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ESP PERFORMANCE ANALYSIS OPERATING WITH STABLE WATER-IN-OIL EMULSION

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Abstract: *One of the most widely used artificial lift methods in terms of oil production is the Electric Submersible Pump (ESP). This method stands out for its high production capacity and operation in severe conditions. One of the conditions the ESP system can face is multiphase flow, such as finely dispersed water in crude oil continuous medium, commonly known as emulsions. Due to the complex rheological behavior involved, the emulsion effective viscosity is one of the biggest challenges in ESP systems, since it can heavily decrease its performance and also lead to operational instabilities near the phase inversion point. This work aims to analyze the effective viscosity inside an ESP under water/oil stable emulsion flow. The experiments were carried out in a closed flow loop at the Experimental Laboratory of Petroleum – LabPetro at CEPETRO – UNICAMP using an eight-stage ESP operating with oil/water emulsion flow. The stable emulsion was prepared using mineral oil, 1 wt% of SPAN 80 on oil and tap water to represent the crude oil/water emulsion. Experiments were performed for a rotation speed of the ESP of 2400 rpm and a temperature of 30°C for 12, 20 and 32% of water cut. An indirect model was used to determine the effective viscosity of the emulsion within the ESP. An increase in the emulsion's effective viscosity due to the decrease in the ESP dimensionless flow rate was observed from the experimental investigation. An increase in the relative viscosity of the stable emulsion was also evident as the ESP rotational speed increases. Furthermore, ESP performance operating with emulsion decreases as the water cut increases due to the emulsion effective viscosity increment until the phase inversion point. Moreover, the results presented a possible evidence of the non-Newtonian fluid behavior with shear-thinning characteristics during the ESP tests.*

Keywords: *Emulsion effective viscosity, water-in-oil emulsion, electrical submersible pump*

1. INTRODUCTION

In the oil production, artificial lift methods represent a crucial role in maximizing well productivity, especially when the natural reservoir pressure is insufficient. One widely used artificial lift method is the Electrical Submersible Pump (ESP). The ESP offers high efficiency and flexibility, making it the second most commonly used artificial lift method. Its effectiveness in providing energy to the produced fluid and its wide application have established its prominence in the industry. (Takacs, 2017).

The ESP system is usually designed to handle single-phase flow. However, it may operate under multiphase flow in real operations, which can consist of different combinations such as water-oil, gas-oil, and gas-oil-water. These flows exhibit different patterns throughout the oil production process, including extraction, transportation, and processing. One flow pattern observed is the emulsions, which are mixtures of two immiscible fluids.(Tadros, 2013).

Emulsions are colloidal systems that consist of the dispersion of small droplets of one immiscible liquid in another liquid. When dealing with an oil/water emulsion, it can be classified as either oil-in-water (o/w) or water-in-oil (w/o) based on which phase is a dispersed phase (Kokal, 2005).

Different parameters are used to determine the type of emulsion, including the water cut, viscosity of the phases, droplet size distribution, concentration of the dispersed phase, and the presence of emulsifying agents (Rønningsen, 2012; Wong *et al.*, 2015). These parameters collectively contribute to the characterization and behavior of the emulsion regarding its rheological behavior and cinematic stability.

The stability of an emulsion is essential to maintain its uniform appearance and prevent phase separation. Emulsifying agents, such as surfactants, are used to achieve and maintain emulsion stability by reducing the interfacial tension between the liquids and stabilizing the dispersed droplets. These emulsifying agents act as barriers to prevent coalescence and phase separation (Tadros, 2013).

Effective viscosity is an important parameter for pumping and transporting emulsions. It refers to the measure of the resistance to flow experienced by an emulsion due to the combination of the properties of the dispersing phase and the emulsifiers used. The increase in emulsion effective viscosity is primarily associated with the non-Newtonian behavior of the emulsion and the characteristics of fluid composition (Langbauer *et al.*, 2020). Additionally, comprehending the effects of the emulsion effective viscosity within ESP is related to fluid properties, surfactant type, temperature, and flow hydrodynamics (Bulgarelli *et al.*, 2021b).

The effective viscosity of non-Newtonian fluids plays a significant role in the operation of ESP. Non-Newtonian fluids exhibit complex flow behavior, where their viscosity varies with shear rate or shear stress (Langbauer *et al.*, 2020). This behavior affects the pump's performance and efficiency, as the effective viscosity influences the pressure drop, flow rate, and power consumption in the pump system (Valdés *et al.*, 2020). Understanding and accurately characterizing the emulsions effective viscosity are essential for optimizing ESP design and operation.

The main objective of this work is to analyze the performance of an ESP operating with a stable water/oil emulsion. Specifically, the study aims to investigate the influence of the emulsion effective viscosity on the ESP performance degradation.

2. LITERATURE REVIEW

The emulsion effective viscosity has a direct impact on the operation of ESPs, and understanding this relationship is important for designing and optimizing their performance. The effective viscosity affects the pump's ability to lift the fluid, resulting in changes in pressure increment, flow rate, and overall efficiency. Some of the latest works related to ESP operating with emulsion systems are presented below.

Biazussi (2014) proposed a one-dimensional phenomenological model to predict the ESP performance. A experimental matrix was conducted, both in single-phase and gas-liquid conditions, using three different pump models to validate the its assumptions. Comparative curves were generated between experimental data and models for pressure gain and pump performance as a function of liquid flow rate. Based on these results, it was possible to identify how parameter variations, such as suction pressure, rotation, and gas fraction, influenced the pump performance. The single-phase model successfully adjusted the pump performance when operating with water, and by adjusting the slip parameters, it was possible to predict the behavior of pumps with gas-liquid flow in the region of Best Efficiency Point (BEP).

Bulgarelli (2018) investigated the phase inversion phenomenon and the emulsion effective viscosity within an 8-stage ESP. The Biazussi's model was used for viscous single-phase flow and performance curves under single-phase conditions were obtained experimentally. The effective viscosity within ESP was determined using a indirect method proposed by the author. The geometric parameters of the model were adjusted using single-phase (oil and water) data. Subsequently, the model was inverted using emulsion experimental data. A difference in the behavior of effective viscosity between the pipeline flow and within the ESP was observed for water-in-oil emulsion, attributed to the high centrifugal field in the ESP. Additionally, three-phase tests were conducted to analyze the phase inversion, and it was found that the phase inversion event occurs at lower water cuts and higher rotational speeds when the presence of gas is included.

Banjar and Zhang (2019) studied the effects of emulsion effective viscosity within a 7-stage ESP, computationally and experimentally. The researchers specifically focused their analysis on the third stage of the pump by measuring at different oil/water fractions, rotational speeds, and temperatures. A mechanistic model was introduced that utilized Euler's centrifugal pump equations, taking into account all potential energy losses. The authors concluded that the model is capable of satisfactorily predicting results for high rotational speeds, while it was not feasible for low speeds. The authors also proposed a rheological model to determine the emulsion effective viscosity, validating it with experimental data. This model provided good results for medium effective viscosities (5% error) while for low effective viscosities it was imprecise.

Croce and Pereyra (2020) investigated the formation of oil/water unstable emulsions and the phenomenon of phase inversion during the operation of a 7-stage ESP. Viscosity measurements were conducted using a viscometer placed at the pump outlet. The rheology of the emulsion was examined by gradually increasing the water cut. This proportional increase in the water cut led to a phase inversion point occurring between 35% and 40% of water fraction. The authors observed that the emulsion effective viscosity increased as the water cut rose, reaching a maximum at the phase inversion point. However, beyond this point, the effective viscosity decreased. The increase in effective viscosity adversely affected the pump's performance. To validate their findings, the authors compared the results with experimental data on effective viscosity using a mechanistic model implemented in Computational Fluid Dynamics (CFD). Additionally, it was determined the maximum droplet size in the emulsion and conducted various configurations of droplet diameters for different water cuts.

Zhu *et al.* (2020) characterized and predicted the rheological behavior of oil-water emulsions within ESPs. The authors introduced a novel mechanistic model that considered factors such as flow direction, recirculation losses, friction, and leakage flow to accurately predict the boosting pressure in ESPs. Additionally, developed a rheology model based on the Brinkman correlation, taking into account rotational speed, stage number, and interfacial properties. The performance models were thoroughly validated through experimental measurements, demonstrating their ability to predict ESP performance curves and boosting pressure for both water and oil-water emulsions. Moreover, the models predicted the emulsions effective viscosities and identified the points of phase inversion, where the continuous phase changes from oil to water. The results of the model were found to be comparable with experimental data, with an average error of 10% and a maximum error range between 50% and -15%.

Langbauer *et al.* (2020) evaluated the ESP performance operating with non-Newtonian polymer fluids. The tests involved two different types of ESPs with 82 and 7 stages. Measurements included pressure, flow rate, torque, rotational speed, and temperature. Additionally, sensitivity analysis on the intake pressure was performed. The results of the polymer tests revealed significant performance reduction factors for both types of pumps and across all frequencies. Despite the low viscosity of provided polymer concentrations, the non-Newtonian behavior, particularly the shear-thinning behavior, appeared to be responsible for the substantial performance loss. The head and flow rate reduction approached 50% at the pumps' best efficiency point.

Bulgarelli *et al.* (2021b) proposed was a model to predict the relative viscosity of oil/water stable emulsion flow within ESP, considering the continuous phase properties and ESP operational parameters. The viscosity model was compared to the relative viscosity models for emulsion flow in pipelines and the mean absolute percentage error (MAPE) was 14% and 8% for the stable emulsions without and with demulsifier, respectively. For the same emulsion systems, the relative viscosity model was applied to the one-dimensional model to predict ESP performance, with MAPE of 4% and 2% for stable emulsions without and with demulsifier, respectively. The relative viscosity of the stable emulsion, with and without demulsifier, exhibited different behaviors due to interface destabilization and changes in interfacial properties caused by the demulsifier. Additionally, an increase in relative viscosity was observed with increasing ESP rotational speed, possibly due to a reduction in water droplet size.

Bulgarelli *et al.* (2022) presented an approach to characterize the rheological behaviors of stable and unstable water/oil emulsions within the ESP. The researchers introduced a novel criterion based on the slip ratio between the dispersed and continuous phases. By measuring the droplet size distributions and evaluating the slip ratio using centrifugal buoyancy-induced flow, presented a new dimensionless number named Slip Relevance (SR), to categorize various emulsion flow behaviors within the ESP's.

Several previously mentioned studies on emulsions in ESP systems has emphasized the importance of emulsion effective viscosity in determining ESP performance. The contribution of this research work lies in the experimental analysis of ESP performance operating with stable water/oil emulsion. This study is based on comprehensive analysis conducted on the ESP performance curves and the emulsion effective viscosity within the ESP. The dependence between effective viscosity and water cut was verified. Furthermore, the emulsion rheological behavior within a mixed-flow ESP is presented by the first time in the literature.

3. EXPERIMENTAL PROCEDURE

The flow loop used to carry out the experimental study is located in the Experimental Laboratory of Petroleum (LABPETRO) at the Center for Energy and Petroleum Studies (CEPETRO) at University of Campinas (UNICAMP).

The experimental apparatus, presented in Fig. (1), was designed to study the ESP performance operating with water/oil stable emulsion. The water/oil emulsion system was prepared using mineral oil (163 cP @ 30°C), tap water and a commercial emulsifier (SPAN 80). The water/oil stable emulsion is established by shear rate and high turbulent kinetic energy promoted by the ESP and valves.

The emulsion is pumped from a tank using a twin-screw pump. The, the emulsion flows through a temperature control system before reaching the tested ESP (Baker Hughes P100L, 538 series), which is powered by a 50 Hp electric motor. At an operational speed of 3500 rpm, achieves a volumetric flow rate of 66.2 m³/h and generates a water head of 13.1 m per stage. This performance is observed at its BEP, where it reaches an efficiency of 68%, while handling water. The ESP's impeller has an external diameter of 0.108 m and a blade height of 0.017 m. To measure the water fraction in the emulsion, an ROXAR microwave probe (Nemko 05 ATEX 112) is used, which relies on the electrical permittivity of the emulsion. Furthermore, the mass flow rate and density are continuously monitored through a Coriolis flowmeter (Micro Motion, F300 series).

The ESP stages were equipped with nine pressure capacitive transducers (Emerson Rosemount, 2088 series), and two differential pressure transmitters were installed at pipelines before and after the ESP. To measure the emulsion temperature,

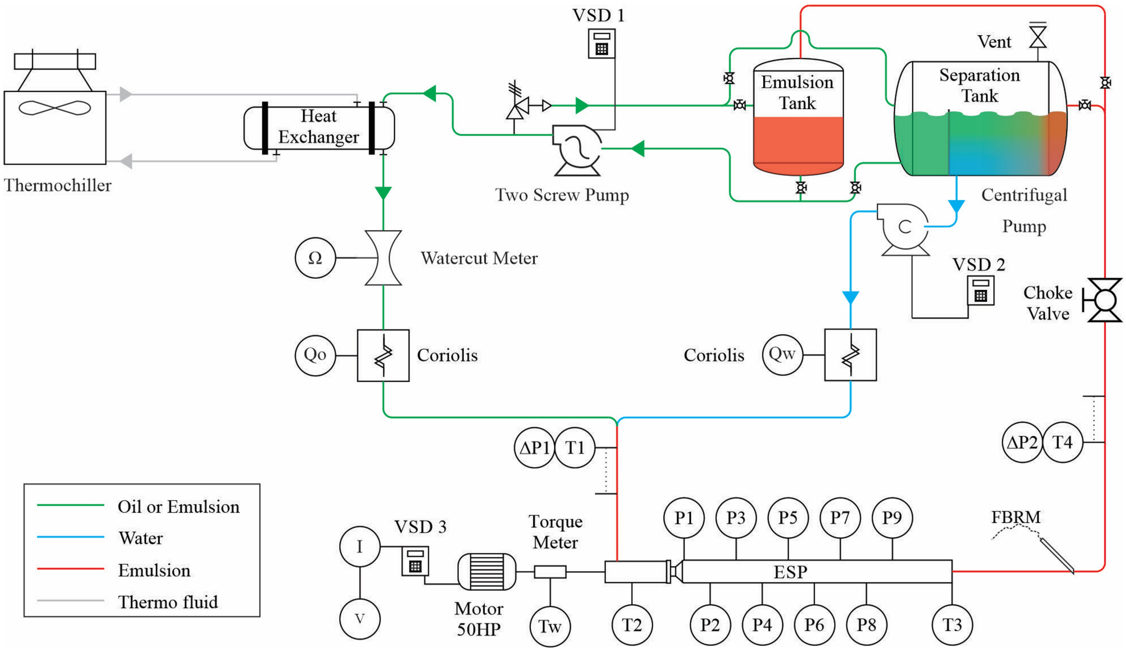

Figure 1. Schematic diagram of the test bench. Figure extracted from Bulgarelli *et al.* (2021b). Reproduced with permission from Chemical Engineering Science; Published by Elsevier in 2021.

Figure 2. Experimental facility.

four resistance temperature devices (4-wired PT-100 with 1/10 DIN uncertainty) were used. Two of these sensors were positioned near the differential pressure transmitters, while the remaining sensors were placed at the ESP inlet and outlet.

During the tests, the rotational speeds of the two-screw pump and the ESP were controlled by a variable speed driver (VSD). The ESP rotational speed was measured using an optical tachometer (Minipa, MDT-2238A). The torque required by the ESP was measured using a torque meter (HBM, T21WN).

The experimental control and data acquisition were conducted using a National Instruments system and a LabVIEW®code. The data acquisition began after achieving emulsion homogenization, which in turn was obtained by stabilizing the droplet size distribution measured by Focused Beam Reflectance Measurement (FBRM) probe at the ESP outlet.

3.1 Fluid Characterization

The ESP performance tests were conducted using mineral oil, which exhibits Newtonian behavior, and tap water. The addition of the SPAN 80 emulsifier to the water/oil mixture resulted in a stable emulsion with an increased phase separation time of several weeks. The experiments were carried out at one oil viscosity, achieved by controlling the temperature.

The oil density was measured using a vibrating tube density meter (Anton Paar, DM5000) over a temperature range of 10 to 60 °C. The oil viscosity was determined using a rotational rheometer (HAAKE MARS III), as illustrated in Figure (3). The temperature dependence of viscosities was fitted by polynomial functions.

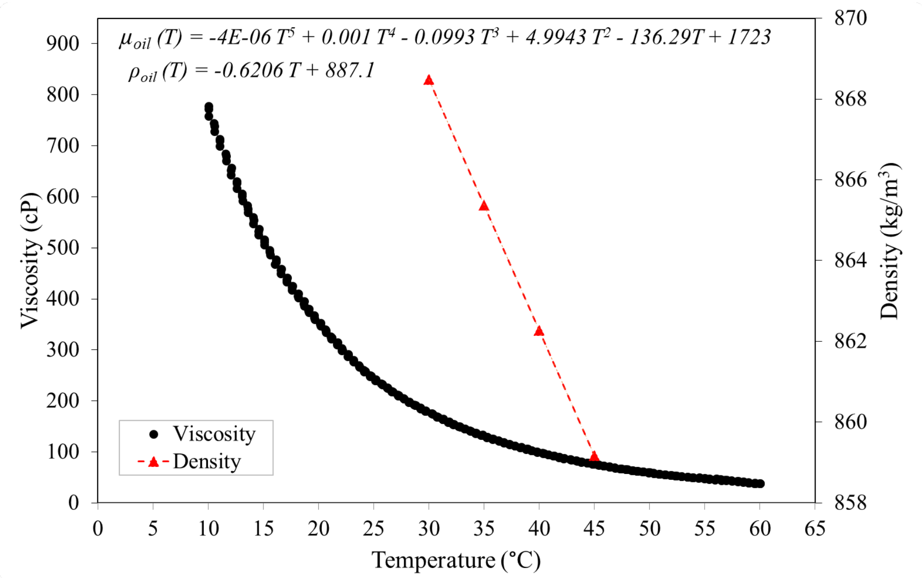

Figure 3. Oil viscosity and density as a function of temperature.

3.2 Water/oil emulsion tests

The experimental tests with emulsion began with the preparation of the emulsion in the emulsion tank. The process involved adding the SPAN 80 surfactant at a concentration of 1wt% of oil to facilitate w/o emulsion stability. Afterward, water was introduced into the emulsion tank to reach, respectively, 12, 20 and 32 v/v%.

SPAN 80 (emulsifier) is a non-ionic surfactant that possesses a Hydrophilic-Lipophilic Balance (HLB) value of approximately 4.3. This particular emulsifier is capable of facilitating the formation and stabilization of water-in-oil emulsion systems. Moreover, it is effective in reducing the surface tension of liquids, which contributes to improved emulsion stability and uniformity.

The test of the water-in-oil emulsion within ESP was conducted at a rotational speed of 2400 rpm and a temperature of 30 °C.

3.3 Emulsion effective viscosity within the ESP

The emulsion effective viscosity within the ESP was obtained using an indirect method presented by Bulgarelli *et al.* (2021a), based on Biazussi (2014) correlation model for the dimensionless head.

The procedure for calculating the emulsion effective viscosity assumes that the emulsion flow within the ESP can be represented as a pseudo single-phase flow. Given knowledge of the ESP's performance prediction model, it is possible to provide the operational data of the emulsion, invert the model, and determine the equivalent viscosity of a pseudo single-phase flow.

The ESP performance was evaluated based on several dimensionless parameters, namely the dimensionless head Ψ, dimensionless flow rate ϕ, dimensionless power Π_m, rotational Reynolds number Re_w, and dimensionless geometry R_R. These parameters are defined in Eqs. (1) to (5):

$$\Psi_m = \frac{\overline{\Delta P}}{\rho_e \omega^2 D^2} \tag{1}$$

$$\phi = \frac{Q}{\omega D^3} \tag{2}$$

$$\Pi_m = \frac{BHP}{\rho \omega^3 D^5} \tag{3}$$

$$R_R = \frac{L_i}{D} \tag{4}$$

$$Re_w = \frac{\rho \omega D^2}{\mu} = \frac{1}{X} \tag{5}$$

where X is the inverse Reynolds Number, thus proportional to the liquid viscosity.

The output variables used in the analysis are defined as follows: average pressure increment $\overline{\Delta P}$, flow rate Q , shaft power divided by the numbers of stages $\overline{BHP}$, fluid density ρ, fluid viscosity μ, rotational speed ω, impeller diameter D, and geometrical characteristics L_i.

The efficiency η is already dimensionless and is related to dimensionless head, flow rate and power:

$$\eta = \frac{\phi \Psi_m}{\Pi_m} \tag{6}$$

The model proposed by Biazussi (2014) establishes a functional relationship between the dimensional parameters.

$$\Psi_m = \frac{1}{4} - k_4 + (-k_1 - Xk_2 + 2k_4k_5)\,\phi + \left[-\left(\frac{X}{\phi}\right)^n k_3 - k_4k_5^2 - k_6 \right] \phi^2 \tag{7}$$

The five parameters (k_2, k_3, k_4, k_5, k_6, n) presented in Table (1) are related to the pump's geometric characteristics and were empirically obtained by (Bulgarelli *et al.*, 2021a) for the ESP tested in this work.

Table 1. ESP geometric parameters fitted to the prediction model proposed by (Bulgarelli *et al.*, 2021a).

Parameter	**Value (-)**
n	0,45
k_1	1,5
k_2	6024,98
k_3	264,96
k_4	0,14
k_5	7,28
k_6	28,54

The parameter k_1 is determined from Eq. (8):

$$k_1 = \frac{D cotg \beta_2}{2\pi b_2} \tag{8}$$

where k_1 represents a constant that depends only on the pump geometry, b_2 impeller outlet width, and β_2 impeller vanes outlet angle.

The emulsion effective viscosity is calculated through the fitting of the ESP performance prediction model. This is achieved by utilizing a large dataset of single-phase ESP performance. Various experiments are conducted, with variations in rotational speeds, flow rates, viscosities, and densities. From this dataset, the dimensionless parameters Ψ, ϕ, and X are determined using Eqs. (1), (2), and (5), respectively. Subsequently, Biazussi's (2014) model is adjusted using Eq. (7), and the constant parameters k_1 to k_6 and n are determined. As a result, the necessary performance prediction model for the tested ESP is obtained.

The next step entails the inversion of the adjusted model to determine the effective viscosity of the emulsion within the ESP. This involves measuring the ESP's performance under a specific operating condition, which includes parameters such as the average pressure increment $\overline{\Delta P}$, oil flow rate Q_o, water flow rate Q_w, oil density ρ_o, water density ρ_w, and rotational speed ω. By utilizing this operating data, the dimensionless head $\Psi_{m,e}$ and flow rate ϕ_e of the oil-water emulsion within the ESP can be calculated.

$$\Psi_{m,e} = \frac{\overline{\Delta P}}{\rho_e \omega^2 D^2} \tag{9}$$

$$\phi_e = \frac{Q_e}{\omega D^3} \tag{10}$$

The emulsion density ρ_e is obtained based on the homogeneous model. This model is a weighting between phases properties, specifically the density and volumetric fraction of each phase.

$$\rho_e = \rho_o(1 - \Omega) + \rho_w\Omega \tag{11}$$

where the sub-indices o and w refer to the oil and water phases, respectively,

The Ω is the water cut based on the homogeneous model considering no slip between phases, Eq. (12):

$$\Omega = \frac{Q_w}{Q_e} \tag{12}$$

where Q_e is the emulsion total volumetric flow rate, Eq. (13):

$$Q_e = Q_o + Q_w \tag{13}$$

By utilizing the oil-water flow dimensionless performance and referring back to Eq. (1), the X_e parameter is computed. Ultimately, the emulsion effective viscosity μ_e is determined by employing Eq. (14).

$$Re_{w,e} = \frac{\rho_e \omega D^2}{\mu_e} = \frac{1}{X_e} \tag{14}$$

Fig. 4 presents the flowchart that illustrates the procedure for calculating the emulsion effective viscosity within the ESP.

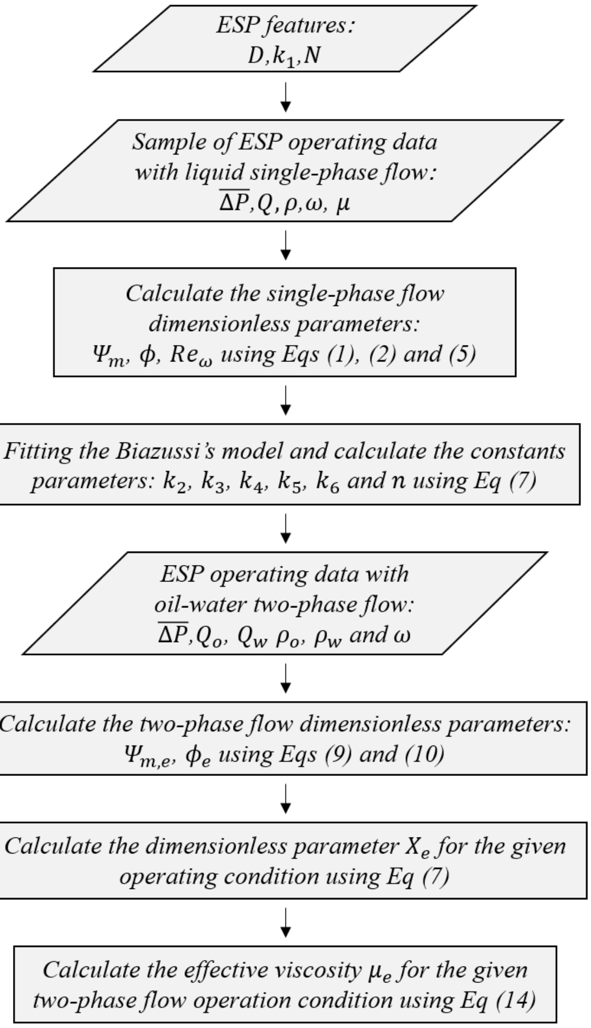

Figure 4. Procedure to calculate the emulsion effective viscosity within the ESP. Figure adapted from Bulgarelli *et al.* (2021a).

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4. RESULTS AND DISCUSSION

This section presents the experimental results and analysis of ESP head operating with a stable oil-water emulsion and the emulsion effective viscosity within the ESP is then analyzed in detail.

4.1 ESP dimensionless head degradation analysis

Figures (5), (6) and (7) show the ESP characteristic curves of the dimensionless head, dimensionless power and efficiency, respectively, operating with stable water/oil emulsions and oil single-phase. Figure (5) shows the ESP head curve operating with stable water/oil emulsions and oil single-phase as reference. These results show how performance degradation occurs as the emulsion effective viscosity increases. The increased fluid viscosity reduces the pump ability to transfer energy to the flow, resulting in a decrease in the provided head. The predominant impact of viscous losses on energy dissipation within the pump impeller and diffuser is mainly attributed to the combined effects of friction and disk losses. As a consequence, the power consumed to operate the pump increases significantly. This deteriorating behavior in the ESP dimensionless head when operating with viscous oil was observed in previous studies Solano (2009); Monte Verde (2016); Zhu *et al.* (2016); Monte Verde *et al.* (2023). It is important to note that the energy consumption terms are affected by the geometry of specific regions within the ESP stage, which is contingent upon the ESP design. Therefore, the evaluation of emulsion flow properties at a local level is necessary for each energy loss.

The decrease in the ESP dimensionless head can also be influenced due to the friction induced increase in the emulsion effective viscosity along the surfaces of the impeller and diffuser channels. The higher viscosity of the emulsion causes additional resistance to fluid flow, leading to higher energy losses due to friction. These energy losses reduce the pressure generating capacity of the ESP, which translates into a decrease in the dimensionless head of elevation.

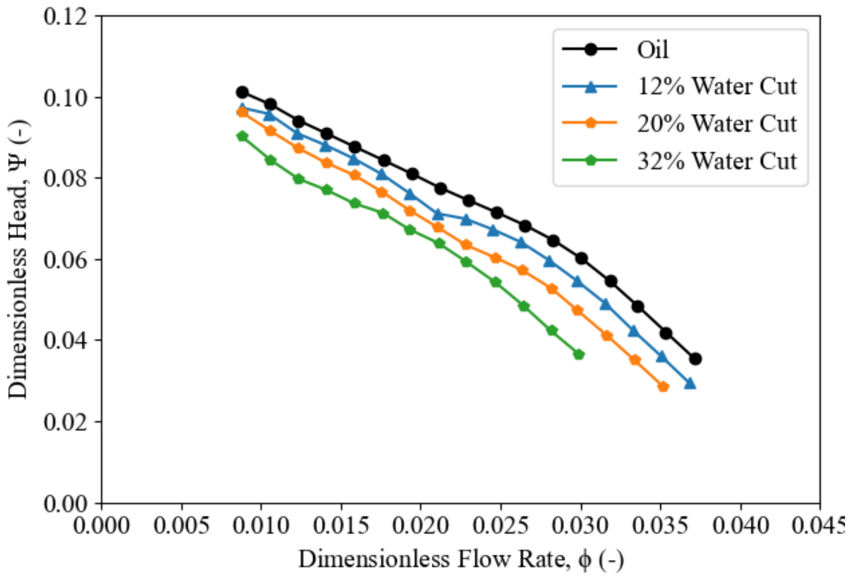

Figure 5. ESP dimensionless head as a function of dimensionless flow for pure oil and emulsion flow with water cut of 12, 20, 32% for 2400 rpm.

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Figure (6) shows the dimensionless power as a function of the ESP dimensionless flow rate operating with stable water/oil emulsion. It is observed that as the emulsion effective viscosity increases, particularly with higher water cut, there is a notable increase in the dimensionless power of the ESP. This increment can be attributed to the disk loss caused by friction between the emulsion and the impeller surface. The relationship between emulsion effective viscosity and the increase in ESP dimensionless power is also influenced by the mixed geometry of the ESP. In a mixed geometry, the friction resulting from the fluid's interaction with the impeller surface intensifies as it passes through narrow channels and accumulation regions. This heightened friction leads to increased flow resistance and, consequently, a more pronounced disk loss (Li, 2013; Biazussi, 2014).

Figure (7) shows a reduction in efficiency as a consequence of increasing the emulsion effective viscosity. The ESP efficiency is closely related to the energy consumption caused by the effective viscosity in stable oil-water emulsions, especially when there is an increase in water cut. As the effective viscosity increases due to the presence of dispersed water droplets in the oil phase, greater energy losses are generated due to friction and resistance to flow. These energy

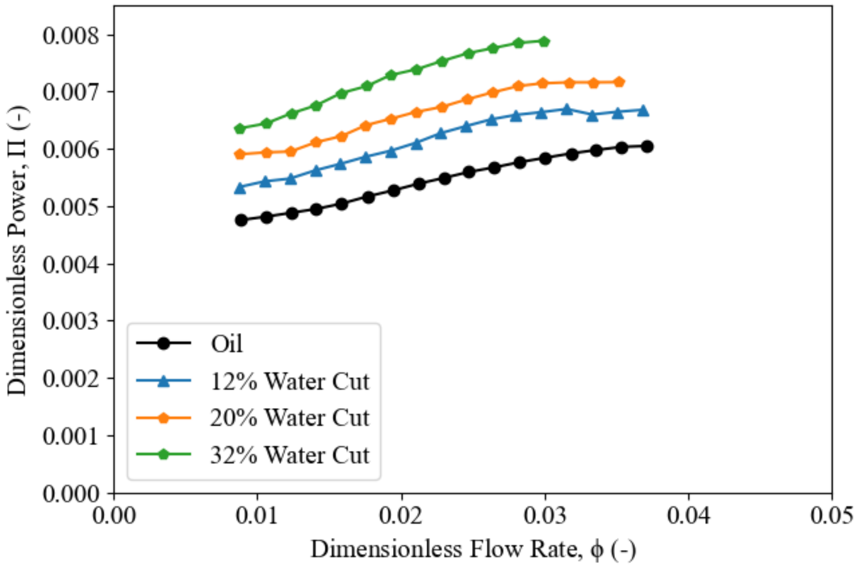

Figure 6. ESP dimensionless power as a function of dimensionless flow rate for pure oil and emulsion flow with water cut of 12, 20, 32% for 2400 rpm.

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losses reduce the efficiency of the ESP, since a greater amount of energy is required to overcome the flow resistance.

Furthermore, the hydrodynamic interaction of the flow in the stable water-in-oil emulsion also influences the ESP efficiency. The structure formed by the water droplets and their interaction with the oil phase generates complex flow patterns, leading to increased flow resistance and higher energy losses (Li, 2013). These factors can result in an additional decrease in ESP efficiency. The drag and disk losses within the ESP are exacerbated by the intricate flow behavior, further contributing to reduced overall performance.

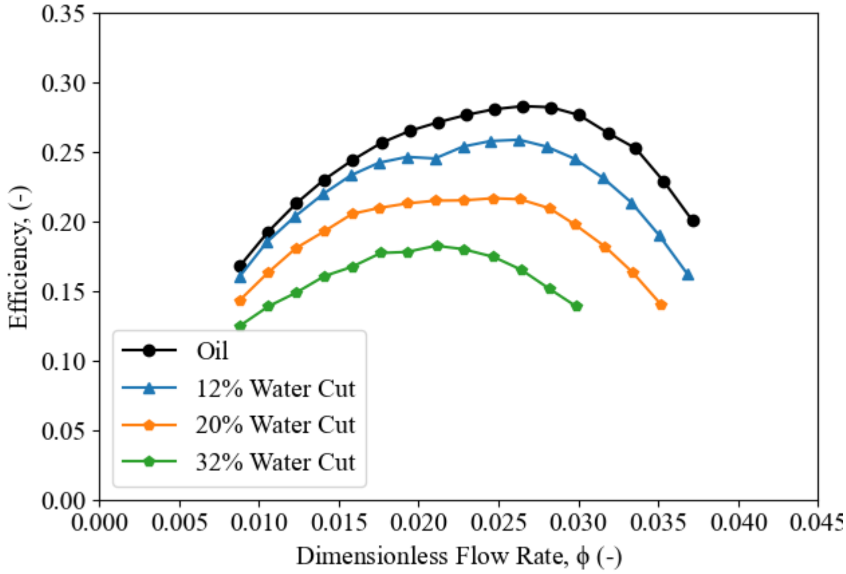

Figure 7. ESP efficiency as a function of dimensionless flow rate for pure oil and emulsion flow with water cut of 12, 20, 32% for 2400 rpm.

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4.1.1 Effective viscosity of water/oil stable emulsion in ESP

Figure (8) shows the relative viscosity of the water/oil emulsion flow within the ESP, which is defined as a ratio between emulsion effective viscosity and oil viscosity, as a function of the dimensionless flow rate for water cut of 12%, 20%, and 32% for 2400 rpm.

A seems like shear-thinning behavior, characteristic of non-Newtonian flows, was observed in the experiments conducted on the ESP water/oil stable emulsion. As the dimensionless flow decreases, the effective viscosity increases for the analyzed water cuts. This decrease in the parameter is attributed to a reduction in the flow rate within the impeller channel, resulting in a decrease in the shear rate of the emulsion flow within the ESP. The emulsion effective viscosity can be influenced by the concentration of the dispersed phase. As the concentration of the dispersed phase increases, the viscosity of the emulsion typically increases as well (Farah *et al.*, 2005; Pal, 2011).

The increase in effective viscosity in a stable water-in-oil emulsion within the ESP is related to shear thinning. This phenomenon is due to the structure formed by the water droplets dispersed in the oil phase, which generate resistance to flow due to the interaction between the phases (Valdés *et al.*, 2020). As the concentration of water droplets increases, this structure becomes more complex, resulting in an increase in the emulsion effective viscosity. In addition, the presence of a surfactant in the system reduces the interfacial tension between the water and the oil, which contributes to the stability of the emulsion and increases its effective viscosity.

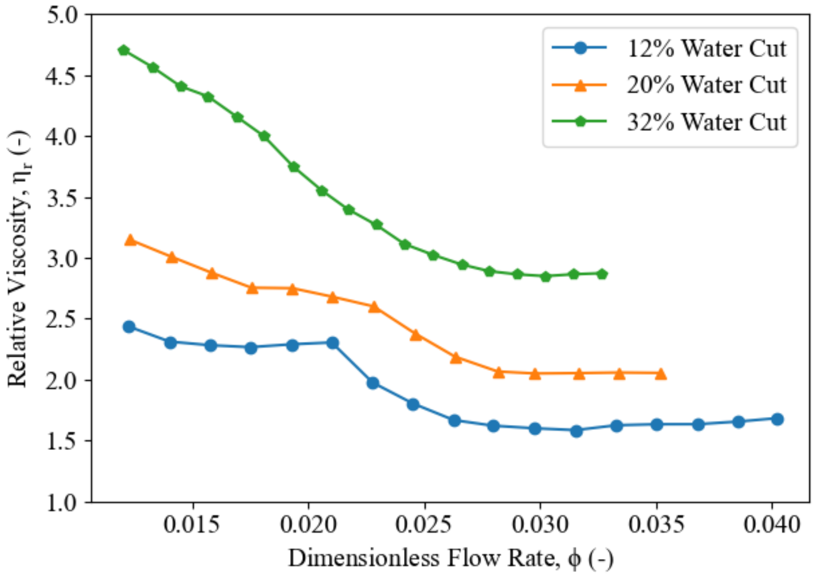

Figure 8. Emulsion relative viscosity as a function of dimensionless flow rate stable emulsion.

5. CONCLUSIONS

This study aimed to analyze the influence of emulsion effective viscosity on the ESP performance. An 8-stage ESP was used to operate with stable water/oil emulsion flow. The stable emulsion was created by mixing mineral oil, 1 wt% of SPAN 80 in oil, and tap water to simulate a typical crude oil/water emulsion. The emulsion effective viscosity within the ESP was determined using an indirect method proposed by Bulgarelli *et al.* (2021a), which was obtained from the water/oil emulsion performance curves.

In this work, a noticeable degradation in the ESP dimensionless head was observed, which was attributed to an increase in the water cut in the emulsion. This increase in the water cut led to a significant rise in the emulsion effective viscosity. As a consequence, the higher viscosity necessitated greater flow resistance, resulting in a decrease in the ESP performance. A non-Newtonian behavior was observed in the oil-water emulsion system within the ESP, which means that its effective viscosity can change depending on the shear rate and shear stress. This may be associated with deformation and rupture of dispersed water droplets in the oil under high shear rates within the ESP, which affects the emulsion effective viscosity. As the shear rate increases, such as the flow velocity or the agitation within the ESP, the water-in-oil emulsion experiences changes in its effective viscosity. Similarly, as the applied shear stress increases, the emulsion effective viscosity decreases.

The ESP performance is significantly affected by the emulsion effective viscosity and the friction-induced losses. As the emulsion viscosity increases, the pump's ability to transfer energy to the fluid decreases, resulting in a reduction in the provided head and power. This deterioration is primarily attributed to the combined effects of friction and disk losses within the impeller and diffuser channels. The decrease in the dimensionless head and power of the ESP can be influenced by the mixed geometry of the pump, which intensifies the friction and flow resistance. These findings highlight the importance of considering the emulsion properties and pump design in optimizing the energy efficiency of ESPs operating with viscous emulsions.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Banjar, H. and Zhang, H.Q., 2019. "Experiments and emulsion rheology modeling in an electric submersible pump". *International Petroleum Technology Conference 2019, IPTC 2019*. doi:10.2523/iptc-19463-ms.

Biazussi, J., 2014. "A drift-flux model for gas-liquid flow in electrical submersible pump operating with low viscous liquid". *PhD thesis. University of Campinas, Unicamp*.

Bulgarelli, N.A.V., 2018. "Experimental study of electrical submersible pump (esp) operating with water / oil emulsion estudo experimental de bomba centrífuga submersa (bcs) operando com emulsão Água / Óleo experimental study of electrical submersible pump (esp) operating wit". p. 135.

Bulgarelli, N.A.V., Biazussi, J.L., Verde, W.M., Perles, C.E., de Castro, M.S. and Bannwart, A.C., 2021a. "Experimental investigation on the performance of electrical submersible pump (esp) operating with unstable water/oil emulsions". *Journal of Petroleum Science and Engineering*, Vol. 197, p. 107900.

Bulgarelli, N.A.V., Biazussi, J.L., Verde, W.M., Perles, C.E., de Castro, M.S. and Bannwart, A.C., 2021b. "Relative viscosity model for oil/water stable emulsion flow within electrical submersible pumps". *Chemical Engineering Science*, Vol. 245, p. 116827.

Bulgarelli, N.A.V., Biazussi, J.L., Verde, W.M., Perles, C.E., de Castro, M.S. and Bannwart, A.C., 2022. "A novel criterion based on slip ratio to assess the flow behavior of w/o emulsions within centrifugal pumps". *Chemical Engineering Science*, Vol. 247, p. 117050.

Croce, D. and Pereyra, E., 2020. "Study of oil/water flow and emulsion formation in electrical submersible pumps". *SPE Production & Operations*, Vol. 35, No. 01, pp. 026–036.

Farah, M.A., Oliveira, R.C., Caldas, J.N. and Rajagopal, K., 2005. "Viscosity of water-in-oil emulsions: Variation with temperature and water volume fraction". *Journal of Petroleum Science and Engineering*, Vol. 48, No. 3-4, pp. 169–184.

Kokal, S., 2005. "Crude-oil emulsions: A state-of-the-art review". *SPE Production & facilities*, Vol. 20, No. 01, pp. 5–13.

Langbauer, C., Pratscher, H.P., Ciufu, A.C., Hoy, M., Marschall, C. and Pongratz, R., 2020. "Electric submersible pump behavior for pumping non-newtonian fluids". *Journal of Petroleum Science and Engineering*, Vol. 195, p. 107910. ISSN 09204105. doi:10.1016/j.petrol.2020.107910. URL `https://doi.org/10.1016/j.petrol.2020.107910`.

Li, W., 2013. "Model of flow in the side chambers of an industrial centrifugal pump for delivering viscous oil". *Journal of fluids engineering*, Vol. 135, No. 5, p. 051201.

Monte Verde, W., 2016. "Modelagem do desempenho de bombas de bcs operando com misturas gás-óleo viscoso". *Universidade Estadual de Campinas*.

Monte Verde, W., Kindermann, E., Biazussi, J., Estevam, V., Foresti, B. and Bannwart, A., 2023. "Experimental investigation of the effects of fluid viscosity on electrical submersible pumps performance". *SPE Production & Operations*, Vol. 38, No. 01, pp. 1–19.

Pal, R., 2011. "Rheology of simple and multiple emulsions". *Current opinion in colloid & interface science*, Vol. 16, No. 1, pp. 41–60.

Rønningsen, H.P., 2012. "Rheology of petroleum fluids". *Annual Transactions of the Nordic Rheology Society*, Vol. 20, pp. 11–18.

Solano, E.A., 2009. "Viscous effects on the performance of electro submersible pumps (esp's)".

Tadros, T.F., 2013. "Emulsion formation, stability, and rheology". *Emulsion formation and stability*, pp. 1–75.

Takacs, G., 2017. *Electrical submersible pumps manual: design, operations, and maintenance*.

Valdés, J.P., Becerra, D., Rozo, D., Cediel, A., Torres, F., Asuaje, M. and Ratkovich, N., 2020. "Comparative analysis of an electrical submersible pump's performance handling viscous newtonian and non-newtonian fluids through experimental and cfd approaches". *Journal of Petroleum Science and Engineering*, Vol. 187, p. 106749.

Wong, S., Lim, J. and Dol, S., 2015. "Crude oil emulsion: A review on formation, classification and stability of water-in-oil emulsions". *Journal of Petroleum Science and Engineering*, Vol. 135, pp. 498–504.

Zhu, J., Banjar, H., Xia, Z. and Zhang, H.Q., 2016. "Cfd simulation and experimental study of oil viscosity effect on multi-stage electrical submersible pump (esp) performance". *Journal of Petroleum Science and Engineering*, Vol. 146, pp. 735–745.

Zhu, J., Zhu, H., Cao, G., Zhang, J., Peng, J., Banjar, H. and Zhang, H.Q., 2020. "A new mechanistic model to predict boosting pressure of electrical submersible pumps under high-viscosity fluid flow with validations by experimental data". *SPE Journal*, Vol. 25, pp. 744–758. ISSN 1086055X. doi:10.2118/194384-PA.

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