Investigation of the flow in a flat bottom cyclone

by

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ABSTRACT

The main objective of this investigation was to determine the velocity profiles of a swirling flow in a flat bottom cyclone, a cylindrical vessel with central discharges used for classifying or separating particles in industrial processes. A two component laser Doppler velocimeter was used to measure the axial and the tangential component of velocity. A perspex model of a flat bottom cyclone 310,5 *mm* high and with a diameter of 102 *mm* was installed in an experimental rig under controlled water flow conditions. The velocity profiles were measured for two different overflow tube (vortex finder) diameters and three different values of pressure drop Dp in the cyclone. For each cyclone, three different values of both under flowrate through the apex tube and over flowrate through the vortex finder were thus originated, the Reynolds number Re varying in the range $1{,}37x10^4 \div 2{,}80x10^4$. Velocity data were measured on four symmetrical vertical halfplanes of azimuthal coordinates q = 0º, 90º, 180º, 270º respectively. The experimental results have shown that the flow is approximately a forced vortex near the air core and a free vortex in the region between the radial coordinate of $v_{q,M}$, the maximum of the tangential velocity, and the solid wall. The value of $v_{q,M}$ grows with Dp and it is virtually the same for changes in z. The radial position of $v_{q,M}$ varies lightly through the vessel and it moves radially outwards when the feed pressure increases. In the axial direction the velocity field gives two opposite axial flows separated by a cylindrical surface, where the axial velocity is zero. It has been observed that $v_{z,M}$, the maximum of the axial velocity, increases with Dp and decreases linearly with z. The measurements obtained by laser Doppler velocimetry (LDV) have exhibited that both v_z and v_q present greater fluctuations near the solid wall and near the air-liquid interface. Then the turbulence is neither homogenous nor isotropic, since the RMS values of v_z are also greater than RMS values of v_q, except near the air core where they are of the same magnitude. Finally, we have observed that the velocity profiles are axisymmetric with exception of the region near the apex discharge and near the air core. The LDV data obtained varying the Re number have proved that the flow does not depend on feed pressure, since the flow changes only its magnitude, while the velocity and the turbulence profiles maintain a constant pattern. Again, when the experimental tests were developed varying the vortex finder diameter only a change in the magnitude of the flow was detected, yielding similar velocity and turbulence fields.

1. INTRODUCTION

Since 1891, when Bretney patented the conical hydrocyclone, basically two cyclone shapes have been applied industrially, the conical and the cylindrical one. The conical cyclone is the most widespread dynamic classifier while the cylindrical classifier with central discharges or flat bottom cyclone is used in a lesser extent, although during the last years the use of the flat bottom cyclone in the mining and chemical industry has grown considerably. The general flow pattern inside a cyclone is a three-dimensional swirling flow known as a Rankine's vortex, combination of a forced vortex and a free vortex. The flow is completed by an axial movement in two opposite directions, one towards the apex (underflow discharge) near the walls and one more towards the vortex finder (overflow discharge) near the centre of the vessel, where an air core forms. Some authors investigated this flow and reported their measurements using LDV for the conical cyclone, among others Hsieh and Rajamani (1991) and Fisher and Flack (1998) who measured velocity profiles in a hydrocyclone and an industrial cleaner respectively. The former authors gave a complete mapping of tangential v_q and axial v_z velocities in the hydrocyclone and calculated the radial velocity from the continuity equation. On the other hand Fisher and Flack (1998) made experimental measurements of radial velocity and confirmed the three-dimensional nature of the swirling flow. However only a few studies have been carried out to determine the flow pattern in cylindrical cyclones. Baranov et al. (1984), who using an electrodiffusion method measured the tangential velocity v_q, have studied a cylindrical cyclone with an upper central discharge and an under peripheral discharge. Being r the radial coordinate they showed that v_q modifies its radial profiles from the top, where is $v_q \approx k\,r$, to the bottom of the cyclone where v_q describes a Rankine vortex. Using laser Doppler velocimetry Chiné et al. (1996) studied a similar cyclone and reported measurements of axial and tangential velocities. In their work they applied a back-pressure at the tangential under exit and, confirming the Baranov's results, showed also that the swirling flow depend on these pressure conditions. Then the axial velocity profile indicated the existence of less sharp transition region between the two main opposite flows, if compared to the conical cyclone profile. To properly evaluate numerical predictions, Hoekstra et al. (1998) studied the precessing vortex core (PVC) in a gas cyclone applying both LDV and PIV (Particle Image Velocimetry) techniques. By applying a simple model it was shown that the PVC has an important effect on the RMS values of velocity. Recently Chiné and Concha (1999) have compared flow patterns in conical and flat bottom cyclones showing that v_q is similar in both types of vessel while the axial velocity is different. In fact although there is the same profile made of two axial opposite flows, in the flat bottom cyclone v_z changes nearly linear with the axial coordinate z. The slope of the v_z curve decreases with z up to the bottom region where v_z is nearly zero, except in the area close to the air core where we find an upward flow. The following paragraphs describe the experimental work and present velocity data in a flat bottom cyclone measured by laser Doppler velocimetry, as a result of a research (Chiné, 1999) carried out to map the swirling flow in this vessel.

2. EXPERIMENTAL WORK

2.1 Cyclone and test rig

A flat bottom cyclone model made with well-machined perspex material was used in the laser Doppler measurements. The cyclone has a diameter D of 102 *mm* and a total height H of 310,5 *mm*. The flow enters the cyclone through an involute inlet tube with a 16 *mm* x 43 *mm* rectangular crossing area. The cylindrical section of the cyclone is 301 *mm* deep while the short bottom conical section has a height of 9,5 *mm* and an included angle of 154º. The exit of the overflow is through a vortex finder with two different diameters D_O of 32 *mm* (*cyclone 1*) and 25 *mm* (*cyclone 2*). For both cyclones 1 and 2 the diameter D_U of the apex underflow discharge is held invariable to 19 *mm*.

Water at room temperature (19÷20 ºC) was fed to the model under controlled flow conditions. The fluid was pumped from a 0,665 m^3 sump by using a 4 *Hp* pump and regulated by a set of valves. Feed pressure and flow rates were monitored with very accurate manometers and rotameters, as shown schematically in Fig. 1, while the discharged flows were measured by using a sharp crested weir mounted above the sump. To minimise the optical refraction of the laser beams at the curved cyclone walls, the model was immersed in a water-filled jacket. Finally, to generate tracer particles for the LDA measurements latex painting particles were added to the fluid.

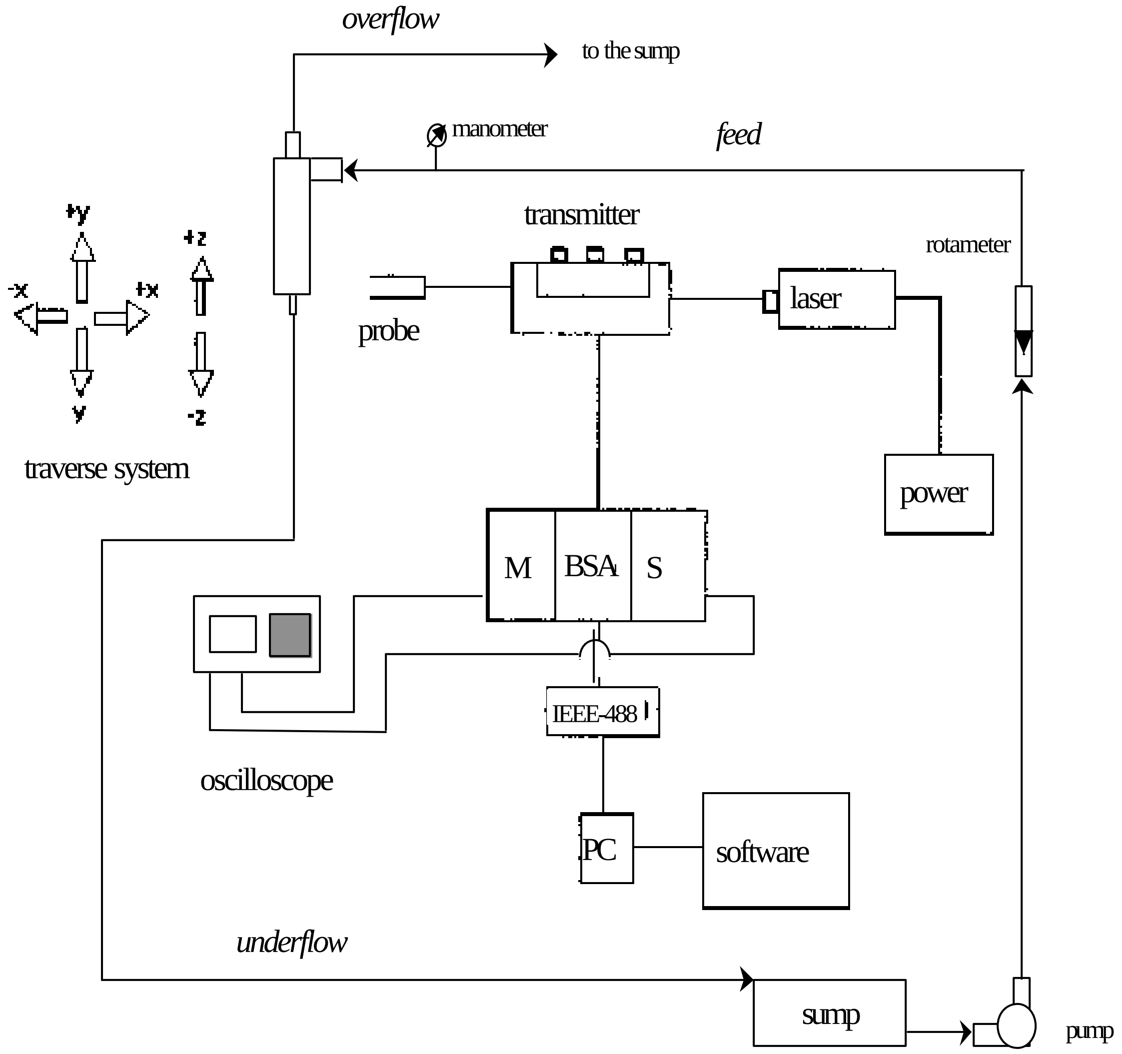

Fig. 1 The experimental rig.

2.2 Experimental Technique

The velocity profiles inside the vessel were measured using a commercial laser Doppler velocimeter, which is shown in Fig. 1. The velocimeter was a Dantec two-component fibre-optic system with Burst Spectrum Analyzers (BSA) and an automatic computer-controlled, three component traverse system. Coherent light with wavelength in the range 457÷514,5 *nm* was directed to a transmitter box from a 300 *mW* Argon-ion laser, where frequency shifting to remove the direction ambiguity of the velocities and colour separation was performed. Green (514,5 *nm*) and blue (488 *nm*) light was then used to measure axial velocity and tangential velocity respectively. A Bragg cell split the light in two beams with a 40 *MHz* frequency shift. These beams then passed through a dispersion prism which provided the two green an two blue light beams. The shifted and direct beams were led to an output aperture, where fibre manipulators were used to focus the beams into the fibre optic cables. Then a probe with a 160 *mm* focal length and a beam intersection angle of 0,236 *rad* caused the four beam to intersect. The same lens collected the scattered light coming back from the measurement volume, then the light was separated into green and blue components and directed to two photomultipliers. The Doppler signals were processed in two BSA with Fast Fourier Transform in order to extract the Doppler frequencies. The experimental data were transferred via an IEEE-488 interface to a computer for processing. During the measurements the probe was moved using a highly accurate three component (x-y-z) traverse system controlled by a computer via an RS-232 interface.

As it was said before, the cyclone was immersed in a water filled jacket. This way, the change in the refractive index n , as well as the grade of refraction were lower as the light passed from the surrounding water (n = 1,33) to the perspex (n = 1,49) than they would have been in absence of the jacket.

The position of the laser beam intersection within the fluid was obtained by using an empirical relationship after measuring the real path of the light. This was achieved by moving the measurement volume between the opposite extreme locations at the inner side of the cyclone wall.

Velocity data were measured on four symmetrical vertical positions chosen on the curved walls (azimuthal coordinates q = 0º, 90º, 180º, 270º). Being r and z the radial and axial coordinate respectively, the laser beams were focused on a median vertical r, z halfplane crossing the model, one for each azimuthal coordinate q. On the median vertical plane, seven vertical z measurement levels were chosen giving a uniform measurement axial step Dz equal to 40 *mm*, with exception of the last section, where the axial step was set to 30 *mm*. For a given z coordinate, the first measurement point was placed near the wall of the cyclone and the last point was chosen in proximity of the air core. Radial steps Dr of 2,7 *mm* and 0,675 *mm* were applied. Finally, a sample of typically 1000 Doppler bursts was taken for each measurement point in all the experimental work.

3. RESULTS

For both cyclones 1 and 2 the velocity profiles were measured at three feed pressure values Dp, which originated different values of under Q_U and over Q_O flowrate, through the apex tube and the vortex finder tube respectively. Table 1a and 1b give the operating conditions for cyclones 1 and 2 respectively.

Table 1a: Operating conditions for cyclone 1.

Cyclone 1: $D_O = 32\ mm$, $D_U = 19\ mm$, $D_O / D_U = 1{,}68$

Pressure drop Dp (psi)	Inlet velocity V_{in} (m/s)	Flowrate Q (m^3/s)	Over flowrate Q_O (m^3/s)	Under flowrate Q_U (m^3/s)	Q_U/Q_O	Reynolds number Re	Swirl number S
4	2,06	$1{,}42x10^{-3}$	$1{,}27x10^{-3}$	$0{,}15x10^{-3}$	0,118	$1{,}77x10^4$	4,13
6,5	2,75	$1{,}89x10^{-3}$	$1{,}76x10^{-3}$	$0{,}13x10^{-3}$	0,074	$2{,}36x10^4$	4,14
9	3,26	$2{,}24x10^{-3}$	$2{,}11x10^{-3}$	$0{,}13x10^{-3}$	0,062	$2{,}80x10^4$	4,23

Table 1b: Operating conditions for cyclone 2.

Cyclone 2: $D_O = 25\ mm$, $D_U = 19\ mm$, $D_O / D_U = 1{,}32$

Pressure drop Dp (psi)	Inlet velocity V_{in} (m/s)	Flowrate Q (m^3/s)	Over flowrate Q_O (m^3/s)	Under flowrate Q_U (m^3/s)	Q_U/Q_O	Reynolds number Re	Swirl number S
4	1,60	$1{,}10x10^{-3}$	$0{,}73x10^{-3}$	$0{,}37x10^{-3}$	0,507	$1{,}37x10^4$	4,14
6,5	2,15	$1{,}48x10^{-3}$	$1{,}10x10^{-3}$	$0{,}38x10^{-3}$	0,346	$1{,}85x10^4$	4,00
9	2,57	$1{,}77x10^{-3}$	$1{,}35x10^{-3}$	$0{,}42x10^{-3}$	0,311	$2{,}21x10^4$	4,09

In Table 1a and 1b V_{in} is the inlet velocity, Q is the feed flowrate, $Re = V\,D/n$ is the Reynolds number, $V = 4Q/p\,D^2$ is the mean velocity axial velocity in the cyclone, D is the cyclone diameter and n is the water cinematic viscosity. To quantify the vortex intensity in the cyclone, the swirl number $S = \int_{R_W}^{D/2} r^2 v_q v_z dr \bigg/ \frac{D}{2}\int_{R_W}^{D/2} r v_z^{\,2} dr$ was used, where R_W is the vortex finder external ratio. Numerical integration of S was made using an integration interval equal to the experimental measurement step. The values of v_q and v_z used in the computation are velocity data for $z = 65mm$, measured above the vortex finder entry region. The final value of S is the mean of the values calculated for $q = 0^o, 90^o, 270^o$.

The LDV measurements carried out on the four halfplanes $q = 0^o, 90^o, 180^o, 270^o$ have given axisymmetric velocity profiles with exception of the region near the apex discharge and the air core. Then we will analyse here only the velocity profiles for the halfplane $q = 90^o$.

For the cyclone 1, fig. 2a and 2b give the experimental profiles for the axial v_z and tangential v_q velocity when Dp is equal to 4 and 9 *psi* respectively. In both cases the experimental results show that the flow is approximately a forced vortex near the air core and a free vortex in the region between the radial coordinate of $v_{q,M}$ (the maximum of the tangential velocity) and the solid wall. Also there are two opposite axial currents separated by a cylindrical surface where the axial velocity is zero. The radial coordinate of $v_z = 0$ is constant along the cyclone down to the bottom. The slope of v_z curve decreases with z and for $z = 295mm$ and, if we excluded the region near the air core, the axial velocity is practically zero.

In fig. 3a we plot $v_{z,M}$, the maximum of the overflow axial velocity: it increases with Dp and decreases linearly with z. Fig. 3b gives the values of $v_{q,M}$ which grows with Dp and it is virtually the same for changes in z. We observe that the radial coordinate of $v_{q,M}$ varies lightly through the vessel and moves radially outwards when the feed pressure increases, as fig. 2 confirmed. The LDV data indicate (fig. 3c) that $v_{z,m}$, the maximum of the underflow axial velocity, increases with Dp and decreases with z. In figs. 4a, 4b and 4c the values of v_z, its RMS values and the intensity of turbulence are plotted for $z = 105mm$ and $Dp = 4; 6{,}5; 9$ *psi*, while the tangential velocity data are given in figs. 5a, 5b and 5c. Both v_z and v_q present greater fluctuations near the solid wall and near the air–liquid interface, then the turbulence is not homogenous, even though corrections would be made near the air core because of the precessing vortex core (Hoekstra et al. 1998). Finally it has been observed that the turbulence is not isotropic, since the RMS values of v_z are always greater than RMS values of v_q, except near the air core where they are of the same magnitude.

The change of velocity with the variation of the vortex finder diameter (cyclone 2) is presented by means of fig. 6, where we give the LDV profiles obtained for Dp equal to 4 and 9 *psi* respectively. Although the reduction of the vortex finder diameter produces a larger flow towards the apex, the structure of the flow is the same, as it could be expected. Again the flow does not depend on feed pressure, since the flow changes only its magnitude, while the velocity and also the turbulence profiles maintain a constant pattern.

4. CONCLUSIONS

Axial and tangential velocities and their RMS values have been measured in a flat bottom cyclone by laser Doppler velocimetry. The technique provided to be a useful tool in characterising the swirling flow in the cyclone. The results of the experimental work show that the inlet pressure affects only the magnitude of the velocities, but does not change the flow pattern. As in a conical cyclone, the tangential velocity describes a Rankine vortex while the axial velocity originates two opposite flows and furthermore it changes near linearly with the z coordinate. For both components of velocity the turbulent fluctuations are greater near the wall and the air core, but the RMS values of the axial velocity are always bigger than the RMS of the tangential velocity.

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