Experimental Study of a Hydrocyclonic Oil-Water Separator for Downhole Separation*

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Abstract

This paper presents experimental measurement and analysis of a liquid-liquid hydrocyclone separator to separate oil/water emulsion with 90% water cut. Measurements have been carried out at various temperatures and in-flow rates. Samples were taken before and after the separation and analyzed using InfraCal Oil/Grease Analyzer (HATR-T2). The results showed that, the hydrocyclone separator achieves separation efficiencies higher than 80%, in the flow split region between 0.6 – 0.7 for all the temperature cases considered in the experiments. Within inlet velocities range of 2.5 – 4.5 m/s, the hydrocyclone performance seems to plateau with separation efficiency remaining virtually constant for all the flow and temperature cases. The peak efficiencies for the cases at 25 ^oC, 30 ^oC, 40 ^oC, 50 ^oC and 60 ^oC temperatures were averagely around 80.9%, 84.1%, 85.9%, 86.5% and 87.5%, respectively. Fluid temperature slightly impacts the hydrocyclone separation performance. Separation efficiency was observed to increase with decreasing pressure drop ratio (PDR) and by reducing PDR from 0.76 to 0.74 resulted in marginal performance enhancement. Finally, increasing temperature increased the flow turbulence and affect the separation efficiency.

Keywords: Hydrocyclone, Water Cut, Downhole, Separation Efficiency, Flow Split

1 Introduction

The production of oil from an oil well is often associated with the production of some amount of water, the quantity of which can vary depending on the nature, and characteristics of the oil reservoir. There are instances where the produced water cut can be significant, (more than 80 % (Ogunsina and Wiggins 2005)) and this poses a major challenge to oil operators as the produced water causes many threats and disadvantages. The excessive water cut will call for additional maintenance for production equipment and downhole treatment for corrosion, bacteria growth, scale formation, and naturally occurring radioactive material (Ogunsina and Wiggins 2005); and this is accompanied by huge economic burden. Oil operators in the handling and treatment of produced oil-water streams at the surface have used conventional gravity separators which are bulky, heavy and expensive for separation. However, most of the above given threats can still not be dealt with by the use of conventional gravity-based vessels. In addition, with many of today's oil production operations being done offshore, there is not enough space to contain the large volumes of water produced. Space is limited and it is also costly to accommodate any bulky and heavy separation facility on the rig (Gomez *et al.* 2002) even if there is space. The use of hydrocyclones at the downhole provides an economical, effective and environmentally friendly alternative for handling produced water and oil. Their design is not complex, have stationary parts, easy to install, easy to operate and need no chemical additives for separation. Moreover, the purchase and maintenance costs of hydrocyclones are also relatively cheaper (Gomez *et al.* 2002, Osei *et al.* 2015) compared with other separation vessels/facility. No wonder hydrocyclones have excelled in many fluid stream applications such as that of solid/liquid, liquid/liquid and gas/liquid (Bowers *et al.* 2000). The use of hydrocyclonic separator in wells by way of either push through or pull through process (Bowers *et al.* 2000) provides a strong and promising way to limit excessive water production at the surface whereby the separated produced water can be used to boost and maintain the reservoirs pressure via its reinjection into the formation (Osei *et al.* 2015, Khan, 2003).

The hydrocyclone types use in oil-water separation are termed liquid-liquid hydrocyclones (LLHCs) and their use to separate oil and water was first proposed by Simkin and Olney (1956) and became widely accepted and popular in the 1980s (Schubert 1992, Gomez, 2001). The early works of Simkin and Olney (1956), Burril and Woods (1970), Mahajan and Pai (1977), Sheng et al. (1974), Hitchon (1959), Thew *et al*. (1984) and Colman and Thew (1988) showed efficient separation of liquid-liquid streams by the use of hydrocyclone. They provided a big exposure and opened the door for many researchers to study more into the liquid-liquid hydrocyclonic separation which finds many applications today.

Downhole oil-water separation (DOWS) system analysis done by many researchers (Ogunsina and Wiggins 2005, Suárez and Abou-Sayed, 1999,

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Matthews *et al.*, 1996) have revealed that the hydrocyclone DOWS type is the most widely used one that can provide efficient separation of oil from higher water cut mixture whereby the separated water stream has less than 200 ppm residual oil. Again, in terms of volume of fluid to be handled, the hydrocyclone-type DOWS can handle volume of fluid up to 10,000 bpd compared to the gravity separator-type DOWS which can handle only up to 1,000 bpd (Veil *et al.*, 1999).

This work was done to provide more reliable data to support the limited experimental data on LLHCs for separation technology. The objective of the study was to carry out experimental investigation into the impact of flowrate, pressure and temperature on the performance of LLHC. It aimed at looking at the case where the water cut was 90% and coming out with guides for the effective performance of LLHC.

2 Resources and Methods Used

2.1 Experimental Facility

This study was carried out in the Advanced Fluid Dynamics Research Laboratory at the Universiti Teknologi PETRONAS, Malaysia, using the experimental rig constructed for liquid-liquid separation. The schematic of the experimental two-phase, oil-water, flow loop is shown in Fig. 1. It is an instrumented state-of-the-art rig which can take on as many as three different liquid-liquid separators simultaneously. However, each separator must be run one at a time.

The oil and water are stored in two separate tanks; each tank has a volume of about 216 litres. The tanks have submersible heaters fixed at the bottom that can be used to heat the water and oil they contain. Each tank is connected to a separate HMS2-60 Multistage model pump which is made up of stainless steel material and uses 0.75kW/240V/1ph/50Hz motor. The pumps operate at 2900 rpm and deliver between 1.0 – 3.5 m^3/hr @ 20 – 50 mH. Both pumps are equipped with return lines that can be used to regulate the flowrate of the fluid leaving the tank and to provide the required oil-water feed composition for the test. The fluid from each tank is pumped into a metering section which comprises of pressure gauges, control valves and flow meters to further provide information about the fluid pressure and flow rate.

The metered oil and water then flow into the mixing unit via a mixing junction to obtain oil/water dispersion. The mixing unit was made up of a tank of volume of about 60 litres with an agitator stirrer mixer having a shaft of about 0.55 m and three levels of blade paddle separated at a distance of 0.13 m from the end. There were three blades at each level, separated at an angle of 120^o.

A booster pump is installed after the mixing unit and can be used if the pressure of the mixed fluid is not enough to transport it to the hydrocyclone separator. The fluid enters the LLHC and is separated into underflow fraction (mostly water) and overflow fraction (mostly oil). Samples of the fluid are taken prior to and after entry into the cyclone separator to check the oil concentration using InfraCal TOG/TPH Analyzer (HATR-T2). Their pressure readings before and after the LLHC separator are also taken. The separated fluids then flow into their various collecting tanks, allow to settle by gravity and the oil later recovered for reuse.

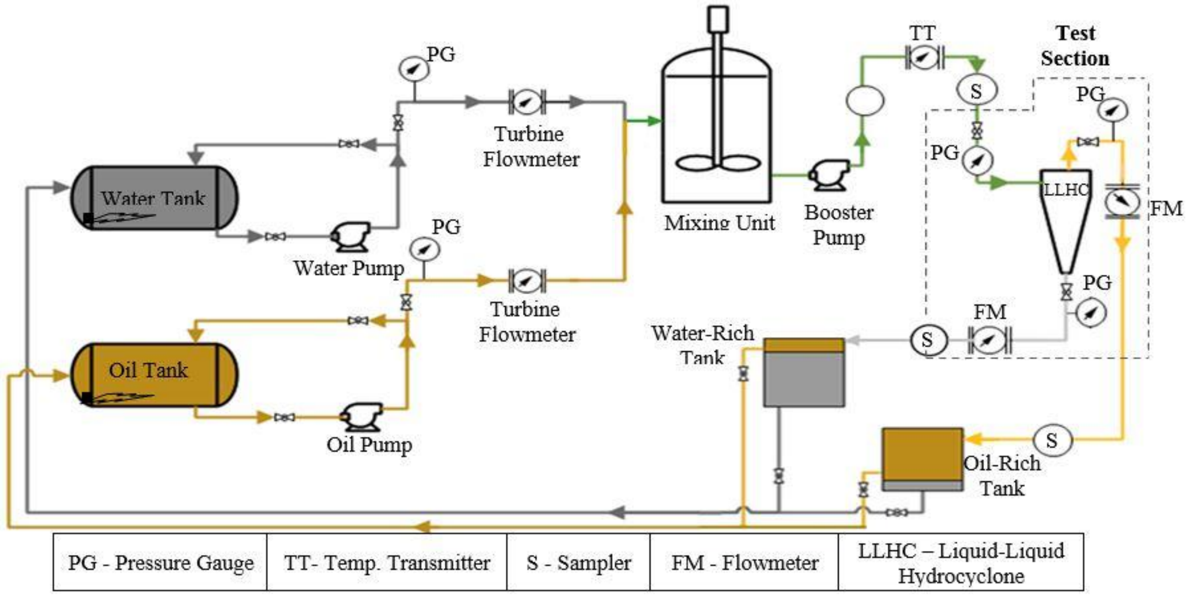

Fig. 1 Schematic of Oil-Water Experimental Flow Loop

The experiment was performed in a continuous mode and the pictorial view of the experimental facility is shown in Fig. 2.

2.2 Working Fluids

The fluids used to carry out this work were tap water and FOMI-70 mineral oil. A black dye miscible in only the oil phase was used to differentiate between the two phases. The oil was not hazardous, could separate fast and had good optical properties and low emulsification. The oil had a density of 830 kg/km^3 at 25 ^{o}C and kinematic viscosity of 0.0206 kg/m.s at 25 ^{o}C. The experimental runs were performed at temperatures ranging between 25 – 60 ^{o}C.

2.3 LLHC Test Section

The working principle of LLHC is the same as that in other hydrocyclone types. Due to the tangential position of the cyclone inlet, the oil-water mixture enters the cyclone and produces a vortex inside it. The density difference between the oil and the water is another important factor that helps in the easy segregation of the fluid particles radially within the separator. The light oil droplets occupy the core of the cyclone whereas the heavy water droplets form the outer core and drag against the cyclone walls. A reversal flow is created at the core of the cyclone when the underflow outlet is set at higher pressure than that of the overflow and the core fluid fraction flows counter currently to the main flow (Al-Kayiem *et al.,* 2014, Bowers *et al.,* 2000).

The test unit was designed after several runs of numerical simulation using ANSYS CFD where the LLHC proposed by Colman and Thew (1988) formed the basis. Analysis was made into cases where the single inlet hydrocyclone with the characteristic dimeter of 30 mm had inlet chamber heights of 30 mm and 60 mm. The simulation took into account the use of different tapering cone angles of the hydrocyclone, specifically 3.0^o, 5.0^o and 7.6^o. This is because, it is at this conical section that most of the separation takes place and the best angle is needed for effective separation. The LLHC with the 30 mm inlet chamber and 7.6^o cone angle ensured high separation performance and therefore was selected and fabricated for this experiment study. The picture of it is shown in Fig. 3. It shows the tangential inlet and the two outlets for the separated fluids to escape (i.e. the oil and the water outlets). The supports are provided so that the LLHC can be mounted vertically.

Fig. 4 shows the LLHC test section mounted in the rig where the mixed oil-water feed is introduced tangentially to the upper cylindrical section of the separator. This causes the mixture to spin inside the hydrocyclone and as it migrates to the narrowing section of the hydrocyclone, its angular velocity and centrifugal force increase due to the decreasing diameter at the narrowing/tapering sections. It is at this section of the cyclone where the bulk of the separation takes place. The mixture particles are therefore arranged with the lighter ones being at the center of the hydrocyclone whilst the heavier ones migrate toward the walls of the hydrocyclone.

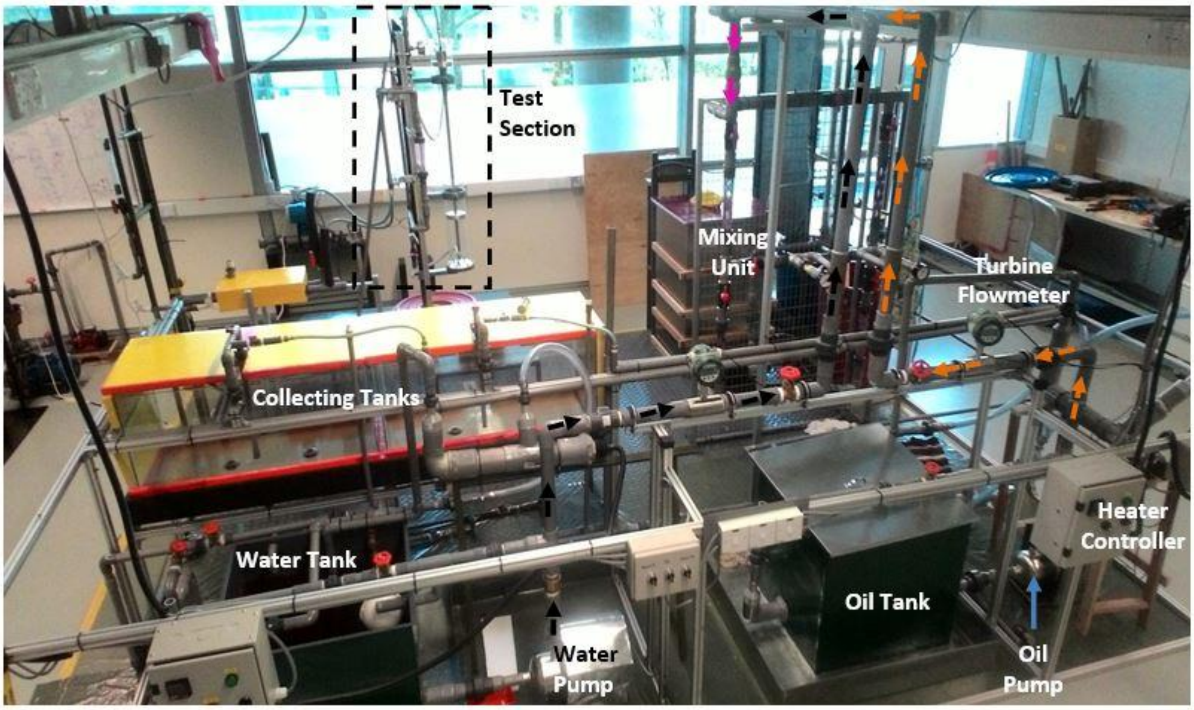

Fig. 2 Pictorial View of the Oil-Water Experimental Flow Loop

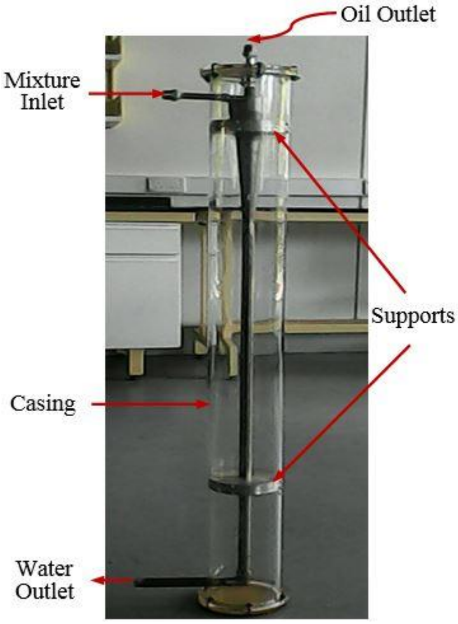

Fig. 3 Fabricated LLHC Test Section before Installation

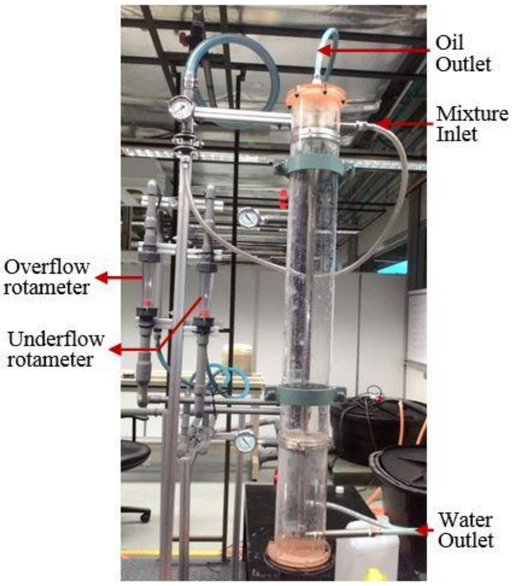

Fig. 4 Fabricated LLHC Test Section Installed in the Rig

The lighter fractions at the center of the separator are carried by the upward reversal flow to be discharged as overflow. The heavier fractions spin against the walls to the apex of the hydrocyclone to be discharged as underflow.

2.3 Performance Indication Factors

The performance of the liquid-liquid hydrocyclone separator can be determined by the following important parameters:

2.4 Oil Separation Efficiency

This provides information about how much of the oil presented at the inlet has been recovered at the overflow. It can be expressed mathematically as (Kharoua *et al.*, 2010, Gomez *et al.*, 2002):

$$E = \frac{Q_{oil\_overflow}}{Q_{oil\_inlet}} \tag{1}$$

where E is the oil separation efficiency, $Q_{oil\_overflow}$ is the flowrate of oil at the overflow and Q_{oil_inlet} is the flowrate of oil at the feed inlet.
By utilising the continuity equation:

$$C_{oil\_overflow} \times Q_{overflow} = C_{oil\_inlet} \times Q_{inlet} - C_{oil\_underflow} \times Q_{underflow} \tag{2}$$

where $C_{oil\_overflow}$ is the concentration of oil at the overflow, $Q_{overflow}$ is the flowrate at the overflow; C_{oil_inlet} is the concentration of oil at the inlet; Q_{inlet} is the flowrate at the inlet, $C_{oil\_underflow}$ is the concentration of oil at the underflow and $Q_{underflow}$ is the flowrate at the underflow.

By imposing Eq. (2) on Eq. (1) gives:

$$E = \frac{C_{oil\_overflow} \times Q_{overflow}}{C_{oil\_inlet} \times Q_{inlet}} \tag{3}$$

$$E = \frac{C_{oil\_inlet} \times Q_{inlet} - C_{oil\_underflow} \times Q_{underflow}}{C_{oil\_inlet} \times Q_{inlet}} \tag{4}$$

$$E = 1 - \frac{C_{oil\_underflow} \times Q_{underflow}}{C_{oil\_inlet} \times Q_{inlet}} \tag{5}$$

Therefore, the oil separation efficiency can be determined.

2.5 Flow Split

This represents the ratio of the total overflow flowrate to the total inlet flowrate. It is sometimes referred to in literature as the reject ratio, split ratio or overflow volume percent (Gomez *et al.*, 2002, Meldrum 1988, Young *et al.*, 1994). It is mathematically given as:

$$F = \frac{Q_{overflow}}{Q_{inlet}} \times 100\% \tag{6}$$

3 Results and Discussion

This work considered the case where the water cut in the oil is high, up to 90%. The water-to-oil ratio was 9:1. The inlet pressure was varied from 31 kPa to 282 kPa while the flowrate was varied between 0.49 and 1.46 m^3/h. The experiment was conducted under five different temperatures, ranging from 25 ^oC to 60 ^oC. The data is analyzed and presented to show the influence of the flow parameters on the performance and separation efficiency of the designed LLHC separator.

3.1 Flow Split and Temperature Effect

The flow split provides information about the amount of fluid introduced at the feed inlet that exits at the overflow outlet. Fig. 5 presents the effect of flow split on separation efficiency taking into account the temperature of the mixture. As depicted in Fig. 5, the performance of the LLHC separator depends on flow split. For the designed LLHC, the separation performance generally increases with increasing flow split but the performance becomes marginal for some time as the flow split value increases after which performance may not be appreciable and drop. The fall in the separation efficiency after the optimum flow split (at which the efficiency is highest) is reached can be attributed to the increase in volume of water as the flow split increases. In the studied cases, very high oil separation efficiencies can be achieved with flow splits between 0.6–0.7 for the temperature cases considered. The fluid temperature impacts the cyclone performance.

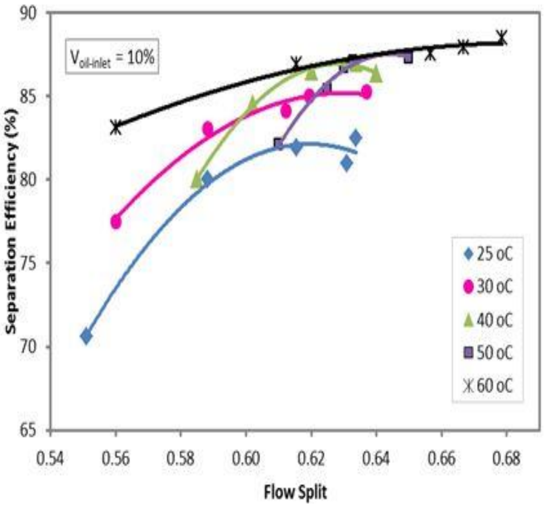

Fig. 5 Effect of Flow Split and Temperature On Separation Efficiency

3.2 Effect of Inlet Velocity and Temperature on Separation Efficiency

The separation of the oil from the water within the LLHC separator is as a result of the forces imposed on the oil droplets in the spinning fluid (Young *et al.* 1994). The higher the fluid velocity at the inlet, the higher will be the centrifugal force and the swirling intensity to segregate the fluid particles. Consequently, the residence time reduces. Fig. 6 shows the effect of the fluid inlet velocity on the performance of the hydrocyclone separator at different fluid temperatures.

It is evident from the results demonstrated in the figure that, separation improves as the inlet fluid velocity increases. However, the enhancement of separation is fast, up to a certain velocity value after which the performance plateaus or increases marginally. Between the inlet velocities of 2.5 – 4.5 m/s, cyclone performance seems to almost reach its peak with separation efficiency remaining virtually constant. This was obviously seen in all the cases studied. Considering the separation efficiency at different temperature cases, on the larger scale, separation improves slightly with increase in fluid temperature. The peak efficiencies for the cases at 25 ^oC, 30 ^oC, 40 ^oC, 50 ^oC and 60 ^oC temperatures were averagely around 80.9%, 84.1%, 85.9%, 86.5% and 87.5% respectively.

The fluid inlet velocity and temperature both influence the nature of the flow inside the LLHC. The combined effect of the two is shown in the Reynolds number. Fig. 7 was therefore made to show the effect of Reynolds number (*Re*) at the various temperatures considered in this study. Increasing temperature increases the Reynolds number as it lowers the kinematic viscosity of the fluid. The fluid then becomes less dense and less viscous to flow fast; thereby increasing the turbulence.

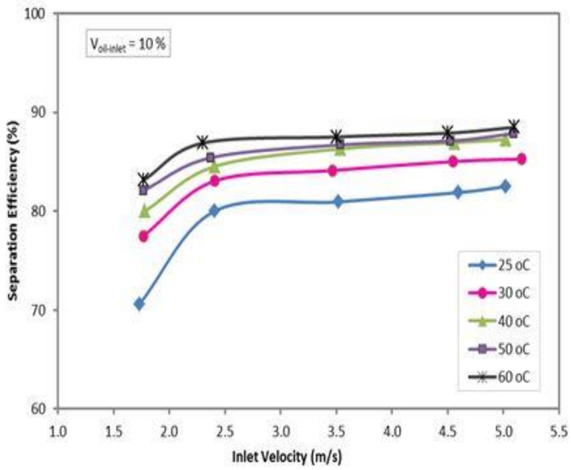

Fig. 6 Effect of Inlet Velocity and Temperature on Separation Efficiency

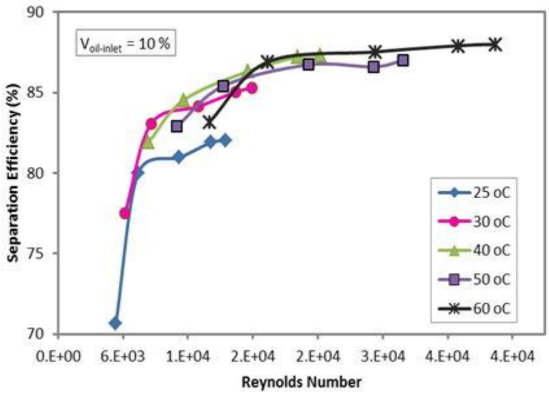

Fig. 7 Reynolds Number versus Separation Efficiency

Increasing flowrate increases the centrifugal force built within the LLHC thereby ensuring good segregation of the fluid particles. However, attempts should be made not to increase the flow's turbulence beyond the rate at which it will breakdown the oil droplets into smaller sizes and cause the formation of emulsion; both of which will cause reduction in the separation efficiency of the hydrocyclone separator.

The Reynolds number was calculated by taken into account the volume fraction of each fluid at the inlet. The flow within the LLHC is turbulent over the entire velocity range of 1.7 – 5.2 m/s considered in this study. It can be observed in all the plots that increasing Reynolds number increases the cyclone's performance significantly from the beginning to a point after which the performance almost stabilizes over a range of *Re* (See Table 1). Beyond this stabilization point, efficiency may increase marginally.

Table 1 Range of *Re* at which Separation Efficiency Stabilizes

Temp (°C)	*Re* Range	Plateau Separation Efficiency (%)
25	$8.0 \times 10^3 – 1.12 \times 10^4$	≈ 81.0
30	$8.6 \times 10^3 – 1.30 \times 10^4$	≈ 84.1
40	$2.2 \times 10^4 – 2.42 \times 10^4$	≈ 87.0
50	$2.52 \times 10^4 – 2.80 \times 10^4$	≈ 87.0
60	$2.93 \times 10^4 – 4.04 \times 10^4$	≈ 87.9

3.3 Effect of Pressure Drop

There will be a change in pressure between the point where the fluid enters the cyclone and the point(s) where the fluid exits. The flowrate, which is a function of the fluid velocity, has a part to play as long as pressure drop is concerned. Fig. 8 therefore presents the relation between the flowrate and the pressure drop of the studied LLHC. The case at 30 °C was used to explain this relationship. There is the existence of two distinct pressure drops across the LLHC separator because of its two outlets and one inlet – the pressure drop to the overflow stream, ΔP_{io}, and the pressure drop to the underflow stream, ΔP_{iu}. The former is the difference between the pressure at the inlet and the pressure at the overflow exit whereas the latter is the difference between the pressure at the inlet and the pressure at the underflow exit. The pressure drop to the underflow stream is the most significant; it will always be the greater one and ultimately determines the hydrocyclone capacity (Meldrum, 1988). This fact is demonstrated by Fig. 8.

At any given flowrate, ΔP_{iu} is greater than ΔP_{io} which means that more flow passes via the overflow outlet compared to that passing through the spigot of the hydrocyclone separator and vice versa. This is normally required so as to pave way for more oil to escape via the overflow outlet to increase the oil separation efficiency. The effect of Reynolds number on the pressure drop to the underflow stream for the various temperature cases is as shown in Fig. 9.

The relationship between the two pressure drops is also important and can be used for flow control purposes.

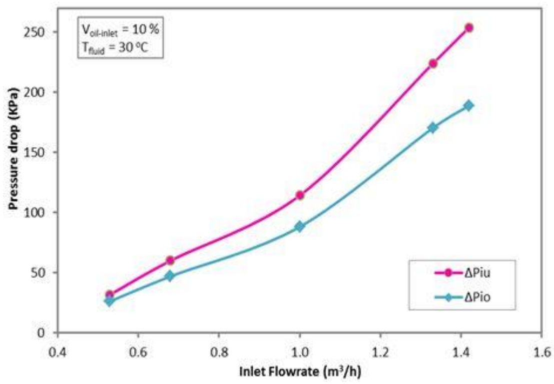

Fig. 8 Inlet Flowrate – Pressure Drop Relationship

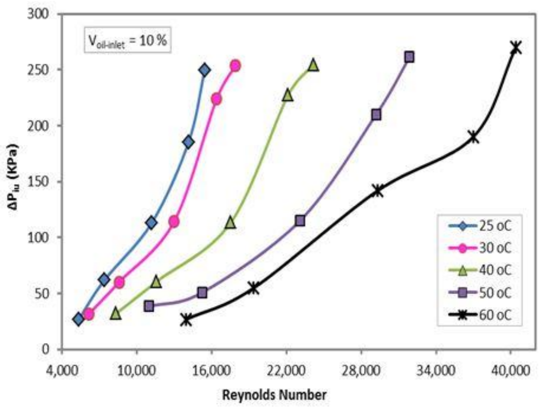

Fig. 9 Effect of Reynolds Number on the Pressure Drop to the Underflow Stream

The two are generally combined in the form of a ratio ($\Delta P_{io}/\Delta P_{iu}$), which is termed the pressure drop ratio (PDR). Generally, maintaining a higher PDR will ensure more fluid passage to the underflow outlet and vice versa. Fig. 10 is therefore made to depict the effect of PDR on the separation performance of the studied LLHC separator in the quest of separating the produced oil from the voluminous water quantity.

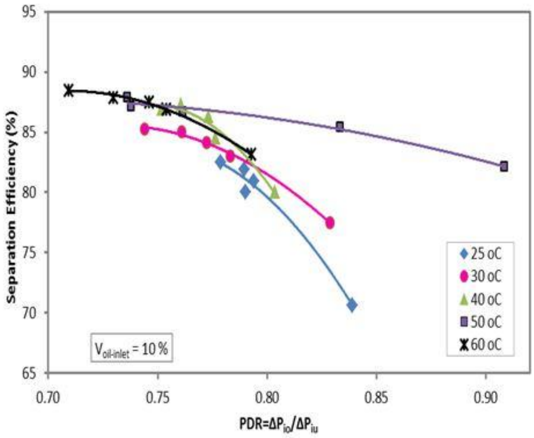

Fig. 10 Effect of PDR on the Separation Performance

It was found out that decreasing PDR increases the separation performance as most of the oil escapes through the vortex finder to be separated. Efficiency rises quickly with decreasing PDR and tends to become marginal when the peak efficiency is reached. At this point further decrease in PDR is not likely to cause any significant increase in performance.

4 Conclusions and Recommendation

From this research, a new two-phase liquid-liquid multiphase separation facility has been designed and constructed for testing LLHC separators. It is an instrumented state-of-the-art rig and can take on as many as three different liquid-liquid separators (each operated one at a time). After the work, the following conclusions can be drawn:

(i) The LLHC separator achieved most of the high oil separation efficiencies (> 80%) in the flow split region between 0.6 – 0.7 for the temperature cases considered.

(ii) Between the inlet velocities of 2.5 – 4.5 m/s, cyclone performance reached its peak with separation efficiency remaining virtually constant for all the various cases studied.

(iii) The peak efficiencies for the cases at 25 ^{o}C, 30 ^{o}C, 40 ^{o}C, 50 ^{o}C and 60 ^{o}C temperatures were averagely around 80.9%, 84.1%, 85.9%, 86.5% and 87.5% respectively.

(iv) ΔP_{iu} was greater than ΔP_{io} at any given flowrate to enable more oil escape via the overflow outlet than at the underflow outlet and the separation efficiency increased with decreasing PDR.

(v) Finally, increasing temperature increases the Reynolds number thereby causing a rise in the flow turbulence which increases the cyclone's performance but only to a certain point.

The results obtained from this work provide a guide that can be used for the successful and efficient operation of the designed LLHC separator and future work should be extended to cases where the oil content is higher than 10% to check the cyclone's performance.

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