Electrostatic and tribological phenomena and their effect on the braking torque in the shaft–oil–lip seal system

Juliusz B Gajewski¹, Marek J Glogowski
Institute of Heat Engineering and Fluid Mechanics, Wrocław University of Technology, Wybrzeże Wyspińskiego 27, 50-370 Wrocław, Poland
Email: juliusz.b.gajewski@pwr.wroc.pl

Abstract. The former research [1] was carried out on the influence of tribocharging in a system: metal rotating shaft–oil–lip seal on its work, especially on changes in the shaft braking torque with the increasing angular shaft velocity and oil temperature. The results obtained suggested that there be a possibility of reducing the braking torque by an external electric field. The compensation for the electric field generated in the system by natural tribocharging was proposed. The reduction in the braking torque seemed possible while applying an external DC electric field to the system. In general, the torque tended to increase with the increasing DC electric field for a variety of the oils and lip seals used and for different shaft angular velocities (rotational speeds) and oil temperatures. The braking torque reduction was achieved only for one lip seal and some different oils, which was and is a promising, expected result. The research results were yet presented elsewhere [1–3] and here some novel attempt has been made to interpret the results obtained in their physical—tribological and especially electrostatic—aspects since there has been a lack of such an interpretation in the literature of the subject.

1. Introduction

Every engine including motorcar engines has some lip seals that are used for sealing the rotating parts and protecting against the leakage of oil out of the engine interior and the penetration of impurities from the outside. During the operation of a rotating shaft–lip seal–oil system intense friction occurs that causes great, irreversible energy losses, an increase in fuel consumption, wear of a lip of lip seals, and finally substantial operating expenses.

Up to now the lip seals have been improved through the modification of a shape of a lip and of the material of which the seal was produced [4, 5]. Moreover, different additives to oils have been selected to reduce the friction between a shaft, an oil film, and a seal [6, 7]. All those steps improved the performance of engines but we will show that the other steps we had taken have also given promising results.

Tribocharging can exert a certain effect on the braking torque [1] especially its increase and regardless of this we hoped there could be some beneficial effect of a DC electric field built up across an oil film between two surfaces of a rotating shaft and a lip seal on the torque reduction. Unfortunately, many experiments performed with the use of different lip seals, shafts, motor and gear oils, and their combinations ended with adverse effects—the braking torque increased even more substantially than without the DC electric field applied. Of some lip seals tested only those experiments with one fluoro-carbon lip seal and many oils proved that there was a real possibility of reducing the braking torque of

¹To whom any correspondence should be addressed.
rotating shafts; the results obtained were surprisingly good and repeatable according to expectations. The braking torque decreased with an increasing DC electric field strength for different rotational speeds or linear velocities of the shaft and oil temperatures [2, 3].

Since most of the experimental results achieved have already been published [e.g. 1–3], the most crucial question was to try to interpret the beneficial effect obtained in the tribological and especially electrostatic aspects. And this is the main subject of this paper as presented below.

2. Experimental system

All the experiments with the different engine oils and lip seals were carried out in the experimental set-up built on the basis of the simplified model of an oil sump (here: an oil chamber) of a real engine.

The schematic diagram (figure 1) shows an experimental set-up which consists of: the housing of an oil chamber (1); a lip seal (2); the stiffening ring of a seal (3); an oil tested (4); an air bearing (5); the sensor of a torquemeter (6); an electric motor (7); a steel shaft (8); a microprocessor-based system for controlling the rotational speed $n$ and for measuring the torque $M$ of the shaft and the temperature $T$ of oil (9); an oil heater (10), and a DC power supply (11). The chamber was filled with the oil tested up to a geometrical axis of the earthed rotating shaft.

The DC power supply energized a stiffening ring of the lip seal to produce a compensating DC electric field of two polarities between this ring and the earthed rotating shaft as shown in figure 2. The external DC electric field was used to compensate for a natural field of the charged oil molecules and oil polar molecules, and to decompose distribution of the oil molecules in the region near the shaft surface in such a way to minimize the braking torque of the rotating shaft.

3. Material and experimental data

The experiments were conducted for different oils and lip seals. Here the results are presented for one oil and one lip seal. Polish motor oil LOTOS 15W40 was tested whose kinematic viscosities were 112.6 and 13.8 mm²·s⁻¹ at 40 and 100°C, respectively. Its viscosity index was 132 and dielectric constant was 2.2. The fluorocarbon lip seal 88 mm in diameter was used whose dielectric constant was 2.2.

The oil temperature was regulated from 70 to 120°C, and the shaft rotational speed was changed between 500 and 3000 rpm. The DC voltage changed from 0 to ±1800 V (discharge limit).

4. Experimental results

4.1. Discussion of the experimental results

The shaft braking torque changes as a function of the DC voltage applied to the shaft–oil–lip seal system are presented in figure 3. The torque variations with the DC voltage producing the DC electric field across the oil film are shown here for steady linear velocities of 2.3 (a) and 9.2 m·s⁻¹ (b), and oil temperatures of 70 (black marks) and 110°C (white marks). Both above linear velocities refer to shaft rotational speeds of 500 and 2000 rpm, respectively. Some of the results obtained are here presented only for the 88 mm in diameter fluorocarbon lip seal and the fresh oil LOTOS 15W40.
The braking torque in the case, when the negative DC voltage $U_{DC}$ was applied to the system, decreased more than 30% at the maximum (figure 3a) within a range of the voltages applied and for a lower oil temperature of 70°C. For the elevated temperature (110°C) the torque reduction is slighter and is around 22%.

For 9.2 m·s$^{-1}$ the consideration yields poorer results which are the 11% torque reduction for 70°C and the 4% increase in the torque for 110°C. The DC voltage was a negative one.

The application of the positive DC voltages to the system resulted in the much less visible torque reduction. The reduction in the torque was generally better for a lower range of the rotational speeds and the negative voltages.

The maximum absolute value of the DC voltage ($\pm 1800$ V) was limited by visible electrostatic discharges during the many laboratory experiments performed. Of course, one can predict that the braking torque could decrease steadily for the higher voltages above the voltage threshold for different oils and lip seals under other conditions.

4.2. Interpretation of the results

The motor and gear oils are made from a mineral or synthetic base stock. Different chemical compounds are added to improve their lubrication, superior performance and longevity, and anti-wear properties, as well as other properties and characteristics. Such additives are, amongst other things, the compounds of polar structure (polar compounds) that are attracted to the metal surface of a rotating shaft by physisorption (van der Waals), chemisorption, and electric (Coulomb) forces to make a contact with the surface. The polar and other charged molecules constitute a rather firm, adhesive layer called a boundary layer.

The boundary layer consists of two–three sublayers of molecules of a total thickness (height) of 0.1–0.5 µm. The molecules are specific chemical compounds (additives) which, strongly “glued” to the shaft surface, must protect any metal surface against dry friction and lubricate it. Also there are
some other oil molecules, which become charged as a result of tribocharging, and electrokinetic phenomena during the relative motion of the shaft, oil and lip seal, and which form the layer.

The polar molecules, ions, and charged molecules located just at the shaft surface and most strongly adsorbed to it form the sublayer of the densest, strongest arrangement—the Helmholtz double layer (the inner layer). The further sublayers (the Gouy-Chapman diffuse layer and subsequent layers) are not that strongly attracted to the shaft closest sublayer. The dense sublayer at the shaft surface makes the oil film at this region denser than in its middle part and hence the oil density is greater near the shaft than elsewhere in the oil film as is the oil viscosity. Such an arrangement of the sublayers can cause the velocity gradient in the oil film to be greater in this case than when the number of polar molecules and other charged molecules and particles is significantly smaller in the shaft zone.

The external DC electric field applied to the system and directed oppositely to the natural field can cause the braking torque to rapidly decrease at the very first moment. At the same time the density and viscosity of oil at the shaft region can dramatically decrease since the polar and charged molecules, ions etc. can be detached by electrostatic forces and additionally repelled by the same polarity ions and molecules. If a lip of the lip seal is made from such chemical components that in contact with oil can have the specific electrochemical features then one could expect that most of the molecules, ions and particles are attracted to the lip surface by additional forces including the zeta potential. The process is stronger and more effective for the negative polarity. It is likely that the potential difference between the oil–lip seal interface and the earthed shaft is greater for the negative polarity than for the positive polarity. This makes additionally the boundary layer at the shaft sparser and sparser according to an increase in the electric field strength. The layer then becomes practically a monomolecular one (monolayer) whose tribological nature and characteristic, especially the viscosity cause the friction and the shaft braking torque to be significantly reduced compared to the conditions without any external DC electric field. One can imagine that almost all or most of the molecules and ions from the further sublayers of the boundary layer migrate towards the oil–lip seal interface.

It is supposed that for both DC voltage polarities the resultant electric field of the two fields between the shaft and lip seal acts similarly though more weakly for the positive voltage applied, namely it always causes the charged molecules and ions—and other charged (e.g. solid) particles, if exist—to migrate towards the interface at the lip seal surface. This could mean that in both cases the shaft potential is lower than the zeta potential at the oil–lip interface and the negative ions, negatively charged molecules, some polar molecules, and particles, if at all, are attracted to this interface. Thus the monolayer is mainly composed of the positively charged molecules whose density/viscosity is lower for the negative DC voltage and the braking torque reduction is more effective.

5. Concluding remark
The results obtained and repeated four times to determine the results repeatability, which was very good, and their thorough analysis show that it is likely that certain lip seals, when in contact with motor and gear oils, “produce” the interface which along with the auxiliary external DC electric field leads to the rotating shaft braking torque reduction. This in turn can reduce the energy losses and fuel consumption, minimize operating expenses, and prolong the lip seals durability. Such an outcome is beneficial, desired, and prospective because of the research results applications to, for example, the automobile industry. Also the future economical and ecological aspects are of vital importance.

6. References
[1] Gajewski JB and Głogowski MJ 2005 J. Electrostat. 63 1049.
[2] Gajewski JB and Głogowski MJ 2007 Tribol. Int., 40 49.
[3] Gajewski JB and Głogowski MJ 2007 Tribol. Int., 40 56.
[4] Bock E and Vogt R 2003 Sealing Technol. 11 6.
[5] Gawliński M 1997 Sealing Technol. 40 8.
[6] Wiehler K and Wollesen V 1999 Sealing Technol. 63 8.
[7] Harvey TJ, Wood RJK, Denuault G and Powrie HEG 2002 J. Electrostat. 55 1.