Numerical studies on the separation performance of liquid-liquid Hydrocyclone for higher water-cut wells

H Osei1, H H Al-Kayiem1 and F M Hashim1
1Mechanical Engineering Department, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia

E-mail: harrisdecany@yahoo.com

Abstract. Liquid-liquid hydrocyclones have nowadays become very useful in the oil industry because of their numerous applications. They can be installed downhole in the case of a well that produces higher water-oil ratios. The design of a liquid-liquid hydrocyclone for such a task is critical and every geometric part of the hydrocyclone has a part to play as far as separation is concerned. This work, through validated numerical technique, investigated the liquid-liquid hydrocyclone performance for the cases of single-inlet and dual-inlets, with different upper cylindrical lengths, specifically, 30mm and 60mm. It was observed that the hydrocyclones with the 30mm upper cylindrical section perform better than the ones with 60 mm upper cylindrical section. It was again noted that, even though higher number of tangential inlets increases the swirl intensity, they have the tendency to break up the oil droplets within the hydrocyclone because of increasing shear and jet flow interaction.

1. Introduction
The influx of water into the well has been known for more than 100 years and is regarded as one of the biggest problem during oil production [1]. The fact is that, there is a time in the production life of a reservoir where production reaches its peak and the produced oil is often associated with increased water production. This is normally the case when the field is matured and has produced for many years [2]. A contributing factor to this increased water influx is the upward dynamic force resulting from wellbore drawdown which causes the water underlying the oil zone to rise to a height after which it becomes unstable and finally breaks into the well [3]. As a result of that, higher water-cut wells therefore have the tendency of depleting fast the pressure of an oil reservoir and indirectly causing low oil productivity. A suitable way is therefore needed to limit the production of water and at the same time increase oil production.

Hydrocyclone is one of the separation devices that have found application in industry for many years and its use and installation downhole can help overcome this problem by separating the oil and water, after which the oil is pumped to the surface and the water injected back into the formation to maintain the reservoir pressure and boost the oil inflow into the well. Hydrocyclone has proved to be an important device when it comes to the separation of liquid-liquid, gas-liquid and liquid-solid streams or products. It is simple in design, low in cost, easy to operate, low in maintenance and high in separation efficiency. It is very compact, has no moving parts and does not need any chemical additives. No wonder it provides a competitive method for oily water treatment. In spite of the wide application of hydrocyclones, their accurate design is often difficult because there are many mathematical relationships for predicting the separation efficiency and the pressure drop based on
semi-empirical models which are restricted to hydrocyclone geometry and operating conditions from which they are deduced [4].

In the oil production industry, the use of liquid-liquid hydrocyclone (LLHC) for the treatment of oily water cannot be underrated especially when production is from higher water-cut wells. Some matured fields can produce higher water volumes in the range of more than 70% when compared with the oil. This can lead to early well abandonment and inability to recover hydrocarbon. In such cases, wellbore separation of produced fluids (oil/water) by the use of liquid-liquid hydrocyclone and same well disposal of the separated water is an environmentally friendly tool that provides a unique opportunity to reduce operating costs and enhance the economic viability of such higher water-cut wells while at the same time reducing pollution [5]. The selection and design of hydrocyclones for downhole oil-water separation are therefore important and needed.

This paper seeks to show how numerical simulation can be an effective tool in the design of liquid-liquid hydrocyclone to accomplish oil/water separation in the downhole. It presents the effects of the length of the upper cylindrical section and the number of tangential inlets of the hydrocyclone on the separation performance. The results would lead to improvement in the design of the LLHC, and in turn, reduce the water production at the surface and the oil production cost in higher water-cut wells.

2. LLHC geometry

There are many possibilities in the design of LLHC geometry for optimizing its structure and improving the oil–water separation efficiency. LLHC for higher water-cut wells consists of a set of cylindrical and conical sections. Figure 1 shows a conventional liquid-liquid hydrocyclone. It is very important to ensure that the inlet chamber and the reducing sections are designed to achieve higher fluid tangential acceleration, reduce both the pressure drop and the shear stress to an acceptable level. The shear stress has to be minimized to avoid droplet breakup which can lead to reduction in separation efficiency. The tapered section is where most of the separation is achieved. The low angle at the tapering section maintains the swirl intensity with high residence time. The smallest fluid droplets migrate to join the reverse flow at the axis of the LLHC so as to be separated through the overflow exit [6, 7].

![Figure 1. Conventional LLHC [8].](image)

3. Flow dynamic of LLHC

A typical LLHC is illustrated in figure 2. The feed enters into the upper cylindrical section through the tangential inlet(s) which cause(s) the feed to swirl inside the hydrocyclone. As the fluid moves through the LLHC to the apex, the centrifugal force and the fluid angular velocity increase because of the nature of the narrowing cross-sectional area of the cyclone. The centrifugal force developed
accelerates the settling rate of the fluid particles thereby separating them according to size, shape, and differential density. The fluid segregation is witnessed in the creation of two spiral movements within the hydrocyclone – primary spiral towards the walls of the hydrocyclone and secondary spiral at the core of the hydrocyclone. The development of the secondary spiral is also as a result of the high swirling intensity at the inlet. This causes an increase in pressure near at the walls of the cyclone with a decrease in pressure at the core and therefore by ensuring a higher pressure at the underflow outlet than that at the vortex finder, the fluid at the core is forced to flow countercurrent to the main [7, 9].

The secondary spiral constitutes the reverse flow and carries the lighter fraction of the fluid (oil) to the vortex finder which is the opening through the cover for the top cylindrical part of the hydrocyclone. Fluid through the vortex finder are termed overflow. The heavier fraction of the fluid (water) is carried by the primary spiral and drags down against the walls of the LLHC to be discharged at the spigot as underflow [8]. There is the tendency of the creation of some recirculation zones at the inlet region and this is associated with the high swirling. These zones will have long residence time, very low axial velocity and normally diminish as the flow enters the lower conical section of the LLHC [7].

![Image](Figure 2. Typical LLHC (a) showing parts and (b) showing flow dynamics [6, 10].)

4. Numerical simulation
Numerical studies were carried out using ANSYS–CFX software to test the efficiency of the hydrocyclone designs. Two hydrocyclone cases with the upper cylindrical section, L1 = 60 mm and 30 mm, with all other geometrical lengths maintained were considered. Study was also made into the situation where there are one and two tangential inlets. 3–D computational model was selected for the study and figure 3 shows the meshing of the hydrocyclone types. The optimized mesh density for a reasonable solution for the different cyclone designs was around 160,000 computational cells. Different oil-water mixture compositions were considered. The total inlet flow rate was assumed to be 2 m/s. SSG Reynolds Stress Model was used because it is more suited for complex flows and is also more accurate for swirling and rotational flow. The simulation was run and convergence was achieved at a residual target of 1x10–4.
5. Result and discussion

This section shows figures having plots of oil volume separated versus radial distance at the oil outlet. The fluid mixture compositions considered were 25% oil-75% water and 30% oil-70% water. This section will show results of these different fluid mixtures as they are introduced into the one inlet type and twin inlet type of hydrocyclones having different upper cylindrical lengths. The oil separation volume for the hydrocyclone with $L_1=60$ mm is read from the primary y-axis whereas the oil separation volume for the hydrocyclone with $L_1=30$ mm is read from the secondary y-axis. The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used.

The plot in figure 4 shows the case where the LLHC has only one tangential inlet with 25% oil-75% water as the inlet fluid composition. From the figure 4, it can be seen that separation is better in the case of the LLHC with $L_1=30$ mm. While it records efficiencies in the range of 90.5–92.3 %, the cyclone with $L_1=60$ mm records efficiencies between 70.00–75.16 %.

The results from the same one tangential inlet LLHCs but in this case having 30% oil-70% water as the inlet fluid composition is also presented in figure 5. The separation efficiency patterns here follow the same trend like that in figure 4 since the same sets of cyclones are been used. However, there are some slight differences in the separation volumes. The LLHC with $L_1 = 30$ mm still outperforms the $L_1=60$ mm type. The efficiencies are in the range of 99.14–99.27 % for $L_1=30$ mm type and 71.00–76.02 % for the $L_1=60$ mm type.
Investigation was also made for twin tangential inlets carrying the fluids. The plots in figure 6 are for the case of using 25% oil-75% water as the inlet fluid composition. From the figure, the performance of the hydrocyclone with longer upper cylindrical column lags behind that with the shorter upper cylindrical column. The L1=30 mm type produces separation volume values that range between 89.2–92.1 % against 76.79–79.43 % separation values for the L1=60 mm type.
Figure 6. Oil separation efficiency in LLHC with two tangential inlets using 25% oil 75% water mixture.

Figure 7 shows plots made after having used the 30% oil-70% water as the inlet fluid composition in the doubled inlet LLHC. The LLHC with L1=30 mm in this case again performs better than the L1=60 mm type producing efficiencies in the range of 84.59–88.84 % and 76.75–9.42 % respectively. The drop in the efficiency values recorded here is due to some fluids in the recirculation zones escaping without being classified and also some oil droplets breaking down because of the turbulence.

Figure 7. Oil separation efficiency in LLHC with two tangential inlets using 30% oil 70% water mixture.

The results obtained from this work provide a useful guide in the design of liquid-liquid hydrocyclone to control excessive water production from oil wells. Due to the limited wellbore space, LLHCs used in downhole oil-water separation (DOWS) are narrow and tall in design requiring a minimum of 0.1397 m casing size.
6. Conclusions
A liquid-liquid hydrocyclone has successfully been modelled and simulated computationally using ANSYS-CFX commercial software. The simulation results demonstrate that the LLHCs with the 30 mm upper cylindrical column provide higher separation efficiency compared to the ones with 60 mm upper cylindrical height. The separated oil volumes from the hydrocyclones with L1 = 30 mm are all above 90 %, giving way to approximately 10 % of water to be produced with the oil. 100 % separation efficiency is not possible as some water will escape with the oil and vice versa. Again, the separation performance was not appreciable in the case of using twin tangential inlets and even dropped in the case of the hydrocyclones with L1 = 30 mm which is attributable to shear and break down of the oil droplets. In conclusion, liquid-liquid hydrocyclones with one tangential inlet and short upper cylinder would lead to higher separation efficiency of oil/water mixture.

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