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Experimental analysis on the behavior of water drops dispersed in oil within a centrifugal pump impeller

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ABSTRACT

This paper aims to investigate the behavior of water drops in a continuous oil medium inside a centrifugal pump impeller working at eight operational conditions (up to 1200 rpm and 2.8 m^3/h) with two-phase liquid-liquid flows. Water-in-oil dispersions were produced with low water cuts of about 1% in volume, thus the dispersed phase became arranged as water drops. Experiments for pump performance and flow visualization were conducted using a high-speed camera and a pump prototype with a transparent shell. Flow images revealed that the large water drops usually deform, elongate, and break up into smaller ones, especially at high pump rotations and oil flow rates, while small water drops tend to keep their spherical geometry without deformations and fragmentations. A sample of drops were tracked and their equivalent diameters, residence times, and velocities were calculated. The tracking indicated that the water drops travel random trajectories in the channels, generally undergoing a deceleration along their pathway. Furthermore, the residence times and the average velocities of water drops strongly depend on the flow conditions. For the conditions tested, the water drops presented equivalent diameters between 0.1 and 5.0 mm, average velocities from 0.4 to 1.7 m/s, and residence times between 30 and 152 ms. For a more complete analysis, the results achieved in this study are constantly compared with results available in literature regarding oil drops in oil-in-water dispersions.

1. Introduction

Two-phase liquid-liquid flows are present in the daily life of human beings, from simple activities to complex industrial processes. In a wide range of industries, in food, chemical, and pharmaceutical processes, the liquid-liquid dispersions are usually a desirable product. However, in some situations, their presence may be harmful to the whole process. The last case is the situation frequently found in the petroleum production systems.

In the petroleum industry, centrifugal pumps are widely employed to lift fluids from wells to topside facilities, for example. Nowadays, it is estimated that approximately 10% of the oil supply in the world is produced with centrifugal pumping installations [1], which are used as an artificial lift method named electrical submersible pumping (ESP). This important technique can be applied in onshore and offshore wells, being able to handle high volumes of fluid with high temperatures in abrasive environments [2].

When water is present inside the petroleum reservoir, the high shear and turbulence inside the ESP system can promote the breakup of the phases into small drops, producing dispersions and emulsions, which can be oil-in-water (O/W) or water-in-oil (W/O) types. As an important characteristic of W/O mixtures, it can be highlighted that their apparent viscosity may be higher than the viscosity of the separated liquids [3–5]. Therefore, W/O dispersions can represent top issues related to flow assurance in oil production because their high effective viscosity can affect the pump performance and, consequently, can cause a substantial increase in the operational costs. Improving the physical understanding on multiphase flows in centrifugal pumps is fundamental to the advancement of technologies that can lead to more efficient ESP designs.

The first studies on multiphase flows inside rotating machinery had their focus on two-phase gas-liquid flows. These initial investigations were motivated by the nuclear industry, where centrifugal pumps were used in reactor cooling systems. In the petroleum industry, Estevam [6] was the first researcher to develop a pump prototype for visualization of gas-liquid flows. The author observed two patterns: dispersed bubbles

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Nomenclature

m_o	oil mass flow rate [kg/s]
Q_o	oil volume flow rate [m^3/s]
Q_w	water volume flow rate [m^3/s]
ϕ	water cut [v/v%]
T_1	temperature in the prototype [°C]
T_2	temperature in the separator [°C]
N	impeller rotational speed [Hz]
ω	impeller angular speed [rad/s]
ω_s	pump specific speed [–]
P_1	pressure in prototype inlet [Pa]
P_2	pressure in prototype outlet [Pa]
ΔP	pressure increment [Pa]
g	gravity [m/s^2]
ρ_w	water density [kg/m^3]
ρ_o	oil density [kg/m^3]
μ_w	water viscosity [Pa s]
μ_o	oil viscosity [Pa s]
$\sigma_{o/w}$	interfacial tension [N/m]
F_i	interfacial force [N]
Δp_i	pressure jump across interface [Pa]
τ_d	disruptive stress [Pa]
τ_σ	interfacial stress [Pa]
τ_μ	viscosity stress [Pa]
ε	turbulent energy dissipation [m^2/s^3]
R	impeller outer radius [m]
D	impeller diameter [m]
A	surface area of a drop [m^2]
d	equivalent diameter of a drop [m]
d_{32}	Sauter mean diameter [m]
d_{95}	95% maximum diameter [m]
n	number of drops [#]
Re_S	Reynolds number – Stepanoff [–]
Re_G	Reynolds number – Gülich [–]
Re_{MV}	Reynolds number – Monte Verde [–]
Re_ω	rotational Reynolds number [–]
H	pump head [m]
$H_{w,BEP}$	water pump head at BEP [m]
$Q_{w,BEP}$	water flow rate at BEP [m^3/s]
$C_{H,BEP}$	correction factor for pump head [–]
$C_{Q,BEP}$	correction factor for flow rate [–]
t	instant of time [s]
Δt	time interval [s]
t_{res}	residence time of a drop [s]
x, y	position of a drop [m]
$\dot{x}$, $\dot{y}$	time derivatives of position [m/s]
$\boldsymbol{V}$	relative velocity vector [m/s]
V	velocity magnitude of a drop [m/s]
V_{avg}	average velocity of a drop [m/s]
$f(t)$	generic function of time [–]
$\dot{f}(t)$	derivative of generic function [–]
Ca	capillary number [–]

Subscripts

i	i-th value of a discrete parameter
w	water
o	oil

Abbreviations

ESP	electrical submersible pumping
BEP	best efficiency point
HSC	high-speed camera
FC	flow condition
O/W	oil-in-water
W/O	water-in-oil
VSD	variable speed drive
LED	light-emitting diode
PIV	particle image velocimetry
CFD	computational fluid dynamics

and segregated flow.

Zhu and Zhang [7] wrote a recent review of studies focused on two-phase gas-liquid flows in electrical submersible pumps. Using high-speed cameras, such authors as Barrios and Prado [8], Trevisan and Prado [9], Zhang et al. [10], Monte Verde et al. [11], and Cubas Cubas [12] identified flow patterns within impellers and analyzed the behavior of bubbles at different flow conditions. Other authors as Murakami and Minemura [13], Minemura and Murakami [14], Sabino [15], and Ofuchi et al. [16] investigated the forces that govern the dynamics of individual gas bubbles in rotating equipment. The comparison between bubbles and drops, however, is not appropriate, as liquid-liquid interactions may be quite different from liquid-gas interactions, which are mainly dominated by gas compressibility, turbulence, and drag imposed by the liquid motion.

On the other hand, forces acting on liquid drops are often attributed to properties such as viscosities and interfacial tensions. A quantitative relationship between interfacial and viscous forces is frequently obtained by calculating non-dimensional numbers, such as the capillary [17] and Ohnesorge [18] numbers. The shape of a single drop, for example, can be predicted by the Bond, Morton, and droplet Reynolds numbers [19]. However, all these numbers have been developed for pipe flows, so they are not suitable for dispersed drops in impellers. Further studies with focus on liquid-liquid interactions would be appreciated as they could include important factors, such as centrifugal effects, in the analysis of drops in pumping devices.

Nevertheless, there are few studies on two-phase liquid-liquid flows in pump impellers available in the literature and they rarely focus on drop dynamics. Khalil et al. [20], Morales et al. [21], Bulgarelli et al. [22,23], and Perissinotto et al. [24,25] are examples of authors who experimentally investigated dispersions within centrifugal pumps.

Khalil et al. [20] investigated centrifugal pumps working with stable and unstable O/W emulsions. The authors observed that the presence of emulsions reduced the head and the flow rate in the pump. Morales et al. [21] studied the formation of O/W dispersions inside a centrifugal pump where the turbulent breakup was identified as the main mechanism of drop formation. The authors noticed a clear dependence between the pump rotation speed and the oil drop characteristic size: as the rotation increased the oil drops became smaller. Bulgarelli et al. [22,23] investigated the phase inversion phenomena and the drop size distribution in an eight-stage pump working with O/W and W/O dispersions. The authors concluded the phase inversion occurred at water cuts from 10% to 30%, for water and oil as working fluids, and the drop size raised up to the phase inversion point, falling after it.

Using a high-speed camera, Perissinotto et al. [24] studied the behavior of oil drops in O/W dispersions in a centrifugal pump impeller. The researchers qualitatively investigated the flow pattern and geometric shape of oil drops with a viscosity of 0.220 Pa s (220 cP). Characteristic sizes were analyzed with histograms for equivalent diameter distributions. The researchers also studied the kinematics and dynamics of a sample of oil drops, with an evaluation of the forces that govern their motion. The experimental analyses conducted by the authors were numerically investigated by Perissinotto et al. [25] using computational fluid dynamics (CFD) simulations and it was observed a satisfactory agreement between both studies.