

# EXPERIMENTAL CHARACTERIZATION OF THE FLOW FIELD AND OIL DROPLET DISTRIBUTION ACROSS A CYCLONIC VALVE

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**Abstract.** *The present work evaluates the performance of a cyclone-based valve designed to improve the separation efficiency of a two-phase oil-water mixture. The valve is observed to have beneficial effects on the formation of oil droplets in the outlet. The work identifies the basic mechanisms for droplet break up relating them to the actual geometry of the valve. The experiments used water as the continuous phase and model oil as the dispersed phase. Measurements of droplet size distribution are performed with the aid of two different techniques: Focused Beam Reflectance Measurement (FBRM) and a Shadow Sizer (SS) system. These techniques are complementary and allow measurements in the range of 0.3  $\mu\text{m}$  to one millimeter.*

**Keywords:** *Turbulence, oil-droplet size, oil-water separation, experimental measurements*

## 1. INTRODUCTION

Valves are commonly used in the petroleum industry, especially for control purposes. In many oil production pipelines, a steady state operation is not possible since multiple phases flowing simultaneously frequently result in the formation of severe slugging.

Choke valves are typically used to impose a pressure drop whose aim is to regulate the production flow rate and minimize the undesirably large and abrupt fluctuations in the pipe pressure (Taitel, 1986). The main drawback of a choke valve is the high degree of turbulence and shear imposed on the flow that implies large droplet break up and emulsification of the petroleum fluids (Husveg, 2009). Cyclone-based valves were developed to substitute throttling valves so that their imposed centrifugal effects can induce droplet coalescence and prevent emulsion generation.

The purpose of the present work is to characterize experimentally the flow field of a cyclone-based valve, specially designed to reduce typical working levels of turbulence and shear. The valve has beneficial effects on the formation of oil droplets in the outlet section (Marins, 2010). The work identifies the basic mechanisms of droplet break up, relating them to the actual geometry of the valve. The experiments used oil-containing water as the working fluid. Measurements of particle size distribution were performed with the aid of Focused Beam Reflectance Measurement (FBRM) and a Shadow Sizer (SS) system.

## 2. TURBULENT ENERGY DISSIPATION AND EMULSION FORMATION

Oil droplet break up and coalescence are generally evaluated through the Weber number, which expresses the ratio between the statistically averaged pressure force at the scale of a droplet that tends to deform it, and the surface tension force that tends to restore the particle shape to a spherical form. In general, the greater the mechanical energy to be dissipated, the greater the break up rate and the finer the size distribution (Maniero et al., 2012).

For cases where the dispersed phase viscosity has a negligible effect on droplet break-up, Hinze (1955) introduced the

relation:

$$d_{max} = W e_{crit}^{3/5} \left( \frac{\sigma}{\rho_c} \right)^{3/5} \epsilon^{-2/5}, \quad (1)$$

eq:d

where  $W e_{crit}$  is the critical Weber number,  $\sigma$  the interfacial tension and the subscript  $c$  denotes the properties of the continuous phase. Equation (1) provides a prediction of the maximum droplet size that is observed to exist in a turbulent flow field with mean turbulent energy dissipation rate per unit mass ( $\epsilon$ ).

Downstream of an orifice or valve,  $\epsilon$  can be estimated as

$$\epsilon = \frac{\dot{E}}{\rho_c A L} = \frac{\Delta P Q}{\rho_c A L}, \quad (2)$$

eq:epsil

where  $\dot{E}$ , the energy dissipation rate in a control volume of the pipe flow (of area  $A$  and characteristic length  $L$ ), is considered to be a function of the pressure drop across the volume ( $\Delta P$ ) and of the flow rate ( $Q$ ).

Stokes' law shows that droplets in a gravitational field experience a settling velocity that is proportional to the square of their diameters:

$$v = \frac{g d^2 (\rho_c - \rho_d)}{18 \mu_c}, \quad (3)$$

eq:v

where the droplet diameter is given by  $d$ ; the subscripts  $c$  and  $d$  denote respectively the properties of the continuous and dispersed phases. This implies that droplet break up takes place in regions of high turbulent energy dissipation and results in stable emulsions, increasing the residence time of flow mixtures inside large gravimetric separator vessels.

The cyclone-based valve tested here seeks to increase the characteristic length  $L$  and prevent regions of high local energy dissipation  $\epsilon$ , thus maximizing the droplet diameter and reducing the residence time of gravimetric separators.

### 3. DROPLET SIZE MEASUREMENT TECHNIQUES

Particle sizing techniques rely mainly on laser-based systems and image analysis. Only recently, though, these instruments became available for in-situ real time measurements.

From the wide variety of instruments available for particle characterization (see, for example, Merkus, 2009), three main techniques can be selected for emulsion quantification, namely, the Focused Beam Reflectance Measurement (FBRM), the image-based sizing analysis and the Phase-Doppler Anemometry (PDA). These techniques are characterized by providing a size related signal for each individual particle analysed.

The working principle of the Focused Beam Reflectance Measurement (FBRM) is based on the back scattering of a laser light. The FBRM probe is composed of a laser diode beam that is focused through a lens to produce a very small focal point of high intensity on the immediate vicinity of the sapphire window at the probe tip, as shown in Fig. 1. The lens rotates at a known velocity providing a circular scanning beam. When the beam intercepts a drop, the laser light is backscattered and recorded by a detector mounted behind the lens. As both the scanning velocity and the time delay during backscattered light are known, the characteristic length can be determined. The probability of the beam hitting any part of the projected area of the particle is equal, so that a chord length is measured. No assumptions need to be made about the specific shape of the particle. The resulting chord length distribution needs to be transformed into a drop size distribution by a dedicated and appropriate relationship.

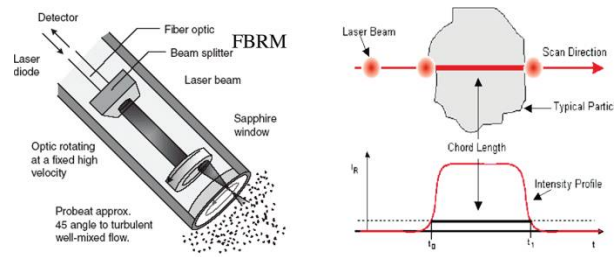


Figure 1: Diagram of the FBRM probe inner components and illustration of the measurement principle (adapted from FBRM User Manual).

An advantage of this technique is that it can measure emulsions at high volume concentrations (up to about 40%) and can also be applied at high pressures and temperatures. The overall size range for chord length distribution measurement is approximately  $0.5 - 2,000 \mu\text{m}$  and its repeatability is about 2%. In addition to its intrusive character, one of the main drawbacks of this instrument is the constant need to clean the probe window. Fouling of the sapphire window in contact with the emulsion may become a problem during long run experiments. The probe should ideally be positioned at an angle of  $45^\circ$  to the flow in order to favour the window cleaning by the main flow and to expose a homogeneous particle distribution to the probe tip.

The fundamental principle of the PDA has been introduced by Durst and Zaré (1975). This technique is actually an extension of the Laser Doppler Anemometry and requires only the use of an additional photodetector. Considering the classical dual beam configuration, the light scattered by a flowing particle will reach the two photodetectors, similarly to an LDA measurement. However, the difference in the optical path length for the reflections from the two incident beams changes with the position of the photodetector. When the particle crosses the measurement volume, both photodetectors receive a Doppler burst of the same frequency, but the phases of the two bursts vary with the angular position of the detectors. Provided that all geometric parameters of the optical components remain constant, it can be shown that there is a functional relationship between the phase difference observed from the two Doppler bursts and the size of the particle. This physical principle is illustrated in Fig. 2.

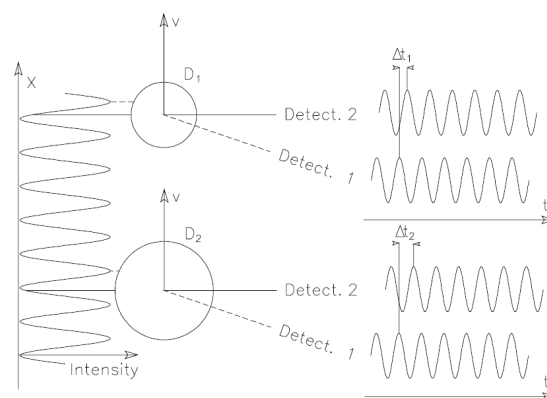


Figure 2: Illustration of the working principle of the Phase Doppler anemometer.

The phase difference measured by two spatially separated detectors  $i$  and  $j$  can be calculated as:

$$\phi_{ij} = \phi_j - \phi_i = \frac{\pi}{\lambda} d(\beta_j - \beta_i), \tag{4}$$

eq:phi

where  $d$  is the particle diameter,  $\lambda$  is the wavelength of the laser light and the difference  $(\beta_j - \beta_i)$  is the phase factor for the two detectors. Thus, a linear relationship between droplet diameter and phase difference can be obtained. The geometrical

phase factor ( $\beta_j - \beta_i$ ) depends on three parameters: i) the scattering mode (reflection, first or second order refraction), ii) the angle of incident beams intersection and on iii) the scattering angle of light collection. For measurements on the refraction mode, the index of refraction of the dispersed medium is required so that measurements can be made. The sensitivity and the size range of the measurements can be altered by adjusting these three parameters.

The clear advantage of the PDA is that it is non-intrusive and can measure particles from a millimeter down to half a micron. Since this technique can provide simultaneous measurement of particle size and local velocity, it is ideal for the investigation of droplet break up due to turbulence effects. The disadvantage is that its use is recommended for spherical particles and since it requires optical access, the particle concentration should be low.

The Shadow Sizer system is a technique based on image analysis and consists of a high speed, high resolution camera and a backlight diffuse illumination of the flow. The images must be acquired appropriately in order to favour a high contrast between the droplets and the background. Then, a contour detection algorithm is used to recognize the particles and calculate the desired variables. For small particles, the images usually need to be produced after magnification in a microscope. The quality of the results depends strongly on the degree of magnification, the quality of the image and the quality of the algorithms.

These three different techniques are complementary and can resolve particles from  $0.5 \mu\text{m}$  to the millimeter range. Since the PDA allows simultaneous measurements of velocity and particle sizes, it can also be used to estimate the dissipation of turbulent kinetic energy along the conic section of the cyclonic valve. The use of images has the advantage of gathering information on both size and shape of the particles. Low particle concentration is required in order to avoid misinterpretation due to possible overlap or coincidence of particles. The chord length measurement provided by FBRM does not have this concentration limitation, but the information is different from particle size. Thus, the chord length distribution may be used as such or a conversion to diameter distribution should be made through a quantitative model.

#### 4. EXPERIMENTAL SET UP

The experiments were conducted at the Laboratory of Compact Separators (NIDF/COPPE/UFRJ) in a real scale cyclonic valve, entirely made of Plexiglas, as shown in Fig. 1a. Water and mineral oil (Eureka 10) were mixed in a reservoir and then pumped through a one inch pipe to the valve. The system operated in a closed loop, as sketched in Fig 1b. The flow rig was equipped with a Khrono Coriolis flowmeter and two Yokogawa pressure transducers to measure the pressure drop across the valve. The present experiments were performed under ambient temperature of  $22^\circ\text{C}$  and flow rate of  $300 \text{ l h}^{-1}$ . Two different volume concentrations were tested: 0.05 % and 0.5%.

The particle distribution was characterized with the aid of a G400 FBRM system using a 9.5 mm diameter probe (Merkus, 2009). The typical scanning speed of this system is  $2.0 \text{ ms}^{-1}$ . The emulsion was characterized at the inlet section. Under the same inlet conditions, droplet distributions at the outlet section of the cyclonic valve and of a typical choke valve were measured independently.

The image-based analysis was performed through a Shadow Sizer system (Dantec Dynamics). This technique consists of a high speed camera (NanoSense MK III) and a constellation led back light that provided high resolution images ( $1280 \times 1024$  pixels) at 1000 Hz maximum frame rate. The camera was fitted with a Nikkor 200 mm f/4.0D lens in order to provide high image magnification. The software Dynamic Studio was responsible for triggering the camera and the illumination system, as well as detecting contour differences on the images to provide statistical results about the flow.

#### 5. RESULTS

The experiments were conducted at a fixed pressure drop for both valves and at a flow rate of  $300 \text{ l h}^{-1}$ . The working fluid is oil-containing water; two different volume concentrations were tested: 0.05 % and 0.5 % of mineral oil (Eureka 10) emulsified in tap water by the use of a churn on the reservoir. The comparison of droplet break up distribution between the choke valve and the cyclonic valve were made under identical flow rates and pressure drops. The experimental data provided by the FBRM are presented below.

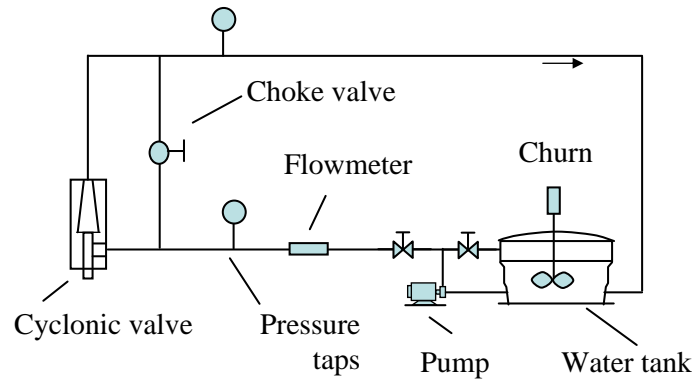
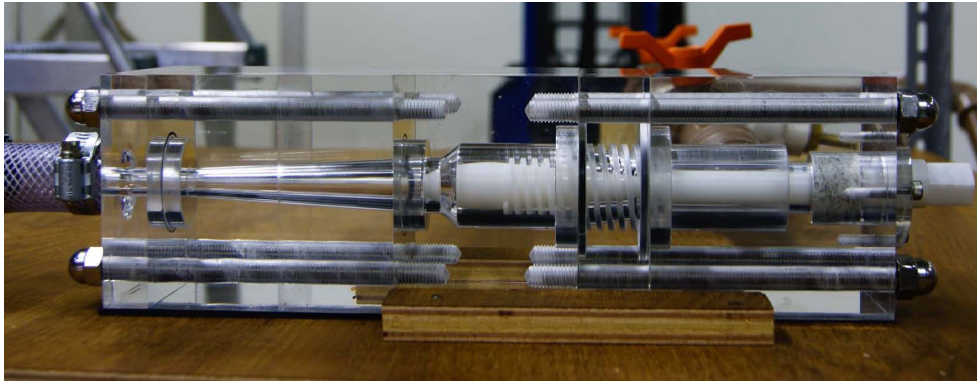


Figure 1. (a) geometry of the cyclone-based valve and (b) schematic drawing of the test flow rig.

fig:valv

Results for the experiments performed with the lower volume concentration emulsion is shown in Fig. 5, where chord length distribution ( $C$ ) is presented for the inlet section as well as for the flow downstream of the choke and the cyclonic valve. It can be seen that the cyclonic valve favours droplet coalescence so that its outlet distribution is slightly distorted towards the higher chord lengths. The choke valve, on the other hand, clearly promotes a significant droplet breakup along the whole range of particle sizes.

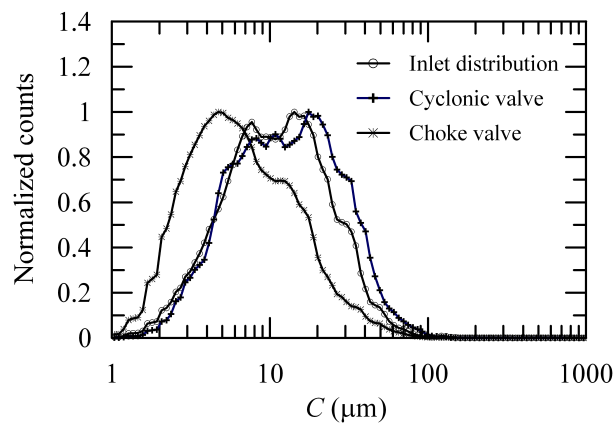


Figure 5: Oil droplet distribution in the outlet of the cyclonic valve in comparison to the outlet of the tested choke valve. The emulsion characterized in the inlet section is also included for reference. This test was performed with 0.05% of oil in water.

A comparison of the median and the mean values of the distributions presented in Fig. 5 are depicted in Table 1. The choke valve reduces the inlet median particle value by a factor of 1.8 whereas the cyclonic valve maximizes this number by a factor of 1.2.

Table 1. Summary of the oil droplet size downstream of the cyclonic valve in comparison to the choke valve.

Test condition: 0.05 % of oil in water.

	Inlet	Choke valve	Cyclonic valve
Median ( $\mu\text{m}$ )	11.45	6.27	13.57
Mean ( $\mu\text{m}$ )	42.61	39.05	46.20

The higher volume concentration emulsion has been investigated solely for the cyclonic valve. Figure 6 presents a comparison between the particle distribution on the inlet and outlet sections of the cyclonic valve for a oil-water concentration of 0.5 %. For the present case, the whole inlet distribution is moved towards larger values, showing that the coalescence effects are acting even on the smallest particles.

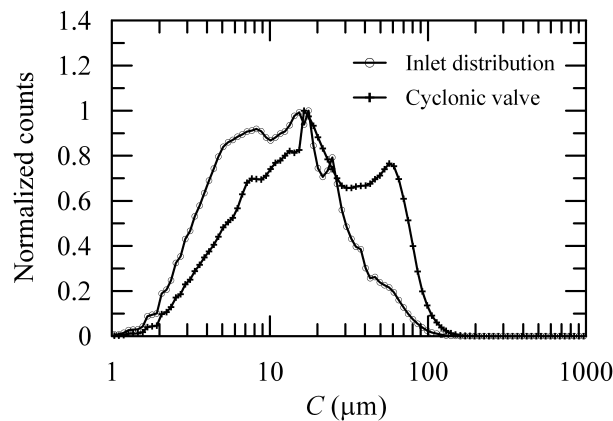


Figure 6: Oil droplet distribution in the outlet of the cyclonic valve in comparison to the emulsion characterized in the inlet section. This test was performed with 0.5% of oil in water.

Table 2 provides the mean and median values of the distributions illustrated in Fig. 6. It can be seen that the mean value at the cyclonic valve outlet is increased by a factor of 1.4.

Table 2. Summary of the oil droplet size downstream of the cyclonic valve in comparison to inlet section.

Test condition: 0.5 % of oil in water.

	Inlet	Cyclonic valve
Median ( $\mu\text{m}$ )	11.75	13.65
Mean ( $\mu\text{m}$ )	44.67	60.99

The chord length results provided by the FBRM shown above were not correlated for estimation of the particle diameter distribution. However, it is reasonable to consider that the particles observed on the considered emulsions have a spherical shape. Assuming the average particle shape is constant over a large number of particles measured, changes to the chord length distribution are then solely a function of the change in particle dimension.

Based on this assumption, Eq. (3) will be evaluated on the basis of mean and median equivalent diameter to estimate the influence of droplet coalescence on the Stokes velocity. Table 3 presents the results for settling velocity regarding the lower concentration emulsion. It is shown that the cyclonic valve can diminish the residence time of the flow mixture inside gravimetric separators by a factor of 2, as far as the median equivalent diameter is considered.

Table 3. Influence of the droplet size on the settling velocity for the test condition of 0.05 % of oil in water, ( $\rho_c = 877.1$ ).

	$V_{in}$ [ $\text{ms}^{-1}$ ]	$V_{ch}$ [ $\text{ms}^{-1}$ ]	$V_{cy}$ [ $\text{ms}^{-1}$ ]
$d_{median}$	0.76	0.41	0.89
$d_{mean}$	2.82	2.59	3.06

Analogous results are shown for the emulsion of higher concentration in Table 4. The settling velocity provided by the cyclonic valve is 36 % higher in comparison to the inlet conditions, when the mean equivalent diameter is considered. Despite the droplet size parameter chosen, it can be seen that the cyclonic valve always favours droplet coalescence and improves the efficiency of downstream gravimetric separators.

Table 4. Influence of the droplet size on the settling velocity for the test condition of 0.5 % of oil in water, ( $\rho_c = 877.1$ ).

	$V_{in}$ [ $\text{ms}^{-1}$ ]	$V_{cy}$ [ $\text{ms}^{-1}$ ]
$d_{median}$	0.78	0.91
$d_{mean}$	2.96	4.04

Measurements of particle size distribution through the Shadow Sizer system were not possible since the oil droplets eventually got stuck on the pipe wall, preventing the visualization the core flow on the pipe centerline. Although the oil chosen for the present experiment is fairly transparent, the film formed by the emulsion deposited on the wall imposes significant changes to the index of refraction, blocking the optical access to the inner flow. Figure 7 illustrates a typical image obtained with the aid of the Shadow Sizer. The droplets situated at the wall can be perfectly measured, but they do not correspond to the actual particle size distribution of the flow inside the pipe.



Figure 7: Typical image obtained from the Shadow Sizer system, where only the droplets deposited on the pipe wall can be characterised.

Despite the present limitation, some clear small spots on the pipe wall allowed visualization of a tiny window of the flow. Through these clearances some particles could be seen on the image and its diameter have been estimated in 39.0  $\mu\text{m}$  mean diameter on the inlet section for the test condition of 0.5 % of oil in water. This value compares within a 12% difference from the mean chord length distribution estimated through the FBRM probe under the same experimental condition (see Table 2).

## 6. FINAL REMARKS

The particle distribution downstream of a cyclonic valve has been experimentally investigated and compared with the corresponding flow generated by a typical choke valve.

The present experiments have shown that the tested cyclonic valve has succeeded in reducing droplet break-up and emulsion formation. It actually favours droplet coalescence and maximizes the settling velocity in downstream gravimetric separators. Measurements were carried out through a FBRM system and a Shadow Sizer system.

Future work on the problem will compare the results provided by the Particle Doppler Anemometer (PDA) with the particle size distribution calculated from the FBRM chord length results. A microscope lens or an endoscope system will be adapted to the Shadow Sizer system in order to allow the image characterization of the droplet sizes.

## 7. ACKNOWLEDGEMENTS

In the course of the research, JBRL benefited from a CNPq Research Fellowship (Grant No 301172/2010-2) and from further financial support through Grant 477354/2011-4. APSF is grateful to the Brazilian National Research Council (CNPq) for the award of a Research Fellowship (Grant No 303982/2009-8). The work was financially supported by CNPq through Grants No 477293/2011-5 and by the Rio de Janeiro Research Foundation (FAPERJ) through Grant E-26/102.937/2011.

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