EXPERIMENTAL CHARACTERIZATION OF A CYCLONE-BASED VALVE

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Abstract. *A new cyclone-based valve is studied experimentally. A pressure loss chart based on the flow rate and stem position is presented. Measurements of mean and fluctuating quantities are made through laser Doppler anemometry.*

Keywords: *Cyclone-based valve, LDA, PIV, pressure loss.*

1. Introduction

In many situations, a steady state operation is not possible in two-phase flow pipes. For example, in an off-shore pipeline-riser system the low liquid and gas flow rates favor the formation of severe slugging.

The process of severe slugging has been described in detail by Taitel (1986), who showed it to consist of four different stages. Slugging causes two-phase systems to operate with undesirably large and abrupt fluctuations in the pipe pressure and in the liquid and gas flow rates at the exit.

To prevent the formation of severe slugging, a standard procedure is to increase the separator back pressure with a choke valve. This normally results in steady state conditions, with stratified flow in the pipeline and bubble or slug flow in the riser.

Unfortunately, in their operation choke valves mix and emulsify petroleum fluids. Indeed, the high degree of turbulence and shear present in choke valves made them an ideal environment for drop break up. The immediate undesirable consequence of drop break up is to reduce the efficiency of oil-water gravitational separation.

The purpose of the present work is to characterize experimentally the internal flow of a cyclone-based valve, specially designed to reduce the working levels of turbulence and shear. This valve has been observed to have beneficial effects on the formation of oil drops in the outlet. The present work identifies the basic mechanisms of drop break up and relates them to the actual geometry of the valve. The experiments used water as the working fluid. Global measurements of pressure drop against flow rate are presented. Local measurements of mean velocity and turbulence profiles are obtained through laser Doppler anemometry (LDA) (Marins et al. (2010)).

The present results have also been obtained with the hope they will serve as a reliable source for the validation of CFD predictions.

2. Emulsion formation in a choke or control valve

Valves adjust their flow rate by varying the position of the stem and hence the available flow area. Part of the flow energy is then dissipated into heat causing a decrease in pressure. In fact, the energy dissipation rate per mass unity (ϵ) is related to the total pressure loss (Δp) by

$$\epsilon = \frac{E}{\rho_c AL} = \frac{\Delta p\, V}{\rho_c AL} \tag{1}$$

where E is the total dissipation rate, A the cross-sectional area of the valve, L the axial length of the valve, V the flow rate and ρ_c the density of the continuous phase.

The formation of emulsion in turbulent flows has been associated (Kolmogorov (1949), Walstra (1993)) with droplet break-up by large eddy-bearing eddies. The eddies provoke pressure fluctuations that are strong enough to overcome the interfacial forces that hold the drops together.

The maximum drop diameter that can withstand further break-up by turbulent field is given by (Hinze, 1955)

$$d_{max} = We_{crit}^{3/5} \frac{\sigma}{\rho_c}^{3/5} \epsilon^{-2/5} \tag{2}$$

where W_e is the critical Webe number and σ the interfacial tension.

The above expression furnishes the maximum droplet size that is observed to exist in a turbulent field with intensity ϵ.

Droplets in a gravitational field are known to experience a settling velocity given by

$$v = \frac{gd^2(\rho_c - \rho_d)}{18\mu_c} \tag{3}$$

where the notation is classical. The droplet diameter is given by d; the subscripts c and d denote respectively continuous and disperse conditions.

What the above equations basically tell us is that an increase in turbulence provokes an decrease in the size of droplets that in turn provoke a reduction of the settling velocity. Droplet break up thus results in more stable dispersions. In the petroleum industry, where the density of oil and water are very close, the existence of small droplets poses a particular serious problem with the formation of a stable emulsion.

These remarks clearly identify choke valves as major emulsion generators. Because the pressure drop across a choke valve is very high, turbulent production and dissipation also tend to be high. Equation 1 shows that a possible way to reduce ϵ for a give pressure drop and flow rate is to increase L.

The above simplified theory only furnishes us a global view of the problem. Depending on the actual geometry of a choke valve, most of the pressure drop can occur over lengths much shorter than L – the characteristic length of the valve – so that droplets much smaller than those predicted by Eq.(2) may be formed. Indeed, the ideal design of valves intended at reducing the break-up of droplets must be aimed at preventing the existence of regions of high ϵ.

In this sense, a complete picture of the problem can only be given by a differential analysis of the flow. This can be made through numerical simulations or experimental tests. The present work aims at obtaining reliable experimental data that can be used to validate numerical simulations of the problem.

3. Experiments

3.1 Experimental set-up

The experiments were carried out in a full-scale cyclonic valve entirely constructed of plexiglass and with the basic geometry shown in Figure 1. Flow is admitted at the cylindrical section of the on right side of the valve and then directed to the left through the outlet the conical section.

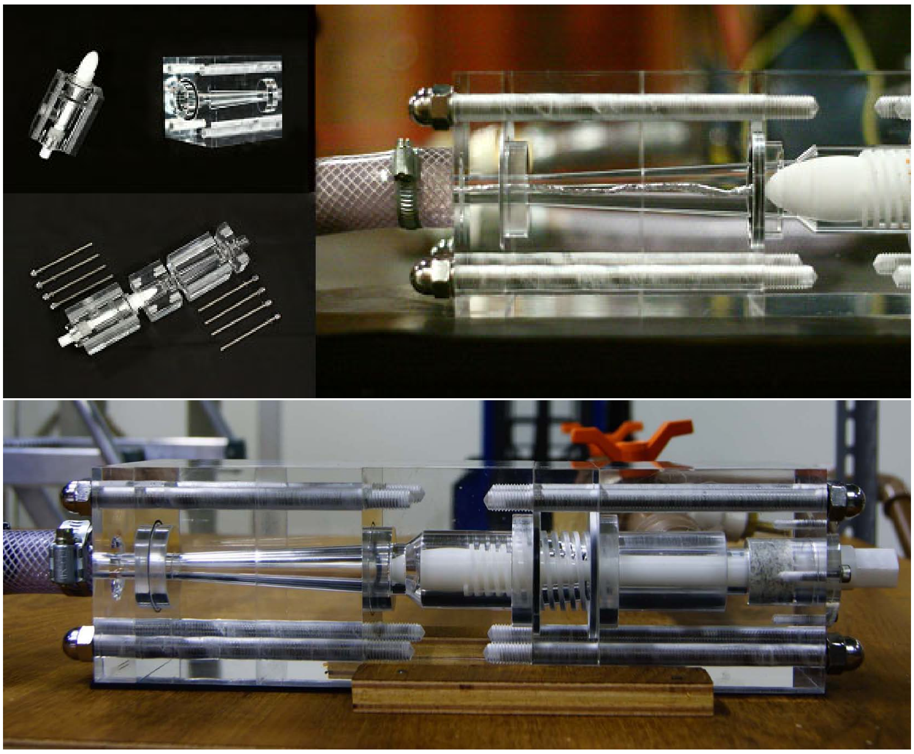

Figure 1. Geometry of the cyclone-based valve. Top photograph shows the parts of the valve with emphasis on the conical section. Bottom photograph shows the whole assemblage.

The cyclonic valve was testes in a 1 inch closed loop system that was operated at a pressure of 3.5 bar. The system basically consisted of a 1 cubic-meter reservoir, a centrifugal pump, a flowmeter, control valves and two manometers installed at the inlet and outlet of the cyclonic valve. The flow rate was further evaluated through integration of velocity profile measurements in the inlet pipe. To that end a LDA was used.

3.2 Measurements

A one-component MSE laser-Doppler anemometer that used a 5W Ar-ion tube laser was operated in the backscatter mode to measure mean and fluctuating profiles of the tangential (V_θ) and axial (V_z) velocity components. The beams were made to pass through a series of conditioning optical elements to achieve a small measurement volume and to improve the optical alignment. The signals from the photomultipliers were band-pass filtered and processed by a burst spectrum analyzer operating in a single measurement per burst mode. A series of LDA biases were avoided by adjusting the strictest parameters on the data processor. For the statistics at each point, 100,000 samples were considered.

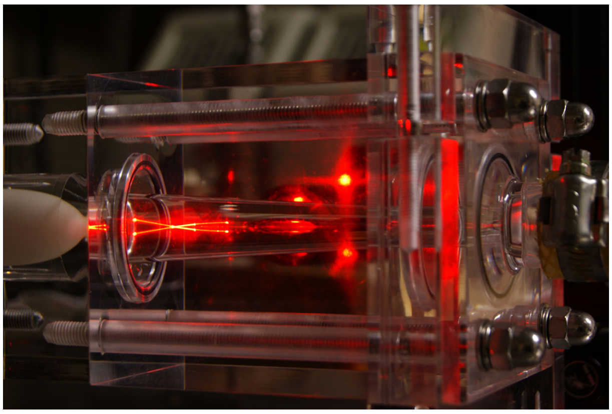

Figure 2. Laser Doppler anemometer in operation.

To minimize the effects of reflection and refraction of the light beams, the external walls of the cyclonic valve (Figure 2) were made flat. However, because the internal walls are conical in shape, the pair of beams cross in different positions. This required the introduction of a physical model to correctly account for the actual position where the beams intersect. Typical uncertainties associated with the tangential (V_θ) and axial (V_z) mean velocity data are below 0.52% and 0.35% of the inlet mean velocity, respectively. Regarding the turbulent fluctuation components – $\langle v'_\theta v'_\theta \rangle^{1/2}$ and $\langle v'_z v'_z \rangle^{1/2}$ – uncertainties relative to the inlet mean velocity were estimated to be 0.36% and 0.25% respectively.

4. Results

The typical pressure loss chart for a control valve is shown in Figure 3. Depending on the position of the stem, different flow passages (orifices) are allowed to the fluid causing higher or lower pressure drops. Smaller orifices lead to higher pressure losses (Opening 1, Figure 3), whereas bigger orifices lead to lower pressure losses (Opening 5).

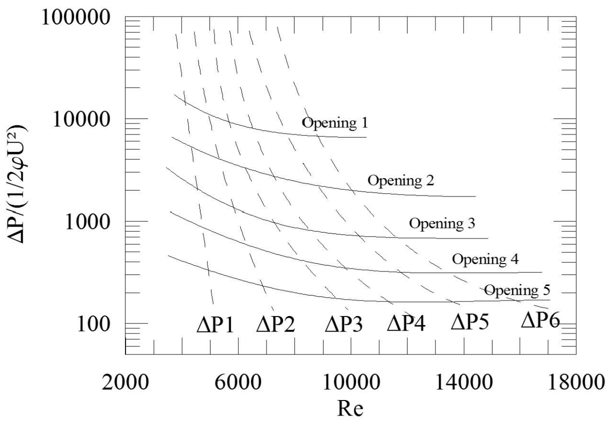

Figure 3. Pressure loss chart for a control valve.

The actual behaviour of the presently tested cyclonic valve is shown in Figure 4, where U (mean velocity) and Re are defined in terms of the inlet conditions. The loss coefficient shown on the vertical axis is observed to change from 1,000 to 100,000. A fully open globe valve normally gives a value of 400.

Preliminary results have shown that the level of emulsion formation resulting from passage of an oil-water mixture in the cyclone-based valve in much lower when compared with commonly used choke valves (globe valve). The positive

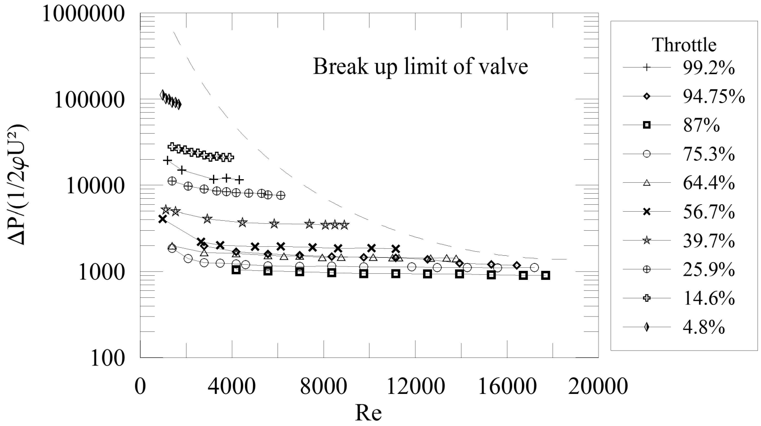

Figure 4. Pressure losses for the tested cyclonic valve.

effect of the low-shear valve on the resulting flow pattern and consequently in the oil-water separation process is shown in Figure 5. Less droplet break-up and fluid emulsification imply in enhanced oil-water separation. The recipient on the left of Figure 5 shows the water(80%)/oil(20%) mixture that is drained from the bottom of a gravity separator 5 minutes after flowing through a globe valve. The recipient on the left shows the mixture that is collected after flowing through the cyclonic valve. The differences are noticeable.

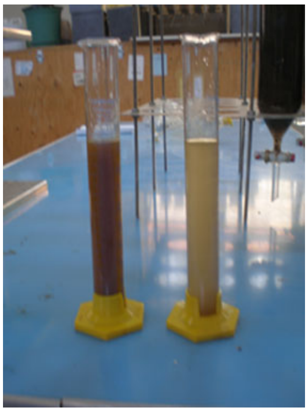

Figure 5. Water(80%)/oil(20%) mixtures collected after flowing through a globe (right) and a cyclonic (left) valve.

In a cyclonic valve, a large volume is involved to dissipate the flow energy. In addition, the presence of centrifugal forces should ease droplet coalescence.

The typical behaviour of the tangential and axial mean velocity components, V_θ and V_z, in the cyclonic valve is shown in Figures 6 and 7. The tangential profiles were measured in two stations, corresponding to cones radius of 7.5 and 8.5 mm. They follow the expected trend, increasing from the wall up to a point where a maximum is reached. From this point on they decrease rapidly to zero. Early studies have divided the tangential profile in two parts: an inner part that closely resembles the rotation of a rigid body and an outer part that behaves like a free vortice with $V_\theta r^n$ = constant. Here, the same trend has been observed.

The axial mean velocity in a hydrocyclone nearly follows a Gaussian profile, it is negative close to the wall and positive in the center (Marins et al., 2010). The negative sign denotes the flow that escapes through the underflow; positive velocity is related to the flow that leaves through the overflow. The velocity profiles in Figure 6 are quite different from those shown in Marins et al. (2010). Since in a cyclonic valve all flow is directed to a single outlet, two velocity peaks are observed close to the wall, with a plateau of nearly zero velocity ($\approx$ 0.25 ms^{-1}) in the neighborhood of the origin. Profiles for the axial mean velocity were measured in four different positions. All profiles are nearly symmetric and satisfy mass conservation.

Figures 5 and 6 have specially been obtained to validate numerical simulations of the problem based on two-equation differential turbulence models. We have seen that the crucial controlling parameter for the formation of an emulsion is ϵ. Unfortunately, ϵ is not easy to be determined in an experimental campaign, in particular, with spatial resolution. For this reason, numerical simulations of the flow in a cyclonic valve are a key factor for the correct design of valves aimed at inhibiting the formation of emulsions.

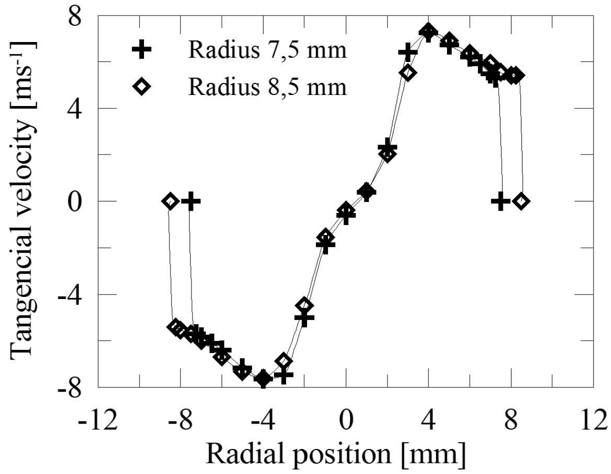

Figure 6. Mean tangential velocity profiles in the valve.

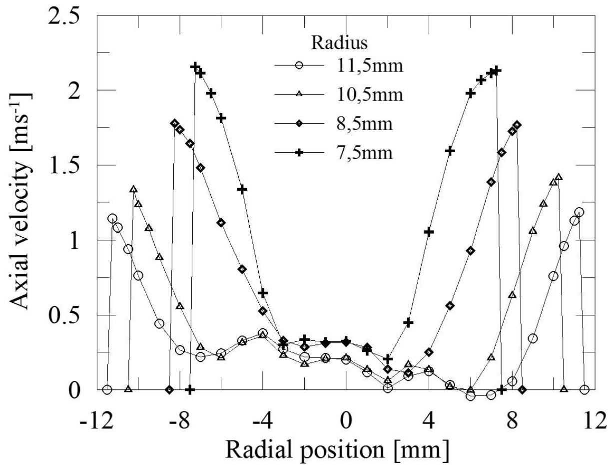

Figure 7. Mean axial velocity profiles in the valve.

5. Final remarks

The present experiments have shown that the tested cyclonic valve has succeeded in reducing droplet break-up and emulsion formation.

The flow in a cyclonic valve aimed at applications in the petroleum industry has been characterized through the LDA technique. Two components of the mean velocity profile have been characterized. The present data is considered accurate enough to serve as reference data for the validation of numerical simulations of the problem.

Future work on the problem will discuss the numerical implementation of turbulence model for the characterization of cyclonic valves. Also, droplet size measurements will be presented.

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