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TRIBOLOGICAL INVESTIGATIONS OF TRIBOSYSTEMS DURING LUBRICATION USING VEGETABLE OILS AND MINERAL-VEGETABLE OIL COMPOSITES CONTAINING METAL-PLATING ADDITIVE. PART I: FRICTION

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Abstract. The investigations carried out in the present paper are dedicated to two main tendencies which can be outlined: studies on the physicochemical properties and the tribological characteristics of oils for hydraulic systems in agriculture and motor oils for two-strokes internal combustion engines. Rapeseed and sunflower oils have been proposed as suitable basis for the oils in hydraulic systems having high content of oleic acid. It has been found out that during lubrication with mineral-vegetable composite HLP-S the moment of friction has lower values than that in the case of lubrication with mineral oil and its variation in the course of time has more stable character unlike the case of conventional mineral oil. The addition of metal-plating additive 'Valena' to the mineral-vegetable oil leads to lowering of the frictional characteristics of the tribosystem and the temperature of the oil: in the case of biodegradable oil for 8 min time interval the moment of friction is decreased with 16%, while the temperature is increased only with 6°C, which is twice lower than that in the case of oil without the additive. For mineral-vegetable oils without and with the additive the moment of friction is decreased with 10–11% in comparison to that in the case of pure mineral oil.

Keywords: lubrication, tribosystems, vegetable oils, metal-plate additives.

AIMS AND BACKGROUND

The basic phenomena and processes, which determine the operational characteristics, the lifetime and the effectiveness of contemporary mechanisms and machines are the friction, the wearing out and lubrication.

The friction is associated with energy losses in the machines, consuming 30–40% of the energy, produced in the world. The wearing out process, as well as its accompanying process of friction, leads to material losses and wasting human resources. It is the reason for the decommissioning of more than 80% of the machine parts. The lubrication is a universal technology in the tribology to achieve efficient operation and control of the technical systems. The lubricating materials,

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possessing some required qualities, appear to be a specific construction element in the composition of the rubbing nodes and system in the machines. Lubrication also contribute a considerable share to the pollution of the environment with thermal, acoustic, solid, liquid and gaseous toxic emissions.

One of the contemporary directions in the development of tribology in the next decades is connected with the elaboration and application of lubricating materials belonging to the 4th and to the 5th generation having some additives, which should be less toxic or non-toxic, and they should provide considerable decrease in the amount of friction losses and the degree of wearing out[1–12].

During the recent 10–15 years one observes an intensive development of the world production and investigations, associated with ecologically clean lubricating materials and liquids from renewable sources on the basis of vegetable oils, as well as some new composites containing both vegetable and mineral oils lubricating materials[11–15]. The greatest share on the market lubricants, whose composition has more than 25% of quickly biodegradable components, is attributed to the hydraulic oils and they represent 27% of the total volume of the sold products. Some 24% in this classification refers to oils for chain-driven machines in the agriculture and forestry, 14% are oils, used for shuttering concrete in building construction and 14% – in the form of plastic lubricants. During the last 10 years it is observed that the annual increase in consumption varies from 2 to 4%.

Until the present moment the tendency in the utilisation of such materials refers mainly to ecologically significant fields such as forestry, agricultural technique and building construction. The hydraulic systems are widely occurring in different branches of the agriculture and they find application in machines and equipment for processing technologies, machines for meliorating activities, machines for soil treatment and collecting the harvest. They have great functional importance for the machines taken as a whole.

At this stage the problem of replacing the mineral oils by ecological oils is approached from two directions: partial substitution of the mineral oils by vegetable-mineral composites, mixed at a definite ratio, and their complete replacement by vegetable oils, containing some additives.

The great interest in vegetable oils as lubricating products originates from their basic advantages in comparison to the petroleum products – they are non-toxic, quickly degradable, renewable and easily accessible[16–19]. It has been established that in regard to the physicochemical and tribological characteristics (wear resistance, scratch resistance) the vegetable oils satisfy the operational requirements only for some of the machines under specific conditions. The vegetable oils (rapeseed, sunflower, linen, castor, palmate, cotton and other oils) contain considerable amount of organic surfactants (surface active compounds SAC) in the form of unsaturated fatty acids – oleic, stearic, erousic, linolenic and other acids. During friction of the surfaces they are forming polymolecular layers of spatially orientated dipoles, which possess anisotropic mechanical properties – large impact/pressure resistance and low resistance in tangential direction. These layers have air-cushion effect in the place of contact during the friction, they impede the direct interaction between roughnesses and the insertion of abrasive particles hampering the wearing out of the surfaces. The air-cushion effect of the polymolecular layers under alternating dynamic or impulse loadings reduces and/or prevents the processes of destruction. In this way the organic surfactants in the vegetable oils appear to be natural anti-wear additives, especially in cases of mixtures of vegetable and mineral composites.

Priority in the investigations of many researchers is the rapeseed oil, which at present finds the widest application among all the vegetable oils.

Two main tendencies can be outlined: studies on the physicochemical properties and the tribological characteristics of oils for hydraulic systems in the agriculture and motor oils for two-strokes internal combustion engines. Rapeseed and sunflower oils have been proposed as suitable basis for the oils in hydraulic systems having high content of oleic acid. The studies, made by a series of authors, are connected with the choice of appropriate additives to pure vegetable oils and to vegetable-mineral composites for promoting their oxidative and thermal stability[20]. In Refs 21 and 22 were studied the tribological characteristics in gear transmissions having hydraulic control in case of lubricating with vegetable-mineral composites on the basis of rapeseed oil. Some authors[23] propose the use of rapeseed oil as a component in plastics lubricant composition for greasing of supporting bearings of tractor chains. Another paper[24] reports a comparative study of the tribological characteristics of 4 types of vegetable oils during friction in four-pellet machine. It has been shown that the minimum degree of wearing out of the pellets is achieved in the case of rapeseed oil, which fact is also confirmed by the studies of other authors. The linen and the cotton oil have comparatively lower wear-resistance indices.

The main conclusion, drawn by a series of authors is that the promising raw material for the production of mixed mineral-vegetable lubricating composites for their utilisation in hydraulic systems, tractor transmissions and two-stroke internal combustion engines appears to be the rapeseed oil. In the case of hydraulic systems at lower loadings, in comparison with the transmissions, one can use also some other vegetable oils – for example flax (linen) oil.

There is only limited information in the current literature concerning studies on the tribological characteristics in contacting systems, lubricated by vegetable oils having multi-functional additives. In this case the term 'multi-functional additives' denotes such composites, which contain substances, ensuring the improvement of several properties and characteristics at the same time: such as anti-oxidative and thermal stability, wear-resistance, anti-frictional and scratch-resistance characteristics. The results, reported in Refs 25, 26 and 27, are focused on the processes of friction and wearing out in the contact system, consisting of pig-iron СЧ21 and steel 15X upon lubricating with rapeseed oil. It has been ascertained that the doping of the rapeseed oil with a multi-functional additive 'Valena' enhances the oxidative stability and it achieves lower friction coefficient and lower degree of weaing out. The biodegradability of rapeseed oil with 'Valena' additive has the same degree of bodegradability as that of the pure rapeseed oil, i.e. the presence of 'Valena' does not reduce the biodegradability of the oil[28,29].

The task of the present work was to carry out a comparative study of the tribological characteristics of the tribosystems upon lubricating with biodegradable oils on vegetable basis and combined with mineral oils, and to find out some options for their improvement using the multifunctional metal-plating additive 'Valena'.

EXPERIMENTAL

Materials. The study was carried out applying 5 kinds of oils, divided into two groups. The first group includes two kinds of oils: No 1 – 100% vegetable oil Bio-DM and No 2 – 95% vegetable oil Bio-DM with the addition of 5% metal-plating additive V. The second group includes three kinds of oils and composites: No 3 – 100% mineral oil HLP; No 4 – mineral-vegetable composite, consisting of 65% mineral oil HLP and 35% sunflower oil S; No 5 – mineral-vegetable composite, consisting of 60% mineral oil HLP, 35% sunflower oil S and 5% metal-plating additive V. Table 1 lists the notations of the studied lubricating oils and composites. The specified notations of the oils, available on the market, do not correspond to their commercial names.

Table 1. Notation of the composition of the studied vegetable oils and mineral-vegetable composites

Groups of oils	Type of oil	Notation of the oil	Composition of the oil
	1	Bio – DM	100% vegetable oil
I	2	Bio – DMV	95% vegetable oil + 5% metal-plating additive
	3	HLP	100% mineral oil
II	4	HLP – S	65% mineral oil + 35% sunflower oil
	5	HLP – SV	60% mineral oil, 35% sunflower oil + 5% metal-plating additive

The biodegradable oil Bio–DM was prepared from renewable resources and it has 100% vegetable origin. It contains a complex of additives for promoting the adhesion properties when the oil is between the surfaces of the chain and the leading rim of the motor cutter in the agriculture and in the forestry. The adhesion additives prevent the fast leakage of the lubricant from the cutting chain. The use of 100% biodegradable oil is beneficial for the protection of the environment – protecting the soil and the ground waters from toxic compounds, which are contained in the mineral oils. Figure 1 illustrates the principle of lubricating the chains and the cutting blades in machine-cutters.

The basic advantages of the oil Bio-DM, as they are specified by the manufacturer, are the superior lubricating properties; pure natural product on vegetable basis; fast micro-biological solubility and the option to use it both during the summer and during the winter (freezing point < –20°C).

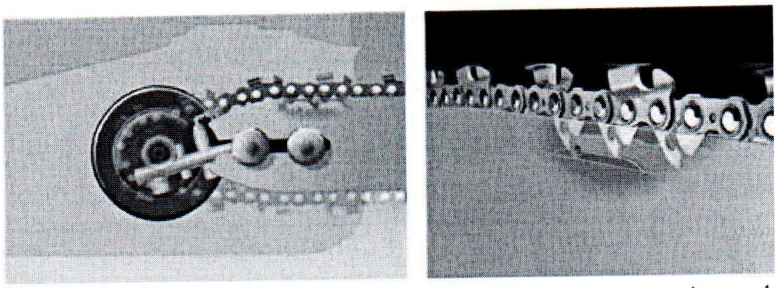

Fig. 1. Lubrication of motor cutter chain, whereupon the leading units are scooping up the oil and then pushing it towards the joints

The mineral-vegetable composite HLP-S was prepared at the Centre of Tribology at Machine-Technological Faculty of the Technical University – Sofia.

The metal-plating composite 'Valena' represents a multifunctional metal-containing oil-soluble composite, registered as a patent in 2005 in Russia by the authors Valentina Babel, Dmitriy Garkunov, Sergey Mamikin and Peter Kornik. This additive is designed for improving the tribological properties of lubricating materials and more specifically – the anti-frictional, wear-resistant and anti-scratching properties, as well as protection from hydrogen wearing out. It represents a thick liquid of dark green colour, which dissolves well in oils and plastic grease, forming a solution, in which the metal is present in the form of molecules or ions. The solubility of the additive is due to its specific composition – metal salts of organic and inorganic acids. The metal salts of the inorganic acids are salts of copper, cobalt, lead, tin, nickel (chlorides, bromides, iodides). The applied metal salts of organic acids are usually salts of metals displaying variable valences and the number of the carbon atoms is $C_{15}\ldots C_{18}$.

The improvement of the tribological properties of the lubricating material with this additive is achieved by means of realising the effect of selective transferring during the process of friction. The essence of this effect consists in the formation of protective metal-plating film of thickness varying from 100 nm up to 3 μm, called servovital. This film is formed in the actual contacting spots in the process of rubbing under strictly defined regime of contact interaction – loading, sliding velocity, contact temperature, physicochemical characteristics of the contacting solid-state materials and the lubricant. This servovital film compensates the wearing out in the process of friction and it serves as protective screen for the penetration of hydrogen into the superficial layers of the metal, i.e. it prevents the hydrogen wearing out.

Density and viscosity-thermal characteristics of the studied lubricating materials. Experimental results were obtained about the density and dynamic viscosity of three oils: biodegradable oil Bio-DM, mineral oil HLP and mineral-vegetable composite HLP-S. The dynamic viscosity has been determined using a viscosimeter of Hoepler.

Figure 2 illustrates graphically the dependence of the density on the temperature of the oils. As it can be seen, upon increasing the temperature the density is decreasing linearly for all the three studied oils. It is noticeable that the biodegradable oil Bio-DM has the highest density, both at 20°C, as well as upon increasing the temperature up to 75°C.

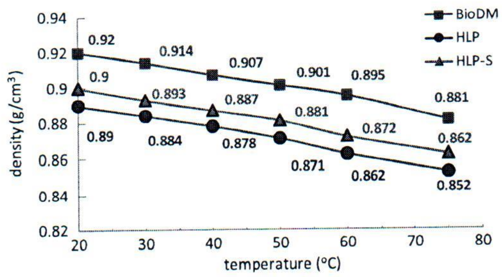

Fig. 2. Variation of oil density as a function of temperature

The dependence of the dynamic viscosity on temperature within the temperature interval from 20 up to 75°C for the three oils is represented in Fig. 3.

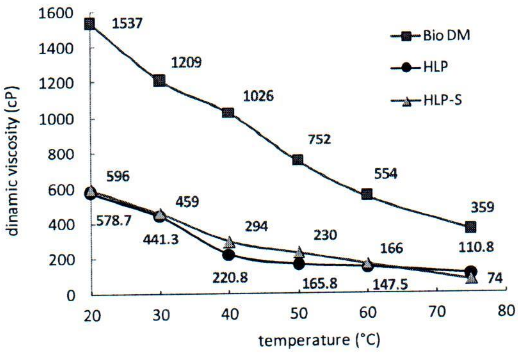

Fig. 3. Dependence of dynamic viscosity of the tested oils on temperature

It is seen that upon increasing the temperature from 20 up to 60°C the dynamic viscosity is decreasing to a different degree for the different oils. In the case of 100% biodegradable oil Bio-DM the viscosity is decreased 2.8 times, for the mineral oil HLP – the decrease is 3.9 times, while for the mineral-vegetable composite HLP-S – 3.6 times.

At temperature 20°C the viscosity of 100% biodegradable oil Bio-DM is 2.6 times larger than the viscosity of the mineral oil HLP and that of the composite HLP-S. This is due to the presence of a large quantity of adhesion additives with high density and long molecular chains in the vegetable oil, which ensure the retention of the oil in the open tribosystem.

Friction in contact systems in cases of lubrication with vegetable oils and mineral-vegetable composites. Investigation of the characteristics of friction under conditions of boundary lubrication using five types of lubricating oils (Table 1) in the specific case has been carried out. Effect of normal loading on the moment and on the coefficient of friction; Variation of the temperature of the oil under different loadings; Influence of the metal-plating additivea 'Valena' on the reduced coefficient of friction and on the temperature of the oil at different normal loadings.

Device and methodology. Investigations of the characteristics of friction – moment of friction, coefficient of friction and temperature of the oil in tribosystems under conditions of lubrication without and with metal-plating additive in the tested oils were carried out by a laboratory device DM 28M, shown in Figs 4 and 5.

The studied tribosystem represents a complex of 4 rolling pellet bearings, located in the bearing head. The device consists of a body (corpus), in which a driving shaft is mounted. There is a testing bearing head, connected to the end of the driving shaft, in which the four rolling bearings are positioned – 2 of them in the middle and the other 2 at the end. The outer rings of the two middle bearings are located in one common chamber, while the outer rings of the two bearings are positioned at the end inside the body of the bearing head of tightened joints, i.e. they form intimate contact with the body of the head. The inner rings of the bearings are connected with tightened joint to the driving shaft. In this way the movement of the driving shaft is transferred to the inner rings of the bearings and by means of the rolling pellets of the outer rings of the bearings. In their turn they transfer the movement of the corpus bearing node and the bearing head tries to rotate in the direction of rotation of the shaft. So in this way during the rotation of the shaft the emerging friction moment entrails the bearing head and together with it also the bulk phase of oil, to which the middle bearings are attached.

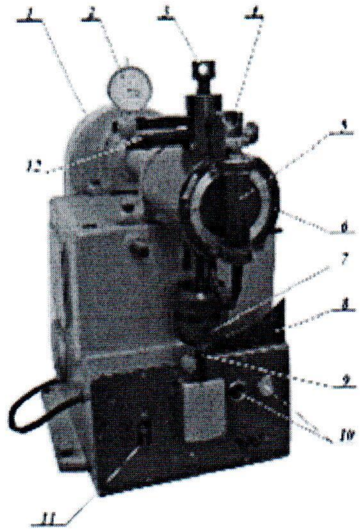

Fig. 4. Front view of DM 28M
1 – belt transmission in jacket; *2* – indicator; *3* – screw for loading; *4* – stand for thermometer; *5* – piston leveler of the oil; *6* – bearing head; *7* – load of the pendulum; *8* – scale for the moment of friction; *9* – pendulum; *10* – buttons for switching on and off the electric motor; *11* – button for switching on the chain; *12* – dynamometric beam

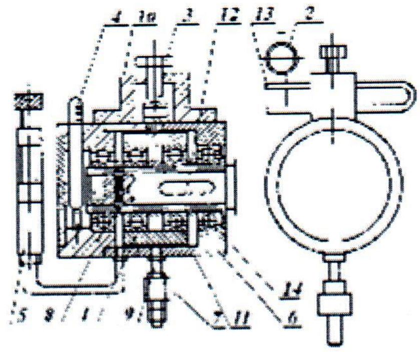

Fig. 5. Scheme of bearing head
1 – outer box; *2* – indicator; *3* – screw for loading; *4* – thermometer; *5* – leveler of the oil; *6* – body; *7* – load of the pendulum; *8* – pellets; *9* – pendulum; *10* – clamp; *11* – middle bearings; *12* – driving shaft; *13* – dynamometric beam; *14* – endmost bearings

The magnitude of the moment of friction M_r is measured by the deviation of the pendulum with respect to the vertical axis, which one can read on the scale, in units Nm. The loading P on the bearings is set to a given value by means of the screw 3, by loading of the dynamometric beam and the value is being red on the scale of the indicator 2, rated in units Newton. The oil is poured into the bearing node through an opening, while its level is regulated by shifting the piston of the leveler. The temperature is measured by means of the thermometer, inserted in the oil. The limitation of the abrupt rotation of the bearing head upon switching on the electric motor is achieved by means of the restrictors.

The methodology for investigating the moment of friction M_r and the reduced coefficient of friction μ_r consists in the following: The turnover number of revolutions is set by adjusting the belt transmission; Oil is poured in (with and without additive) and the oil level is regulated by shifting the piston of the leveler 5; The equilibrium position of the pendulum 9 is regulated by means of the load 7; The electric motor is switched on and the pendulum at the initial moment deviates abruptly from its initial vertical position; The device is left to operate for 5 min, aiming at achieving co-working and reaching a stable position of the pendulum and thereafter one reads the indication of the pointer of the pendulum on the scale, calibrated in Nm units, which corresponds to the value of the moment of friction M_r; Using the remote revolution counter (cyclometer) one can monitor the number of revolutions of the shaft aiming at measuring the friction moment when reaching a constant number of revolutions; The moment of friction M_r is measured in regime without any loading, whereupon one reads the indications on the scale for 2 min interval; A certain loading value is set P by means of the loading screw 3. The value of the loading is to be read on the scale of the indicator 2, calibrated in Newton units. At each loading value set P one measures the moment of friction M_r. The duration of the action at each loading is 2 min. These operations are repeated for each experimental run with the various lubricating materials. When the old lubricating material is replaced by a new one the bearing head is cleaned by removing the previous oil experiment by washing with gasoline or solvent and then it is dried up with warm air. All the experimental runs are carried out at one and the same level of the oil up to the centre of the bearing pellets, whereupon it is guaranteed that the lubricating conditions in the bearing head are identical.

The reduced coefficient of friction μ_r in the bearing node is determined based on the following formula:

$$\mu_r = \frac{2M_r}{P\,d}, \qquad (1)$$

where the internal diameter of the bearing is $d = 0.04$ m.

RESULTS AND DISCUSSION

Using the above described device and the methodology five types of oils have been studied, which are described in Table 1. Tests have been carried out with each oil sample under conditions without any external loading, i.e. $P = 0$ N and at loadings $P_1 = 1130$ N; $P_2 = 1635$ N; $P_3 = 2725$ N and $P_4 = 5650$ N. The moment of friction

M_r is read for each setting of the loading after friction time interval of 2 min, and thereafter the next greater loading value is set.

Friction in case of lubrication with biodegradable oil Bio-DM with and without the metal-plating additive 'Valena'. Results have been obtained for the reduced moment of friction, the coefficient of friction and the temperature of the oil for the oils Bio-DM and Bio-DMV in both cases without any loading and at the four set values of loading. The experimental results are represented in the form of graphical dependences.

Figure 6 represents the changes in the moment of friction versus the time in the case without any external loading, while Fig. 7 illustrates the changes in the temperature of the oil for the same moment of time for the Bio-DM oil with and without the additive 'Valena'.

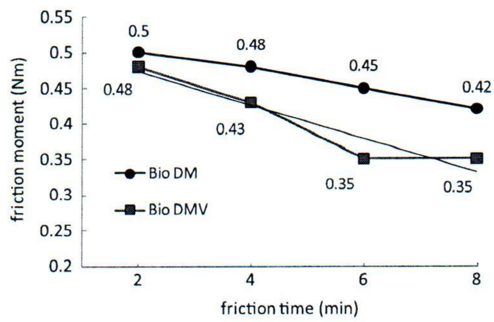

Fig. 6. Variation of moment of friction with time during lubrication using biodegradable oil Bio DM with and without additive under conditions without any loading

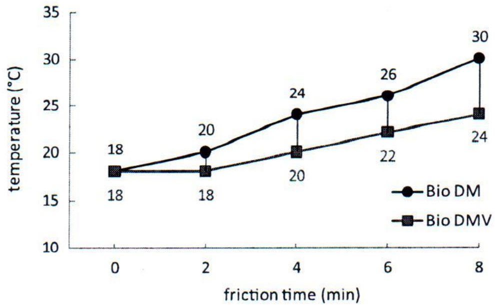

Fig. 7. Dependence of temperature of biodegradable oil Bio DM with and without additive 'Valena' as a function of time of friction without any loading

It is seen in Fig. 7 that on increasing the time interval of friction the moment of friction is decreasing for both types of oil. The moment of friction for time interval of 8 min in the case of oil Bio-DM without additive is decreased with 0.08 Nm, while in the case of friction using oil with 'Valena' additive the friction moment is reduced with 0.13 Nm, i.e. with 1.6 times higher than the moment of friction in the case of oil without additive. Another interesting result, associated with the influence of metal-plating additive 'Valena' on the moment of friction, is that after 6 min time interval the moment of friction preserves a constant value.

The temperature of the oil is increasing with the increasing of the time interval of friction almost linearly. In case of lubricating with biodegradable oil Bio-DM for 8 min time interval the temperature is increased with 12°C, while during lubricating with the same oil with 'Valena' additive (Bio-DMV) the temperature is increased only with 6°C, i.e. twice lower value (Fig. 7).

On increasing the loading the variation of the moment of friction displays a complex non-linear character, as one can see in Fig. 8.

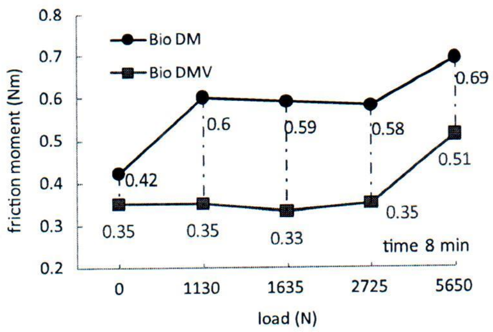

Fig. 8. Dependence of moment of friction on loading during lubrication with biodegradable oil Bio DM with and without additive for friction time interval of 8 min

In the case of biodegradable oil Bio-DM without additive up to loading of 1130 N the moment of friction is growing up, while thereafter during the consecutive increasing of the loading 2.4 times up to 2725 N it is only slightly decreasing – it almost preserves a constant value within the limits 0.58–0.6 Nm. During the consecutive 2 times increase of the loading the moment of friction is growing up 1.2 times reaching the value 0.69 Nm.

In the presence of the additive 'Valena' within the range of loadings from 0 up to 2725 N the moment of friction remains almost unchanged and at loading 5650 N it grows up and reaches the value 0.51 Nm, which is lower than the value of the friction moment for the oil Bio-DM without additive for the entire range of studied loadings (Fig. 9).

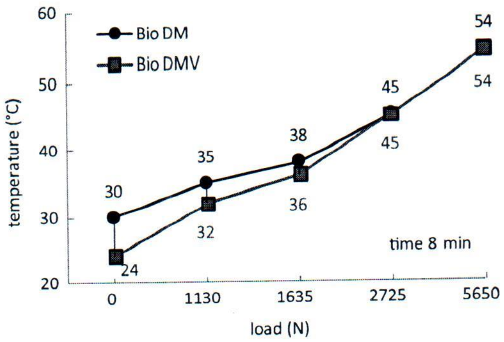

Fig. 9. Variation of temperature of biodegradable oil Bio DM with and without additive with loading for time interval of friction 8 min

The variation of the temperature of oils Bio-DM and Bio-DMV on increasing the loading manifests a linear character (Fig. 9). Up to a certain loading value in the presence of 'Valena' additive the oil temperature has lower values within the interval from 6°C without loading up to 2°C at loading 1635 N. At high loading the temperature of the two oils has one and the same value.

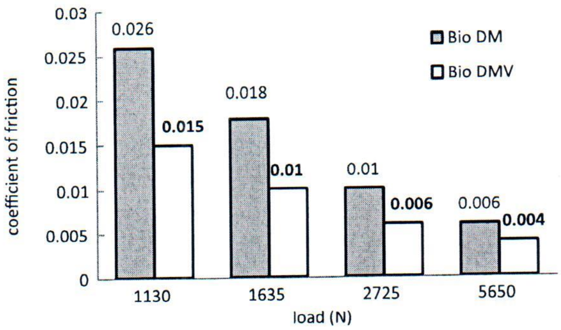

Fig. 10. Diagram of coefficient of friction under various loadings during lubrication with biodegradable oil Bio DM with and without additive for one and the same time interval of friction 8 min

Figure 10 represents the diagram of the reduced coefficient of friction for biodegradable oils without additive Bio-DM and with the additive 'Valena' Bio-DMV under different loadings. On increasing the loading the coefficient of friction for the two oils is decreasing, but in the case of the oil with additive 'Valena' Bio-DMV it has lower values. The difference in the coefficient of friction for the two oils is greater at the lower loadings – $P_1 = 1130$ N and $P_2 = 1635$ N.

Friction during lubrication with mineral oils and mineral-vegetable composites HLP, HLP-S and HLP-SV. Experimental results have been obtained regarding the moment of friction, the coefficient of friction and the temperature of the oil for the three kinds of oils, belonging to the second group HLP, HLP-S and HLP-SV. Figure 11 represents the graphical dependences of the friction moment changes as a function of the time interval of friction for the three kinds of oils in the case of no outer loading.

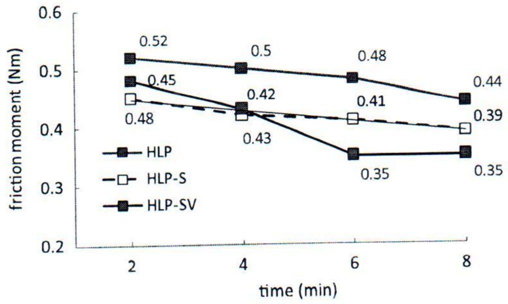

Fig. 11. Variation of moment of friction as a function of time interval without any loading during lubrication with mineral oil HLP, biodegradable oil HLP-S and HLP-SV

It is seen in Fig. 11 that the moment of friction for all kinds of oils is decreasing linearly with the time interval of friction, i.e. a process is occurring during the co-operation of the components of the bearing node. The greatest value is manifested by the moment of friction in case of lubrication with mineral oil HLP, while the lowest value is in the case of lubrication with biodegradable oil HLP-SV, i.e. including the additive 'Valena'. In this case the moment of friction for a time interval of co-operation 8 min is decreased with 0.13 Nm, i.e. with 27%, while in the case of the mineral oil the moment of friction is decreased with 15%, i.e. almost twofold difference.

During lubrication with biodegradable oil HLP-S without additive the moment of friction is lower than that of the mineral oil HLP with 13% during the entire period of friction. During the period of co-operation using lubrication with oil HLP-S the moment of friction is decreasing with 13% in regard to its initial value.

One can notice in Fig. 11 another interesting result, namely that in the case of oil with the additive 'Valena' HLP-SV the process of co-operation is terminated after 6 min, while the moment of friction already remains permanent – 0.35 Nm. In the cases of the other two oils the moment of friction continues to be decreasing, however it has values, smaller than those of the oil HLP-SV with the additive 'Valena'.

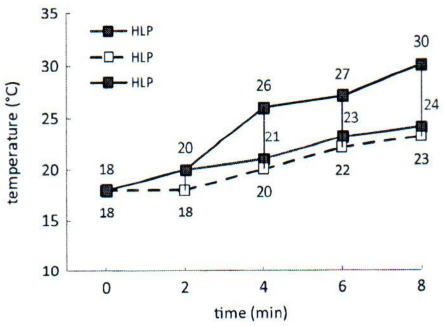

Fig. 12. Dependence of temperature on time interval of friction without any loading during lubrication with mineral oil HLP, biodegradable oil HLP-S and HLP-SV

Within this period of friction of 8 min in the case without any loading the temperature of the oil is the highest for the lubricant HLP-SV with additive 'Valena' (Fig. 12) in comparison with the other two oils. This result is not surprising, taking into account the following circumstance: the effect of the additive 'Valena' upon the contacting surfaces is expressed in the formation of thin copper film of thickness 3 μm having low resistance in the case of tangential sliding. This fact explains the smaller value of the moment of friction, which is clearly seen in Fig. 11. The formation of this protective film, called by its discoverer D. Garkunov servovital film, is occurring under strictly determined conditions of friction, among which the most essential factor is the high temperature during friction.

The influence of the loading on the moment of friction for the three kinds of oils is represented in Fig. 13. For the mineral oil HLP and biodegradable oil HLP-S without the additive 'Valena', the character of the curves is one and the same, whereupon they differ only in absolute values. The moment of friction in the case of biodegradable oil HLP-S is smaller within the whole range of studied loadings. At higher loading 5650 N the moment of friction during lubrication with biodegradable oil HLP-S is lower with about 29% than that of the mineral oil.

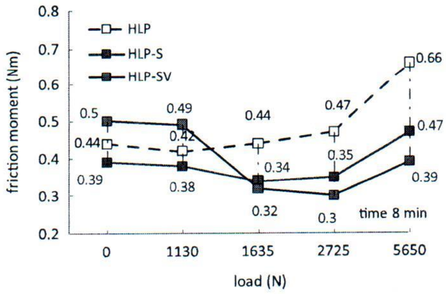

Fig. 13. Variation of moment of friction versus loading in cases of lubrication with mineral oil HLP, biodegradable oil HLP-S and HLP-SV

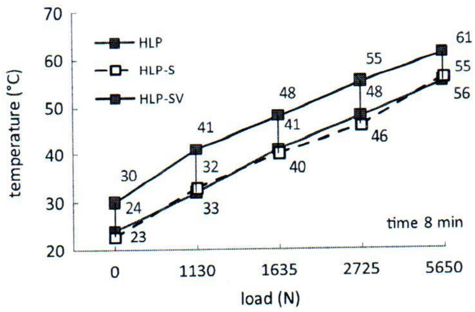

Fig. 14. Variation of temperature versus loading in cases of lubrication with mineral oil HLP, biodegradable oil HLP-S and HLP-SV

The influence of the additive 'Valena' in the biodegradable oil is expressed in changing of the character of the curve. Under loading higher than 1130 N the moment of friction is abruptly decreased with about 40% and then it preserves a constant value under loadings up to 2.4 higher than the initial one. Under loading values 5 times greater than the initial ones the moment of friction starts growing up from 0.3 up to 0.39 Nm.

The low values of the moment of friction under various loadings with the lubricant HLP-SV are in correspondence with its higher temperature (Fig. 14).

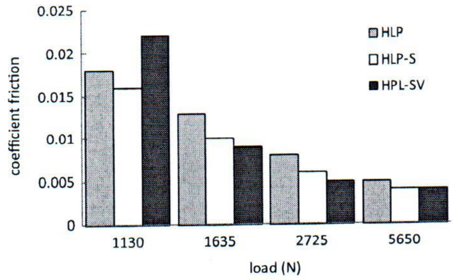

Fig. 15. Diagram of coefficient of friction under various loadings during lubrication with mineral oil HLP, biodegradable oil HLP-S and HLP-SV

A more visual idea about the variation of the friction as a function of the loading can be obtained from the comparative diagram of the coefficients of friction for the three oils of the second group, represented in Fig. 15. The dependence of the reduced coefficient of friction on the loading for the three oils has exponential character, whereupon the steepest dependence is that of the biodegradable oil with additive 'Valena'.

After dismantling of the bearing node one could observe the presence of a thin film of thickness 3 μm having reddish colour on the surface of the shaft (Fig. 16). This film has been obtained as a result of the occurrence of complex physicalchemical and mechanical processes of selective transition of the chemical element copper onto the steel surface of the shaft.

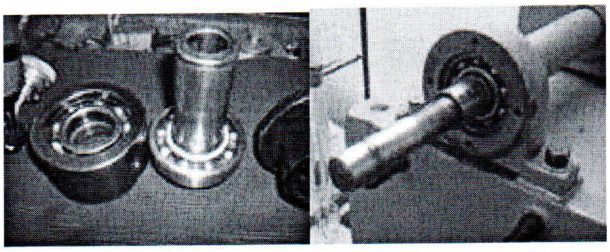

Fig. 16. Photograph of the elements of the bearing node having metal-plating copper film formed after friction for 8 min under loading 5650 N and lubricating oil HLP-SV

In brief we can summarise the following items: the metal-plating additive 'Valena' contains compounds of copper in the form of molecules and ions, which under strictly observed conditions of friction – rate, loading, temperature, chemical nature, physicochemical properties of the materials and type of the lubricating material – they are transferred into the crystal lattice on the surface layer of the steel and with the course of time they are forming a thin film. The so-formed film has porous structure. On one side it compensates micro-roughness along the surface and makes it smoother, while on the other side – due to its low tangential resistance it reduces the plastic deformation in the surface layers during friction. As a result of this both the moment of friction and the coefficient of friction are decreased.

CONCLUSIONS

The main results of the present work can be summarised as follows:

– It has been ascertained that on changing the temperature with 40°C within the interval from 20 to 60°C the dynamic viscosity is decreased to a different extent for the various oils, as follows: Bio-DM – 2.8 times, HLP – about 4 times, while for HLP-S – 3.6 times. In view of these results we could accept that the presence of sunflower oil in the mineral oil leads to more gradual variation of the viscosity on increasing the temperature.

– It has been found out that during lubrication with mineral-vegetable composite HLP-S the moment of friction has lower values than that in the case of lubrication with mineral oil and its variation in the course of time has more stable character unlike the case of conventional mineral oil HLP.

– The addition of the metal-plating additive 'Valena' to the mineral-vegetable oil (HPL-SV) leads to lowering the frictional characteristics of the tribosystem and the temperature of the oil:

– On increasing the normal loading the coefficient of friction for all kinds of oil is decreased. The lowest value is displayed by the coefficient of friction in tribosystems with mineral-vegetable composition HLP-S at all values of the applied normal loading. The most rapid decrease is in the case of coefficient of friction observed with mineral-vegetable oils with additive 'Valena'.

– An effect is registered, concerning the selective transfer in contacting system during lubrication with mineral-vegetable composite with 5% additive 'Valena' – HLP-SV. This effect is expressed in the formation of thin lubricating film of red colour of thickness 2÷3 μm on the rubbing surfaces of the shaft and the internal ring of rolling bearings. The presence of transferred film, containing the chemical element copper, leads to decrease in the coefficient of friction. This result shows compatibility of the metal-plating additive 'Valena' in the mineral-vegetable composite, containing sunflower oil.

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