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An investigation of particle behavior in gas–solid horizontal pipe flow by an extended LDA technique

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ABSTRACT

An extended Laser Doppler Anemometry (LDA) technique has been developed to measure the distributions of particle velocities and particle number rates over a whole pipe cross-section in a dilute pneumatic conveying system. The first extension concentrates on the transform matrix for predicting the laser beams' cross point in a pipe according to the shift coordinate of the 3D computer-controlled traverse system on which the probes of the LDA system were mounted. The second focuses on the proper LDA sample rate for the measurement of gas–solid pipe flow with polydisperse particles. A suitable LDA sample rate should ensure that enough data is recorded in the measurement interval to precisely calculate the particle mean velocity or other statistical values at every sample point. The present study explores the methodology as well as the fundamentals of measurements, using a laser facility, of the cross-sectional distributions of solid phase. In the horizontal gas–solid pipe flow (glass beads less than 110 μm), the experimental data show that the cross-sectional flow patterns of the solid phase can be classified by annulus-like flow describing the axial particle velocity contours and stratified flow characterising particle number rate distribution over a cross-section. Thus, the cross-sectional flow pattern of the solid phase in a horizontal pipe may be annular or stratified dependent on whether the axial particle velocity or particle number rate is the phenomenon studied.

1. Introduction

Dilute phase pneumatic conveying has been widely applied in the process industries to transport granular materials. Hence, numerous papers on gas–solid experiments, theoretical analysis and numerical simulation have been published in the last three decades, especially concerned with measuring the velocity of gas–solid flow. Since Laser Doppler Anemometry (LDA) is a non-intrusive method with high accuracy, it has been extensively utilized to investigate particle velocities in gas–solid flow. Here, the latest LDA application in our laboratory is introduced.

Among previous publications on using LDA to study particle-laden gas flow in pipes or channels, Sommerfeld listed and summarized the eleven most important studies from 1970 to 2002 on measuring particle mean velocity or velocity profile in a horizontal or vertical pipe or square channel [1]. Subsequently, Morsi et al. explored the characteristics of turbulent gas–particulate flow in the vicinity of a single tube by LDA [2]. Juray De Wilde et al. used LDA to study gas–solid mixing in the inlet zone of a dilute circulating fluidized bed [3]. Urmila Datta et al. developed dual plane electrical capacitance tomography (ECT) to measure particulate velocity components which were verified using LDA [4]. Some researchers also used LDA to investigate the gas–solid flow behavior in a curved 90° bend in a duct [5,6]. Most of these experiments only record the data at a few tens of sample points along the axis of the section in a pipe or channel, from which the velocity profile was deduced. So far, there is still a lack of experimental data on the particles local velocities over a whole cross-section. Since the time-averaged value is normally used to represent the local velocity at a point where particles pass over a time interval and these particles with their different velocities (dependent on their Stokes numbers) have different spatial intervals, the accuracy of the time-average value will be affected by the number of data points recorded by LDA. In other words, consideration of the sample rate of LDA will improve the measurement precision. However, papers discussing this phenomenon are rare. In the case of flow in rectangular channels, one of the flat walls acts as a window for the coherent light beams used in the LDA. The presence of the transparent window will shift the position of the interference fringes slightly but will not affect their orientation. In the case of a circular pipe, particularly a curved one, both the position and the orientation of the fringes will be affected with corresponding errors in the position to be attributed to the measured velocity. Thus, it is necessary to study the optical properties of the beams passing through a curved-walled duct for pipe flow research.

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Nomenclature

(a, b, c)	the direction vector of a beam	α_r	crossing-angle between refracted beam and its normal
n_i, n_r	medium refractive index on incident or refracted side	D	pipe diameter
$t_{\min}$	the minimum temporal interval between two adja cent particles	t_k	time interval between two adjacent particles
(x_0, y_0, z_0)	reference point of a beam	(x, y, z)	a point coordinate on a line
y_i	beam's height on incident or refracted sidebeam's initial height	y_0	beam's translation height
L	the running distance of a beam	y_r	beam's height after refraction
M_{R1}	optic transform matrix at a pipe outer surface	M_T	optical translation matrix
$\overline{N}$	total number of particles	M_{R2}	optical transform matrix at a pipe inner surface
S	optical system matrix	R	lens' radius
U_p	particle instantaneous velocity	T	measurement interval
$\boldsymbol{V}_i$	unit vector of an incident beam	$\{U_{pk}\}$	particle velocity sample space
$\boldsymbol{V}_r$	unit vector of the refracted beam	$\boldsymbol{V}_n$	the unit vector of the normal ray at a point
		α_i	the crossing-angle between incident beam and its normal vector

In this study, the relationship between the beams' crossing point (the LDA fringe pattern) and the shift coordinate of the traverse system were investigated. This relationship is expressed by a transform matrix. Then, the minimum sample rate of LDA was evaluated according to the current fluid conditions. A suitable value of the sample rate and the laser power for the LDA measurements over the whole pipe cross-section were evaluated by experiments. Finally, the measured data of particle velocities and particle number over a series of pipe sections are illustrated by contour diagrams in which the particle mean velocity evolution and gas–solid flow pattern may be deduced. These comprehensive results will be useful to validate the results of the numerical simulations.

2. Experimental

2.1. Pipe system and particles

A pilot-scale model of a pneumatic conveying system was built using transparent Plexiglass pipes. This was a positive pressure system which consisted of a centrifugal fan, a feeder and a cyclone as well as the three 2 m long glass pipes, one T piece and one elbow (as shown in Fig. 1). The coordinate of the pipe system is O*xyz* whose origin is located at the center of a pipe cross-section. This could be used to investigate the behavior of gas–solid flow in the horizontal pipe, the elbow and the vertical pipe. To reduce the risk of electrostatic effects due to particle-wall collisions, every metal

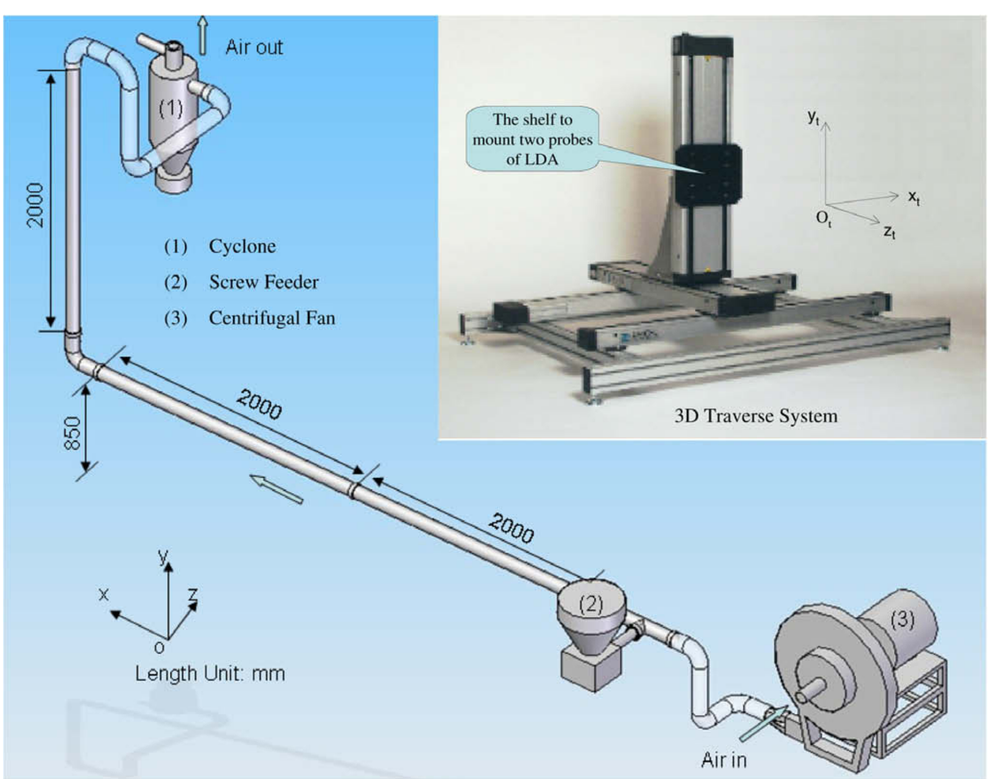

Fig. 1. Sketch of the experimental rig and the 3D traverse system.