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How do the temperature, angular velocity and electric fields affect mechanical and electrokinetic phenomena in a friction junction?

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ABSTRACT

In the friction junction, that is in a rotating metal shaft–base oil–rotary lip seal system, dynamic phenomena occur which are of mechanical and electrical nature. During the shaft's rotation the components of an oil film – a gap between the surfaces of a shaft and a lip of a rotary lip seal – are caused to move about within the film under the action of a centrifugal force. The relative movement of different particles and molecules in turn brings about tribocharging and results in establishing an electric field within the gap. The field and so acting the *Coulomb* force also affect the distribution of charged species as does the *van der Waals* attractive force. To analyze the effect of the above factors as well as the temperature of oil in the gap measurements of the shaft's braking torque and the voltage between the rotating metal shaft and a stiffening ring of a lip seal for different ranges of the base oil's temperatures and of the shaft's angular velocities are performed. In the experiments the synthetic PAG (polyalkylene glycol) and PAO (polyalphaolefin) base oils and a fluorocarbon rotary lip seal are used.

1. Introduction

The paper deals with the dynamic phenomena that occur in the friction junction, that is in a rotating metal shaft–base oil–rotary lip seal system. The system is an interfacial one and consists of two interfaces: shaft–oil film and oil film–lip seal. When a shaft rotates intense tribocharging occurs and an electric field forms that generates the flow of charge within an oil film between two electrical double layers at both surfaces of a shaft and a lip of a rotary lip seal.

Here the oil means a base one. A base oil is a selected mineral, semisynthetic or synthetic material into which different additives are blended to obtain a finished lubricant, for example a fully formulated motor oil as used in cars or machines in which there are moving components of an internal combustion engine.

The pure base oils are electrorheological fluids which are a certain colloidal suspension of finely divided particles in a carrier liquid which is an electrically insulating fluid. Rheological properties are changed through an increase in resistance when an electric field is applied. According to the chemistry of a base stock they can be polar or non-polar chemical compounds. Polyalkylene glycols (PAGs) are polar oils while polyalphaolefins (PAOs) oils exhibit a low level of polarity and can be treated as non-polar ones. From the electrical point of view both oils are semiconducting and insulating, respectively, according to their resistivity.

The fully formulated engine oils containing many different additives to improve lubrication properties and to protect surfaces being in motion and mutual contact against wear have certain features of colloidal solutions. They have a number of different species: ‘natural’ ions and polar molecules, micelles and reverse micelles (electrically charged colloidal particles – aggregates of molecules in the base oil's solution), charged solid particles and so forth. All these components of motor oils take part in the process of tribocharging during a relative motion of parts (the surfaces of a shaft and a lip) and of oil film's layers of the interfacial system considered.

At short distances between both surfaces, that is in an oil film, an electric field is rather strong and established by the charges of different species also including the charged surface of a lip. The charged species can be separated by the centrifugal force when the shaft rotates and by the *Coulomb* force. Also the *van der Waals* attractive force and the electric double layer (EDL) repelling force should be taken into account while analyzing and interpreting the phenomena of separation and aggregation of many different charged and uncharged species in the friction junction's oil film.

To protect such an engine against the leakage of oil and to exclude contamination from the outside, amongst other things, rotary lip seals are widely used. Their lips play an important role in the whole process analyzed. The lip's material is ordinarily fluorocarbon but silicon is sometimes also used in laboratory experiments. Fluorocarbon lips have semiconducting properties.

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During the research one measures the braking torque and the voltage – the potential difference between the grounded rotating metal shaft and a stiffening ring of a lip seal for different ranges of the base oil's temperature and of the shaft's angular velocities. The relationships of both quantities to the temperature and angular velocity are examined. It is of interest that within a narrow range of the oil's temperature a local change in the braking torque occurs and is observed as a local extremum (minimum) while the voltage changes its sign from negative to positive in the same temperature interval. Both phenomena are observed for quite a wide range of the shaft's angular velocities. These phenomena can be explained in terms of certain reversal of charge that can be caused, as is supposed, by the large and favorable specific adsorption potential which affects adsorption of counterions that in turn goes on until the *Stern* layer charge compensates for the shaft's surface charge [1,2].

If the movement of the oil's charged particles towards both interfaces occurs it is interesting whether or not an internal 'natural' electric field so established could enhance this process and, if so, under what conditions? As supposed, such a field exerts influence on both electric double layers under specific conditions which in turn can cause the concentration of charges (coions and counterions) especially at the shaft's surface to increase. The local electric field established is rather so strong that it can cause a considerable increase in apparent viscosity. As a result of this process the friction increases and so does the braking torque of a shaft.

This paper is an attempt to answer this question about the effect of an internal electric field on the mechanical and electrokinetic phenomena in the interfacial system, all the more so as after the literature studies had been carried out it was found that there was a lack of any information on the charging of the system: shaft–oil film–seal and its relationship with the braking torque of rotating shafts and other machine parts. The process of charge exchange at the interfaces of the system is a complex problem and difficult to explain properly and clearly because little is known about the electrochemical processes occurring in such or similar systems [3].

2. Measuring system, measurement method, and materials

2.1. Measuring system and measurement method

Experiments on the dynamic natural charging (tribocharging) of different engine oils for different rotary lip seals are performed in an experimental set-up, as shown in Fig. 1, built on the basis of a model engine's oil sump.

The set-up consists of: the housing of an oil chamber (1); a seal's stiffening metal ring (2); the lip seal tested (3); an insulator (4); the oil tested (5); two angular contact bearings (6); the non-contact tensometric sensor of a torquemeter (7); an electric motor (8); a steel shaft (9) grounded through carbon brushes; a microprocessor-based system for controlling the angular velocity and for measuring the braking torque of the shaft and the temperature of oil (10); a standard capacitor (11); an electrometer (12); an oil heater (13), and a thermocouple for measuring the oils' temperature (14). The chamber is filled with the oil tested up to a geometrical axis of the rotating shaft. The whole chamber is a simplified model of the part (oil sump or crankcase) of a real car engine.

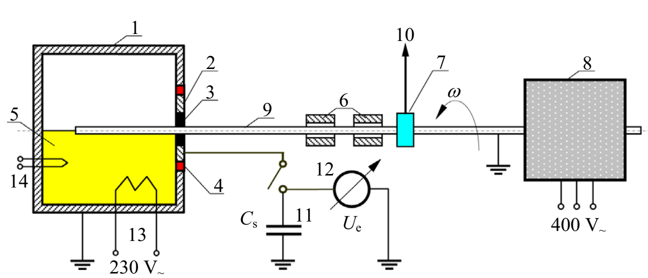

Fig. 1. The experimental set-up for measuring the braking torque and voltage.

The braking torque M is measured with a torquemeter, which also measures continuously the shaft's angular velocity n, and is connected with its sensor mounted on an grounded rotating metal shaft. The torque's sensor is a non-contact and tensometric one.

The torquemeter is incorporated into a separate part of the whole measuring system which in turn enables one to measure the braking torque and the shaft's angular velocity as well as to measure, control and regulate the temperature of the oils tested in an oil chamber. The shaft's angular velocity is precisely and continuously regulated with an inverter.

The voltage U_e established between the seal's stiffening ring being located in the inside of the lip seal and the grounded metal shaft is measured with an Keithley 6517 A electrometer. Formally, the voltage measured is the ring's potential and is a certain measure of an internal electric field and of a tribocharging level because only some lines of force terminate on the metal ring being rather a narrow and small device compared to other nearby metal and grounded objects.

The internal electric field exists naturally between the shaft and the lip seal in the oil film as caused by a tribocharging process. The rotary lip seal is mounted in its isolated seating in the chamber's housing (is electrically isolated from the oil chamber) while the electrometer's high potential input (HI) is connected directly to the lip seal's stiffening ring.

The standard capacitor C_s is connected in parallel to the electrometer's input to filter out higher frequencies from any useful signals' fluctuations as produced by the shaft's rotations and the relative motion of layers in the oil film. The standard capacitor and the electrometer constitute a simple measuring system being an 'electrical' part of the whole measuring system.

The oil chamber is filled with the oils tested up to the shaft's geometrical axis as are original crankcases in internal combustion engines of cars.

2.2. Materials used

The experiments are carried out for the following base oils: synthetic PAO 6 produced by NESTE OIL N.V., Beringen, Belgium and ROKOPOL® D1002 (PAG) produced by PCC ROKITA, Brzeg Dolny, Poland. A specification of the oils tested is shown in Table 1.

The steel shaft roughness is 0.32 mm. An 88-mm diameter fluorocarbon lip seal is used in all the tests performed.

3. Experimental results and discussion

Figs. 2–7 present some trends in changes of the braking torque M and the voltage U_e as a function of the temperature of the oils tested

Table 1
Specification of the base oils tested.

Quantity and unit	PAG	PAO
Kinematic viscosity		
at 40 °C	56.4	30.2
at 100 °C, [mm^2 s^{-1}]	10.5	5.8
Viscosity index[–]	176	138
Density at 15 °C[kg m^{-3}]	990 at 20 °C	825
Resistivity		
at 40 °C	1.3×10^7	2.6×10^{11}
at 100 °C[Ω m]	3.5×10^6	6.4×10^{10}
Relative permittivity		
at 40 °C	5.8	1.9
at 100 °C [–]	5.1	1.9