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Influence of Fluid Viscosity on the Flow Behavior within the Impeller of an Electrical Submersible Pump (ESP)

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Abstract

The electrical submersible pump (ESP) plays a crucial role in artificial lift operations in the oil and gas industry. The viscosity of the pumped fluid significantly influences the flow dynamics within the ESP, thereby impacting the performance of the machine. In this context, flow visualization techniques can unveil intricate details of the flow in ESP impellers, thus providing a deeper understanding of the relationship between flow behavior and pump performance. This is the main idea of the present document, which utilizes the particle image velocimetry (PIV) technique to experimentally investigate a mineral oil flow, $\mu = 14\ cP$, in a transparent prototype of a real impeller, P23 model. The paper reports insights into the flow in the pump's rotating component at different flow rates that correspond to percentages of the best efficiency point (BEP). Average velocity fields and turbulent kinetic energy plots indicate that flow dynamics are highly dependent on the operating conditions of the ESP. A comparison between results for oil and water completes the analysis, as it highlights the effects of viscosity on the flow characteristics. This type of study is useful to validate numerical simulations, support mathematical models, and develop improved impeller designs.

Keywords

Electrical Submersible Pump; Flow Visualization; Viscous Flow.

Introduction

The electrical submersible pump (ESP) is regularly used as an artificial lift technique in oil production. This centrifugal pump works effectively with water, but it usually encounters difficulties when pumping viscous fluids or multiphase flows. In these cases, the machine may experience a decrease in its performance and efficiency, together with operational instabilities that result in financial losses.

The pump behavior depends on the flow dynamics inside the impeller. Hence, researchers have been using flow visualization and measurement methods to understand how and why the ESP performance is affected by its internal flow dynamics. Examples focusing on water flow include Pedersen et al. [1], Krause et al. [2], Keller et al. [3], Li et al. [4], Liu et al. [5], Fonseca et al. [6], Perissinotto et al. [7].

These authors relied on particle image velocimetry (PIV) methods to measure variables related to the water flow [8]. However, viscous flows have not yet been extensively explored using PIV. The oil flow, for example, has been studied in a limited number of papers, e.g. Mittag and Gabi [9]. There is still room for using visualization practices to assess the effects of fluid viscosity on ESP systems.

In this context, this paper presents an experimental study on the velocity fields and turbulence levels of a single-phase mineral oil flow in an ESP impeller by using a planar PIV technique.

Methodology

Test Facility

Experiments were conducted using the same setup designed, assembled, and utilized before to study water flows [10]. It is composed of a flow line with a tank, booster pump, instruments to measure flow rate, pressure, and temperature. This test facility also has a transparent ESP prototype especially developed for flow visualization purposes.

The ESP has an impeller with the same geometry of the P23 model, series 538, by *Baker Hughes*. A frontal photo of the prototype stage, with impeller and volute diffuser, is depicted in Fig.1.

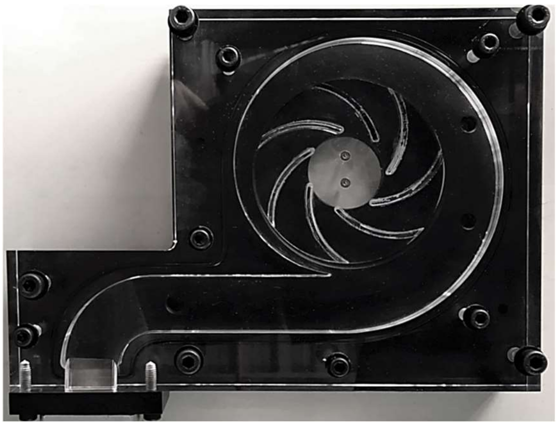

Figure 1. ESP composed of transparent parts [10].

As flow visualization method, we adopted the PIV system DualPower 30-1000 by *Dantec Dynamics*, which provides 30 mJ energy/pulse at 1 kHz rate. Fluorescent PMMA particles doped with rhodamine were added to the mineral oil to work as tracers.

Experiments

The oil used in the experiments has the designation "hydrogenated white oil USP grade", a transparent, colorless, Newtonian liquid. The experiments were performed at $T = 30°C$, in which density is $\rho = 834$ kg/m^3 and viscosity $\mu = 14\ cP$. Such values were confirmed through physicochemical tests.

Three conditions were analyzed by varying the oil flow rates, Q, at percentages of the best efficiency point (BEP) flow rate, Q_{BEP}, as Fig. 2 displays. The rotational speed of the impeller was kept constant under $N = 900\ rpm$. The BEP was determined via preliminary tests with torque measurements.

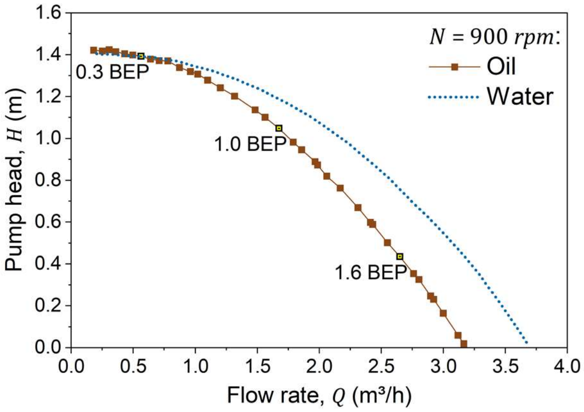

Figure 2. Pump curve highlighting three oil flow rates investigated here: $Q/Q_{BEP} = [0.3, 1.0, 1.6]$.

The procedure is the same already reported in [10]. The PIV experiment captures 500 pairs of images in the *Dynamic Studio* software with the impeller at a fixed angular position measured by an encoder. It ensures that the channels and blades are always at the same position on the entire set of images, a condition necessary for calculating average values.

Calculations

The raw images are processed in *Dynamic Studio* software and *MatLab* and *Python* in-house codes. The first step is applying masks to define the region of interest. The angular displacement between two consecutive frames is then removed so that we can work with relative instead of absolute velocities:

$$\mathbf{w} = \mathbf{u} - \boldsymbol{\omega} \times \mathbf{r} \tag{1}$$

The 500 instantaneous velocity fields are obtained and they give rise to a single ensemble-averaged field, in which the vectors are calculated as follows:

$$\langle \mathbf{w} \rangle = \frac{1}{n}\sum_{k=1}^{n} \mathbf{w}_k \tag{2}$$

The difference between the average and instantaneous velocity fields results in fluctuation fields, a quantity that can be related to the turbulent kinetic energy of the flow, in the 2D plane:

$$K_{2D} = \frac{1}{2}\left(\langle w'_x \rangle^2 + \langle w'_y \rangle^2\right) \tag{3}$$

Results and Discussion

The vectors in Figs. 3 to 5 represent the average relative velocity fields. Impeller rotates clockwise.

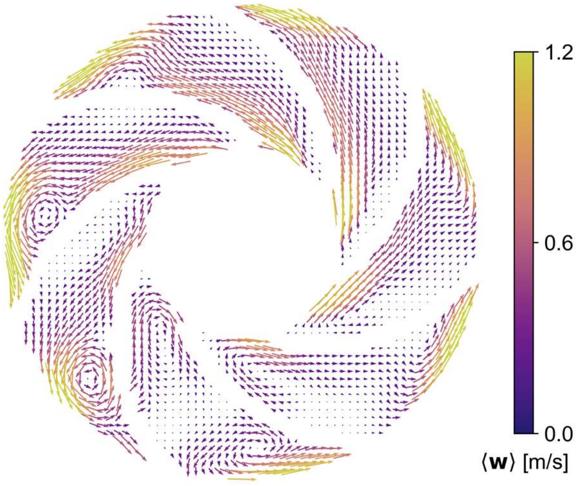

Figure 3. Oil velocity field at $Q = 0.3\ Q_{BEP}$.

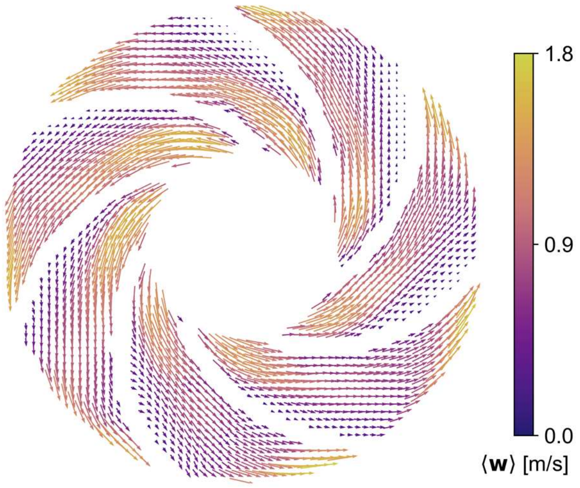

Figure 4. Oil velocity field at $Q = 1.0\ Q_{BEP}$.

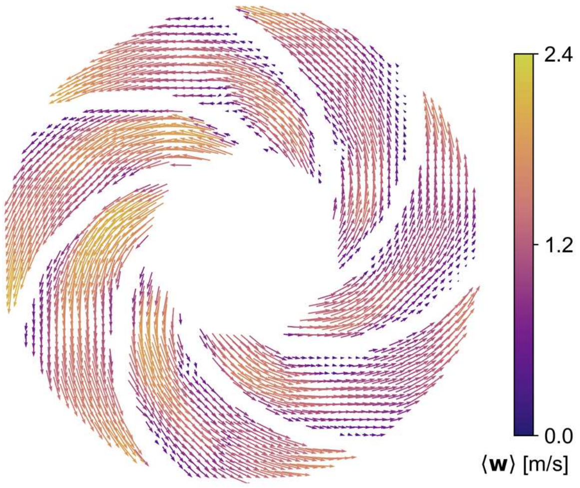

Figure 5. Oil velocity field at $Q = 1.6\ Q_{BEP}$.

It is evident that the magnitudes of velocity vectors are directly related to the oil flow rate. At 0.3 BEP, the flow pattern is intricate and features numerous areas of intense recirculation. At 1.0 BEP, the flow tends to become more outwardly directed, without any vortices at all. Then, for 1.6 BEP, vectors shift towards the suction blades, causing the fluid path to become longer. The streamlines in Fig. 6 intend to make these observations clearer. To extend the analysis, Fig. 7 shows contour plots of turbulent kinetic energy computed in the mineral oil flow.

When comparing the oil results (this paper) with the water results (presented in [10]), some differences emerge: i) At the lowest Q, the positions of vortices vary significantly depending on the pumped fluid; ii) At the highest Q, oil undergoes a less pronounced deviation towards the suction blades than water; iii) At Q_{BEP}, the oil flow is more concentrated on the left side of the impeller and the center of the channels, farther from the blades. This fact suggests a more parabolic velocity profile for oil (high μ) and a flatter profile for water (low μ).

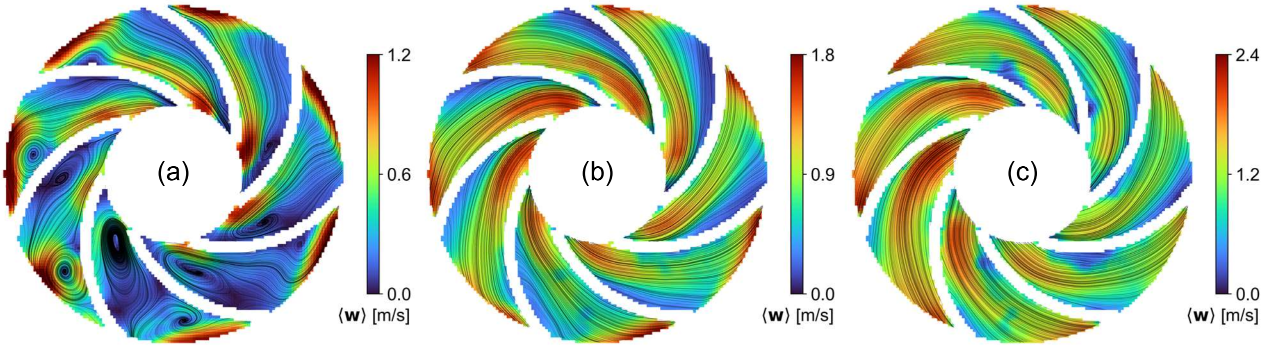

Figure 6. Streamlines of mineral oil flow at (a) $Q = 0.3\ Q_{BEP}$, (b) $Q = 1.0\ Q_{BEP}$, (c) $Q = 1.6\ Q_{BEP}$.

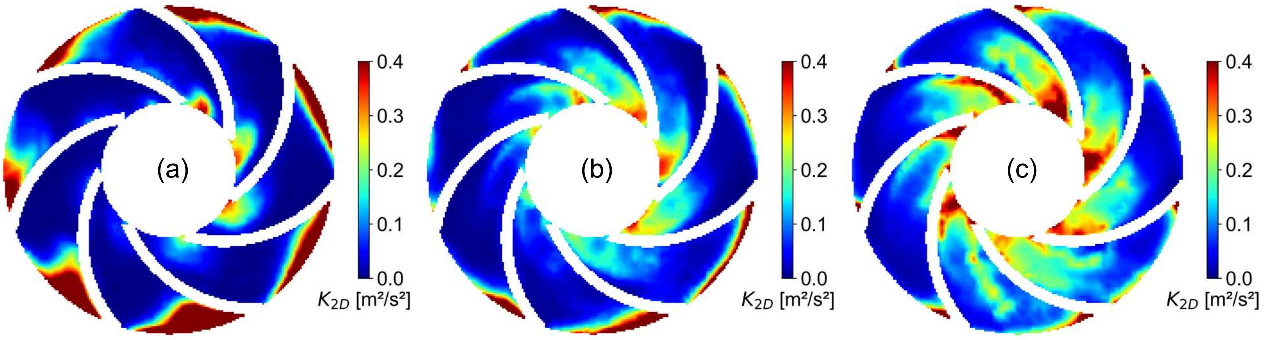

Figure 7. Turbulent kinetic energy for oil flow at (a) $Q = 0.3\ Q_{BEP}$, (b) $Q = 1.0\ Q_{BEP}$, (c) $Q = 1.6\ Q_{BEP}$.

At a first glance, the turbulence levels may appear quite similar across the three flow rates. However, a numerical integration of K_{2D} values throughout the entire impeller reveals that the off-design points exhibit the highest turbulent kinetic energy levels, approximately 40% higher than those at Q_{BEP}.

These findings agree with previous observations in our water flow study [10]. It is expected that velocity fluctuations are minimal at BEP, as this condition is associated with lowest energy losses.

Regarding the distribution of K_{2D} in the impeller, oil has a similar behavior to water too [10]. Turbulence is more intense: i) near the impeller exit at low flow rates and ii) next to its entrance at high flow rates. However, the magnitudes of K_{2D} are greater for oil compared to water [10], for all flow rates.

This discrepancy has two possible explanations [6] i) Turbulence scales tend to increase with viscosity. As PIV has limited spatial resolution, a larger scale may intensify the detection of velocity fluctuations, for constant dissipation; ii) Compared to water, the oil flow has a larger number of coherent structures in relevant energetic modes. They are detected by PIV through proper orthogonal decomposition.

Conclusions

This work explored a mineral oil flow ($\mu = 14\ cP$) in a radial impeller of an electrical submersible pump (P23 model). A transparent prototype of the impeller was constructed to allow for a clear observation of the flow, so that a planar particle image velocimetry approach was utilized to measure both the average and instantaneous velocities, as well as turbulent kinetic energy levels. Tests were executed at three flow rates corresponding to percentages of the best efficiency point ($0.3\ Q_{BEP} \leq Q \leq 1.6\ Q_{BEP}$) while the rotational speed was constant ($N = 900\ rpm$).

Our results indicate that the flow dynamics change depending on the oil flow rate. For the lowest Q, the ensemble-averaged velocity fields reveal that the flow is full of vortices and zones of recirculation. As Q increases, the flow structure gradually shifts and becomes outwardly directed. For the highest Q, the streamlines undergo a deviation toward the suction blades, acquiring a longer path. In addition, the turbulent kinetic energy is higher at off-design points than at Q_{BEP}. These K_{2D} levels are more intense in the impeller entrance at high Q and exit at low Q.

When comparing results for oil (current study) and water (previous study), differences are identified, such as the position of the vortices at low Q and the intensity of the flow deviation at high Q. In addition, due to the viscosity, the oil flows at lower velocities in the vicinity of the blades in comparison to water. The turbulent kinetic energy is higher in the oil than in the water flow, as a possible effect of turbulence scales, coherent structures, and energetic modes. At higher fluid viscosities, the detection of velocity fluctuations in the oil flow may be improved.

Evaluating the influence of the fluid viscosity on the flow behavior in impellers may represent a primary stride towards a comprehensive understanding of energy losses that impair the performance of centrifugal pumps used in the oil and gas industry.

Acknowledgments

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Responsibility Notice

The authors are the only responsible for the paper content.

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