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EXPERIMENTAL STUDY OF THE DISJOINING PRESSURE IN THE CYLINDER OIL FILMS ON MARINE DIESEL ENGINE PISTON RINGS

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Abstract

The paper includes the results of the experimental study of the disjoining pressure in the thin oil films with anisotropic properties on the grey cast iron piston rings. It is shown that the disjoining pressure in the thin film, in a mode of self-regulation, can automatically balance the normal load between a pair "ring – cylinder liner". The received data is used to increase the reliability of marine diesel engines by preventing from sudden failures as the result of piston ring breakage.

Keywords: *isotherm, pressure, oil film, anisotropy, ellipsometry, cylinder-piston group, diesel*

1. Introduction

The organization of modern low speed diesel engines operating requires to improve the control of the friction processes of the mating parts of the cylinder-piston group (CPG) and to protect from the emergency situations. The breakage of forced piston rings of low speed diesel engines is the most common cause of functional failure. However, the cause of this phenomenon have not been studied properly yet.

According to the literary analysis modern ships monitor the condition and functions of the individual essential CPG parts, including piston rings [1,2,11]. But these systems are used in the case of high speed of piston movement at hydrodynamic lubrication with isotropic properties. The piston rings breakage, in particular, can occur during passing through scavenge ports as a result of lubrication breakdown [11]. Thus, there is a need to develop the methods of technical condition identification at low speeds, while the ring passes through scavenge ports, at that the lubrication regime is not hydrodynamic, and the film has anisotropic properties.

It is known that while the piston ring moves through the scavenge port of the cylinder liner the lubricant film drastically reduces, but the friction coefficient has a value $\mu = 0{,}12 \div 0{,}18$, that indicates the absence of dry friction [11]. There is the disjoining pressure in a thin boundary layer of cylinder oil, which increases rapidly as the film thickness reduces at low speeds of the piston ring, due to the structuring of lubricant molecules [4,7,8,9].

The theoretical research of a ring movement process through the scavenge ports, in a case when a film with anisotropic properties separates parts, is not possible without the experimental value of the disjoining pressure in this film [9].

Thus, the lack of the properties research of thin lubricant films with the anisotropic properties on cast iron surfaces, of which the ring as well as cylinder liner are manufactured of, is a deterrent for the improvement of low speed diesel engine reliability by preventing from sudden rings breakage, therefore such studies are relevant.

The work objective is an experimental study of the disjoining pressure in thin oil films on the surface of the cast iron piston rings of low speed diesel vessels.

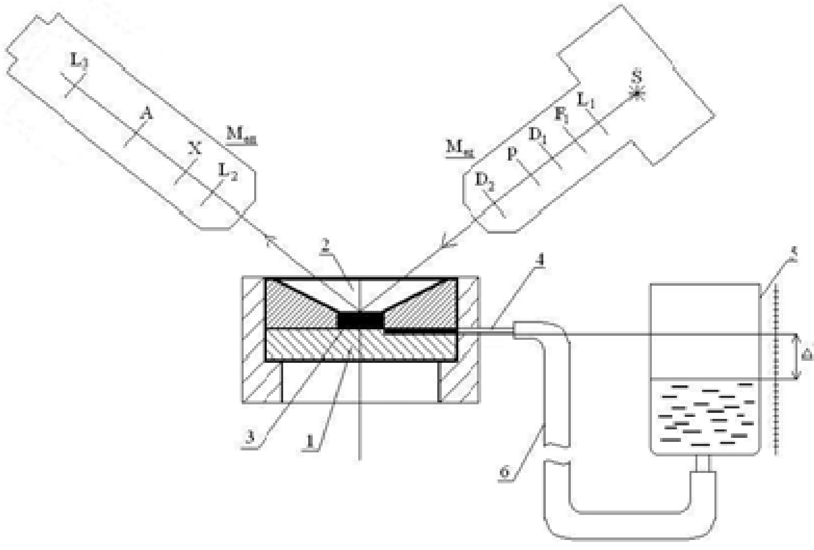
2. Study of the disjoining pressure isotherm in the cylinder oil films

This study was conducted using typical for the low speed diesel engine vessels cylinder oil ENERGOL CLO 50M, and the piston ring taken from the main engine MAN B & W 7S46MC-C.

The metallographic analysis showed that the ring consists of grey cast iron; the base has a ferritic-pearlitic structure. The hardness of the ring is HB2770. The surface was polished to a value $R_a0{,}4 \div 0{,}6$, which corresponds to the surface condition of the piston ring and edges of the cylinder liner in service.

The isotherms of disjoining pressure in a thin lubricant oil film on some steel surfaces, used in diesel engine manufacturing, was studied in the works [6.7]. The beginning of the film formation occurs at different thicknesses and pressures in the film. The film thickness and maximum disjoining pressure level depends on the chemical composition of the metal.

The disjoining pressure isotherms study was conducted on an experimental ellipsometrical plant [5], such scheme is presented below.



$M_{эм}$ *- ellipsometric microscope*

Fig 1. The installation scheme of the disjoining pressure isotherms study in thin oil films on metal surfaces. 1- cast iron sample;2- steel cone;3- oil film; 4-groove;5- pressure vessel;6- hose

The cell of the film was performed as follows: a steel cone with a hole of 1 mm diameter (2) was installed on the polished cast iron sample (1). The oil film (3) was formed in it and connected with the hose (6) to a pressure vessel (5), wherein there was the investigated cylinder oil.

On a Gibbs' theory there exist transition layers at boundary of any adjacent phase, whose properties differ from those of the bulk phase. In the case of interfacial layers overlapping the hydrostatic pressure in the thin layer is different from the pressure of the bulk phase the part of which is the film, ie, Pascal's law is not implemented in the thin film[10,11] . The additional pressure providing the thermodynamic equilibrium of the film was called the disjoining pressure. It can be both positive and negative. The dependence of $\Pi_{(h)}$ – the isotherm of disjoining pressure is the thermodynamic characteristic of the thin film of liquid.

To measure the disjoining pressure it is necessary to provide the mechanical equilibrium of the wetting film, by means of the external pressure. If the system is in thermodynamic equilibrium, and the disjoining pressure is positive, then its value will be the low (negative) pressure produced in the conjugate bulk phase, by lowering the pressure vessel. Conversely, if the disjoining pressure is negative, its value will be excessive hydrostatic pressure. In both cases, the disjoining pressure $\Pi_{(h)}$ will be equal to the difference between the pressure P_1 on the film surface and the pressure P_0 in the bulk phase [4,5,10].

$$P = \rho g\ (H_0 - H_1), \tag{1}$$

where:
ρ -oil density,
H_0 - initial altitude of vessel lowering,
H_1 - final altitude of vessel lowering,
g- acceleration of gravity.

H_0 and H_1 values were determined using a micrometer device respectively, with accuracy $\Delta H = \pm 0{,}1$ mm, that caused the disjoining pressure error $\Delta P = \pm$ I Па.

The experimental time to determine the equilibrium thickness for the wetting oil films with an opening of 1 mm diameter was 30 ÷ 40 minutes.

The position of the zero level H_0 in the pressure vessel, corresponding to the time of film formation from the bulk phase, was determined according to the interference lines condition. It was set for the point at which the movement of convergence and divergence of the interference pattern was stopped.

The film thickness h was measured using the ellipsometric microscope – $M_{эл}$. The methods of the ellipsometric thickness measurement of wetting nonpolar oil films on conductive metal surfaces was developed by the authors and described in detail in the work [7]. The ellipse of the reflected light polarization is described by the ellipsometric angles Ψ and Δ, where tg Ψ - is equal to the relative amplitudes change p- и S - a component, and Δ - the relative phase difference between them. The azimuth of analyzer $A_0{}'$, $A_0{}''$ and polarizer $P_0{}'$, $P_0{}''$ of light extinction were determined during the experiment.

The thickness of layer was calculated using Drude equation [4], which connected the experimental parameters Ψ and Δ and the optical characteristics of the reflected sample, defined with generalized Frenel coefficients R_p и R_s

$$tg\psi \cdot e^{i\Delta} = \frac{R_p}{R_s}\ , \tag{2}$$

where:
tg Ψ - relative amplitudes change,
Δ - phase shift between the P and S components that arises during reflection,
R_p, R_s - Fresnel generalized coefficients for the reflected light.

The equitation (2) has the following form for the presented case of a homogeneous isotropic layer [4]:

$$tg\psi \cdot e^{i\Delta} = \frac{R_{12p} + R_{23p}e^{-2i\delta}}{1 + R_{12p}R_{23p}e^{-2i\delta}} \cdot \frac{1 + R_{12s}R_{23s}e^{-2i\delta}}{R_{12s} + R_{23s}e^{-2i\delta}}\ , \tag{3}$$

Here $\delta = \frac{2\pi}{\lambda_0} n_2 d \sin \varphi_2$, where d is the required layer thickness, and R_{12p}, R_{12s}, R_{23p}, R_{23s} are defined accordingly:

$$R_{12p}=\frac{n_2\cos\varphi_1-\cos\varphi_2}{n_2\cos\varphi_1+\cos\varphi_2}\qquad R_{23p}=\frac{n_3\cos\varphi_2-n_2\cos\varphi_3}{n_3\cos\varphi_2+n_2\cos\varphi_3}$$
$$R_{12s}=\frac{\cos\varphi_1-n_2\cos\varphi_2}{\cos\varphi_1+n_2\cos\varphi_2}\qquad R_{23s}=\frac{n_2\cos\varphi_2-n_3\cos\varphi_3}{n_2\cos\varphi_2+n_3\cos\varphi_3},\tag{4}$$

The task is complicated by the need to take into account the effects of the electromagnetic waves weakening in the metal substrate. In general case, the equation (3) is formulated for the inhomogeneous wave and can be solved by the introduction of complex refractive index, taking into account the damping effects. In the presented case $n_3 \Rightarrow N_3 = n_3 - i\kappa_3$ and n, k- are the coefficients of substrate refraction and absorption. The following values n = 3,9, k = 6.96. are for cast iron.

Thus, the equation (3) with (4), is a complex expression, and hence, the simultaneous equations is required to be solved to find the layer thickness:

$$Re\left(tg\psi\cdot e^{i\Delta}-\frac{\left(R_{12p}+R_{23p}e^{-2i\delta}\right)\left(1+R_{12s}R_{23s}e^{-2i\delta}\right)}{\left(1+R_{12p}R_{23p}e^{-2i\delta}\right)\left(R_{12s}+R_{23s}e^{-2i\delta}\right)}\right)=0$$
$$Im\left(tg\psi\cdot e^{i\Delta}-\frac{\left(R_{12p}+R_{23p}e^{-2i\delta}\right)\left(1+R_{12s}R_{23s}e^{-2i\delta}\right)}{\left(1+R_{12p}R_{23p}e^{-2i\delta}\right)\left(R_{12s}+R_{23s}e^{-2i\delta}\right)}\right)=0\tag{5}$$

The experimental isotherm of disjoining pressure of the oil film on the cast iron surface with roughness (R_a0,4), obtained at a temperature of 295 ° K is shown in Fig. 2. The isotherm is close to an exponential form that corresponds to the works [6].

$$P=\frac{A}{h^3},\tag{6}$$

A - Hamaker constant

The isotherms in the oil films on cast iron corresponds to the area of positive values of the disjoining pressure Пs > 0. They are of the decreasing nature. From this it follows that the disjoining pressure in the thin films, in the mode of self-regulation, can automatically balance the normal load, between the pair “ring – cylinder sleeve”. Each new value of pressure has new equilibrium thickness of the film.

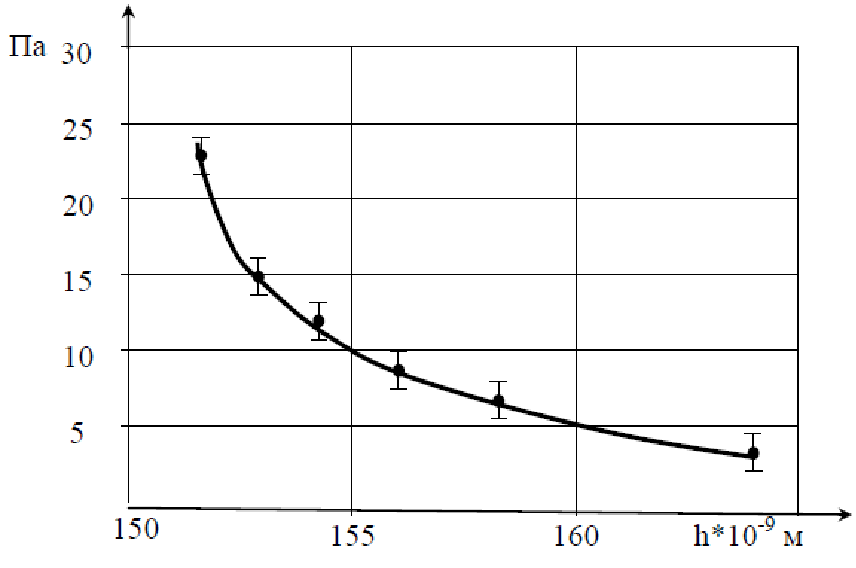


Fig. 2. The disjoining pressure change in a thin film of lubricant ENERGOL ClO 50M on the cast iron piston ring, depending on the film thickness

The maximum value of the disjoining pressure was determined from the graph constructed in the semi-logarithmic coordinates of dependence lnP (h) on the film thickness h. The maximum value of the disjoining pressures for the cast iron is equal to $\Pi_{(h)}$=140000Па .

The distinctive feature of the oil films with anisotropic properties on cast iron is the small amount of change in the film thickness from the beginning of its formation to the minimum at which the pressure in the film begins to increase sharply. For the films on the cast iron the thickness is 10 ÷ 12 nm. In comparison with the thickness of the films on steels (Fig. 3) [6,7] we can see that on steel 35 XMA,of which the piston heads and MAN B & W were manufactured, it is equal to 126 nm, which is an order of magnitude greater than that of cast iron.

The value of the disjoining pressure is the sum of the molecular component $\Pi m_{(h)}$, at low film thicknesses and structural $\Pi s_{(h)}$:

$$\Pi_{(h)} = \Pi m_{(h)} + \Pi s_{(h)}.$$

According to the obtained results the chemical composition of the substrate has a significant effect of on the change in the degree of orientation molecules order as the film thickness changes, that determines the amount of the structural constituent of the disjoining pressure $\Pi s_{(h)}$. Obviously, that such a difference in the obtained values of $\Pi_{(h)}$ can be explained by the different contributions of the molecular component of the disjoining pressure, which is essential for small film thicknesses. Previously, the effect of the molecular components on the disjoining pressure value was defined for polar liquid film on dielectrics [3,5].

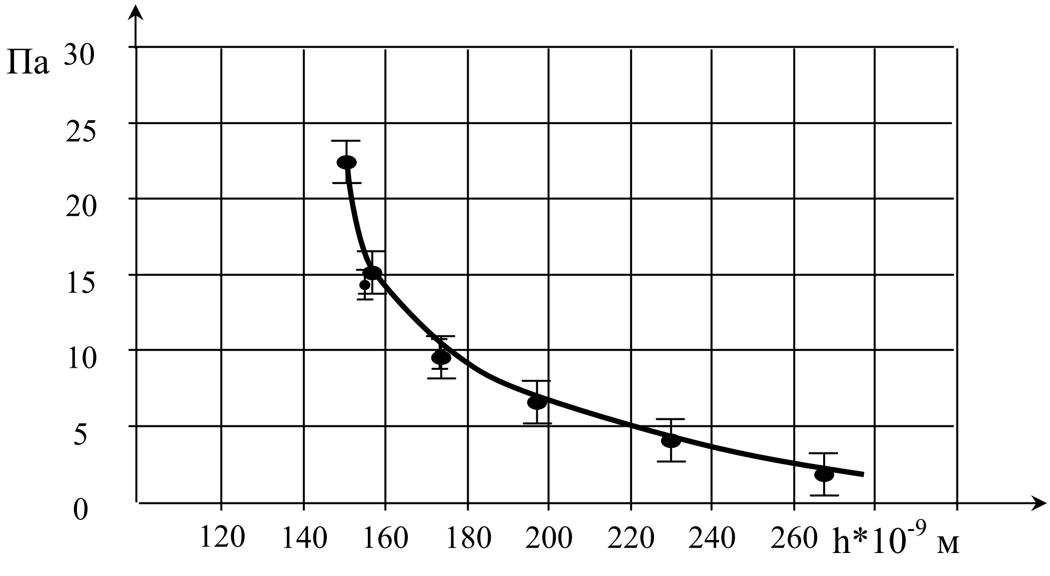


Fig.3. The dependence of the disjoining pressure in the oil film ENEKOL GLO 50M on its thickness on steel SH15

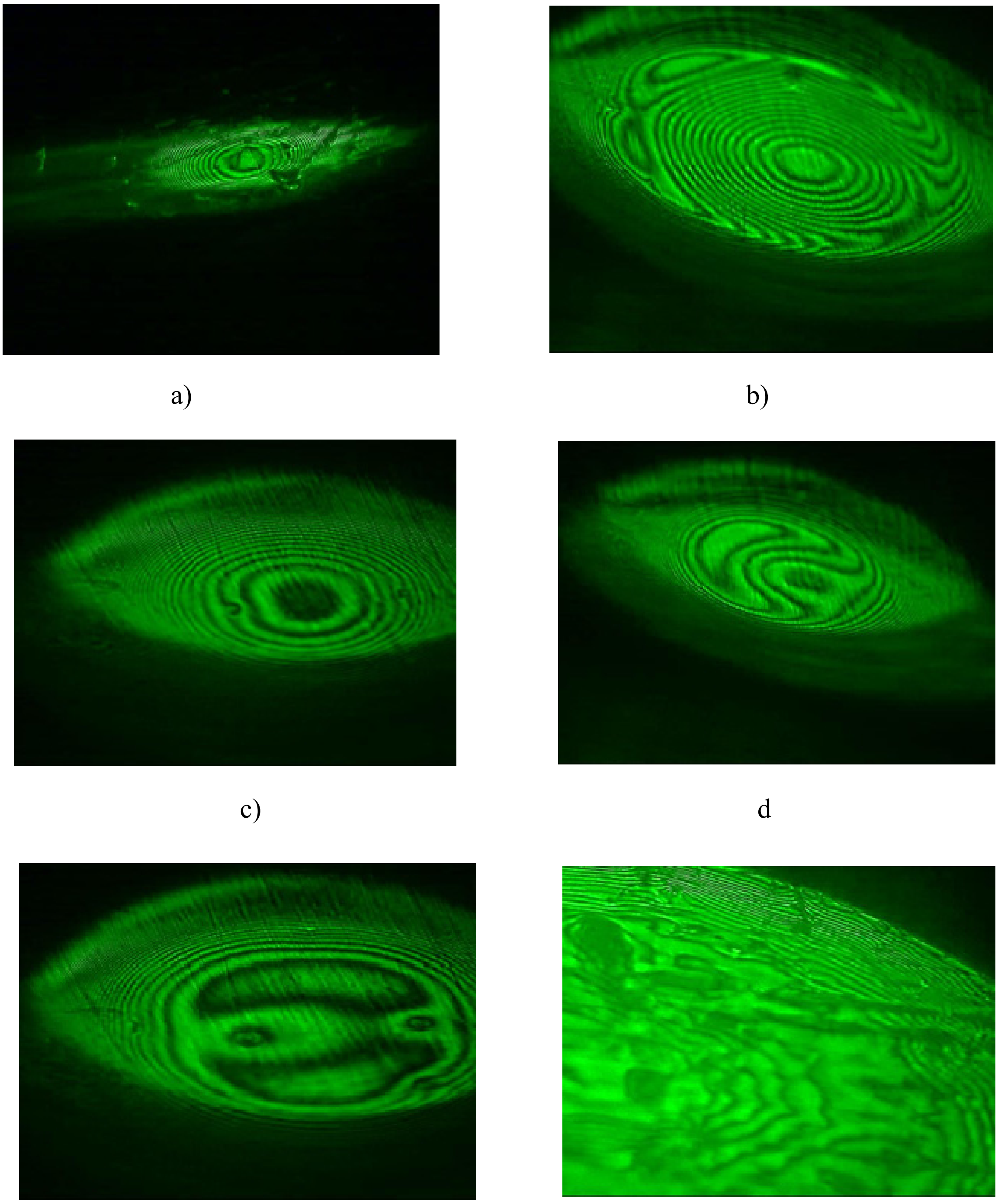
The analysis of the received values of disjoining pressure shows that the use of $\Pi s_{(h)}$ as the exponent is not always correct, and the real dependence of structural constituent on the film thickness is more complicated.

The analysis of the photomicrographs of the thin oil film on the surface of iron shows that the film is not flat by its nature. (Fig. 4)

The distribution of the interference lines demonstrates the formation of the film with the anisotropic properties in the center of the cell and the increase of the film area as it is growing thinner (Fig 4.b, c, d, e). An interference pattern is formed by the graphite inclusions (Fig.4f).

The control of lubricating film with anisotropic properties, determined by the disjoining pressure, make it possible to compensate the normal load on friction zone, therefore energy loss and the amount of conjugated surfaces deterioration can be reduced.

The obtained results enable to improve the identification methods of piston ring working capacity according to the lubricant state in order to prevent an emergency on board.



a) b)

c) d

e) f)

Fig. 4.The photomicrographs of the oil film on cast iron: formation (a), the minimum film thickness (f)

Conclusions

1. For the first time the isotherm of the disjoining pressure in the cylinder oil films on cast iron was experimentally obtained. It corresponds to the positive pressure region Π_s. There is force in a thin cylinder oil film directed to the opposite side of the ring pressure on the port of cylinder liner.
2. It is determined that the isotherm of disjoining pressure in the cylinder oil films on iron and steel surfaces are of the decreasing nature. It ensures the process of self-regulation of piston rings pressure on the cylinder liner. Each new pressure value has a

new equilibrium thickness. The process of self-regulation is automatic and it does not require the human intervention.

3. The comparison of the experimental isotherm of the disjoining pressure in the oil film on steel and iron surfaces have the following results:

- the film formation on steel and cast iron occur at different film pressure and thickness. The film formation on steel occurs at interval of 240 ÷ 280 nm, and with a much smaller thickness of 163 ÷ 165 nm on grey cast iron;
- the film thickness from the beginning of its formation and before the sharp pressure increase is 130 nm for steel. It is higher than on cast iron, that is only 10 ÷ 12 nm;
- the minimum film thickness on the iron surface where the disjoining pressure has a maximum value is in the range of 155-160 nm;
- the maximum disjoining pressure in the cylinder oil film was determined. It is equal to Π_s=0,14 МПа;

The further development of the piston rings movement process study, in the presence of thin oil films with the anisotropic properties, using the obtained data of the disjoining pressure on cast iron, will enable to improve the reliability of marine low speed diesel engines. Identification methods of piston rings technical condition and prevention from the sudden failures in the result of the piston rings damage will be developed.

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