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Modeling of heat transfer conditions in cooling lubricant emulsions with low-boiling continuous media in narrow gaps

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ABSTRACT

The article analyzes the behavior of the cooling lubricant emulsions of oil-in-water type in a limited volume of narrow gaps. Vapor phase which has been generated by heating the emulsion to a temperature that exceeds the boiling point of water, modifies substantially the conditions of interaction between the dispersed droplets of oil with friction surfaces. Nucleation and growth of vapor bubbles stimulates heat transfer due to the pulsating character of motion of the emulsion and associated with it breakup of the oil droplets. A model of "hot" turbulence has been proposed in the double emulsion of the dispersed phase (oil and steam), initiated by the growth of vapor bubbles. In order to assess the effectiveness of the cooling lubricant emulsion, the mechanisms of hydrodynamic fragmentation of droplets of lubricating oil under conditions of narrow gaps were taken into account. The model was used to estimate the empirical constants in the dependence of the critical temperature from volumetric concentration of oil for AA 5182 aluminum cooling lubricant emulsion E1 (Januszkiewicz et al., 2004), separating the lubrication regime from the "dry" slip regime. It was shown that the model estimates are in good agreement with the experimental data. Therefore, the obtained results indicate that the model representations of this work do not contradict the physical nature of the complex process of heat transfer.

1. Introduction

Manufacturing processes in various industries use large amounts of expensive working and process fluids. The fluids in the form of compositions of the oils, emulsions, aerosols play a significant role in almost all branches of engineering. In particular, they are used for cooling of the working surfaces of workpiece and tool during the machining of metals, lubrication of tools and machines. The removal of heat, modification of the working area with surface-active additives contributes to the quality of treatment, increases the equipment life and improves the working conditions of production staff. The effectiveness of many metals treatment technologies is associated with the use of a variety of cooling and lubricating fluids in the form of heterogeneous dispersed systems. Therefore, the study of their hydrodynamic and thermal characteristics in a specific industrial environment is one of the vital technical and scientific problems.

For the solution of these problems technology of minimum cooling and lubrication (MQCL) [1–3], environmentally friendly machining [4], providing a better quality of surfaces in the industrial machining environment [5] are aimed. The authors performed complex investigations which have shown the significance of the conditions of emulsion mist formation, as well as the detailed contact of single droplets with the object surface. Quantitative and qualitative results of the analysis of the initial indices of the emulsion mist generation in the process of machining under the conditions of the MQCL method contribute to the understanding of the role of various factors in the formation of the complex heat transfer processes. These include the size and distribution of droplets, surface wettability, air pressure, nozzle distance and flow velocity [1]. It should be noted that the emulsion mist represents an important class of dispersed systems, since the dispersion medium (air) in contrast to the liquid emulsion allows you to observe the real state of the processes. Therefore, they serve as a source of visual physical representations that can be used in specifications under similar conditions models of more complex heat transfer processes during evaporation of emulsions.

Heat transfer processes in liquid emulsions with the phase transformations differ in their content and character. They consist of a large number of combinations of elementary physical phenomena, the content of which depends on physico-chemical, thermohydrodynamics and geometric parameters. The number of elementary phenomena and their interactions determine physical content and complexity of the heat transfer modeling. The heat transfer

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conditions from the point of view of phase transitions are significantly different in emulsions with a low-boiling and a high-boiling dispersed phase with regard to the critical temperature of the continuous medium.

Formation of the viable vapor phase nuclei and growth of vapor bubbles in a limited volume of droplets of the dispersed phase or in a large volume of continuous medium are associated with different boiling regimes. In addition, concentration and distribution of the vapor phase in the emulsion volume determine the structural form and the hydrodynamic mode of the emulsion motion. And the latter ones, in their turn, determine the mechanisms of the simultaneous momentum and heat transfer as well as the efficiency of heat transfer processes in general.

The most famous experimental works associated with liquid emulsions are devoted to the thermo-physical boiling characteristics of the low-boiling dispersed phase droplets [5–9]. A positive effect of using emulsions of this type for cooling is that it eliminates the film boiling regime, inhibiting heat removal from the heated surface. The high-boiling continuous medium alters the heat exchange of the heated surface and localizes the vapor phase inside the boiling droplets of the dispersed phase. However, the vaporization mechanisms in the volume, limited by the interfacial boundary surface, differ radically from the conditions of boiling in an unlimited volume. Deformable interfacial surface not only replaces the solid heating surface, but also creates new conditions for the vapor phase formation [10–12]. Analysis based on the experimental data of heat density, determined a complex nonlinear nature of this physical phenomenon [13].

For a reasonable interpretation of the results of such analysis, it is necessary to have information on the composition of the most simple, elementary physical phenomena, identifying the nature of the heat transfer process formation in emulsions. Phenomenological description of the boiling processes even in homogeneous liquids remains in the approximation of the maximum reasonable assumptions, which need to be clarified by experimental studies [14,15].

Heat transfer mechanisms are completed and complicated by the interdependence of the motion mode and its hydrodynamic characteristics. They are related considerably to concentration, size distribution and droplets breakup of the dispersed phase. The momentum transfer in liquid emulsions presents its mechanisms of the elementary physical phenomena that complete and modify the heat transfer processes [16,17]. Clarification of the detailed views using direct experimental observations is even more problematic for the other type of emulsions with the low-boiling continuous medium. It presents technical difficulties with a focused film formation under intensive vaporization conditions. The subject description of such physical phenomena can be based only on the results of the high speed filming or on the high-speed pressure sensors measurements. Besides, creation of conditions for the implementation of various possible elementary physical phenomena and unambiguous interpretation of the observed effects remain problematic [15,18].

An objective description of such physical phenomena can be based only on the results of indirect data related to the research of dispersed systems of different composition. But they consist of a large number of combinations of elementary physical phenomena, composition and relationships which are formed depending on the physico-chemical, thermo-hydrodynamics and geometric parameters. The number of elementary phenomena and their interactions determine the physical content and the complexity of the modeling of heat transfer [19]. Under such circumstances, even particular structures of these processes in various subject areas cannot be identified without using the data of experimental studies.

The article is focused on research problems related to the behavior of cooling lubricant emulsion under conditions of nucleate boiling in a narrow gap between the sliding surfaces using a physical analogy with the boiling in the microchannels of uniform coolant [20–22] and fragmentation of droplets of the cutting fluid turbulent flow of air through the nozzle [1–3]. So emulsions of oil-in-water are widely used to improve lubrication of the friction surfaces and for cooling of the tool during metal cutting. Due to high speed of the metal processing operations by pressure, an efficient heat transfer is also required. Under the circumstances the application of only undiluted oil is not enough for the temperature reducing; it is dispersed in water and is used in the form of an emulsion [1,23,24].

When the emulsion is heated to temperatures exceeding the boiling point of water, representing a continuous medium, a vapor phase is formed, which changes significantly conditions of the dispersed oil droplets interaction with the friction surfaces. Therefore, understanding of the mechanisms of the complex heat transfer processes, occurring during boiling of immiscible fluids in emulsions between the contacting surfaces, is of practical importance. However, the status of emulsion with a double dispersed phase (oil and vapor) that contributes to the heat transfer efficiency under the conditions is understudied up to the present moment.

Estimating the parameters of the proposed model, the results of an experimental study of the behavior of cooling lubricant emulsion in a special setup are used, presented in Ref. [24]. The authors investigated the influence of the concentration of dispersed oil on the friction modes with the height of the surface irregularities. For emulsions $E1$ and $E2$ the existence of a critical temperature was established, at which the coefficient of friction between the contacted surfaces increases dramatically. This phenomenon reflects the characteristics of the boiling regimes of emulsions in narrow gaps arising in the area of partial contact between two metal surfaces. The conclusions of the work [1] about the parameters of the emulsion mist generation have also been used, which influence the layer of tribofilm formation.

2. Models of heat exchange in boiling emulsions in narrow gaps

2.1. Model for bubble boiling

The boiling of homogeneous liquids in microchannels of various cooling devices has been studied by many researchers [25–27]. Despite the complexity and ambiguity of the processes occurring in microchannels, it was found that the determining factor of heat transfer even at high overheating is a mechanism of bubble boiling.

On the basis of the subsequent analysis of the results of studies Labuntsov developed the nucleate boiling homogeneous liquid at the heating surface [28]. He proposed an approximate theory of nucleate boiling and the resulting equations for velocity and density of the heat flow during boiling of a homogenous liquid. According to the theory of Labuntsov, heat flux density q transferred from the heated surface to a boiling on it a homogeneous liquid, consists of two components:

$$q = q_1 + q_2, \tag{1}$$

q_1 is the value, which is determined by the thermal conductivity of viscous sublayer with thickness δ. Therefore,

$$q_1 \sim k_c \frac{T_w - T_s}{\delta}, \tag{2}$$

where T_w, T_s – the surface temperature and the saturated vapor of fluid, k_c – the thermal conductivity of the continuous medium.

The thickness δ is defined on the analogy with the near-wall turbulence [29]

$$\delta \sim \frac{\nu_c}{\bar{u}}, \tag{3}$$

where ν_c – the kinematic viscosity, $\bar{u}$ – the average speed of the pulsation motion of the boiling liquid.

The average kinetic energy of this pulse of motion $\rho_c\bar{u}^2$ represents the energy which is transferred by the liquid boiling to the growing vapor bubbles:

$$\rho_c\left(\frac{dR}{dt}\right)^2 R^2 f_w \sim \rho_c\bar{u}^2, \tag{4}$$

where R – the current radius of the vapor bubble, f_w – the number of active boiling centers per heated surface unit, t – time.

A synthesis of the approximate model of nucleate boiling of Labuntsov has been done to simulate the boiling of emulsions [30]. The birth and growth of viable bubbles of a critical size in continuous medium creates in the emulsion the pulsation movement of such turbulent mixing. These pulsations contribute to the processes of fragmentation and coalescence of dispersed drops of oil.

The size of the steam bubbles formed in a superheated emulsion layer with hydrocarbons as a continuous medium in the narrow gap between the sliding surfaces is determined by the following ratio [28]:

$$R \sim \sqrt{\frac{k_c(T_w - T_s)}{r\rho_v}}\sqrt{t}, \tag{5}$$

where r – the specific heat of vaporization, ρ_v – the density of the vapor phase.

Near the heating surface, the number of nuclei of active boiling f_w with critical radius R_* is defined as [28,31]:

$$f_w \sim \frac{1}{R_*^2}, \quad R_* = \frac{2\sigma T_s}{r\rho_v(T_w - T_s)}. \tag{6}$$

Then the average kinetic energy of the pulsation motion $\rho_c\bar{u}^2$, based on the characteristics of nucleate boiling (4–6), will be presented in the form:

$$\rho_c\bar{u}^2 \sim \rho_c\left(\frac{k_c}{\sigma T_s}\right)^2 (T_w - T_s)^4. \tag{7}$$

The size of the pulsations in such "hot" turbulence corresponds to microscale hydrodynamic, while "cold" turbulence is the order of magnitude of the vapor bubbles.

2.2. Model of fragmentation drops in turbulent flow

The fragmentation of droplets under isothermal turbulent flow with them in immiscible fluid is a mixed stochastic process. The theory A.N. Kolmogorov connects the resistance to breakup of the droplets with the predominant influence of the local turbulence structure.

Resistance of a droplet according to the Kolmogorov–Hinze model is associated mainly with interfacial tension [32,33], opposing to the turbulent velocity fluctuations:

$$d_{\max} = C_1\frac{\sigma}{\rho_c\bar{v}^2}, \quad \text{if} \ d_{\max} > \lambda_0 \tag{8}$$

or the ratio of viscous and surface forces:

$$d_{\max} = C_2\frac{\sigma}{\mu_c\frac{\partial\bar{v}}{\partial r}}, \quad \text{if } d_{\max} < \lambda_0. \tag{9}$$

where σ – the interfacial tension, λ_0 – the microscale turbulent fluctuations, μ_c, ρ_c – the dynamic viscosity and density of the continuous medium, $\bar{v}$ и $\partial\bar{v}/\partial r$ – the average velocity of turbulent pulsation, C_1, C_2 – the experimental constants.

The Kolmogorov–Hinze model complies with the conditions of use of coolant-lubricant fluid in the form of an aerosol. Droplets are formed when the liquid through the nozzle is broken by the turbulent air flow [1–3].

The isothermal movement of cooling lubricant emulsions in narrow gaps of the hydrodynamic turbulent regime cannot be achieved. However, at temperatures higher than the saturation temperature $T > T_s$ the boiling of the continuous medium occurs. Under non-isothermal conditions during the bubble boiling of emulsions between the gliding surfaces movement is associated with more complex physical phenomena In particular, the formation and growth of vapor bubbles contribute to the "hot" turbulence development of the emulsion flow. In turn, it creates conditions for the breakup of the oil droplets similar to the hydrodynamic turbulence.

Because of the small size of the gap between the lubricated surfaces that is of the order of several microns, we can draw physical representations of the boiling coolants in narrow gaps. Under these conditions the growth of bubbles is limited and defined by the critical size of a viable nucleus of the vapor phase about 0.1 μm. Therefore, the fragmentation of oil droplets can be related to the dynamic and surface forces ratio (8).

Taking into account the energy of pulsation motion (7), the relationship for maximum resistant to breakup droplet size (8) into the boiling liquid will be:

$$d_{\max} = C_1\frac{\sigma}{\rho_c(T_w - T_s)^4}\left(\frac{\sigma T_s}{k_c}\right)^2. \tag{10}$$

3. Simulation of behavior of lubricating emulsions during evaporation of the continuous medium

3.1. Model of friction regimes in narrow gaps

The effectiveness of the lubrication is largely determined by the mass (or size) of oil droplets in the contact area of surfaces, their dispersed composition, as well as by the convective heat transfer. Turbulence of the steam bubbles of the continuous medium, located in a narrow space, becomes a significant factor under the incomplete surface contact conditions. It makes the implementation of the specific breakup and coagulation mechanisms of oil droplets that form the composition of the dispersed phase.

The nature of heat transfer depends also on the size and quantity of oil droplets between the sliding surfaces. The boiling of the continuous medium, on the one part, contributes to the cooling of the contact area. However, on the other part, forming and growth of bubbles of the vapor phase increases and creates turbulence of the continuous medium volume. In order to provide lubrication at a given temperature it is necessary to limit the reduction of the dispersed oil droplets mass in the contact area to some critical value. For providing lubrication at the given temperature it is necessary to limit the reduced mass of the dispersed oil droplets in the contact zone to some critical value. Let Δm be the mass of the dispersed phase of the emulsion in the volume ΔV between two contact surfaces on a contact area S. They are connected by the correlation:

$$\Delta m = A\Delta V, \tag{11}$$

where A – the physical quantity, defined as some average density of dispersed phase in this volume.

As a condition for the lubrication mode changes and a sharp increase in the friction coefficient a minimum average value of oil can serve relative mass content between the sliding surfaces and it is defined as:

$$x = \frac{A}{\rho_d} = x_{\min} = \text{const}, \tag{12}$$

где ρ_d – the density of the dispersed phase.

3.2. Modeling transition regimes of friction

The boiling of the lubricating oil emulsion with the low-boiling continuous medium (water) in narrow gaps combines the characteristics of boiling homogeneous fluid and emulsion of water-in-oil [11–14]. Suppose that h_{max} – is the total maximum height of the roughness, a – is the size of the gap between contact surfaces on the area S. Then the equation (4) can be written in the form:

$$n_w V_{max} S \rho_d \sim A(h_{max} + a)S, \tag{13}$$

where ρ_d – the density of the dispersed phase (oil), n_w – the number concentration of a single droplets layer in the emulsion at the surface contact area, V_{max} – the maximum volume of droplets, resistant to breakup in the narrow gap between the sliding surfaces.

Taking into consideration that the surface concentration is $n_w \sim \sqrt[3]{n^2}$, $V_{max} = \frac{\pi d_{max}^3}{6}$, the equation (13) will be written as follows:

$$\rho_d \sqrt[3]{n^2} d_{max}^3 \sim A(h_{max} + a), \tag{14}$$

where n – the number concentration of oil droplets in the emulsion, d_{max} – maximum droplet diameter, resistant to breakup.

Considering the relationship of counting n and bulk W concentration $W = n\frac{\pi d^3}{6}$, the Eq. (14) will be written as follows:

$$A = C_3 \frac{\rho_d d_{max} \sqrt[3]{W^2}}{(h_{max} + a)}, \tag{15}$$

where C_3 – the experimental constant.

Let us denote the value of the relative mass of the dispersed phase content in the friction zone as $x = A/\rho_d$. With this in mind the Eq. (15) takes the form:

$$x = C_3 \frac{d_{max} \sqrt[3]{W^2}}{(h_{max} + a)}. \tag{16}$$

Then, taking into account condition (12), the Eq. (16), which determines the transition of lubrication regime from the "dry" slide mode, will be written as follows:

$$h_{max} + a = C_3 \frac{d_{max}}{x_{min}} \sqrt[3]{W^2}, \tag{17}$$

Therefore, based on Eq. (17) and considering the dependence of the droplet size d_{max} (10) for the boiling emulsion, we obtain the following expression for the mass concentration:

$$x = C_4 \frac{1}{(h_{max} + a)} \frac{\sigma}{\rho_c (T_w - T_s)^4} \left(\frac{\sigma T_s}{k_c}\right)^2 \sqrt[3]{W^2}. \tag{18}$$

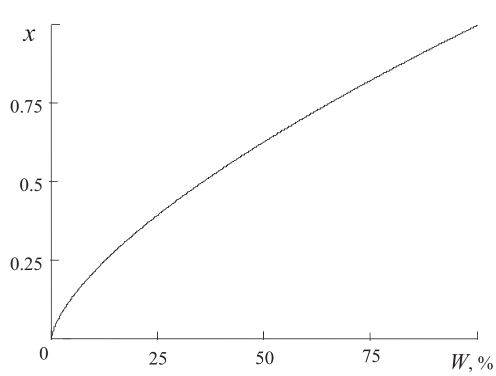

Fig. 1. Dependence of mass concentration of dispersed phase x in zone of lubrication on the volumetric concentration of oil W.

Fig. 1 represents the dependency of mass concentration of dispersed phase x in the lubrication zone on the volumetric concentration W. According to the Eq. (14), the relationship is non-linear.

For critical temperature overheating:

$$(T_w - T_s) = C_5 \sqrt{\frac{\sigma T_s}{k_c}} \sqrt[4]{\frac{\sigma}{\rho_c x_{min}(h_{max} + a)}} \sqrt[6]{W} \tag{19}$$

The final expression for the critical temperature, measured in °C, takes the following form:

$$T_w = 100 + C_5 \sqrt{\frac{\sigma T_s}{k_c}} \sqrt[4]{\frac{\sigma}{\rho_c x_{min}(h_{max} + a)}} \sqrt[6]{W}, \quad ^\circ C. \tag{20}$$

4. Characteristics of experimental setup and materials

To evaluate the results of the model studies, the experimental data received by Januszkiewicz et al. were used on a special installation [24].

Lubricated wear tests were performed on samples made of aluminum alloy AA 5182 and commercially pure aluminum (AA 1100). The nominal composition of the AA5182 alloy is 5% Mg, 0.35% Fe, 0.1% Ti, 0.2% Mn, 0.25% Zn, and the balance is aluminum (w/w) (see Fig. 2).

Oil-in-water emulsions were prepared by shearing two types of neat oils in water usually at 5% (v/v) concentration, using a homogenizer at 15,000 rpm for 5 min. The average oil droplet sizes (volume distribution) of the emulsions were measured as 1.5 μm for $E1$ and 0.2 μm for $E2$. The viscosities were 20 and 33 cSt at 40 °C for $E1$ and $E2$ material respectively.

Tribological tests were performed using a wear and friction tester with ball-on-ring configuration modified to: (1) operate at temperatures up to 300 °C; (2) apply emulsion continuously; as well as (3) measure electrical resistance between the counter-surfaces. By increasing the temperature at constant load and sliding speed with an approximate rate of 1 °C/s, a sudden change in friction or electrical resistance between the counter-surfaces was indicative in the lubrication mechanism [24].

5. Estimation of parameters the model of lubrication and discussion

Model representations of a complex heat exchange during boiling and fragmentation of the emulsions "oil-in-water" in the narrow gaps between the sliding surfaces are based on a qualitative physical analogy. They depend largely on the results obtained in experimental and numerical studies of heat transfer in dispersed systems [1–10,24–28,34].

In such cases it is necessary to test the validity of the proposed model on the quantitative data of experimental studies. This article uses data from the work [24] to determine the critical temperature, the excess of which leads to the "dry" slide mode, at a fixed concentration of oil. Presented in Fig. 3 calculated curve is obtained from the model equations (20) for the critical temperature, the exceeding of which leads to the "dry" friction regime, on concentration of the dispersed lubricant corresponds with the experimental data.

The boiling continuous medium in emulsion of lubricating oil-in-water type prevents visual observation of the oil droplets behavior. The analogy with boiling of droplets at the heating surface does not reflect all the peculiarities of the droplets boiling in emulsions in the narrow gaps. This means that there should be more physical representations, associated with homogeneous boiling of the coolant in narrow gaps. We need to consider the relationship between the oil droplets and the vapor bubbles generated

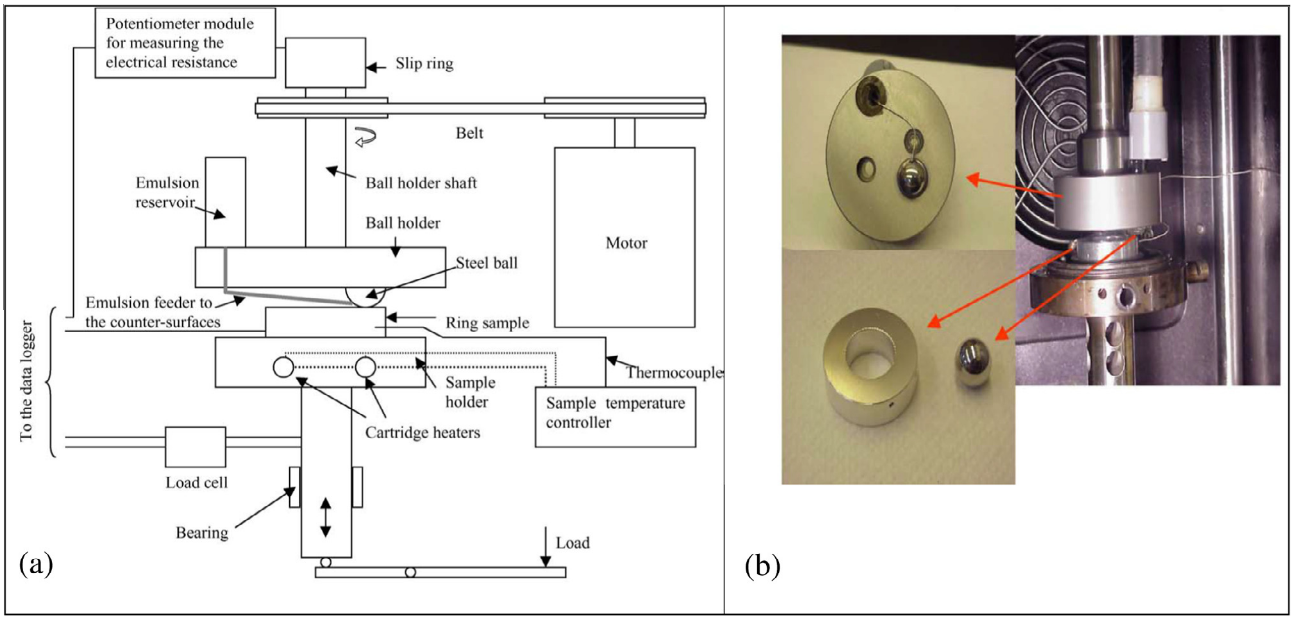

Fig. 2. Diagram (a) and photograph of the friction tester in a ball-on-ring configuration (b) [24].

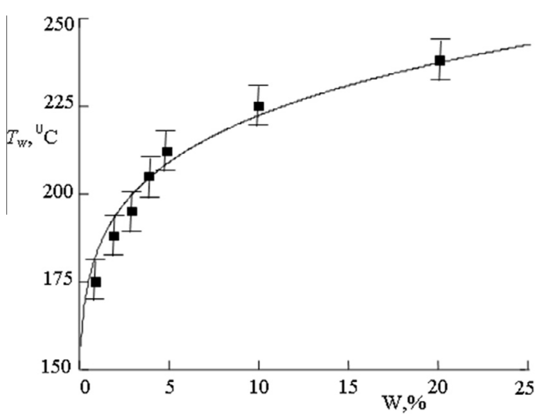

Fig. 3. Model dependence of the critical temperature T_w from the volume concentration of oil W of the emulsion $E1$ in the lubrication zone. Parameters value: $a = 1$ μm, $h_{max} = 0.5$ μm, $C_5 = 12.4$.

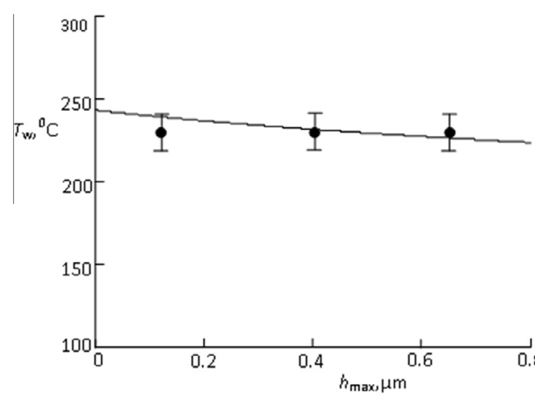

Fig. 4. Model dependence of critical temperature T_w on the maximum height of the roughness h_{max} for emulsions $E1$. Parameters value: $a = 1$ μm, $W = 13\%$, $C_5 = 12.4$.

by the water boiling. In particular, the initiations of viable nucleus of vapor phase of the emulsion "hot" turbulence and the oil droplets breakup are under their influence.

Fig. 4 represents the calculated curve for the dependence of the critical temperature from the model equations (16) on the maximum height roughness of the sliding surface. The points on the graphs show the data of experimental measurements of critical temperatures with their error intervals for the emulsion $E1$ [24].

The match of the model curve with the experimental data allows speaking about the decisive role of the droplets fragmentation processes of the emulsion during the bubble boiling of the continuous medium in narrow gaps. It is important to note that in both cases the admissibility of the constant C_5 also indicates a rather general nature of the model representations of the behavior of cooling lubricant emulsions in narrow gaps between the sliding surfaces.

In the contact zone of droplets the dispersed phase of the emulsion will be exposed to two competing processes: coalescence and fragmentation. At a temperature lower than the saturation temperature of the continuum $T < T_s$, the determining process is a coalescence of the droplets. As a result, the emulsion is stratified and on the surface of the contact liquid film of the dispersed phase is formed. A similar process of formation and growth of such a film, and its characteristics were studied in Ref. [34].

At $T > T_s$, when it starts boiling continua and there is a "hot" turbulence, the process of the droplets fragmentation of the dispersed phase becomes crucial. The fragmentation of droplets in the contact zone leads to a decrease in their size. In the case when the size of the channel is much larger than the diameter of the droplets, any of boiling modes of a homogeneous liquid can take place, including the film boiling regime.

Otherwise, when the droplet size exceeds the size of the narrow channel, the film boiling regime in the continuous media becomes impossible. The temperature increase during the boiling of a continuous medium leads to a decrease of the mass concentration of the dispersed phase in the contact zone. This makes favorable conditions for the "dry" friction regime between the contacting surfaces.

6. Conclusion

In this paper a model of lubricating emulsion is proposed which can be used to determine mechanisms of heat transfer in narrow gaps. In order to show the possibility of applying physical notions regarding the "hot" turbulence, the problem of the modes of lubrication in the contact zone of sliding surfaces was solved. Original relationship was derived for maximum size of droplets, which are not subject to fragmentation under the influence of the pulsation motion of bubbles in the boiling liquid. Further studies have been conducted to show the significance of the effect of the oil drops fragmentation on behavior of lubricating emulsions:

(1) A model of oil droplets fragmentation in cooling lubricant emulsions under conditions of "hot" turbulence, which was initiated by means of steam bubbles during boiling of the continuous medium, has been considered. A model of behavior at critical temperature has been proposed and analyzed, separating the regimes of lubrication and "dry" sliding from the volume concentration of oil.
(2) Dependencies have been proposed for calculation of the mass concentration of the dispersed phase in the area of lubrication and the critical temperature of the transition from the lubrication regime to the "dry" slip regime. They do not contradict the experimental data [24] for the "oil-in-water" emulsions at temperatures exceeding the boiling point of the continuous medium of the emulsion.
(3) It has been shown that the decrease in the droplet size resulting from the fragmentation can lead to the film boiling regime of a continuous medium. The comparison of the obtained results and data of experiments confirmed the decisive role of the droplets fragmentation of the dispersed phase of the emulsion if the "dry" friction occurs.

The developed model contributes to a better understanding of the behavior of lubricating emulsion and to an efficient organization of technological process with minimum cooling and lubrication.

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