Lubrication of Offshore Mechanical Components: Towards sustainable & reliable power production

Juan Guillermo Zapata Tamayo, Sergei Glavatskih

Abstract—**As wave and tidal energy generators advance towards full-scale deployment and commercialization, addressing challenges in the marine environment regarding the lubrication of the components integrating the Power-Take-Off (PTO) system become crucial. Environmental acceptable lubricants that can be biodegraded such as water-soluble polymers are being considered as an alternative to control friction and wear in ocean energy generators. However, compared to synthetic lubricants or mineral oil, they have shown limitations in preventing corrosion, wear, and excessive friction, which can result in premature failure of moving parts. This study explores the potential of different water-soluble polymers as environmentally-friendly lubricants that meet stringent regulations and provide effective protection against wear and corrosion in offshore conditions. The analysis focuses on the polymers ability to form an elastohydrodynamic film, mitigate surface degradation, prevent corrosion, as well as their rheological properties at different concentrations. The findings reveal that large polymers such as PAG when added in low concentrations in the water can form a separating film under high contact pressure in the low-speed region, while viscosity has shown to have less impact on the ability of the polymer to form a full film. Increasing polymer concentration in the aqueous solution negatively affects the corrosion resistance of steel components at the expense of improving the film-build up. These results offer valuable insights for designing lubrication solutions to protect offshore energy devices.**

Index Terms—**Lubrication, water-soluble polymer, ocean power generation, tribology, corrosion, environmental acceptable. . . .**

I. INTRODUCTION

WITH the growing demand for renewable energy sources, tidal and wave energy converters have emerged as a promising complementary alternative to solar and wind power. Wave and tidal devices offer an immense potential to harvest the energy from the vast ocean area. Different wave and tidal energy conversion devices have been developed in the last decade [1], [2]. The kinetic energy transported by the waves and tides can be harvested by means of a power take-off (PTO) system. The different PTOs configurations commonly used include horizontal and vertical axis turbine-based, oscillating hydrofoils, linear generator-based, and hydraulic unit-based systems. The power-take off (PTO) system serves as the link between the primary interface facing the waves or tides and the electric generator, facilitating the conversion of this energy into usable electrical power. The PTOs can be classified according to the conversion working principles into hydraulic, mechanical or a direct electrical drive [2], [3]. However, in order to guarantee the reliable operation of the PTO under the harsh weather conditions encountered in the marine environment, a hydraulic PTO system has been often preferred. The mechanical components integrated into a tidal or wave energy converter that allow to capture, convert and transmit the power harvested from the ocean are prone to face deterioration independent on the design and working principle.

Despite the outstanding progress of the the technology, the research and investment efforts have mainly concentrated on reaching a higher power output, ensuring device survivability in harsh ocean conditions, and optimizing cost-effectiveness and efficiency of the concept [4]. However, aspects related to the operation and long term maintenance of the PTO such as the lubrication, and wear mechanism affecting the moving parts has not received major attention. As a consequence of the relative motion between the contacting surfaces that integrates the primary interface and PTO, frictional forces are generated, eventually leading to excessive wear or surface deterioration. The frictional forces are highly depended on the type of motion, contact parameters, environment and material properties. The constant exposure to corrosive seawater, as well as the dynamic forces from tides and waves, put under a significant stress the mechanical components, which can result in premature failure, leading to leakage that can be adverse for the environment, and that can deteriorate the conversion efficiency compromising the economic viability of the concept [5]–[7]. Understanding how the specific environmental factors encountered in the offshore environment that can arise along real operation conditions and can have a influence on friction, wear, corrosion and the different deterioration modes of the moving parts is critical to design and plan the necessary maintenance and ensure the optimal performance and long term durability of

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the mechanical components of PTO systems.

New technologies such as the use of advanced coatings, self-lubricating materials, and biodegradable lubricants, are being explored to enhance operational lifespan of offshore machinery. The piston/rod is a key component of a hydraulic PTO, which is usually actuated by a heaving oscillating buoy to produce a flow to drive a variable displacement hydraulic motor, or a turbine connected to an electric generator [8], [9]. The hydraulic fluid used to drive the motor or turbine acts as a lubricant, so its performance and deterioration modes are highly influenced by the physical and chemical properties of the hydraulic fluid. Sealing rings, used to avoid leakages of the hydraulic fluid into seawater, as well as prevent contamination of the working fluid, are highly susceptible to failure if rough corrosion products are generated on the surface of the piston rod. The high pressure piston chamber sealing o-ring is subjected to reciprocating motion induced by the heave and surge motion of the primary interface interacting with the waves, thus in combination with the poor lubricity of water can lead to severe damage [7]. The surface around the middle stroke region of the piston/rod is simultaneously subjected to shear stress arising from the interaction with the sealing rings, and cyclic bending stresses induced by the marine tidal flow, thus increasing the risk of premature crack formation and pitting nucleation in the contacting region exposed to a corrosive environment.

Environmentally acceptable hydraulic fluids (EAHF), which can biodegrade in case of leakage, constitutes an alternative to conventional lubricants such as synthetic esters, polyglycols, and polyaplhaolefins. However, when water is used as a power transmission, friction losses arising from its low viscosity can be significantly detrimental of the reciprocating rings sealing capability due to reduced hydrodynamic lubrication, negatively impacting the power transmission efficiency. In order to reduce the time between maintenance intervals of the PTO unit, improving the hydrodynamic lubrication has shown to be an effective approach to compensate for the poor lubricity of seawater [8], [9].

One of the biggest challenges in the long term operation for wave and tidal generators is to find a suitable lubricant to protect from excessive wear the moving parts of the PTO at the same time that the strict environmental regulations are meet. Environmentally friendly lubricants soluble in water are preferred to minimize the pollution risk of the ecosystems. A hydraulic PTO lubricated with sea-water base fluids offers an excellent alternative to oil based working fluids, mainly due to the low cost, and environmental compliance. This work aim to study a water-based lubricant with enhanced film formation capabilities, and corrosion resistance in order to protect the moving parts in offshore machinery from excessive wear as well as prevent leakages to the environment.

TABLE I
BULK LUBRICANT PROPERTIES

	Kinematic viscosity 40C mm^2/s	Refractive Index
Glycerol	235	1.469
PAG	220	1.456
Reference lube	4.81	1.012

II. MATERIALS AND EXPERIMENTAL DETAILS

A. Lubricant formulations

A synthetic polyalkylene glycol PAG copolymer composed of repeating units of ethylene oxide (EO) and propylene oxide (PO) is used to prepare the aqueous solutions in this study. The ethylene oxide blocks are responsible for the hydrophilic properties exhibited by the polymer making possible to prepare aqueous solutions to control its rheological properties.

In the same way Glycerol which has multiple hydroxyl (OH) groups allowing to strongly interact with water though hydrogen bonding has been used as a cost effective alternative to PAG. The water-based lubricants were prepared by diluting the bulk polymer with distilled water at concentrations ranging from 5% to 50%. In the same way a fully formulated commercially available hydraulic fluid for marine applications was used for purposes of comparison.

B. Film thickness measurements

Film thickness measurements were conducted to gain understanding on the film forming properties of the different lubricants and to design potential formulations to protect the mating surfaces from wear at different speeds that can be encountered in the offshore environment. The film thickness measurements were carried out using a ball-on-disc configuration, EHD rig designed by PCS Instruments (UK) [10]–[12]. As can be observed in Fig 1, a steel ball is partially submerged in the fluid to be tested, and then loaded against a transparent glass disc generating a point contact under pure rolling conditions. The steel ball has a diameter of 19.05 mm, and the disc a diameter of 60 mm. The film-thickness measurements were carried out at 23°C to facilitate comparison between lubricants at a temperature close to operating conditions in the offshore environment. A load of 12N was applied, corresponding to a mean contact pressure of 300 MPa. This pressure was chosen based on the maximum design stress that the moving parts are expected to encounter during operation. The counter glass disc is coated with a semi-reflective Chromium space layer that enable the use of an optical interferometer to measure the central film thickness in the point contact established between the steel ball and the glass disc. The measurements were obtained at an average entrainment speed of 1000 mm/s. Before running each experiment the test samples were ultrasonically cleaned using isopropanol and dried in an oven to remove any residue in the surface that could interfere with the measurement. The lubricant pot was filled with the fluid to be tested

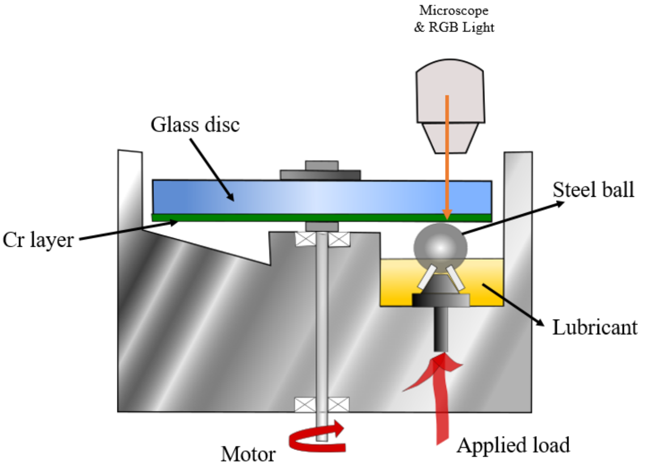

Fig. 1. Schematic representation of the ball on disc test instrument coupled with optical interferometry to perform film thickness measurement.

covering half of the ball in contact with the upper disc, to allow the ball continuously drag lubricant to the contact.

C. Rheological measurements

The rheological properties of the aqueous solutions were investigated using a Discovery Hybrid Rheometer DHR (TA Instruments UK) with a plate on plate geometry [13]. The tip plane diameter was 39.99 mm. The measurements were conducted according to the standard ASTM D445 to facilitate comparison between lubricants at both 20°C and 40°C, maintaining a constant shear rate of 10^2 s^{-1}.

D. Electrochemical measurements

The material used to perform the electrochemical measurements is high carbon chromium steel 52100. The samples were embedded into a resin leaving a exposed surface area of 76 mm^2. The exposed area was polished using abrasive silicon carbide sandpaper P400 - P1200. The samples were ultrasonically cleaned and dried in the oven before starting the electrochemical test. A three-electrode electrochemical cell, as shown in Fig 2, was used to perform the open circuit potential measurements. The potential values were measured against a Ag/AgCl half cell. In this configurations the 52100 steel sample is the working electrode, and platinum was used as the counter electrode. The cell is connected to a computer controlled AutoLab potentiostat/galvanostat (PGSTAT 204) [14], [15]. The open circuit potential (OCP) was recorded during 6 hours after the working electrode was exposed to the lubricant. A laser Microscope OLYMPUS OLS5100 was used to analyse the surface of the working electrode after each measurement.

III. RESULTS AND DISCUSSION

Figure 3 shows the kinematic viscosity plotted versus the bulk polymer concentration in the aqueous solution at a temperature of 40°C for the PAG and

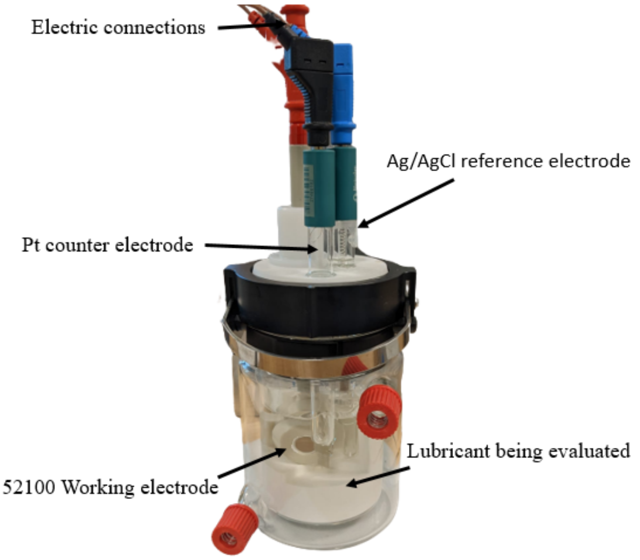

Fig. 2. Three-electrode electrochemical cell configuration employed to measure the open circuit potential (OCP) of the polymer aqueous solutions.

Glycerol mixtures in a concentration ranging from 5 to 50%wt. It can be noticed that as the concentration of the water-soluble polymer increases, the viscosity of mixture increases too, which is an essential property to guarantee the effective protection of the matting surfaces in moving components.

The incorporation of a PAG (polyalkylene glycol) to the mixture has a larger impact on the kinematic viscosity of the mixture compared to the effect of the Glycerol, resulting in a faster and stronger rise in the lubricant viscosity. The PAG polymer offer the possibility to control the lubricant viscosity within the same range as the commercial available lubricant. Thus by varying the concentrations between 15-30% can potentially offer the possibility to design more cost effective lubricants for offshore applications.

On the other hand, as the Glycerol concentration increases, the rise in viscosity becomes less pronounced, which can be attributed to capability of the hydroxil groups in the glycerol molecules to form hydrogen bonds with the surrounding water molecules. In this situation, in order to achieve a comparable viscosity to the one exhibited by a commercial hydraulic fluid, a large concentration that can be up to 50% is required. This contrast between the thickening properties exhibited by both polymers, highlights the importance of understanding the rheological behaviour of polymer water-soluble lubricants and the limitations when formulating hydraulic fluids for offshore applications.

Figure 4 shows the effect of the bulk lubricant concentration on the measured film thickness at a entrainment speed of 1000 mm/s under pure rolling conditions at ambient temperature. The lubricant viscosity is strongly linked to the capability of the fluid to form a separating film between two surfaces in relative motion under load conditions, here a higher viscosity supports a consistent film that can carry the load and prevent the wear generated by the asperities in the contact region. For both polymers the central film thickness

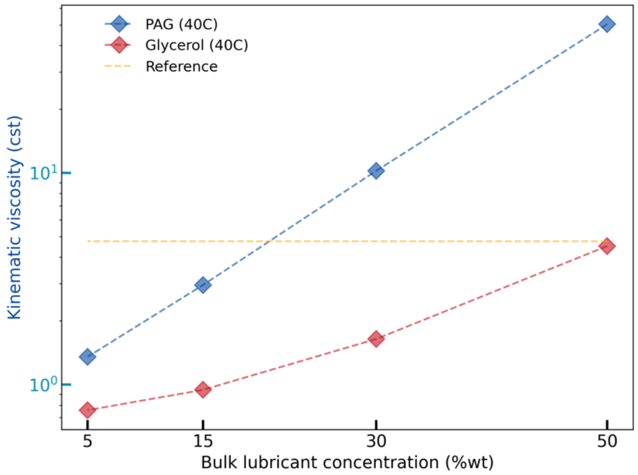

Fig. 3. Kinematic viscosity versus bulk polymer concentration of the aqueous solutions at 40°C. The yellow line is added to indicate the reference viscosity for a commercial hydraulic fluid for comparison

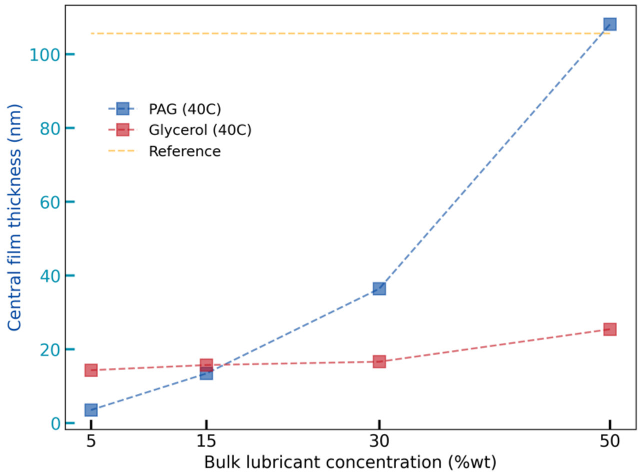

Fig. 4. Lubricant film thickness versus bulk polymer concentration of the aqueous solutions at 40°C, obtained with an applied load of 12N, and an entrainment speed of 1000 mm/s. The yellow line indicates the reference film thickness achieved with a commercial hydraulic fluid for comparison.

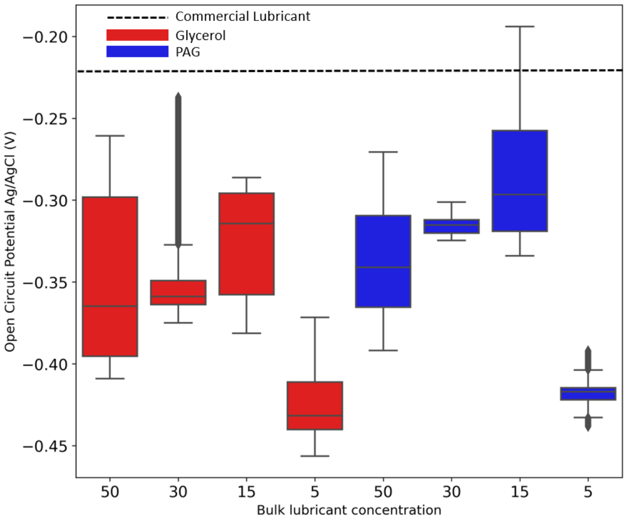

Fig. 5. Open circuit potential (OCP) versus bulk polymer concentration of the aqueous solutions at 23°C. The yellow line indicates the reference OCP achieved with a fully formulated commercial hydraulic fluid for comparison.

in the contact region increases as the concentration in the aqueous solution rises, but the specific rate at which it increases varies depending on the polymer type. Since the rise in viscosity does not correspond in the same proportion with the observed rise in film thickness, other factors such as the interaction between the polymer molecules and the free water in the solution may be responsible for the changes in the film formation and the ability of the lubricant to wet the mating surfaces.

As the concentration of glycerol rise, the corresponding increase in film thickness is less pronounced when compared to PAG, which exhibit a exponential growth. Compared to Glycerol, the PAG allows to obtain a thicker film at high concentrations. It is necessary to add 50% to match the film provided by the commercial hydraulic fluid. Despite that the hydraulic fluid exhibits a significantly lower viscosity compared to a PAG 50 %wt aqueous solution, it matches its film forming capabilities, indicating that there are other factors influencing the film-build up of the water soluble solutions besides viscosity. The same analogy can be established for the Glycerol aqueous solutions that exhibits comparable viscosity, but do not have the same film forming ability. Further experimentation is required to gain understanding on the mechanism and properties that influence film-build up with water soluble polymers, a key aspect towards designing new environmentally friendly and biodegradable lubricants for offshore applications.

Figure 5 shows the impact that the bulk lubricant at different concentrations has on the average open circuit potential (OCP) for the samples immersed in the different formulations during a period of 6 hours. It can be noticed that for both PAG and Glycerol, as the concentration of bulk polymer decreases in the aqueous solution from 50%wt to 15%wt, the average OCP shift to less negative values in the noble direction, indicating that the steel sample is more susceptible to experience corrosion in the concentrated solution, while a lower concentration 15%wt and 30%wt, are more beneficial to prevent material dissolution and possible corrosion reactions that can deteriorate the steel surfaces properties.

However when the concentration falls to 5%wt a drastic decrease towards more negative values in the OCP can be observed for both lubricants. The OCP is useful to understand the thermodynamic stability of the steel sample when exposed to the different polymer aqueous-solutions. When the polymer concentration is 5%wt, the more negative potentials indicates a higher tendency of the metallic atoms on the steel surface to lose electrons, meaning it is more likely to behave as an anode leading to material dissolution, which from the point of view of offshore machinery can be detrimental for the long term reliability of the PTO components.

The more noble potentials can be obtained for Glycerol and PAG at a concentration of 15%wt. At high concentrations, the high availability of molecules at the

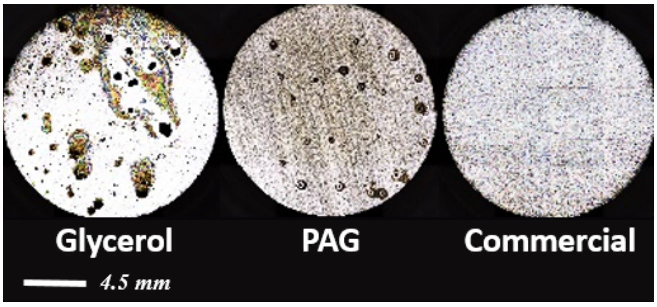

Fig. 6. Optical micro-graphs of the steel samples corroded after being immersed in aqueous solutions: left) Glycerol 15%wt, central) PAG 15%wt and right) fully formulated hydraulic fluid.

interface of the metal can interfere with their adsorption onto the active sites of the surface, thus hindering the protective effect provided by the polymer against the detrimental action of free water molecules in the aqueous solutions.

It seems that a low polymer concentration, the availability of molecules being adsorbed at the surface are not sufficient to avoid the diffusion and accesses of corrosive species to the interfacial area. Variations in the local potential values can result as a consequence of the non-uniform adsorption of the polymer in the interfacial area, resulting in localized corrosion that is known as pitting corrosion, see Fig 6. The formation of deep pits can be linked to the drastic drop in potential registered at 5%wt. It seems that at 15%wt an uniform and continuous protective film on the metal surface can be generated with both polymers which positively translates in a surface less prone to undergoing corrosion.

Figure 6 shows the degradation that the surfaces of the tested steel samples experienced after 6 hours of immersion in the formulations at a concentration of 15%wt. Here it can be confirmed that 15%wt PAG is more effective in protecting the surface compared to glycerol due to the most noble OCP registered. It worth to mention that the different mixtures tested in this study are not fully formulated. This means that they lack additives such as metal passivators, corrosion inhibitors, and detergents, which explains the large difference compare to the fully formulated hydraulic fluid. Therefore, the 15%wt PAG can be further improved, it offers the potential to design hydraulic fluids that effectively inhibit corrosion in offshore applications. In general, PAG can be up to 5 times more expensive than conventional mineral hydraulic fluids. Thereby, using a concentration no higher than 20%wt will allow to keep a competitive price.

While glycerol is commonly found it in the formulation of commercial hydraulic fluids, it seems that PAG represents a better alternative due to several desirable properties in the marine environment, including its ability to create a thicker lubricating film, achieve higher viscosity levels and provide comparable good surface protection against corrosive species, all of this at low concentrations. Overall, it is evident that the selection of a water-soluble lubricant base exclusively on the viscosity behaviour is not enough to guarantee an effective protection of the moving parts in offshore machinery. While viscosity is an important parameter, gaining a multidisciplinary insights regarding the lubricant film build-up properties, as well as their electrochemical behaviour play a important role in design a water-based lubricant. This may help lubricant manufactures to make better decisions regarding the design of lubricants for Wave and tidal energy devices enabling extended equipment lifespan, as well as minimizing down-times due to maintenance activities that can affect the economic viability of projects towards the commercial phase.

IV. CONCLUSION

PAG (polyalkylene glycol) aqueous solutions have shown the ability to create a thicker film, achieve higher viscosity levels, and provide enhanced surface protection against corrosive species at reduced polymer concentrations, offering enhanced performance over glycerol aqueous solutions when used as a lubricant. These characteristics make PAG based lubricants a promising alternative for lubrication in offshore machinery, where corrosion resistance and long-term reliability are essential.

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