DROPLET SHEAR IN OIL/WATER EMULSION PRODUCED BY CENTRIFUGAL PUMP AND GEAR PUMP

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ABSTRACT

Before being fed into the separators, a pump is often used to maintain adequate flowing pressure of oil/water emulsion in a production conduit, especially in a depleted or matured reservoir. Droplet shearing and size reduction due to the pump highly affect the separation performance. This paper aims to present an experimental investigation on the shearing of oil droplets in an oil/water production fluid passing through a high rpm single-stage centrifugal pump (C-pump) and a lower rpm gear pump. A cross polarizer microscope has achieved sample analyses. The experiments have been carried out at various water/oil ratios, from 70/30 to 90/10, with two different temperatures of 50 ºC and 80 ºC. Further, the viscosities of the fluid sample from both pump outlets are correlated with the water cuts. The results are presented in a graphical format showing the droplet size distributions of different cases from the two tested pump types. There is a general trend of higher shear intensity and smaller mean oil droplets with the C-pump than the gear pump. Water cut and the temperature seem to have a small effect on the shearing of the droplets. Further, the viscosity correlation for the fluid collected from two pump outlets at different temperatures and water cuts shows a slight decrease in viscosity with the shear rate. However, it is highly affected by the water cut and temperature.

Keywords: Droplet shear, emulsion, oil/water separation, produced water, water cut, water/oil emulsion.

1 INTRODUCTION

When the oil field matures, water cut production increases significantly, and in some fields, most produced fluids are water. Therefore, there are no any economic incentives for the produced water to be separated efficiently, henceforth adhering to government regulations before discharge (She and Xu [1]). Produced water is treated initially with a hydrocyclone located either in the downhole or in the surface before sending it to another production conduit. Hydrocyclones are used in several industries to separate two different components with the strong centrifugal force generated by the swirling flow. As a result, hydrocyclones are more common in the oil and gas industry. It is very common to find solid/liquid and solid/gas cyclones in industry, though, due to the small density difference between the phases, the application of hydrocyclones to separate two immiscible liquids is less common and more challenging [2, 3]. In terms of space and efficiency in separation, it could be an alternative for existing gravity-based separation technology.

Two key portents that differentiate oil water treatment from industrial water treatment are turbulence and oil droplet shearing [4]. They depend upon the input to and output from the hydrocyclone either tangentially or axially and output from top or bottom, which is termed counter-current reverse flow or co-current axial flow as shown by Kitoh [5] and Dohnal and Hájek [6]. Among hydrocyclones, there are two different types of liquid–liquid hydrocyclone separation technology, and the key physics behind each separation process is the centrifugal force. In the axial flow separator, the centrifugal force is achieved by the fluid flow across through a stationary swirl generator placed inside the separator, and the fluid moves co-currently downward. Factors influencing the separation in the hydrocyclones are the pressure, flow rates through the hydrocyclone, density difference of the separating phases, oil droplet

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size, oil concentration, viscosity of the continuous phase, and flow split (see, e.g. Husveg [7] and Dirkzwager [8]).

Dalmazzone [9] reported that the oil emulsions could be seen in all aspects of an oil well chain, starting from the drilling process, flow-through reservoir porous media, production, surface operations, and transportations. Among these aspects is the production equipment in the downhole, where the undesirable emulsion represents a big challenge to the efficiency of the downhole hydrocyclone separation.

The flow split is dependent on the back pressure on the reject outlet stream at the heavy phase outlet, and it is directly proportional to the pressure differential ratio (PDR). PDR is the ratio of the pressure difference between the inlet and the oil outlets and the difference between the inlet and the water outlet. Thus, the pressure difference developed across the hydrocyclone also provides the energy required to achieve separation, as reported by Vikan [10]. There are different views on the optimum differential pressure. Arnold and Stewart [11] stated that approximately four bars are required, while the previous researcher suggested that five to six bars are necessary for minimum differential pressure. Usually, a PDR of 1.4 to 2 is desired according to Arnold and Stewart [11] and Flanigan *et al.* [12]. Hence, the performance of hydrocyclone is very much influenced by certain differential pressure. A pump is often used to pressurize the feed flow in cases where adequate pressure is not accessible. The substantial droplet shear across the pump will hamper the separation of fluids further [13, 14].

Oil droplet shear is an inevitable phenomenon of an oil field production fluid. The most prone areas for droplet shearing are from the pump used in artificial lifting techniques, wellhead chokes, across some of the pumps etc. AlShammari [15] concluded that choosing an appropriate device to maintain the emulsion flowing pressure and minimize the oil droplet shear in water is mandatory. An optimum differential pressure difference is required for the hydrocyclone to perform efficiently. A pump is often installed upstream production conduit before the hydrocyclone to achieve this adequate pressure difference in low-pressure systems, such as a depleted or matured reservoir. However, pumps are generally considered potentially damaging the oil droplets (Walsh [16]). This damage potential could be majorly attributed to the pump's nature, whether it is high or low shear. High shear pump can distribute the oil droplet size into a narrower margin while simultaneously maintaining enough pressure for the production fluid, as concluded by Zhang *et al.* [17]. Contrary to that, a low shear pump would not be destroying the oil droplet sizes while boosting the pressure of production fluid [18]. Zhang *et al.* [19] have studied the effect of shear and water cut on droplet size distribution (DSD) in oil–water flow. The study has been carried out using a gear pump. The experiments have been carried out at 300 and 600 rpm. Our investigations have been carried out at the 1450 rpm speed of the gear pump.

It has been realized from the literature review that not sufficient studies have been done on the pumps and their effect on oil droplets shear in produced oil/water emulsion. Moreover, no study has compared the droplet characteristics in emulsions produced by the centrifugal pump (C-pump) and gear pump. Even though few studies pointed out that the shear from a progressive cavity pump is less and very promising, the progressive cavity pump's cost and operational problems point to the direction of investigating more a low-cost and simple alternative.

This study aims to acquire new experimental data comparison on DSD due to the shear effect by two different types of widely used pumps in the industry. The first type is a high-speed single-stage C-pump, and the second type is a low-speed gear pump. The experiments were carried out at various water-in-oil ratios, ranging from 70/30 to 90/10, with two different temperatures of 50 °C and 80 °C. As a common practice to conduct experimental research using mineral oils to simulate the crude oil, mineral oil (FOMI 70) was used in this study as recommended by Zande and Broek [20]. The results have been presented in a graphical format showing the DSD of different cases.

2 PROBLEM IDENTIFICATION

The separation of extra produced water from high water cut fields of crude oil–water dispersions (mixture) has always been a challenge to the separation process. Proper selection of a high-efficiency hydrocyclone, either surface or downhole de-oiling, could eliminate this issue. On the other hand, one of the key factors determining the separation efficiency of a hydrocyclone is the droplet size of oil in water. The production fluid is prone to higher shear intensity due to droplets from various sources, among which pumps are the worst ones. The separation efficiency can be increased by tuning the performance by testing different DSD for the dispersed phases. However, this study compares droplet size variation with water cut, from two different types of pumps outlet, at two different temperatures. The key parameters in this experimental study are as follows:

- Different types of pumps: DSD and droplets shear are measured and compared using a C-pump and a gear pump (Fig. 1). C-pump runs at 2950 rpm, while the gear pump runs at 1450 rpm.
- Water cut ratios: Five different water cut ratios were used – 70:30, 75:25, 80:20, 85:25, and 90:10 at the mixture inlet.
- Working fluid temperature: The investigations have been repeated at two different mixture temperatures – 50 °C and 80 °C.

3 EXPERIMENTAL IMPLEMENTATION

3.1 Experimental flow loop

The oil–water flow facility is an instrumented state-of-the-art rig that simultaneously takes on three different hydrocyclone separators. Figure 2 presents the schematic of the flow loop used in this study.

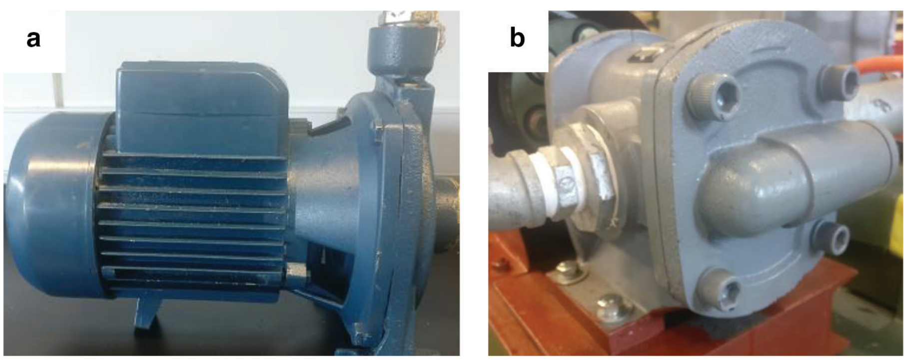


Figure 1: The used pumps in the current research: (a) single-stage C-pump (left) and (b) an internal gear pump (right).

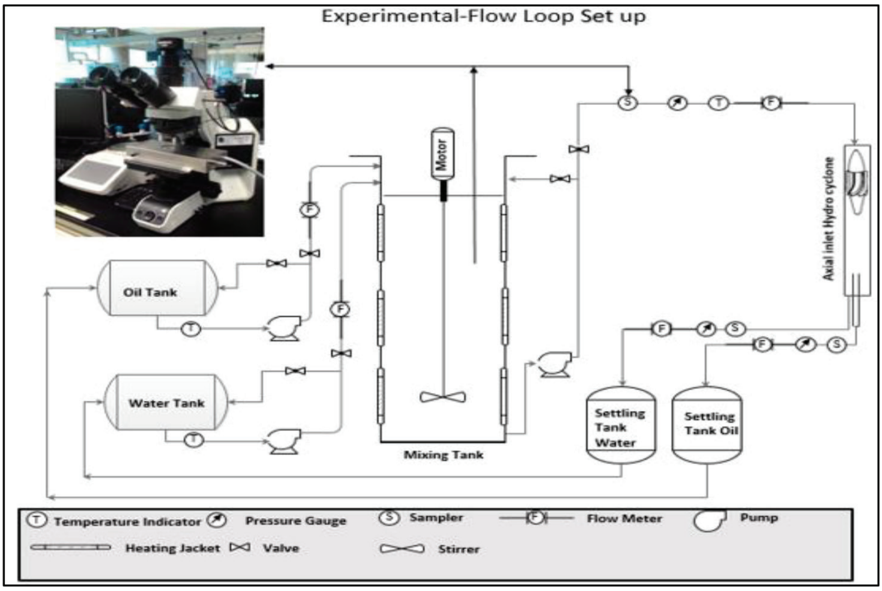


Figure 2: Schematic of oil/water separation flow loop set up.

The experimental facility is made to prepare oil–water fluids of different compositions, feed them into the hydrocyclone test section, and separate the oil and the water. The tank is constructed of stainless steel. Initially, the oil and water are stored in two separate tanks from which fluids are brought into the mixing tank. Each tank is connected to separate pumps, and both pumps are equipped with return lines to permit control of the flow rate of each fluid, oil and water. Each pump supplies fluid to a metering section in a separate pipeline, which comprises pressure gauges, control valves, and flow meters to provide information about the fluid pressure and flow rate. The fluids are mixed in the metering tank and heated to the required temperature before feeding to the liquid–liquid hydrocyclone. The heating of the mixture is provided by installing a heating jacket at three levels outside the tank controlled by thermostats.

The fluid mixture's homogenization is achieved by an agitator mounted on the top of the heating/mixing tank. After homogenization and heating, a pump transfers the mixture from the mixing tank to the hydrocyclone. A sample is collected at the pump discharge point to measure the shear intensity and DSD caused by the two pumps. The droplet size proportional to the shear intensity is studied and well discussed by Zhang *et al.* [17]. The specification of each pump is shown in Table 1.

DSD measurements were analyzed on the fluid collected from the sampling point placed at the C-pump and gear pump discharge point. This work mainly focused on studying the pump effect on droplet size and exposed some results from the hydrocyclones to investigate the shear influence on downstream equipment.

3.2 Working fluid

Sampling points were placed throughout the flow loop before and after pump discharge and the hydrocyclones. Mineral oil (FOMI 70) with brine is used as the working fluid. The mineral

Table 1: Specifications of C-pump and gear pump.

	Centrifugal pump	Gear pump
Model	MCP25/160A	GL-50-5
Material	Stainless steel	Stainless steel
RPM	2950	1450
Power	1.5 kW/240V/2 hp/50 Hz	4 kW/ 415V/5.5 hp/50 Hz
Flow rate	13.5 m^3/h @ 38 mH	8 m^3/h @ 6 mH

Table 2: Properties of the mineral oil.

Properties	ASTM test method	FOMI 70
Physical state	-	Liquid
Color, saybolt	D 156	+30 (colorless)
Odour/taste	-	Odourless/none
Density, kg/m^3		
@ 15 ^{o}C	D 1298	835
@ 25 ^{o}C		830
Kinematic viscosity, kg/m+s @ 25 ^{o}C	D 445	0.0126

oil was added with a small amount of dye to improve flow visualization. The measured properties of the mineral oil are shown in Table 2. The measured density and viscosity of brine at 25 $^{\circ}$C are 1067 kg/m^3 and 0.00089 kg/m.s, respectively. The fluids produced from the hydrocyclone separator are recycled back to the storing tanks.

3.3 Sample analysis procedure

The data acquisition system includes the flow meter, temperature sensors, pressure gauges, and a cross polarizer microscope (CPM). The CPM is a droplet size analyzer. It determines the DSD of a dispersed phase. The key physics behind this is light diffraction or light scattering. When polarized light passes through a droplet sample placed on a slide, the light then scatters and is focused by a lens to detect. Figure 3 shows the CPM used to analyze all samples' droplet sizes. The sample collected from the pump outlet was fed into the slide and analyzed with the microscope. Enough sampling points were fixed in the flow loop set up to collect samples at regular intervals. The inbuilt software Olympus assesses the mean droplet size of oil in the water mixture.

Emulsion viscosity has been estimated using Stokes and the energy balance equation. They are also commonly used to determine emulsion stability. The settling velocity $v_{settling}$ (m/s) is defined as

$$v_{settling} = \frac{s}{t}, \tag{1}$$

where t (sec) is the time taken by the droplet to travel distance, s (m). It is given by

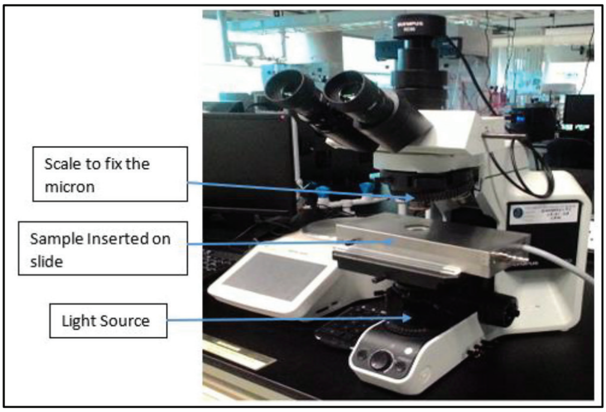


Figure 3: Cross polarizer microscope used for analyzing droplet shear on samples.

$$v_{settling} = \frac{gD^2 - (\rho_c - \rho_d)}{18\mu_m}, \tag{2}$$

where D is the droplet diameter (m), found from the CPM test; $(\rho_c - \rho_d)$ is the difference between water and mineral oil density; μ_c is the viscosity of the mixture; $v_{settling}$ is thus inversely proportional to the viscosity. Subscript c refers to the continuous medium, subscript d refers to a dispersed medium, and subscript m refers to the mixture.

From Stoke's law, eqn (2), it could be observed that the settling velocity at two different temperatures is different. The samples taken from the outlet of both the pumps were subjected to additional tests for the viscosity correlation for two different temperatures, 50 °C and 80 °C.

4 RESULTS AND DISCUSSION

The samples taken from the C-pump and gear pump outlets are subjected to analysis by CPM. The analysis results allow estimations of the DSD and the mean diameter in each sample, at various water cuts, at 50 °C and 80 °C temperatures. For all the tests with two different pumps, the fluid's homogenization is achieved in a mixing tank by stirring the water and oil at 900 rpm for 2 hours while heating up to the required temperature. In addition, the viscosity characteristics of samples produced by the C-pump and gear pump are also investigated and discussed. Moreover, the stability of the emulsion of the two pumps has also been investigated.

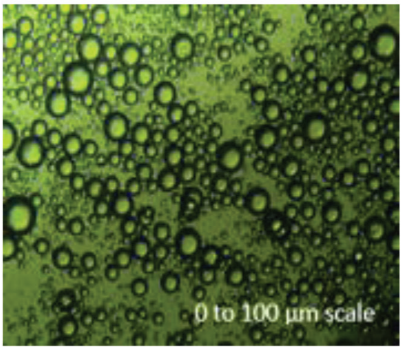
4.1 Droplet size distribution

The droplet size analysis is presented considering pump type effects, water cut variation, and temperature change.

4.1.1 Droplets characteristics from different pump types

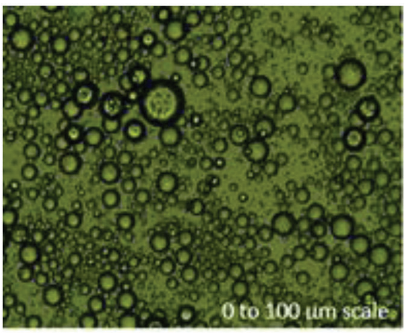
The droplet shear analysis of emulsion samples from a single-stage C-pump with 2950 rpm and gear pump with 1450 rpm have been measured and compared in terms of DSD. Samples of the tests that have been conducted at a temperature of 50 °C and a 90:10 water:oil mixture

a. CPM results of emulsion produced by C-pump



Statistical function	Arbitrary line length (µm)
Mean	21.39
Minimum	12.35
Maximum	34.50
Standard Deviation	4.14
Average Deviation	3.24
Variance	17.11
Median	20.86
count	100

b. CPM results of emulsion produced by gear pump



Statistical function	Arbitrary line length (µm)
Mean	33.5
Minimum	16.32
Maximum	49.47
Standard Deviation	7.82
Average Deviation	6.04
Variance	67.11
Median	32.86
count	100

Figure 4: CPM results of droplet size distribution from emulsion produced by (a) C-pump and (b) gear pump (temperature 50 $^{\circ}$C, water cut 90:10).

by the built-in Olympus software are shown in Fig. 4a and b for the C-pump test and the gear pump test, respectively. These figures were utilized to analyze the DSD of oil in the emulsion. Up to 100 droplets with different diameters were randomly selected. It was assumed that the selected droplets were not hindering the other neighboring droplets. The diameter of each selected droplet, among the 100 droplets, was measured by the built-in Olympus software. Once the 100 selected droplets were measured and analyzed through the software, they were converted into a table and stored for every droplet. The same procedures were used for all the 100 selected droplets to measure the DSD. Then, the data have been utilized to estimate the mean droplets size.

The DSD analysis from the CPM is shown separately for the C-pump and gear pump in Fig. 4a and b, respectively. Droplets distribution in the sample is illustrated on the left, and the droplet size measurement statistical data is on the right. Figure 4a shows the results of the C-pump, while Fig. 4b shows the analysis results of samples taken from the gear pump discharge point. The mean droplets diameter measurement for an emulsion produced by C-pump is 21.39 µm, and the diameters range from 12.35 to 34.5 µm. The mean droplet size measurement for the gear pump is 33.5 µm, and the diameter of the droplets ranges between 16.32 and 49.47 µm.

4.1.2 Water cut effect on the droplet's size

The water cut effect on the droplets size and shearing has been measured and analyzed at water-to-oil ratios of 70:30, 75:25, 80:20, 85:15, and 90:10 using C-pump and gear pump. All measurements have been repeated at temperatures of 50 °C and 80 °C. The measurement results of the sizes of the droplets at 50 °C and 80 °C are presented in Figs 5 and 6, respectively. It was observed that droplet size was reduced with the higher water cut for the two pumps. However, the C-pump caused higher shearing compared to the gear pump. The smaller mean droplet diameter may be attributed to the high speed of the C-pump, which causes higher shearing and breaking down of the oil droplets.

At 70:30 water cut, the mean droplet diameter is 38 µm for the gear pump and 23.7 µm for the C-pump. As the water cut increased to 90:10, the mean droplet diameters were reduced to 33 µm in the gear pump and 20.5 µm in the case of the C-pump. The findings from the C-pump are similar to those of Jing *et al.* [21] on the water cut effect in a C-pump; While the

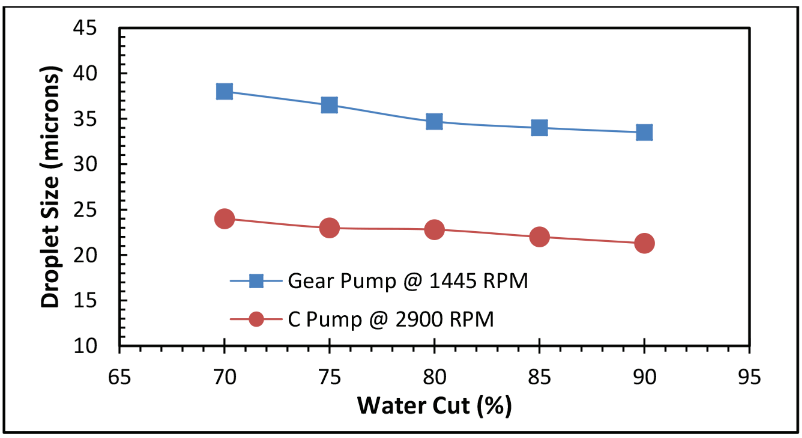


Figure 5: Droplet shear analysis from a single-stage C-pump and a gear pump on different water cuts and constant temperature 50 °C.

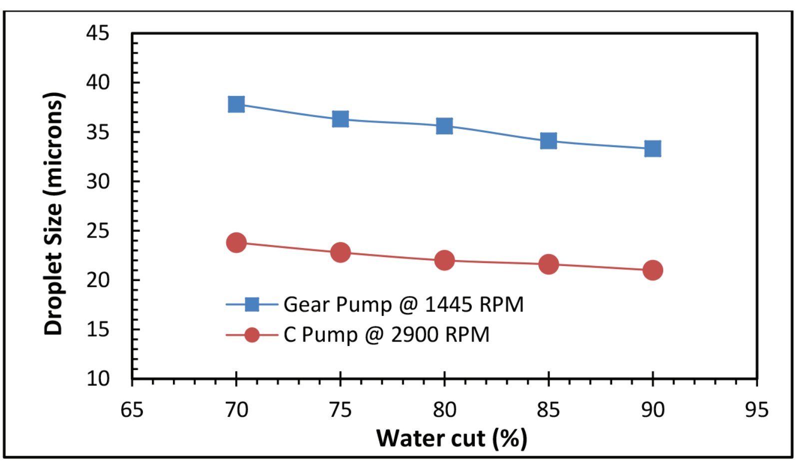


Figure 6: Droplet shear analysis from a C-pump and an internal gear pump on different water cuts at a constant temperature of 80 °C.

findings of the droplet behavior in the case of the gear pump agree with the experimental results of Zhang *et al.* [19], Shad *et al.* [22], and Meldrum [23].

4.1.3 Temperature effect on the droplet size

Results of DSD at 50 °C and 80 °C temperatures demonstrate that the effect of temperature on droplet shearing was found to be minimal. Table 3 shows the mean droplet diameters at 50 °C and 80 °C at 70:30 and 90:10 water cut produced by the two pumps. At water cut 70:30, the mean droplet diameters are reduced by 0.84% for the case of C-pump and 0.53% for the case of gear pump, due to temperature increase from 50 °C to 80 °C. At a water cut of 90:10, the mean droplet diameters are reduced by 1.4% for the case of the C-pump and 0.6% for the case of gear pump, due to temperature increase from 50 °C to 80 °C.

4.2 Emulsion viscosity results

The viscosity has been estimated using the procedure outlined in section 3.3. The settling velocity, $v_{settling}$, could be calculated from eqn (1), then the viscosity, μ_c, is determined by substituting the parameters into eqn (2). The viscosity of emulsion samples from the C-pump outlet at two different temperatures is presented in Fig. 7. It was noticed that the viscosity

Table 3: Measurement results of the mean droplet diameters at various temperatures caused by shearing by the C-pump and gear pump.

Water cut / Pump type	70:30		90:10	
	Temperature		Temperature	
	50 °C	80 °C	50 °C	80 °C
C-pump	24	23.8	21.3	21
Gear pump	38	37.8	33.5	33.3

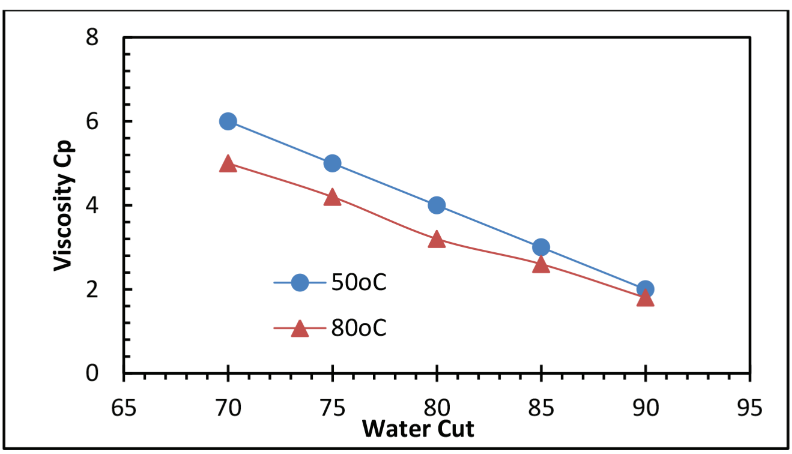


Figure 7: Viscosity variation for different water cut (%) and temperature for fluids analyzed from C-pump outlet.

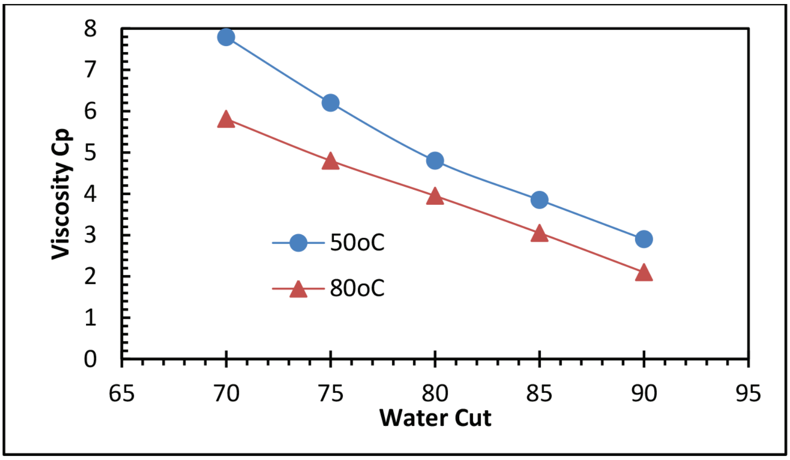


Figure 8: Viscosity variation for different water cut (%) and temperature for fluids analyzed from the gear pump outlet.

increased with a decrease in water cut or hike of dilute phase distribution, but the viscosity was reduced considerably for higher temperatures.

Figure 8 shows the measured viscosity of emulsion sampled at the outlet point of the gear pump. A general trend can be detected, namely that the higher shear in the C-pump produced lower viscosity than the low shear of the gear pump. By selecting a sample of emulsion at 50 °C of 70:30 water cut, the viscosity is 6.02 Cp produced by the C-pump, while the viscosity is 7.88 Cp of the sample produced by the gear pump, i.e. the emulsion viscosity by the gear pump is higher by 23.6% than the emulsion viscosity by the C-pump. Considering the same samples at 80 °C, the difference in the emulsion viscosity is around 13.6%. In the high shear rate by the C-pump, the hydrodynamic force dislocates the flocs. These drops' transformations resulted in aligning themselves in the shear field, which reduces the viscosity further and agrees with Floury *et al.* [26].

4.3 Emulsion stability

Dispersion of droplets of one liquid over the other liquid forms an immiscible emulsion [27, 28]. It was observed in many applications that the emulsion characteristics influence a fast or slow separation of the emulsion into different phases. The major emulsion destabilization is the coalescence, flocculation, creaming, and Ostwald ripening of the droplet–droplet, which is similar to observations by Tcholakova *et al.* [29].

The emulsion stability was checked by visualization and Stokes law for a few hours. It was observed that the key parameter, which influences the emulsion and physical stability, was the droplet diameter. The Stokes law clearly led to the understanding that when the droplet diameter was large, the tendency to coalescence was faster than for the smaller droplets. Thus, the droplet's coalescence rate is directly proportional to their size, which is in good agreement with Dluzewska *et al.* [30].

Initially, coalescence was at a lower rate, as shown in Fig. 9a, and it can be seen in Fig. 9b–d that the coalescence rate relates to the emulsion stability. The settling tests for the 90:10 water cut ratio in the tubes shown in Fig. 9 were utilized to determine the settling velocity. The

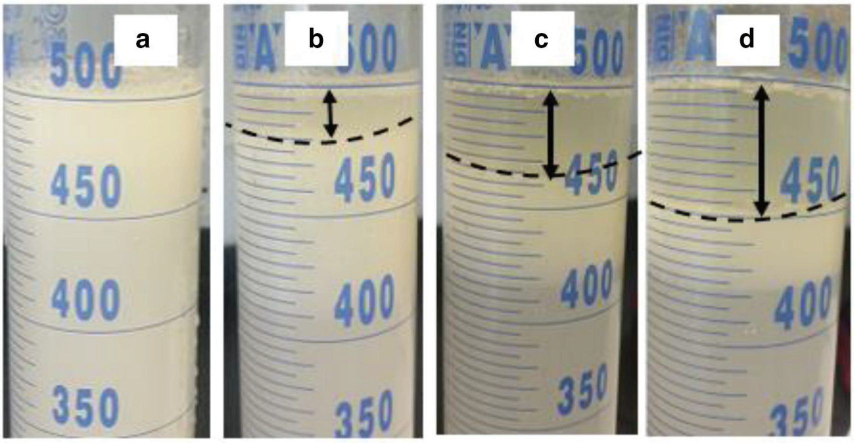


Figure 9: Samples of the procedure for determining settling velocity from Stokes law on a 90:10 water cut ratio at 50 ºC. (a): is immediately after the mixing and put into the cylinder. (b): after 42 s, the sample started to separate; (c): further separation as time increases – in 100 s; (d): settlement after 167 s.

pump outlet samples were fed into a 500-ml cylinder, and the time taken for settling the oil molecules from the mixtures A to D was observed.

However, the higher temperature of the emulsion results in greater settling velocity. With the increase in temperature, the flow of oil molecules moved to the top of the cylinder also increased and separated in a shorter time. A similar observation has been demonstrated by Braginsky and Belevitskaya [24] and Anisa and Nour [25]. Whereas in the case of 50 °C, the flow of molecules was not that fast compared to that at 80 °C.

There are two contradictory issues in the contribution of the temperature to the settling speed of the oil/water emulsion. The first is the oil droplets' size in the emulsion and the second is the viscosity difference between the two liquids. Larger droplets' sizes enhance the coalescence of droplets resulting in larger droplets. The motion of larger oil drops is slower than smaller droplets due to the larger drag by the water phase. But the other parameter imposed by higher temperature is the viscosity change of the two fluids. As the temperature increases, the difference in the viscosities of the two fluids is less. Water viscosity is highly reduced with temperature increase, while oil viscosity is less reduced with temperature increase. At 50 °C, water viscosity is around 0.547 Pa.s, and that of mineral oil is around 0.035 Pa.s, while at 80 °C, water viscosity is around 0.3355 Pa.s, and mineral oil viscosity is around 0.018 Pa.s. As such, the slip of oil droplet is easier in high emulsion temperature than in low emulsion temperature, enhancing the emulsion settlement. In conclusion, the effect of viscosity on the settling velocity is larger than the effect of droplets' size; hence, as the temperature of emulsion increases, the upward slip of oil molecules or settling velocity is correlated to viscosity difference larger than correlation to droplet size increment.

5 CONCLUSIONS

Shear effect on DSD in oil/water emulsion caused by a single-stage C-pump and gear pump is investigated experimentally and presented. Results indicate that different types of pumps produce different DSD due to different shear intensities. The shear rate is higher, while the DSD are smaller for a C-pump that runs at 2950 rpm than the gear pump that runs at 1450 rpm. Five different water cut ratios have been investigated, and the results show that as the water cut reduces or the dispersed phase volume fraction increases, the shear rate is reduced for both pumps. The shearing becomes less, and the DSD turns out to be slightly larger when the water cut is reduced from 90% to 70%, which demonstrates that the effect of shear rate on dispersed phase by the two pumps is minimal. The test has been done for two different temperatures at 50 ºC and 80 ºC, and the results indicate that the temperature influence on the DSD is minimal. The settling of oil molecules to the top of the cylindrical container is increased and separated quickly for samples with larger droplets diameter.

There is scope for further investigations on DSD with real fluids in systematic approaches considering proper homogenizations and elaborating over a wide range of temperature and pressure, including wide varieties of pumps and running speeds.

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