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Short communication

Experimental study of solid–liquid two-phase flow in a hydrocyclone

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Abstract

By using a new type of laser measuring instrument, a particle dynamics analyser (PDA), radial and axial velocity components and the size of solid particles in a hydrocyclone were measured, and the concentration distribution of the solid particles was obtained. In analysing and discussing the separation mechanism of the solid particles, as well as the main causes of the leakage of coarse particles to the overflow and the abrasion on the hydrocyclone wall, some new opinions are put forward.

Keywords: Hydrocyclone; Two-phase flow; Particle size; Velocity; Concentration

1. Introduction

Up to now, great progress in the study of liquid-phase flow fields in hydrocyclones has been made. However, because of a lack of advanced measurement techniques, the study of solid-phase flow has been stagnant for a long time. Almost all of the previous experimental studies on particles in a hydrocyclone have focused on and their size and density distributions. Few reports on the concentration distribution are available. Studies on the velocity distribution of solid particles in a hydrocyclone, except for a few measured discussions [1–3] have mostly focused on theoretical analysis and numerical simulation [4–6]. Because the flow field in a hydrocyclone is complex, the motion of solid particles should be determined experimentally before a clear understanding of the separation mechanism can be obtained and before a theoretical foundation to optimize and improve the separating efficiency of the hydrocyclone can be developed. A new type of laser Doppler measuring equipment, named the particle dynamics analyser (PDA), has been verified as being of use for the simultaneous measurement of motion of liquid and solid particles in two-phase flow [7–10]. An experimental study of the velocity, size and concentration of the solid particles in a hydrocyclone is reported here involving the use of a PDA.

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2. Measuring principles and apparatus

The PDA is an instrument based on phase doppler anemometry, which is an extension of laser doppler anemometry (LDA) [8]. The PDA estimates the particle size from the phase difference of the Doppler bursts received by the three detectors in the receiving optics [11]. The signals, which are collected at different scattering angular positions, have a phase difference, which is linearly dependent on the particle diameter. The velocity is measured from the frequency of the Doppler burst as with LDA. The basic principle of the concentration measurement is described below.

During the time interval T, a number of particles N have passed through a cross-sectional area A, and at the end of the interval these particles fill a volume

$$\Delta V_i = A_i \Delta x_i = A_i \nu_i T \quad (1)$$

If the travelling velocity of the particles is the same, the particle concentration is

$$\rho_{N_i} = \frac{N_i}{\Delta V_i} = \frac{N_i}{A_i \Delta x_i} = \frac{1}{A_i}\frac{N_i}{\nu_i T} \quad (2)$$

Where ρ_{N_i} is the concentration (number of particles per unit volume) in size class i; N_i is the number of particles in size class i; A_i is the cross-sectional area in size class i; T the elapsed time; v_i is the average velocity of particles in size class i

$$\nu_i = \frac{1}{N_i}\sum_{j=1}^{N_i} \nu_{ij} \quad (3)$$

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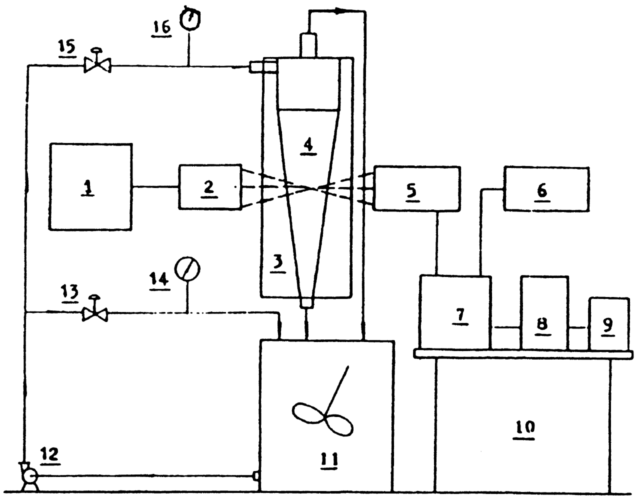

Fig. 1. Scheme of experimental apparatus: (1) laser; (2) optic-fibre laser probe; (3) optical compensating box; (4) hydrocyclone; (5) PDA recciving optics; (6) oscilloscope; (7) signal processor; (8) computer; (9) printer; (10) table; (11) water tank.

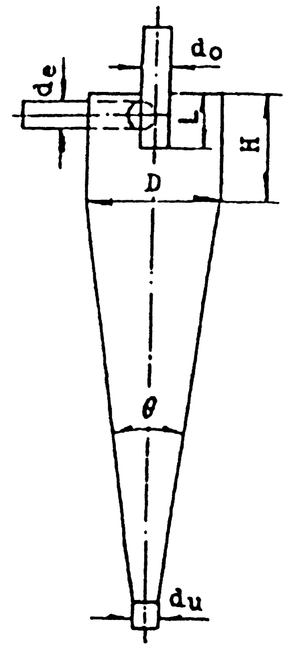

Fig. 2. Hydrocyclone.

The total concentration is then

$$\rho_N = \sum_i \rho_{N_i} \tag{4}$$

Through certain conversions, the volume concentration, mass concentration, volume flux and the mass flux of the particles can be obtained. Volume concentration

$$\rho_v = \sum_i \frac{\pi D_i^3}{6} \rho_{N_i} \tag{5}$$

Mass concentration:

$$\rho_m = \rho \rho_v = \sum_i \frac{\pi D_i^3 \rho}{6} \rho_{N_i} \tag{6}$$

where ρ is the density of the particles. Volume flux.

$$\text{Flux}_v = \sum_i \frac{\pi D_i^3}{6} v_i \rho_{N_i} \tag{7}$$

Mass flux:

The measuring apparatus is shown in Fig. 1. The geometry of the hydrocyclone used is given in Fig. 2 and

$$Flux_m = \sum_i \frac{\pi D_i^3 \rho}{6} v_i \rho_{Ni} \tag{8}$$

Tables 1 and 2 provides the operating parameters of the hydrocyclone and the characteristics of the solid particles. The particles in Table 2 are polyspyrene ($\rho_s = 1.05$ g/cm^3), polyvinyl chloride ($\rho_s = 1.40$ g/cm^3) and quartz sand ($\rho_s = 2.27$ g/cm^3). In order to reduce the optical refraction error produced by the curved surface of the hydrocyclone, an optical compensating box was used, and the error was rectified during measuring.

Table 1
Geometry parameters

D	θ	H	d_e	d_o	L	d_u
80 mm	15°	70 mm	14 mm	16 mm	40 mm	14 mm

3. Results and discussion

3.1. Radial velocity of particles

The radial velocity of particles has a significant effect on their separation in a hydrocyclone, and is the most important velocity component for the separation of solid particles from the liquid. As illustrated in Fig. 3, there is a similar regularity of distribution of the radial velocity of solid particles along the radii. In the conical section of the hydrocyclone, the radial velocity increases from the wall to the centre of

Table 2
Experimental parameters

Condition	Operating parameters			Characteristics of solid particles	
	P_e (Pa)	Q_u (ml s^{-1})	Q_o (ml s^{-1})	ρ_s (g cm^{-3})	Particle size (μm)
A	3×10^4	225	214	1.05	0–200
M	3×10^4	180	385	1.40	71–154
N	3×10^4	180	385	1.40	71–154
S	3×10^4	180	385	1.05	200–300
U	3×10^4	180	385	1.05	154–200
V	3×10^4	180	385	2.27	0–200
X	3×10^4	180	385	2.27	0–200

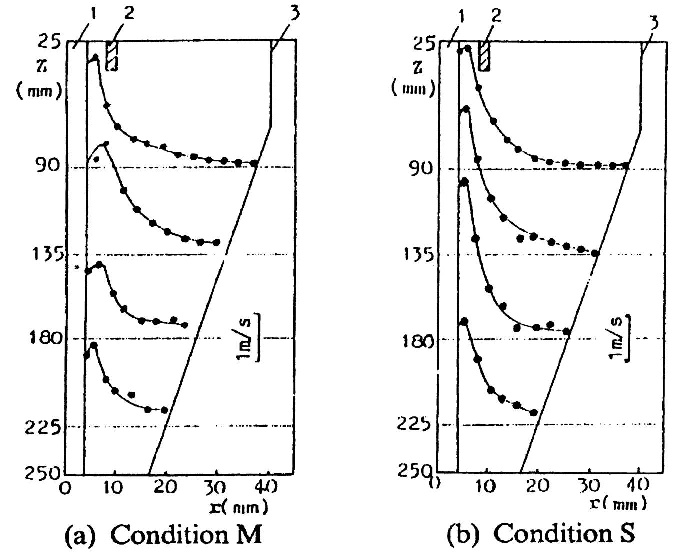

Fig. 3. Radial velocity of particles.

the hydrocyclone, and reaches a maximum near the air core (air–water interface), and then decreases. The radial velocity gradient in the inner helical flow is larger than that in the outer helical flow. The distribution of the radial velocity of solid particles along the radii can be described as follows

$$V_r r^m = C \tag{9}$$

Values for m and C were derived from the authors' experiments

$$m = 1.29 \times 10^{-4} z^2 - 0.041z + 4.60 \tag{10}$$

$$C = 1.44 \times 10^{-2} z^2 - 4.74z + 407.75 \tag{11}$$

When other conditions remain unchanged, from Fig. 3, it can be found that with a decrease in radius, the radial velocity of coarse particles is larger than that of fine particles at the same positions.

3.2. Axial velocity of solid particles

Early researchers assumed that the axial velocity of solid particles in a hydrocyclone was the same as that of the liquid [13]. However, from Fig. 4, it is found that in the upper cores, the velocity distributions of the solid particles are obviously different from those of the liquid. That is, there is a low velocity area between the two LZVV lines for the velocity distributions of the solid particles. The existence of this low velocity area, which is also different from conventional wisdom [12,13], results from a circular eddy in the upper cone region. The solid particles in that area be separated because they can't move down to the lower cone region. In order to improve the performance efficiency of a hydrocyclone, this area should be reduced as much as possible. Because of the similarity of the axial velocity of solid particles within the lower cone section, the axial particle can be described as follows

$$V_z = Ln\left(\frac{r}{a + br}\right) \tag{12}$$

3.3. Velocity vector of the particles

The axial and radial velocity components have an important effect on separation. Fig. 5 shows the measured distribution of the velocity vectors in the radial–axial plane. As illustrated in Fig. 5, a short-circuiting flow phenomenon arises near the outer wall of the vortex finder, where some of the solid particles move down the outer wall of the vortex finder, and are discharged with the overflow. It was found

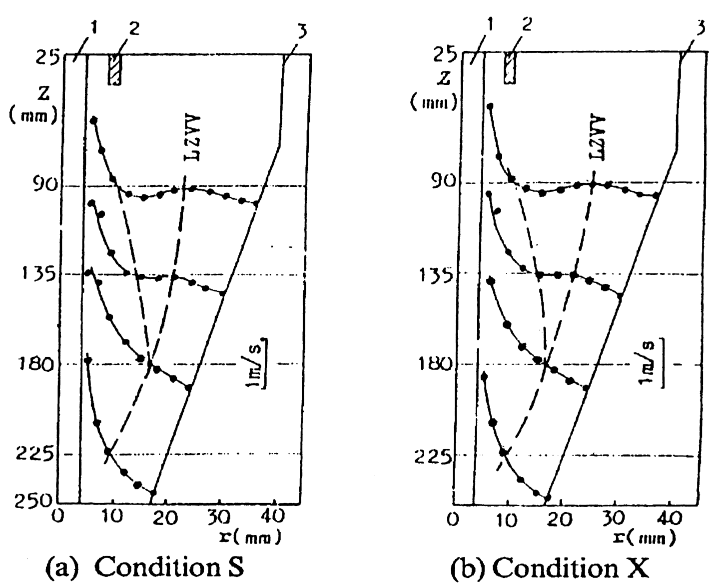

Fig. 4. Axial velocity of particles: (1) air core; (2) vortex finder wall.

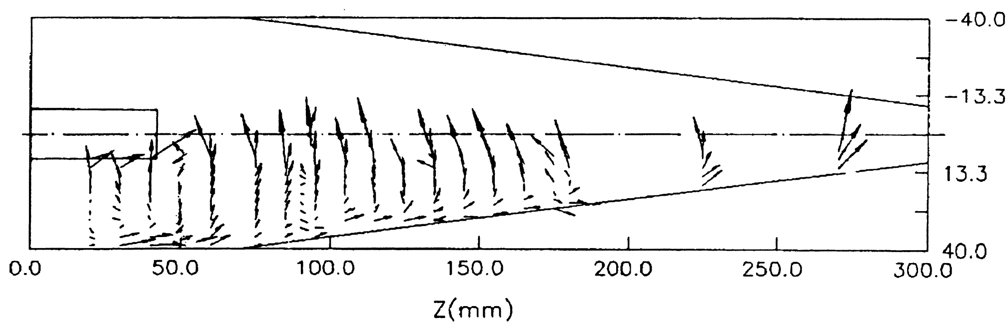

Fig. 5. Velocity vector of particles (Condition A).

from the profiles that solid particles below the bottom of the vortex finder can traverse along the radii towards the hydrocyclone wall. This demonstrates that not all particles in the inner helical flow will discharge with the overflow, and that some particles in the inner helical flow may enter the outer helical flow below the bottom of the vortex finder and will be separated again. These results indicate that the equilibrium orbit theory, which assumes that the particles in the inner flow are discharged with the overflow and these in the outer flow are discharged with the underflow [13], should be modified. In a hydrocyclone, the moving direction of the particles is decided by the liquid-phase radial velocity U_r and the centrifugal setting velocity of particles in the radial direction W_0. When $U_r > W_0$, the solid particles traverse towards the centre of the hydrocyclone; otherwise, they traverse towards the wall. No matter what direction the solid particles traverse along the radii, they can be separated from the suspension and discharged with the underflow if they are in the outer helical flow near the spigot. However, the solid particles moving into the inner helical flow in the cone region will move upwards into the cylindrical region as they traverse towards the centre, then, near the bottom of the vortex finder, a part of them will traverse towards the wall and be separated again. The law of motion of the particles shows that the LZVV line is not the critical separating surface of the solid particles in a hydrocyclone. In addition, because of the difference between the solid-phase velocity and the liquid-phase velocity, the air core is very unsteady, and the larger the particle size, the more obvious this becomes.

3.4. Size distribution of particles

Fig. 6, shows the distribution profiles of solid particles in the hydrocyclone in which the size of the solid particles increases on going from the centre towards the wall. This result is in agreement with previous theoretical studies on size distribution [4,12–14]

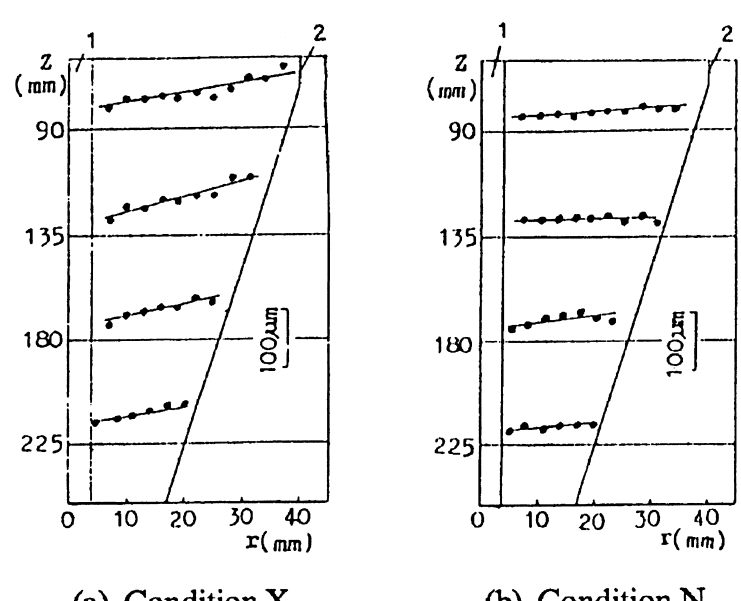

Fig. 6. Average particle size versus position.

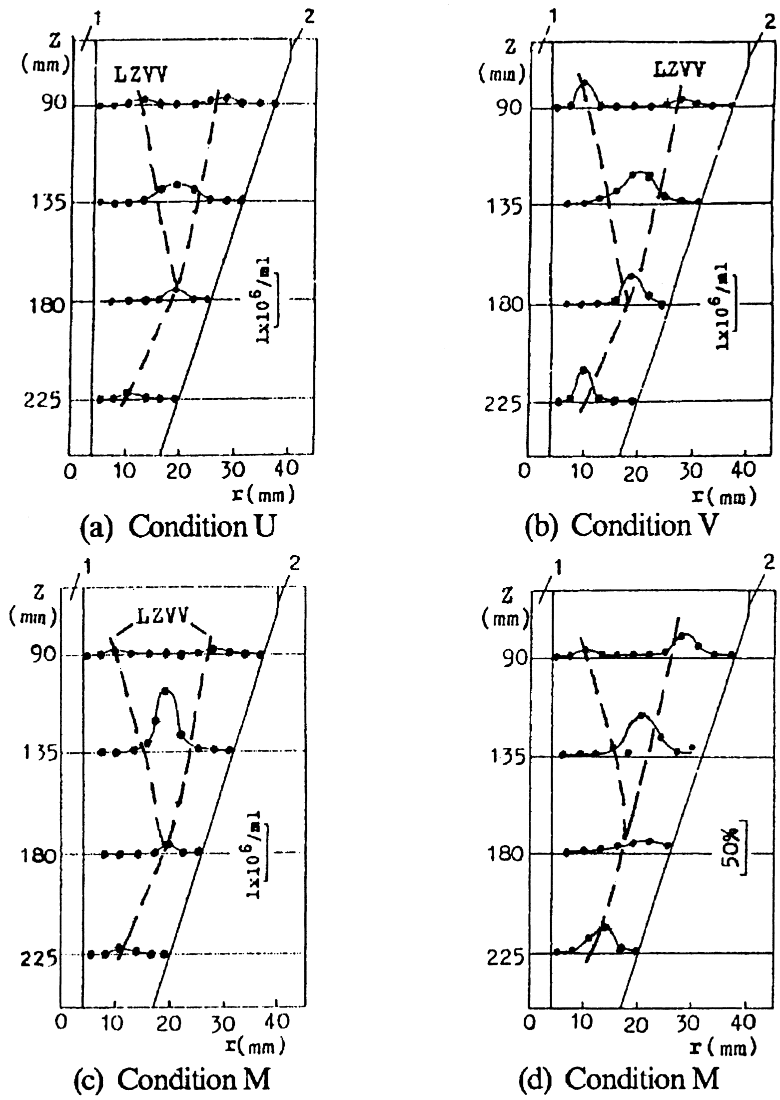

Fig. 7. Distribution of the concentration of particles.

3.5. Concentration distribution of particles

The concentration distribution of solid particles is shown in Fig. 7, where the concentration unit is the number of particles per cubic centimetre. Fig. 7 illustrates that the concentration maximum is not near the hydrocyclone wall, as might be thought, but near the LZVV lines of the solid particles. There are two zero axial velocity points about 20 mm below the cylindrical section junction with the conical section, and there are two peaks of concentration distribution at the same position. It can be seen that there is a close relationship between the axial velocity and the concentration (Fig. 4 with Fig. 7). At the LZVV2 line composition of the velocity components of solid particles reaches a minimum; therefore, the particles have a tendency to accumulate there. The low concentration of particles near the wall of the hydrocyclone, as seen in Fig. 7, suggests that the abrasion of the hydrocyclone wall is not likely to be due to high particle concentration in the wall region. Fig. 6 indicates that the largest particles are closest to the wall, thus abrasion of the wall is more likely to be due to the high momentum of these large particles.

4. Conclusions

By using a PDA to measure a two-phase flow field of a solid in a liquid, the study of particle motion in a hydrocyclone has been advanced to a new stage. Not all the solid particles in the inner helical flow discharge with the overflow; some of them also again be moved towards the wall. The LZVV lines are not an absolute boundary for separation. The particles that move down along the outer wall of the vortex finder lead to the leakage of coarse particles through the overflow, which will affect the separating performance of the hydrocyclone to some extent. The size of the solid particles decreases from the wall of the hydrocyclone towards the centre. The concentration maximum is not near the hydrocyclone wall, but near the LZVV lines for the solid particles. Reducing or eliminating the area between the two LZVV lines, which is a low efficiency area, will lead to an increase in the separating efficiency. One of the main causes of abrasion on the hydrocyclone wall is the collision of coarse particles, with large momentum, with the wall.

5. Nomenclature

a	constant
b	constant
C	constant
LZVV	loci of zero vertical velocity
P_e	inlet pressure
Q_u	under flow rate
Q_o	overflow flow rate
r	hydrocyclone radius
V_r	radial velocity of solid particles
V_z	axial velocity of solid particles
Z	axial distance
μ	liquid viscosity
ρ_s	particle density

Acknowledgements

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