity, solids concentration and solids fluxes simultaneously at five axial levels (z = 0.76, 1.27, 1.67, 3.10 and 4.42 m) and seven radial locations (r/R = 0.00, 0.25, 0.50, 0.75, 0.88, 0.94, 1.00) in a 0.2 m diameter riser, operating over a wide range of solids circulation fluxes (198 kg/m^{2}s ≤ G_s ≤ 350 kg/m^{2}s) and superficial gas velocities (6 m/s ≤ U_g ≤ 8 m/s).

EXPERIMENTAL

Apparatus

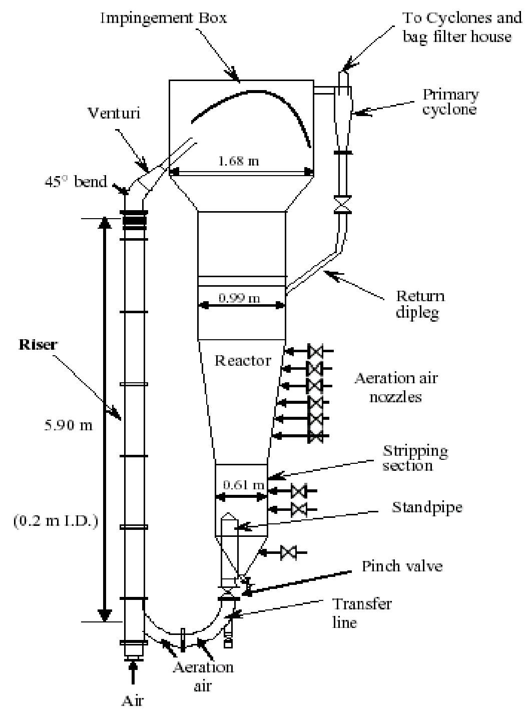

Figure 1 Schematic of fluid coker cold model with riser

Experiments were carried out in a Plexiglas riser (i.d. 0.2 m, height 5.9-m) of a cold model fluid coker as shown in Figure 1. Details of the experimental system are given elsewhere (9, 10). Here the coker reactor was used as a dense bed feeder. The net solids circulation flux (G_s) through the riser was measured by monitoring the pressure drop across the venturi constriction at the top of the riser while simultaneously determining the solids mass flux in the standpipe using a fibre optical velocimeter probe to find the solids void fraction and velocity. The airflow rate and superficial gas velocity (U_g) in the riser were determined by an orifice meter. The solid particles utilized in this study were fluid cracking catalyst (FCC) particles of mean diameter 70 μm and apparent density 1700 kg/m^3.

Measurement Method

The 3-fibre optical probe measurement system developed by Liu et al. (11) was used to determine simultaneously local instantaneous solids volume concentrations, velocities and fluxes. The 2-mm-thick probe tip consists of three quartz fibres in contact with each other, each with a diameter of 0.26 mm. The central fibre projects light into the multi-phase suspension, while the other two fibres receive back-scattered light from moving particles. Each velocity data point was determined by cross-correlating the signals collected by the receiving fibres over a time period of ~10 to 40 ms at a sampling frequency of ~280 kHz. After calibration, averaging the intensity of the signals over the same brief time period gives the instantaneous solids concentration. During the particle velocity measurements, particles may reverse directions, or a flow structure travelling non-vertically passing one fibre may not be detected by the second fibre, causing the cross-correlation coefficients to be low or indeterminate. Such uncorrelatable or poorly correlated data need to be eliminated. In this study, in order for the results to be acceptable, the correlation coefficients were required to exceed 0.7, and individual calculated velocities were required to differ by no more than four standard deviations from the average. Further details of the measurement system and its calibration are given elsewhere (10).

Careful calibration is vital in order to accurately measure solids concentrations. Previous researchers have used a number of different calibration techniques and have pointed out that it is difficult to obtain an accurate and reproducible calibration method for heterogeneous suspensions. Most calibrations have been performed in liquid-solid systems because of their capability to provide stable high-concentration solid suspensions (8, 12-16). However, in view of the differences in the optical properties (in particular, the refractive index) between gases and liquids, the validity of such calibrations in gaseous suspensions is questionable and needs to be examined carefully. Many other researchers (1, 17-20) have utilized dropping/trapping techniques to calibrate their probes and have obtained non-linear calibration curves. One difficulty encountered during dropping/trapping tests has been a decrease in the stability of the calibration unit at high solid concentrations. Some researchers (12, 13) have preferred to calibrate their probes inside gas-fluidized beds in order to obtain calibration curves reflecting the required scale and flow. Lischer and Louge (21) and Zhang et al. (22) calibrated their optical fibre probes by integrating the probe signal measured by traversing it across the entire diameter of the bed and comparing the results with apparent solids volume fractions inferred from pressure drop measurements.

In the present study, all of the aforementioned calibration techniques were employed, and the results were compared. Detailed examination of the different calibration techniques for the optical fibre probe (10) suggested that the calibration curves should be adapted to the actual unit after being obtained in other simplified systems. For this purpose, a Boltzmann-type calibration equation was selected, and its constants were obtained by matching the cross-sectional average probe signal obtained by traversing it across the entire diameter of the bed and the apparent solids volume fractions inferred from simultaneous measurements of pressure drops across the probe measurement location. It must be pointed out that many different radial distributions of solids hold-up can give the same cross-sectional average. This causes no problem if one is only dealing with cross-sectional averages, but if the radial distributions are needed for analysis, an additional criterion is required to check the cross-sectional averages and to obtain the correct radial distributions. Since the optical fibre probe used in this study can measure solids hold-up and circulation flux simultaneously, comparing the cross-sectional average net solids flux with the overall solids circulation flux determined independently provides an alternative means of checking the accuracy of the calibration equation. It was found that when the best calibration equation, based only on the cross-sectional average solids hold-up, was employed, agreement between the cross-sectional average solids flux and the overall solids circulation flux was poor. Other researchers have not been able to measure solids hold-up and solids flux simultaneously using a single optical probe. Therefore, they never encountered or confronted this issue. On the other hand, in this study, both solids hold-up and flux values were examined carefully, and the calibration equation was selected to satisfy best both the solids hold-up and flux criteria. Further details of the calibration are provided elsewhere (10).

RESULTS AND DISCUSSION

The local time-mean particle velocities and concentration-weighted particle velocities measured at z = 0.76 m and z = 3.1 m for U_g = 6 m/s and G_s ~ 340 kg/m^{2}s are compared in Figure 2. The concentration-weighted time-mean particle velocities are seen to be smaller than the particle velocities averaged directly over time at most radial locations. The difference between them arises because there is a correlation between the fluctuations of velocity and voidage (23), low instantaneous voidages tending to be associated with downwards or reduced-upwards particle velocities. This difference is more pronounced in the bottom dense section and the annular region of the riser, due to strong interactions between particle velocity and solids hold-up at high densities. This interaction can be seen more clearly in Figure 3 where we plot traces of instantaneous solids hold-up, particle velocity and concentration-weighted particle velocity, measured at r/R =0.75 for both z = 0.76 m and z = 3.1 m, with U_g = 6 m/s and $G_s \approx$ 340 kg/m^{2}s.

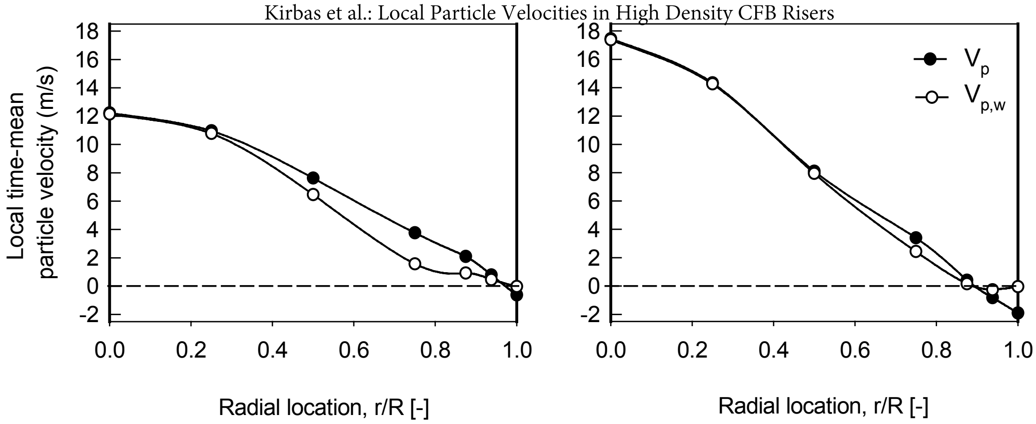

Figure 2 Comparison of radial profiles of time-average and concentration weighted time-mean particle velocities for U_g = 6 m/s and $G_s \approx 340$ kg/m^{2}s at (a) z = 0.76 m; (b) z = 3.1 m.

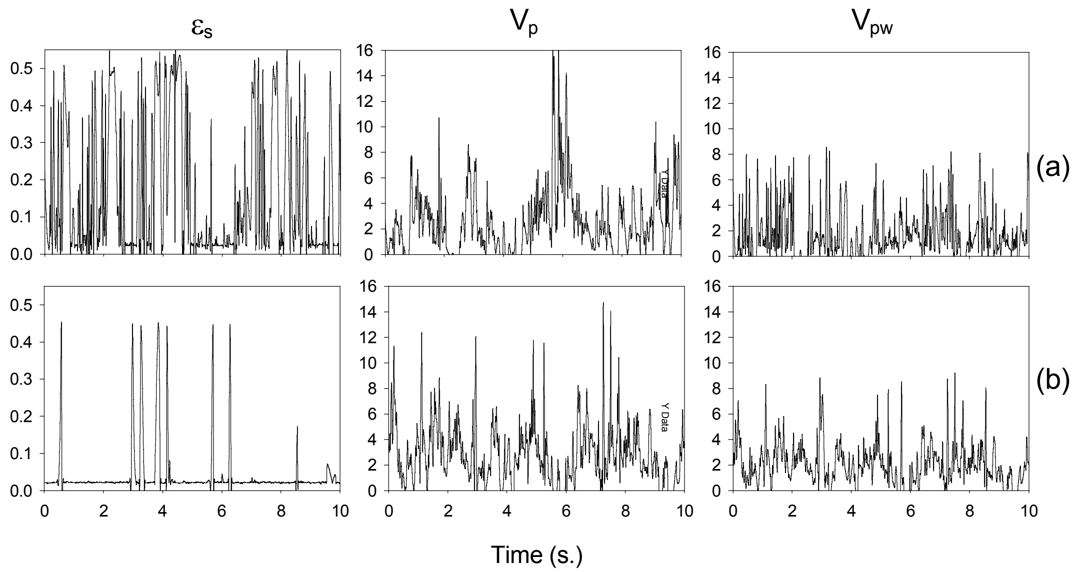

Figure 3 Instantaneous solids hold-up, particle velocity and concentration-weighted time-mean particle velocities for U_g = 6 m/s and G_s ~ 340 kg/m^{2}s measured at r/R = 0.75 and at (a) z = 0.76 m and (b) z = 3.1 m.

To provide an overall picture, an extensive experimental investigation of radial profiles of concentration-weighted particle velocities covering a wide range of solids fluxes, gas velocities and levels was carried out. Figure 4(a) plots profiles of local $\overline{V}_{p.w}$ at different axial locations for U_g = 6 m/s and various solids circulation fluxes. The particle velocity reached a maximum at the centre and gradually decreased towards the wall of the riser. For most cases, an increase in solids circulation flux led to an increased local particle velocity in the central region. The increase in particle velocity with increasing G_s was more apparent in the top relatively dilute section, whereas towards the bottom of the riser, the radial profiles were not very sensitive to G_s for the range of conditions covered. As seen in the figure, in the top section of the riser, negative velocities occurred near the wall, although their magnitudes were very small (< 1 m/s). As one moves downward from the top to the bottom section of the riser for the same operating conditions, the radial location where the particle velocity becomes negative moved outwards towards the wall. A similar trend was observed when the solids circulation flux was increased at a fixed axial location.

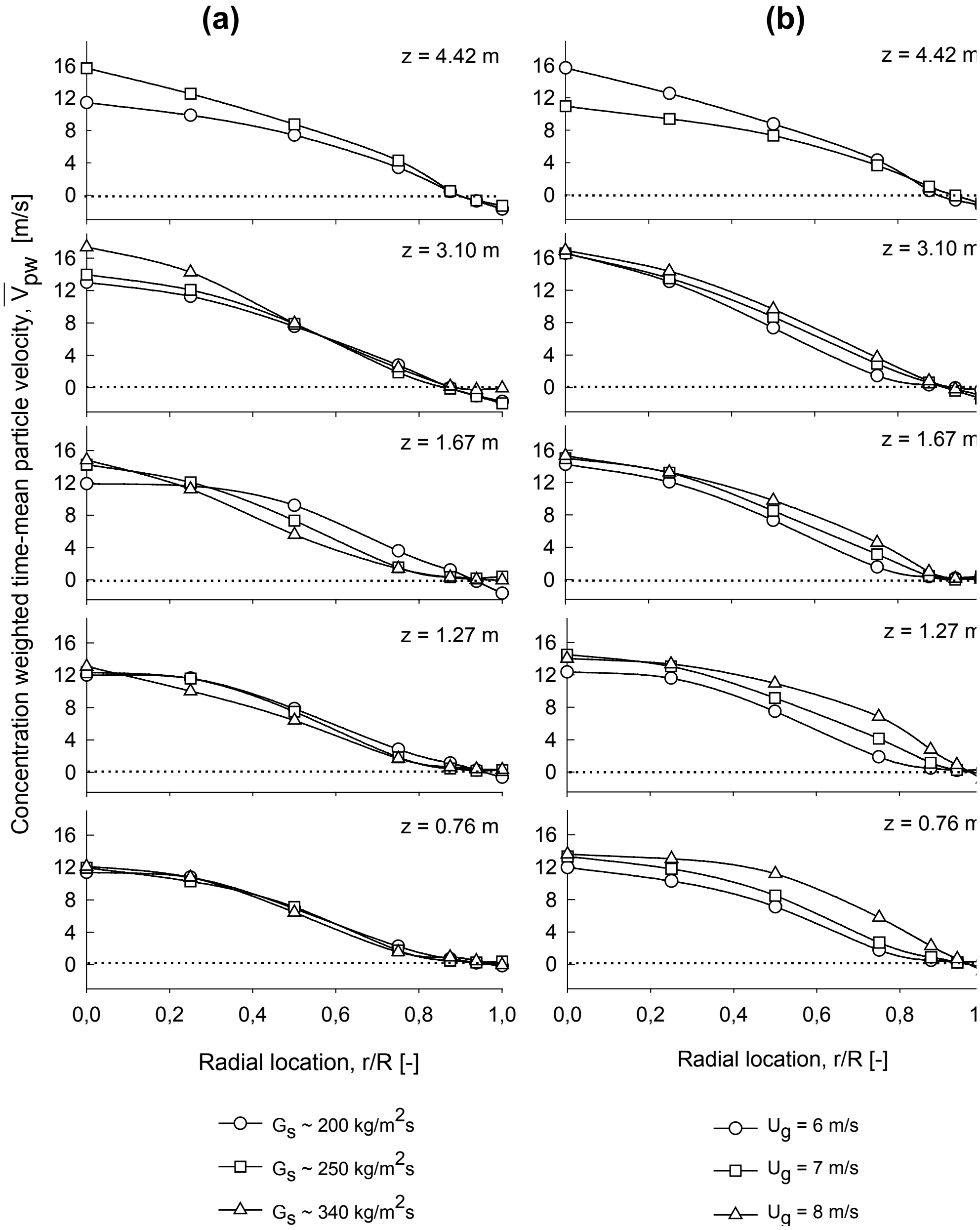

Figure 4 Local concentration-weighted time-mean particle velocity profiles at different axial locations for:
(a) U_g = 6 m/s and various solids circulation fluxes
(b) G_s ~ 250 kg/m^{2}s and various superficial gas velocities

The effect of superficial gas velocity on the radial $\overline{V}_{p.w}$ distributions at different heights for U_g = 6, 7 and 8 m/s and G_s ~ 250 kg/m^{2}s is presented in Figure 4 (b). As U_g increased, $\overline{V}_{p.w}$ increased in the core of the riser, whereas the wall region remained almost unchanged. If the particle velocity profiles are compared at different axial locations for U_g = 6 m/s and G_s ~ 250 kg/m^{2}s, it can be seen that the region with negative particle velocity values near the walls of the riser is diminished as one moves from the top towards the bottom of the riser for unchanged operating conditions. The particle velocity profile also starts to flatten in the wall region at z = 1.27 m, suggesting increased uniformity of flow under dense suspension (24) conditions.

CONCLUSION

With the objective of performing an extensive investigation of radial profiles of concentration-weighted particle velocities, the local transient particle velocity and solids concentration were measured simultaneously using a three-fibre optical probe at five axial levels (z = 0.76, 1.27, 1.67, 3.10 and 4.42 m) and seven radial locations (r/R = 0.00, 0.25, 0.50, 0.75, 0.88, 0.94, 1.00) in a 0.2 m diameter riser, operating over a wide range of solids circulation fluxes (198 kg/m^{2}s $\leq G_s \leq$ 350 kg/m^{2}s) and superficial gas velocities (6 m/s $\leq U_g \leq$ 8 m/s). The concentration-weighted time-average particle velocities were found to be smaller than the particle velocities averaged directly over time at most radial locations. Due to strong interactions between particle velocity and solids hold-up, especially under high-density conditions, the difference between these two averages was found to be more pronounced in the bottom dense section and in the annular region of the riser. The local transient concentration-weighted particle velocity distributions were strong functions of height, as well as operating conditions. With a change in the operating conditions, the local concentration-weighted particle velocity in the relatively dilute core region of the riser changed more significantly than those in the wall region.

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NOTATION

$G_s(t)$	instantaneous local solids flux, kg/m^{2}s
G_s	net solids circulation flux, kg/m^{2}s
$\overline{G_s}$	time-mean local solids flux, kg/m^{2}s
H	height of riser, m
r	radial coordinate, m
R	radius of riser, m
T	integration time, s
U_g	superficial gas velocity, m/s
$V_p(t)$	instantaneous local particle velocity, m/s
$\overline{V_p}$	time-mean local particle velocity, m/s
$\overline{V_{p,w}}$	time-mean local concentration-weighted particle velocity, m/s
z	axial coordinate, m
Greek letters	
$\varepsilon_s(t)$	instantaneous local solids hold-up, -
$\bar{\varepsilon}_s$	time-mean local solids hold-up, -
ρ_p	particle density, kg/m^3

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