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## POTENTIAL FOR EXPANDING THE RANGE OF FLUID FRICTION WHILE MINIMISING FRICTION RESISTANCES AND IMPROVING AN OIL FILM'S LOAD BEARING CAPACITY

### MOŻLIWOŚCI ROZSZERZENIA ZAKRESU TARCIA PŁYNNEGO Z MINIMALIZACJĄ OPORÓW TARCIA I PODNIESIENIEM NOŚNOŚCI FILMU OLEJOWEGO

**Key words:**

fluid friction, boundary layer, parameters of friction, triboelectrical phenomena.

**Abstract:**

Traces of mechanical wear appear on co-working surfaces in the operation of precision fluid bearings. This should not be the case, since fluid friction and uninterrupted oil film should be present in a friction pair, which is a concept that this paper attempts to outline. The way friction forces, resistance, and oil film vary as unit pressure rises linearly is discussed. Three stages of the variations are distinguished. At the first stage, the oil film thickness and force of friction remain steady while the resistance declines. Stage two is temporary: Triboelectrical phenomena already escalate considerably and begin to decide effects of the friction process while a lubricant loses rheological properties of the Newtonian fluid. Hydrodynamic friction continues at the third stage, yet the triboelectrical effects are decided by stabilised triboelectrical phenomena. The third range can be identified as boundary friction where the layer separating surfaces is thicker than in the area of Newtonian rheology. This is very good in respect to wear, but higher-energy (not electrically neutral) particles cause increases in friction resistances. This range seems to exhibit a very high potential for being controlled with an adequate selection of oil based additions.

**Słowa kluczowe:**

tarcie płynne, warstwa graniczna, warunki tarcia, zjawiska triboelektryczne.

**Streszczenie:**

W trakcie eksploatacji precyzyjnych łożysk ślizgowych na współpracujących powierzchniach pojawiają się ślady zużycia mechanicznego. Zjawisko takie nie powinno mieć miejsca, gdyż w węzle ciernym powinno występować tarcie płynne z nieprzerwanym filmem olejowym. W publikacji przedstawiono, w jaki sposób zmieniają się wartości siły tarcia, rezystancji oraz filmu olejowego wraz z liniowym wzrostem nacisku jednostkowego. Wyodrębniono trzy etapy zachodzących zmian. W pierwszym etapie zaobserwowano utrzymywanie się na zbliżonym poziomie grubości filmu olejowego i siły tarcia, przy jednoczesnym zmniejszaniu się wartości rezystancji. Etap II jest etapem przejściowym, w którym znacząco narastają już zjawiska triboelektryczne i one zaczynają decydować o efektach procesu tarcia, a środek smarowy traci właściwości reologiczne cieczy newtonowskiej. W etapie III nadal występuje tarcie hydrodynamiczne, ale o efektach tarcia decydują ustabilizowane zjawiska triboelektryczne. Wobec powyższego zakres trzeci możemy identyfikować jako tarcie graniczne, w którym warstwa rozdzielająca powierzchnie jest grubsza niż w obszarze reologii newtonowskiej. Jest to bardzo korzystne z punktu widzenia zużycia, ale cząsteczki o wyższej energii (nieobjętne elektrycznie) powodują zwiększenie oporów tarcia. Wydaje się, że ten zakres posiada bardzo duże potencjalne możliwości sterowania nim poprzez odpowiedni dobór dodatków do bazy olejowej.

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## INTRODUCTION

Traces of mechanical wear appear on co-working surfaces in the operation of precision fluid bearings. This should not be the case, since fluid friction and uninterrupted oil film should be present in a friction pair. The problem can be explicated by attempting the hypothesis that the film is disrupted after co-working elements have travelled a certain distance in specified conditions, i.e. friction pair temperature and relative velocity of co-working elements. A number of authors point out that the film interruption is connected to the length of friction surface in a friction pair [L. 3].

As the distance a frictional surface travels in relation to the other surface increases, heat is released in the friction area [L. 8]. Some of the heat is discharged by the surfaces in friction and the remaining heat is accumulated in the oil film. The rates of the thermal energy discharge and temperature increment in the lubricant layer are issues of paramount importance to processes in the friction area, in turn, reducing the viscosity of a substance. For the parameters of friction and pressure in the friction pair to be optimum, the viscosity alteration should be accompanied by a changing width of the gap between the solids between which the process of friction takes place. As surfaces of friction pairs are unable to adapt

to these varying temperature conditions (designs of plain bearings are rigid), we no longer have control over the behaviour of the oil film. A solution (though not ideal) is to determine a length of the friction surface that will prevent temperature growth caused by heat accumulation

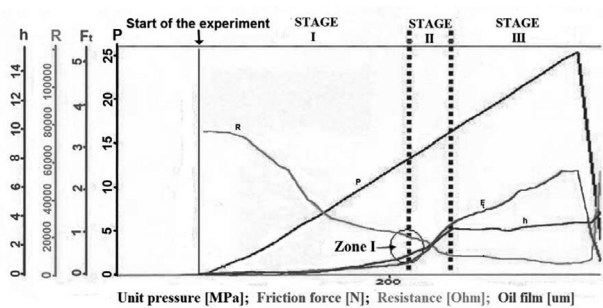


Fig. 1. Sample testing of a model lubricant (paraffin oil without additives) with a linearly increasing unit pressure  $P$ , constant relative velocity  $1 \text{ m/s}$ , and set pair temperature of  $293 \text{ K}$  and length of friction surface  $1 \text{ mm}$  [L. 5]

Rys. 1. Przykładowe badania wykonane dla modelowego środka smarowego (oleju parafinowego bez dodatków) przy liniowo narastającym nacisku jednostkowym  $P$ , stałej prędkości względnej  $1 \text{ m/s}$  i ustalonej temperaturze węzła  $293 \text{ K}$  oraz długości powierzchni tarczej  $1 \text{ mm}$  [L. 5]

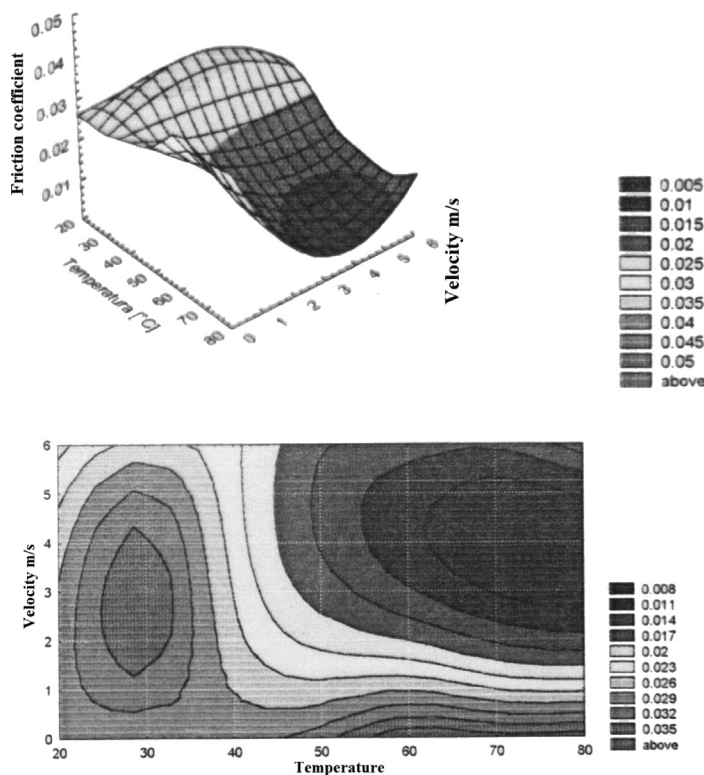


Fig. 2. Friction coefficient as a function of friction pair temperature and sliding velocity at linearly increasing unit pressures [L. 4]

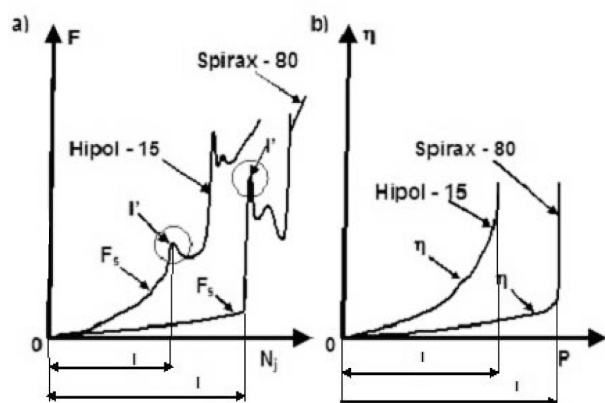
Rys. 2. Współczynnik tarcia w funkcji temperatury węzła tarcia i prędkości ślizgania przy liniowo narastających naciskach jednostkowych [L. 4]

in the layer separating the two friction surfaces from reaching values at which the load bearing capacity of the film declines substantially. This is the first condition of maintaining a continuous, uninterrupted oil film.

The second condition is the choice of a lubricant that will minimise motion resistances, including that in boundary friction.

A great potential emerges, therefore, for applying new additives based on organic compounds, liquid crystals, ionic liquids, and other compounds whose chemical structure will display low friction resistances in these conditions.

The proposition that the range of fluid friction can be extended due to unit load bearing capacity of the oil film while reducing resistances is substantiated by the results illustrated in **Fig. 1**, where the diagram, produced as part of a tribological experiment, shows just such friction resistance variations while the film oil's thickness is transformed by an increasing load of the friction pair.



**Fig. 3. Illustration of viscosity variations as a function of pressure in two oils and reflection of this fact in the range of hydrodynamic friction [L. 2]; a:  $F_s$  – friction force,  $N_j$  – unit pressure,  $I$  – range of hydrodynamic friction,  $I'$  – start of escalating triboelectric phenomena and end of friction force increase dependent on rheological properties of the Newtonian liquid; b:  $\eta$  – viscosity coefficient as a function of pressure,  $P$  – pressure (ranging from 0 to 2000 MPa),  $I$  – range of viscosity rising as a function of pressure, with the range's end being the start of lubricant vitrification.**

Rys. 3. Ilustracja charakteru zmian lepkości w funkcji ciśnienia dwóch olejów i odzwierciedlenie tego faktu w zakresie tarcia hydrodynamicznego [L. 2]: a:  $F_s$  – siła tarcia,  $N_j$  – nacisk jednostkowy,  $I$  – zakres tarcia hydrodynamicznego,  $I'$  – początek narastania zjawisk triboelektrycznych i koniec zakresu narastania siły tarcia zależnej od właściwości reologicznych cieczy newtonowskiej; b:  $\eta$  – współczynnik lepkości w funkcji ciśnienia,  $P$  – ciśnienie (w zakresie od 0 do 2000 MPa),  $I$  – zakres narastania lepkości w funkcji ciśnienia, a koniec zakresu jest początkiem zeszklenia substancji smarowej.

The results are divided into three stages (I, II and III) in order to identify an area of hydrodynamic friction (Range I), the range of transition from the hydrodynamic to boundary friction (Range II), and the area of a boundary layer where the layer's unit load bearing capacity rises dramatically (Range III), where the range of boundary fluid friction expands, the thickness of the oil film “ $h$ ” increases, although friction resistances “ $F$ ” undergo adverse increases.

**Figure 2** illustrates a method of defining the range of minimum friction resistances for hydrodynamic friction, or Range I in **Fig. 1**, without optimising the length of friction path (for the length of friction path equal to 1mm).

**Figure 2** shows the way the friction coefficient varies in a model friction pair lubricated with an oil base containing organic additions as sliding velocity and temperatures change. For the sake of comparison with real lubricants, diagrams of friction forces as a function of linearly rising unit pressures are given for commercial oils Spirax-80 and Hipol-15, which illustrate the fact that, in the range of hydrodynamic friction (Range I), friction force increases in a manner very similar to increases in congealing force (viscosity) as a function of pressure in testing by means of a high-pressure viscometer. Force variations beyond Range I could indicate a transition from hydrodynamic fluid friction to boundary friction. It should also be pointed out that the range of transition to the boundary friction is dependent on oil type (base and additions), which is reaffirmed by experiments depicted in **Fig. 3**.

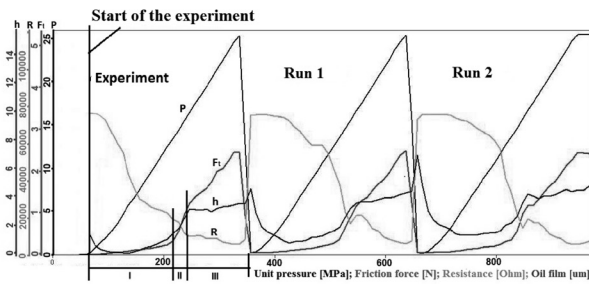
## MODEL TESTING

A tribometer patented in Poland, the US, and Germany was used in the testing [L. 9, 10, 11], while the testing procedure is detailed in the doctoral dissertations [L. 7, 12], with [L. 7] presenting an additional channel of oil film thickness measurement. The methods of testing and sample shapes are described in detail in those publications. A block diagram of the test stand and the particular measurement channels are presented as well.

Each test was repeated a minimum of six times, with only three runs described in this paper not to blur the overall picture, especially as the results clearly show good reproducibility.

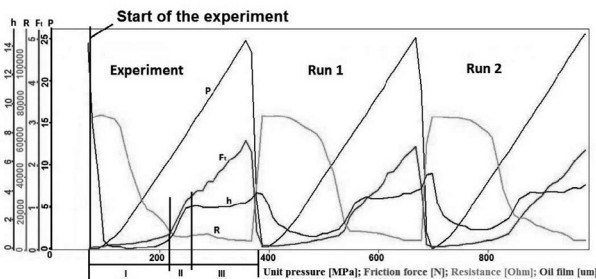
Experiments using both pure paraffin oil and additions were repeated a minimum of six times. Paraffin oil serves as the basic lubricant. 1% mass of stearic acid and stearyl alcohol were used as additives.

Three runs of each option are displayed in **Figures 4a, 4b, and 4c**. **Figure 4a** shows the experiment in the environment containing paraffin oil and stearic acid additions. **Figure 4b** shows the experiment in the environment containing paraffin oil and stearyl alcohol additions. **Figure 4c** shows the experiment in the environment of only pure paraffin oil.



**Fig. 4a.** Variations of friction force  $F_t$ , friction zone resistance  $R$ , and oil film thickness  $h$  under the influence of linear unit pressure  $p$  variations at a constant sliding velocity  $v = 1$  m/s and temperature  $T = 313$  K for a friction pair lubricated with the model oil containing a stearic acid addition

Rys. 4a. Przebiegi zmian siły tarcia  $F_t$ , rezystancji strefy tarcia  $R$  oraz grubości filmu olejowego  $h$  pod wpływem liniowej zmiany nacisku jednostkowego  $p$  przy stałej prędkości ślizgania  $v = 1$  m/s w temperaturze  $T = 313$  K dla węzła tarcia smarowanego olejem modelowym z dodatkiem kwasu stearynowego

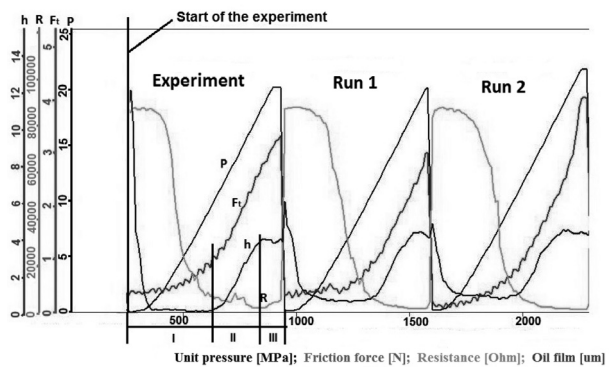


**Fig. 4b.** Variations of friction force  $F_t$ , friction zone resistance  $R$ , and oil film thickness  $h$  under the influence of linear unit pressure  $p$  variations at a constant sliding velocity  $v = 1$  m/s and temperature  $T = 313$  K for a friction pair lubricated with the model oil containing a stearyl alcohol addition

Rys. 4b. Przebiegi zmian siły tarcia  $F_t$ , rezystancji strefy tarcia  $R$  oraz grubości filmu olejowego  $h$  pod wpływem liniowej zmiany nacisku jednostkowego  $p$  przy stałej prędkości ślizgania  $v = 1$  m/s w temperaturze  $T = 313$  K dla węzła tarcia smarowanego olejem modelowym z dodatkiem alkoholu sterylowego

This tribological experimentation using the additives implies that the measured quantities ( $R$ ,  $h$ , and  $F_t$ ) are different in that the base oil additions cause visibly sharper transitions from hydrodynamic to boundary friction. Hence, the conclusion that the full range of fluid friction can be controlled by means of additives.

Friction force and resistance exhibit maximum variations after the additions. Once surfactants are added to paraffin oil, friction force is reduced by approx. 25–30% compared to the force for paraffin oil in the case of hydrodynamic friction. Maximum oil film thickness remains unchanged compared with the results for the paraffin oil sample. Once the additives are present in the friction zone, the minimum thickness of the emerging boundary layer then increases a little. The nature of friction force, resistance, and oil film thickness variations



**Fig. 4c.** Variations of friction force  $F_t$ , friction zone resistance  $R$ , and oil film thickness  $h$  under the influence of linear unit pressure  $p$  variations at a constant sliding velocity  $v = 1$  m/s and temperature  $T = 313$  K for a friction pair lubricated with the model oil

**Nomenclature:**  $h$  – oil film thickness [ $\mu\text{m}$ ],  $R$  – friction zone resistance [ $\Omega$ ],  $F_t$  – friction force [ $\text{N}$ ],  $P$  – unit pressure [ $\text{MPa}$ ]

Rys. 4c. Przebiegi zmian siły tarcia, rezystancji strefy tarcia oraz grubości filmu olejowego pod wpływem liniowej zmiany nacisku jednostkowego przy stałej prędkości ślizgania  $v = 1$  m/s w temperaturze  $T = 313$  K dla węzła tarcia smarowanego olejem modelowym. Oznaczenia dotyczące rysunków:  $h$  – grubość filmu olejowego [ $\mu\text{m}$ ],  $R$  – rezystancja w strefie tarcia [ $\Omega$ ],  $F_t$  – siła tarcia [ $\text{N}$ ],  $P$  – nacisk jednostkowy [ $\text{MPa}$ ]

driven by externally applied tribological testing involving chemical additives is evidence of triboelectric phenomena in the friction zone as well. The dramatic decline of resistance and rapid growth of the lubricant layer thickness in the friction zone is proof, e.g., in the friction pair lubricated with (model) paraffin oil, intense triboelectric phenomena begin. The process commences in conditions of  $P$ ,  $v$ ,  $T$  similar to those applied to friction in lubrication free from chemical additives. Less intense triboelectric processes in the experimentation conducted in the presence of stearic acid and 1-octadecanol (stearyl alcohol) is the only apparent difference. This is demonstrated by a resistance in the friction zone under maximum loading that is greater than in the experiments using the base oil. This may be caused by additives in the friction pair which bind with friction surfaces and weaken triboelectric processes (they are better insulating coatings).

The testing proves some triboelectric processes take place in the friction zone. Emissions of electric charges are their symptoms. They become more intense as increasingly greater loads are applied to the friction pair, the electric resistance drops dramatically, and the oil film thickness increases rapidly.

In addition, the rising sliding velocity of friction elements delays triboelectric processes, since the dramatic decline of resistance is delayed over time as the velocity increases. What is more, the growth of



velocity causes the strengthening and thickening of boundary layers. On the other hand, effects of friction pair temperature variations within the 40°C range have a virtually negligible impact on triboelectric processes.

Variations of unit pressure applied by means of counter specimens to a rotating sample had a maximum effect on the intensity of triboelectric phenomena. Intense triboelectric processes in the friction pair commenced in the unit pressure range 5–10 MPa and were also dependent on the remaining quantities applied ( $v$  and  $T$ ). As the loading escalated, the intensity of the processes rose.

A boundary of intense triboelectric phenomena in the modelled friction pair can be determined; however, it will be ‘fluid’ and dependent on quantities of  $P$ ,  $V$ ,  $T$ . [L. 7]

Areas of the Ranges I, II, and III are also marked in **Figures 4a, 4b, and 4c** in the same parameters of friction for pure paraffin oil and paraffin oil with the additions (stearyl alcohol and stearic acid). The transition from fluid hydrodynamic friction (Range I) to temporary fluid boundary friction (Range II) and on to the range where triboelectric processes intensely escalate, causing the oil film thickness to grow and resistance to reduce (Range III), is the type of fluid boundary friction we identify. This testing is based on a constant length of the sample in friction, 1 mm.

## CONCLUSIONS

The way friction force, resistance, and oil film vary as the unit pressure rises is discussed in this paper. Three stages of the variations are distinguished. At the first stage, the oil film thickness and friction force remain steady while resistance declines. Friction effects in this area are decided by rheological phenomena proper to Newtonian liquids. Stage II is transitional: Triboelectric phenomena escalate significantly and begin to decide effects of the friction process, while the lubricant loses rheological properties of a Newtonian liquid. Friction force and the thickness of the oil film increase, while resistance continues to diminish. Hydrodynamic friction continues at the third stage, but friction effects are decided by stabilised triboelectric phenomena. Although unit pressures continue rising linearly, the thickness of the oil film layer (within a certain range of values) and resistance stabilize, but the friction force continues to rise. This implies that motion resistances between elements in friction increase as uncontrolled triboelectric phenomena emerge in the friction area.

$\mu$  increases as a function of pressure  $P$  is of the same nature as growth of friction force  $F$  as a function of unit pressures  $N_j$ . This implies fluid hydrodynamic friction is dependent on rheological properties of a lubricant. Friction resistances in the hydrodynamic friction zone are dependent on rheological properties, that is, on

a lubricant. Increasing pressure reaches values at which a lubricant liquid is ‘vitrified’. Therefore, continued viscosity testing makes no sense.

**Figure 3** shows friction forces are lower when Hipol-15 is applied as lubricant than when Spirax-80 is used. This relates to the fact a faster growth of friction resistances causes the heat release to rise faster.

Triboelectric phenomena arise in the point designated as **I’** in **Fig. 3**, because the transformation of Newtonian into non-Newtonian liquid structures is associated with formation of polar (electrified) particles that interact and in effect produce other friction resistance, but these coagulation resistances are dependent on the friction zone temperature. The range of fluid friction (strength of the hydrodynamic layer) is dependent on the rheological properties of a lubricating fluid.

As the sample diagram (**Fig. 3**) is analysed in relation to friction force variations for a linearly rising unit pressure at a constant temperature 20°C and set relative sliding velocity (rotating sample – counterspecimen)  $V = 1$  m/s, recorded friction zone resistance and changes of oil film thickness for pure paraffin oil, more ranges can be distinguished that characterise the following friction types:

- Range I is associated with rheological properties of a lubricant (pure paraffin oil). This agrees with the range of hydrodynamic friction discussed in connection with **Figure 1**.
- Range II is associated with emergence of electrically non-neutral particles like ions, ion radicals, electrified radicals, and polarised particles and unbroken chains of lubricant. This is a range of dynamic and non-stabilised variations under increasing loads of the friction zone.
- Range III is associated with stabilisation of parameters of friction and presence of electrified and ionised lubricant particles. The friction zone resistance declines dramatically from the very start of this range, which should characterise metallic contacts of surfaces in friction, although this is not the case, as the recorded thickness separating the surfaces in friction begins to increase. This is evidence of a changing lubricant structure, which shifts from a Newtonian liquid to a current conducting liquid. The shift is not abrupt, although the transformations commence as early as in the second range. The third range can be identified, therefore, as boundary friction where the layer separating the surfaces is thicker than in the area of Newtonian rheology. This is very good for wear, although particles of greater energy (not electrically neutral) cause friction resistances to increase. This range seems to offer very high potential for control with an appropriate choice of oil base additives. These additives can include the following: liquid crystals, ion liquids, or other polar compounds used as lubricant additives yet not tested for reducing friction in this range.

An extensive research programme emerges from the foregoing discussion. A variety of lubricants would need to be tested in variable conditions and an attempt should be undertaken to explain how a ready (set) lubricant structure affects friction resistances in this range in order to reduce these resistances. Diverse compounds (including liquid crystals and ion liquids) would need to be addressed as part of preparations and

only then can the most interesting substances be selected and tested on varying lengths of friction surfaces to attain not only minimum friction resistances but also maximum load bearing capacity of the oil film, thereby passing to the tribological practice of typical operational conditions and producing friction pairs of minimum friction resistances, high load bearing capacity, and 'wear-free' operation.

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