SPE Brazil Flow Assurance Technology Congress
Rio de Janeiro, Brazil, November 06 – 08 2024

INFLUENCE OF LARGE HEAVY INERTIAL PARTICLES ON TURBULENT STATISTICS AND FRICTION FACTOR IN PIPE FLOW

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Abstract
Most studies on particle laden flows have focused either on small heavy particles or large neutrally buoyant particles. We present results in the regime of large and heavy particles. We investigate the particle-turbulence dynamics over a parameter space covering a wide range of particle-volume fractions (Øv), Stokes (St) and Froude (Fr) numbers. First, the effect of inertial particle concentration on the skin friction drag is determined and a correlation for the growth rate of the friction factor with volume fraction of particles is obtained. Using time-resolved PIV measurements, we show that the carrier phase turbulence is modulated even at particle concentrations as low as 0.3% indicating that particle-induced stresses due to distortion of fluid streamlines cannot be neglected.

Keywords
particle-laden flow; turbulent flow; friction factor

Introduction
Turbulent particulate flows are important both in nature and in many industrial applications. Examples include droplets in the clouds, fluidized beds, pharmaceutical sprays, scale formation in pipes among many others. A fundamental physical understanding of these flows is therefore crucial. It is well known that particle dynamics can be influenced by the carrier fluid leading to phenomena such as clustering and turbophoresis (the migration of particles towards the wall down the gradient of turbulence intensity)[1]. On the other hand, the presence of particles can significantly modify the carrier phase turbulence. In the literature, turbulence reduction due to increased dissipation arising from particle drag and enhanced effective viscosity have been reported. Conversely, it has been shown that turbulence can be enhanced due to increased velocity fluctuation resulting from particle wake dynamics [2]. In this study, we investigate turbulence modulation with particles that are much larger than the smallest flow length scale and having a density higher than that of the carrier fluid, as there is very little data on these in the literature. We consider a flow in a pipe aligned with the gravitational vector, thus allowing for the investigation of the two-way coupling between particles and carrier phase turbulence, while excluding the effect of gravity.

Methodology
Experimental measurements were conducted in a rig having a vertical-pipe test section of length 3.45 meters and 44 millimeters in diameter (D). The carrier fluid was recirculated using a positive-displacement pump, the flow direction going from top to bottom. Spherical glass beads having a modal diameter of about 700 microns and a density of approximately 2.5 times that of the carrier fluid were continuously injected into the flow at the top of the pipe but unlike the carrier phase, they were collected at the bottom and not re-circulated. Pressure drop measurements over a length of about 53D were conducted using an Endress Hauser differential pressure transducer. Time-resolved images of both tracers (10 micrometers particles) and the dispersed particles were taken using a planar particle image velocimetry (PIV) system consisting of a high speed camera (Phantom VEO 440), and an Nd:YLF Laser as light source. To separate the larger dispersed particles from the tracers, an 11 x 11 median filter was employed. Adaptive PIV analysis was then conducted on the tracer images to characterize the carrier phase turbulence and a particle tracking algorithm was applied to characterize the dispersed phase. The PIV images were obtained at a distance of 57D from the inlet. To obtain data over a wide range of Stokes, Froude and Galileo numbers, water, and various glycerol/water mixtures were employed as working fluids.

Results and Discussion

Pressure drop measurements indicate an increase in the coefficient of skin friction (f) as the volume fraction of particles is increased (see figure 1).

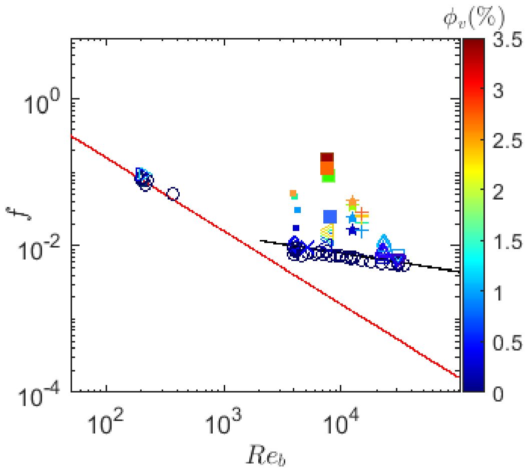

Figure 1. Variation of the coefficient of skin friction with volume fraction (Øv) of particles. Symbols represent different Froude numbers, while red and black lines are the correlations for laminar and turbulent single-phase flows.

This was true for all Stokes and Froude numbers considered (St = 3 to 120, Fr =0.1 to 4). The growth rate, β, of the friction factor (β = df/dØv) was however observed to be only a function of the Froude number (see figure 2).

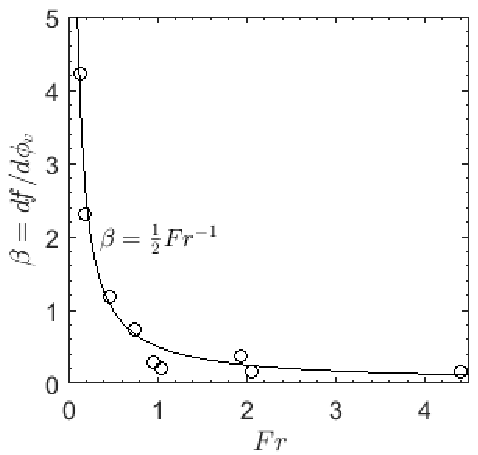

Figure 2. Growth rate (β) of the coefficient of skin friction as a function of the Froude number.

A power-law fit to the data indicates that β scales as Fr^{-1} indicating that for Fr less than 1, the influence of gravity cannot be neglected. Figure 3 and 4 show a comparison between the velocity fluctuations obtained in single phase flow as well as the carrier phase velocity fluctuation profiles in particle laden flow (PLF) at two Reynolds (Re) and Stokes numbers. Even though the particle concentration is small (0.3% by volume), large differences in the turbulence intensities can be observed between the single phase flow case and that of particle laden flow. The particle size is much greater than the Kolmogorov length scale, hence particle induced stresses due to distortion of fluid streamlines cannot be neglected. There is a Stokes number dependence of the peak streamwise velocity fluctuation (rms_{uz}).

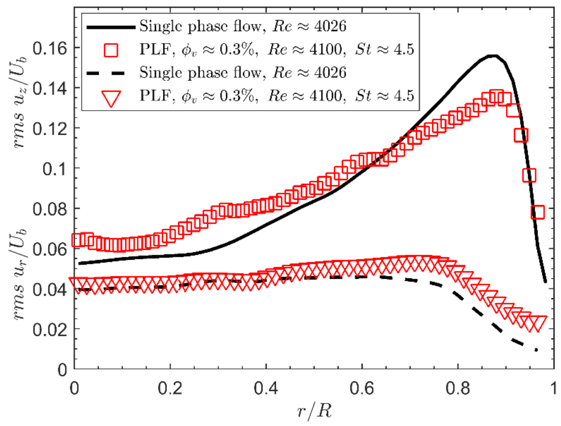

Figure 3. Streamwise and radial turbulence intensities in single phase and dilute particle-laden flow at Re = 4026.

At low Stokes number (4.5), the peak is lower than that of the unladen flow, while at high Stokes number (13), the peak is higher than in the unladen flow.

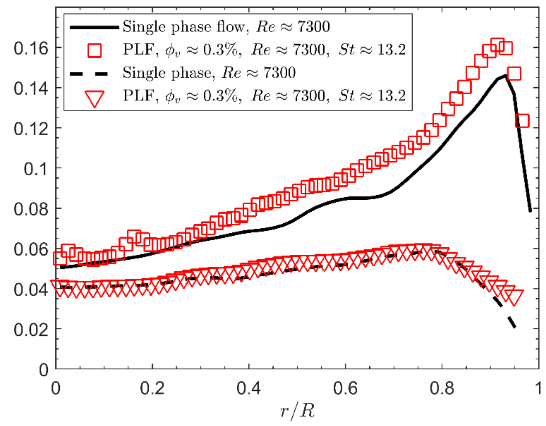

Figure 3. Streamwise and radial turbulence intensities in single phase and dilute particle-laden flow at Re = 7300.

The radial turbulence intensity (rms_{ur}) agrees reasonably well with that in the single phase flow for the high Stokes number case. However, at Stokes number of 4.5, the radial turbulence intensity close to the wall is higher than in the unladen flow. Particle tracking on the dispersed phase shows that the particle velocity is very different from that of the surrounding fluid.

Conclusions

The dynamics of inertial particles much larger than the smallest flow length scale and denser than the carrier fluid, in a vertical turbulent pipe flow have been investigated. An increase in skin friction drag with volume fraction was observed and a power-law growth rate dependent solely on the Froude number was established. PIV and PTV experiments indicate that the carrier phase turbulence is modulated even at low particle concentrations. A stokes number dependence of the peak turbulence intensity in the particle laden flow was observed.

Acknowledgments

The authors gratefully acknowledge the financial support from Shell Brasil through the project “Predictive modelling of inorganic scaling in pipes and equipment subjected to multiphase flows in Pre-Salt conditions” at the Interdisciplinary Center of Fluid Dynamics (NIDF) and the strategic importance of the support given by ANP through the R\&D levy regulation.

Responsibility Notice

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References

[1] Brandt, L. & Coletti, F., *Annu. Rev. Fluid Mech.*, Vol. 54, pp. 159–189, 2022.

[2] Balachandar, S. & Eaton, J.K., *Annu. Rev. Fluid Mech.*, Vol. 42, pp. 111-133, 2010.