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METHOD OF EVALUATION OF LUBRICATING ABILITY OF LUBE OILS, DIESEL OILS AND HEAVY FUEL OILS IN ENERGETISTIC FORMULATION

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Abstract

The paper presents an interpretation of operation of a boundary layer of a lubricating medium. A model of the homogeneous Poisson process has been proposed to assess the deterioration process of the layer's operation. The assessment considers the original interpretation of operation of a boundary layer, as a lubricity measure of a boundary layer of any lubricant. In the submitted proposal the operation of a boundary layer is understood as a transfer of energy E_p, resulting from tribological system load at a given time t, in the form of work L_p which may lead to a breakdown of this layer. The operation is equated to a physical quantity with the unit of measure which is joule-second. Hereby, it has been shown that for this interpretation the operation may be determined not only by a number with the unit of measure [Js], but also in the form of an area of operation presented in a graph made on the "L_p-t" system, where: $L_p(t)$ – work needed to break a boundary layer of a lubricating medium at time t, t – time of operation of the lubricant boundary layer. The paper also demonstrates usefulness of such understood operation of a lubricant boundary layer for assessment of the lubricity of this layer. The usefulness consists in that the layer operation can be defined as the required operation and possible operation. If the possible operation of a lubricant boundary layer is larger than the required, this medium can be used for lubrication of tribological systems. Otherwise, each tribological system undergoes wear.

***Keywords**: operation, lubricating oil, fuel, stochastic process, lubricity*

1. Introduction

Lubricity, like viscosity, is one of the most important properties of lubricating mediums. In shipbuilding such substances include lubricating oils and fuels. Lubricating oils are used, among others, for lubrication of tribological systems like main bearings and crank bearings, pistons with rings mating with the cylinder liners, and in case of crosshead engines – crossheads mating with the crosshead bearings. Whereas, fuels enable lubrication of precision pairs like pistons and cylinder liners in fuel injection pumps, and injector needles and guides. Therefore, the systematic study of lubricity of marine lubricants should not only refer to lubricating oils, but also fuels. Lubrication is required by all tribological systems, not only just these that have been mentioned. It is essential since it allows to reduce both the wear of tribological systems and the energy losses due to friction.

As the lubricity of oils and the lubricity of fuels applied in shipbuilding are equally important in further considerations the terms *lubricating oil* and *fuel* are replaced by the term *lubricating* *medium* which can be both a lubricating oil or fuel.

In tribology there are different types of friction [6, 19]. The most important in engineering is the division of friction into: dry (or more precisely technically dry) friction, boundary friction and fluid friction. Lubricity is especially important for boundary friction. For this friction, lubrication of the mating surfaces of any tribological system is provided by a boundary layer (boundary film). The boundary layer is thin (about 0.5 μm) and is preserved in consequence of the interaction between *the lubricating medium* and the mating surfaces lubricated by the medium. Such a thin layer of *the lubricating medium* is formed as a result of high unit tensions between the mating surfaces in the tribological system and the too low speed of their relative motion. Formation of such a layer and prevention against its breakdown and thus against occurrence of dry friction, is possible when adequate lubricity is provided. For this reason, lubricity is interpreted the most often as the ability of *the lubricant* particles to adhere to the lubricated surfaces, by which production of a stable layer on these areas, enabling their separation, is possible.

2. Interpretation of lubricity and possibilities for its determination

Contemporary views on lubricity of lubricating mediums (oils, fuels) are significantly different [1, 2, 6, 7, 8, 10, 11].

An extensive analysis of the views of different authors on the lubricity, which shows a considerable variety, is presented in the paper [15]. The results of this analysis and of lubricity tests of lubricating mediums led to formulation of the following definition of lubricity: *lubricity is a property of a lubricating medium that characterizes its behavior under conditions of boundary friction*. It determines the ability to produce on solid surfaces (substrates) a stable boundary layer as a result of adsorption (surface sorption) and more precisely: physisorption (physical adsorption) and chemisorption (chemical adsorption) [8]. This means that the lubricity depends not only on the structure of a *lubricating medium*, but also on the properties of the lubricated mating surfaces of the given tribological system. However, it is the property of a lubricant prepared to interact with the rubbing surfaces through interaction resulting from the existence of cohesive forces (different types of intermolecular bonds and intermolecular attractions) in the tribological system.

Taking into account considerations concerning the operation of machines, eg. diesel engines [5, 6, 7], *lubricity* can be defined *as a property of a lubricating medium (and thus of the tribological system) ensuring its correct operation (D) under conditions of boundary friction*. Lubricity characterizes preparation of the substance to form a stable boundary layer as a result of adsorption (physisorption and chemisorption) on solid surfaces. It is obvious that chemisorption increases the lubricity of a lubricating medium. This follows from the fact that the adsorption (surface sorption) is the process of forming surface bonds between the lubricant particles and the particles of the lubricated solid surfaces, while physisorption is caused by the action of intermolecular attractive forces, and chemisorption is a result of forming chemical bonds between the lubricant particles and the particles of the lubricated solid surface [8, 20]. For the applied substances the coefficient of friction may be different, i.e. smaller in case of occurrence of physisorption on the lubricated surfaces, or higher – in case of chemisorption on these surfaces.

The measurement of lubricity is durability of the boundary layer, understood as durability of the existing connection (bond) of a lubricating medium with the substrate (solid surface). The durability can be determined [8]:

- at time of forming the boundary layer, as a result of investigation of the accompanying effects, eg. by measurement of the thermal energy (heat) of sorption; or
- at time of destroying the layer, eg. by measurement of the quantity of energy needed to break the layer.

Durability of the boundary layer can also be determined indirectly through studying the phenomena associated with lubricity such as wear, scuffing (eg. susceptibility to scuffing, what is important in diagnostic tests), or adsorption, thus physisorption and chemisorption (eg. substance susceptibility to adsorption), etc. Lubricity assessed as the lubricant susceptibility to adsorption can be investigated in static as well as dynamic conditions [8].

From the presented definitions and considerations follows that the energy consumption to overcome the friction resistance (forces) in tribological systems of machines depends not only on the lubricant viscosity but also on its lubricity. Therefore, for operation of the machines, not only of marine application, such as internal combustion engines, reciprocating compressors, etc. the tendency should also be to determine the lubricity of the substances. One of the possibilities might be testing the boundary layer operation. This requires to demonstrate the operation in such a form of mathematical dependence that determines measurement of lubricity of the mentioned lubricating mediums which are lube oils and fuels.

3. Operation of the boundary layer as a measurement of lubricity

Operation of *a lubricant boundary layer* will be correct only when it is not broken. Due to the fact that the lubricant ages in the course of time, the endeavor to ensure the durability of the substance and its boundary layer as high as possible is evident. The more bounded the lubricant boundary layer particles to the substrate (lubricated surface), the higher the durability of the layer. When the bond strengths between the *lubricating medium* and the substrate increase, the quantity of energy emitted during formation of this bond rises [8, 15]. This means that measurement of durability of the mentioned *boundary layer* can be based on measurements of effects accompanying formation of the layer. Thus, the duration of a forming boundary layer can be determined through measurements of the thermal effects accompanying adsorption.

The measurement of durability of *a lubricant boundary lay*er may also be based on measurements of the effects accompanying destruction of the layer. In this case, there can be distinguished as follows [8]:

– wear interpretation of measurements of the boundary layer durability,

– energy interpretation of measurements of the boundary layer durability.

Therefore, resistance of the boundary layer to destructive effects can also be a measure of lubricity. To determine durability of the boundary layer it is needed to estimate such a critical value of destructive effects that causes breakdown of this layer. These effects can be expressed in the form of energy or work per unit of area (unit energy or work) [8]. For this approach, the destructive effect is expressed by a product of the load (p) and the relative sliding speed (v) of rubbing surfaces. This product defines the work performed in time due to existing external load and a lubricating film (between rubbing surfaces) per unit of area, thus the unit power (power per unit of the friction area) in accordance with the formula [8]:

$$N_{(1)} = pv \tag{1}$$

where:

p – pressure in the boundary layer, v – relative sliding speed of rubbing surfaces.

It is therefore necessary to determine the value of the mentioned work which causes the destruction of the lubricant boundary layer in a tribological system having larger or smaller predispositions to produce this layer. This approach can also be used to determine the power destroying the boundary layer with regard to the friction area (F), so $N = N_{(1)}F$.

Effects destroying a *lubricant boundary layer* should be considered at a determined time t [6, 7]. Therefore, the work L_p can be considered instead of the power N and its value can be calculated from the formula:

$$L_p(t) = p(t)F(t)v(t)t \tag{2}$$

where p – pressure in the boundary layer, F – friction area, v – relative sliding speed of rubbing surfaces, t – duration of the boundary layer load.

By using the formula (2) the operation of a *lubricant boundary layer* can be determined as a measurement of lubricity from the formula [6, 7]:

$$D(t) = \int_{t_1}^{t_2} L_p(\tau)d\tau = \int_{t_1}^{t_2} p(\tau)F(\tau)v(\tau)\tau d\tau \tag{3}$$

where:

$D(t)$ – operation of a lubricant boundary layer at time t; $L_p(t)$ – work needed to break a lubricant boundary layer at time t; $p(t)$ – pressure in the boundary layer at time t; $F(t)$ – friction area at time t; $v(t)$ – relative sliding speed of rubbing surfaces at time t; t – operational time of the lubricant boundary layer; t_1, t_2 – moments of the interval $[t_1, t_2]$ in which the lubricant boundary layer operates.

In the course of the operational time of a tribological system, due to its wear, operation of a lubricant boundary layer deteriorates in the aspect that the resistance of this layer decreases. This means that the work causing destruction of this layer gets smaller. Reduction of the work can be recorded only when it reaches at least an elementary quantity (portion) ΔL_p, which can be called a quantum, just like in physics for the energy of electromagnetic radiation [6]. As a result of this reduction after determined time, the mentioned work L_p takes such a low value that further use of *the lubricant* under *boundary friction* becomes impossible. In this case the lubricant should be replaced with another. Otherwise, the boundary layer gets broken what results in occurring dry friction (technically dry) causing damage (destruction) of the tribological system.

Such understood operation of a tribological system (eg. a bearing) can be presented in compliance with the formulas (2) and (3), in a coordinate system of "L_p-t ", so in the form of a graph, which can be called *an operation graph*. Such a graph in the coordinates of "L_p-t " is shown in Fig. 1.

Durability (T_r) of the boundary layer of *a lubricating medium* is a random variable. Realization of this variable (t_r) for the given substance may be the time interval $[0, t_{max}]$, so the maximum time of correct operation of the boundary layer, after which this layer gets broken.

In the presented approach, the operation of a lubricant boundary layer can be considered as:

a) demanded operation (D_W), so that one which is necessary to perform a given task by a machine having tribological systems in which the boundary layer exists;
b) possible operation (D_M), so that one which can be done by the boundary layer existing in a given tribological system at the particular technical condition.

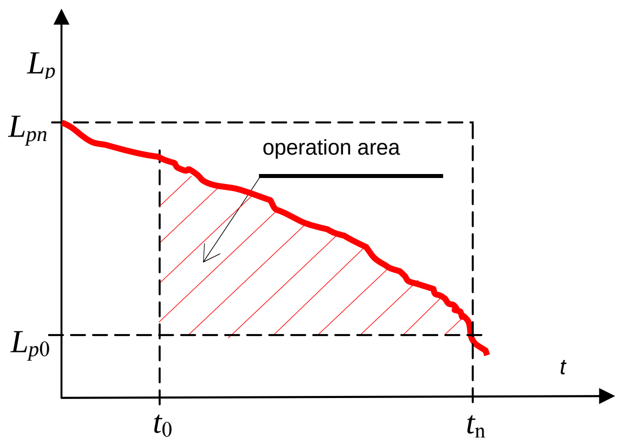

Fig.1. Exemplary graph of boundary layer operation: L_p - work needed to break the boundary layer of a lubricating medium (oil, fuel), t - time of operation (action) of a lubricating medium; t_0, t_n - initial moment and the next moment between which the operation of a lubricant boundary layer is analyzed.

It can be assumed that any operation of a lubricant boundary layer is possible (D_M) when the energy (E_{pM}) generated inside as a result of the load p and the related work (L_{pM}) which might lead to a breakdown of this layer, or heat (Q_{pM}) being an equivalent to the work, will reach at most the boundary value after the time t. The demanded operation (D_W) of a boundary layer is when the energy (E_{pW}) generated inside as a result of the load p, and thus also the work (L_{pW}) needed to destroy this layer or the heat (Q_{pW}) being an equivalent to the work will achieve the demanded (adequate to the operating conditions) values at time (t_W) required to perform the given task. Consequently, it can be accepted that each boundary layer is in ability state (is able to perform the task) when:

$$D_W \leq D_M \tag{4}$$

The maximum possible operation which characterizes a breakdown of the boundary layer and occurrence of dry friction in particular micro areas of contacting surfaces, is in this case a boundary operation. Thus, the possible boundary operation can be expressed by the formula:

$$D_{pG} = L_{pG}\, t \tag{5}$$

where: D_{pG} - maximum possible operation, L_{pG} – boundary operation, so that one by which the beginning of scuffing of rubbing surfaces in the tribological system (eg. sliding bearing) is possible to occur.

The boundary layer can operate (work) properly in accordance with the formula (4) if:

$t_M \geq t_W$, when simultaneously $L_{pM} \geq L_{pW}$.

This means that for practical reasons, this general case must be considered in the following variants:

1) $t_M = t_W$, when simultaneously $L_{pM} = L_{pW}$
2) $t_M = t_W$, when simultaneously $L_{pM} > L_{pW}$
3) $t_M > t_W$, when simultaneously $L_{pM} = L_{pW}$
4) $t_M > t_W$, when simultaneously $L_{pM} > L_{pW}$.

In case when:

$$D_W > D_M \tag{6}$$

the boundary layer should be recognized as destroyed and the tribological systems damaged, and the machine in which they are located is not able to perform a task appropriately to the need.

For modeling the changes of energy or work causing a breakdown of a lubricant boundary layer, a homogeneous Poisson process can be applied [6, 7]. By applying this process a physical interpretation can be formulated for the process of reducing by a constant elementary value e_p the work required to break the boundary layer L_p, which is as follows: from the beginning of operation of this layer (this may be the time $t_0 = 0$) till the time of recording by a measuring device the event A for the first time, consisting in work L_p reduction by the value $\Delta L_p = e_p$, each task can be performed by the tribological system. Further operation of the boundary layer (during task performance by the mentioned system) causes in the course of time successive decreases in values of the work L_p, by the equal values e_p, recorded by the measuring device. Therefore, in case of having recorded till the time t a cumulative number B_t of the occurred events A, described with a homogeneous Poisson process, the reduction of work L_p by the value $\Delta L_p = e_p$ till the time t can be presented by the formula [3]:

$$\Delta L_{pt} = e_p B_t \tag{7}$$

where the random variable B_t has (as it is known) the distribution [6, 7]:

$$P(B_t = k) = \frac{(\lambda t)^k}{k!} \exp(-\lambda t)\,; \quad k = 1,2,\ldots,n\,, \tag{8}$$

where: λ - constant (λ = idem) interpreted as intensity of work L_p reduction by equal values e_p, recorded during tests; $\lambda > 0$.

The expected value and the variance of the process of increasing the number of events A, thus reducing the work L_p by the successively recorded values e_p, can be demonstrated as follows:

$$\mathrm{E}(B_t) = \lambda t\,; \quad \mathrm{D}^2(B_t) = \lambda t \tag{9}$$

Taking the fact into considerations that the greatest energy E_p, thus also the work L_p, is needed to break the lubricant boundary layer (when t = 0) the mathematical relationship describing the work reduction over the time t can be expressed by the formula:

$$L_p(t) = \begin{cases} L_{pmax} & dla \quad t = 0 \\ L_{pmax} - e_p \lambda t \pm e_p \sqrt{\lambda t} & dla \quad t > 0 \end{cases} \tag{10}$$

A graphic interpretation of the relation (10) is shown in Fig. 2.

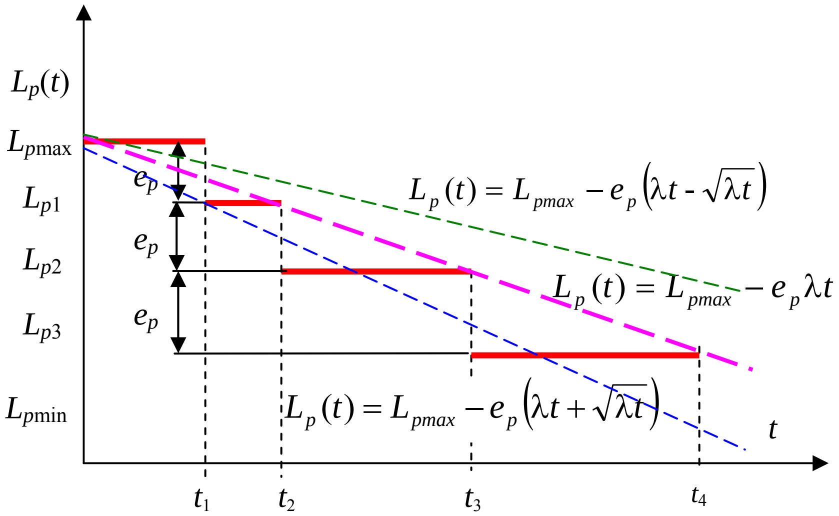

Fig. 2. Graphic interpretation of an exemplary realization of the process of reducing the work needed to break the boundary layer: L_p – work that causes breakdown of the boundary layer, e_p – quantum by which the work L_p changes, t – time

From the formula (10), results that for any time t it is possible to determine the work L_p which can be performed by a tribological system (eg. piston with rings - cylinder liner, bearing, etc.) and from the formula (8) - that it is possible to estimate the probability of occurring such decrease of work L_p. Thus, the probability $P(B_t = k;\ k = 1,2,\ ...,\ n)$ defined by the formula (8), can be recognized as an indicator of the operational reliability of the boundary layer.

4. FINAL REMARKS AND CONCLUSIONS

Operation of the boundary layer in the submitted proposal, is understood as transferring by it the energy E_p, resulting from the tribological system load at determined time t, in the form of work L_p, which may lead to breakdown of this layer. Therefore, it has been compared to a physical quantity that can be expressed with a numeric value and a unit of measure [joule × second].The direct results of such interpreted operation of the boundary layer is the energy transferred by it and the time at which that energy can be transferred. This energy (thus also the work L_p or its equivalent – heat Q_p) and the time are the quantities which unequivocally characterize the operation of the boundary layer. Such understood operation can be considered as a quantity directly characterizing durability of the layer, thus a symptom of its ability. With the increased wear of opposing surfaces in a tribological system and / or deterioration of physicochemical properties of a lubricant (lubricating oil, fuel) under determined conditions and at a defined time, the value of such understood work decreases as a result of deteriorating lubricity and in consequence, increasing the friction work thus the heat of friction. To determine the range of deterioration of operation of the boundary layer it has been applied a stochastic model of reducing work L_p needed to break this layer, in the form of a random process with equal (constant) intervals, homogeneous and independent increments, which is a homogeneous Poisson process.

Operation of the layer in the presented version also has also this advantage that can be analyzed by performing precise measurements, and then can be expressed in the form of:

– number with the unit of measure (Formula 3);
– graph, as a field of area (Fig. 1 and 2).

References

1. Balada A.: Od ropy naftowej do tworzyw sztucznych. WNT, Warszawa 1967.
2. Dębicki M.: Materiały na zebranie naukowe Sekcji Podstaw Eksploatacji Komitetu Budowy Maszyn PAN. Informator WITPIS, Warszawa 1972, s. 224.
3. Girtler J.: Działanie urządzeń jako symptom zmiany ich stanu technicznego. II Międzynarodowy Kongres Diagnostyki Technicznej *DIAGNOSTYKA* 2000, Warszawa 2000, dysk SD, s. [1-8], streszczenie referatu Volume 2, s. 123 i 124.
4. Girtler J.: Work of a compression-ignition engine as the index of its reliability and safety. II International Scientifically-Technical Conference *EXPLO-DIESEL & GAS* TURBINE”01. Conference Procedings. Gdansk-Miedzyzdroje-Copenhagen, 2001, pp.79-86.
5. Girtler J.: Metoda energetyczno-czasowa oceny działania poprzecznych łożysk ślizgowych. Tribologia. Teoria i praktyka 1/2002. Dwumiesięcznik Naukowo-Techniczny SIMP wydawany we współpracy z Polskim Towarzystwem Tribologicznym I Instytutem Technologi Eksploatacji w Radomiu. ITE, Radom, 2002, s.215-226.
6. Hebda M., Wachal A.: Trybologia. WNT, Warszawa 1980.
7. Kolczyński J., Wachal A.: Związek między powierzchniowymi a przeciwzużyciowymi własnościami oleju. Technika Smarownicza nr 2/1976, s.41-44.
8. Wachal A.: Pewne zagadnienia pojęcia smarności. Technika Smarownicza nr 5/1973, s. 129-139..

9. Wierzcholski K.: Kinetyczny opis zjawisk tarcia. Materiały XIII Sympozjum Trybologicznego. Sekcja Podstaw Eksploatacji Komitetu Budowy Maszyn PAN. Częstochowa-Poraj, 1984, s.253-260.
10. Zwierzycki W.: Oleje i smary przemysłowe. Wyd. ITE, Radom 1999.
11. Leksykon naukowo-techniczny z suplementem. Praca zbiorowa. Wyd. IV poprawione. WNT, Warszawa 1989.