Development of a Mathematical Model of the Hydroerosive Wear of the Piston Couple in Hydraulic Machines: Part 1

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Abstract—The paper presents a definition of hydroerosive wear, which occurs in hydraulic machines due to water/air presence in fluid, obtained from a mathematical model. The model includes fatigue processes related to the influence of hydraulic water droplets inside of air bubbles in the surface layer of metal, as well as a sharp increase in temperature caused by adiabatic compression in the piston chamber of a hydraulic machine.

Keywords: math model, hydroerosive wear, hydraulic machines, water, air, fluids, piston couple

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INTRODUCTION

The reliability of many critical hydrodrives depends on the performance of their compounds and volume hydraulic machines. In turn, the reliability of pumps, hydromotors, and cylinders is largely determined by the presence of different types of pollution in hydraulic fluids. The influence of mechanical impurities contained in the working fluid on the wear of friction pairs has received much attention in the scientific literature [1]. However, the question of the wear of friction couples of hydraulic machines when using oil contaminated with water and air has not been studied thoroughly. There are only reports of extremely negative impacts of water and air on the performance of hydraulic machines [2]. Issues of the erosion of materials erosion by cavitations are widely presented in today’s publications, e.g., in [3]. In this paper, we consider the cavitation wear of hydraulic turbines operating under conditions that differ from those of volume hydraulic machines. In [3], the cavitation surface erosion under the action of mechanical hits with air bubbles is investigated using computer simulation. This paper does not consider thermodynamic processes that occur during the condensation of bubbles. In [4], the data of experimental studies of semiconductor surface damage due to bubble cavitation erosion during supersonic cleaning are presented. This paper considers the cavitation bubble models that are widely used in technical acoustics [5]. In piston hydraulic machines, supersonic flow rates are unattainable; therefore, the models of cavitation wear proposed in [5] cannot be applied to predict the resource parameters of hydraulic machines. In this paper, we attempt to develop a model of hydroerosive piston couples wear caused by cavitation under complicated conditions of mineral contamination of process fluids, not only with air, but also with water.

STATEMENT OF THE PROBLEM

Piston, plunger, plate, and other friction couples of volume hydraulic machines are affected with cycles of pressure increases and decreases. As is well known, cavitation, i.e., the discontinuity of fluid flow due to the appearance of bubbles or cavities filled with a gas or vapor, occurs when the pressure is being lowered. In most cases the fluid in pumps flows so quickly through an area of low pressure that the gas does not have time to segregate. So, water vapor enclosed in the air bubbles is released into air contained in the working fluid and having a certain humidity. Following an almost instant pressure increase, bubbles collapse. In [6], it was shown that pressure drops during cavity collapse may reach huge values on the order of hundreds of megapascals, which leads to pitting in the material of the channel walls, vibrations, and acoustic phenomena. At present, there is no satisfactory mathematical model of the process. There are several unresolved issues that are important in practical terms. One must determine, first, the link between the rate of wear due to cavitation and complex physical and chemical properties of the material and, second, the relationship between the rate of hydroerosive wear of friction couples and the hydrodynamic characteristics of the flow.

These issues are still unresolved due to the lack of a common approach to the mechanism of the influence of cavitation on material wear. It has been established
that, at high intensities of hydraulic impact during cavitation, the material is also susceptible to plastic deformations that develop at the bottom of craters (micropits) located on the surface of the material. Thus, cavitation erosion is caused, not only by mechanical action of the hydraulic impact series, but also by the thermofluctuation nature of the process of bubble collapse.

**Hydroerosive Wear Modeling**

The essence of the proposed hydroerosive model wear is as follows. With the passage of the working fluid through a hydraulic machine, which significantly boosts the pressure, the deformation of the bubbles of undissolved air with a corresponding change in temperature takes place. If the temperature increase caused by a pressure increase occurs so rapidly that the heat transfer is negligibly small, after the completion of the compression process, the temperature can be defined as follows:

\[
T_2 = \left( \frac{P_2}{P_1} \right)^{n'/(n'-1)} T_1, \tag{1}
\]

where the subscripts 1 and 2 refer to the initial and final states; \( P \) is the pressure; \( T \) is the temperature; and \( n' \) is the process polytropic exponent, which depends on the physical properties of air or other gas (steam or gas cavitation).

The local temperature rise in the gas bubble can reach very high values. For example, when the pressure rises from 0.1 to 5 MPa, at a polytropic exponent \( n' = 1.7 \) and an initial temperature of 323 K, the final temperature \( T_2 \) inside the bubble will be 1606 K. The ambient air entering the hydraulic system through the hydraulic tank fittings and loose connections always contains water vapors. If the bubble contains a water drop, then, following almost instant temperature increase as in the example above, the same instantaneous evaporation of water drop should occur that is comparable to the effect of an explosion. Shock wave with front consisting of water drops reaches the metal surface resembling a sort of bombing. In addition to the mechanical impact of the exploded drop, plastic deformations of the surface associated with the local temperature rise should take place. Microwrenches that correspond in size to steam bubbles formed during the evaporation of water droplets may appear on the metal surface. In particular, microwrenches on the working surfaces of the pistons of pumps have been noted by the authors after bench testing these pumps in oil contaminated by water (up to 3% by volume) [7].

Assuming that the process of instant droplet evaporation takes place at a constant volume of the gas bubble, under the influence of vapors, the pressure inside increases and, due to the difference in pressure in the bubble and the environment, the lower the pressure in the hydraulic system, the greater the pressure gradient. In this case, the rate of hydroerosive wear of the pistons should decrease with increasing pressure in the hydraulic system. If the hydraulic oil contains both air and water in liquid form, then the number of droplets inside of the gas bubbles will increase, which leads to increase in wear and the number of drop hits. However, due to the high velocity of processes and finite volume of gas bubbles that fill the drops with water is limited, so hydroerosive wear should stabilize when the maximum possible number of drops inside the bubbles is reached. In developing the phase of pressure growth for hydroerosive wear model, we took into account the fatigue phenomena in the surface layer of friction couples and thermodynamic processes.

The calculations will be carried out for 1 m³ of liquid \( (V_1 = 1 \text{ m}^3) \). When oil dissolves air, it also dissolves the water contained in the air. The weight of moisture in vapor form per 1 kg of dry air (\( m'_{a} \)) can be determined at known humidity (\( \varphi \)) from the Clapeyron equation as follows:

\[
m'_{a} = 0.622 \frac{\varphi P_c}{P_1 - \varphi P_S}, \tag{2}
\]

where \( P_S \) is the vapor pressure at saturation temperature \( T_S \) and \( P_1 \) is the atmospheric air pressure.

The coefficient 0.622 is obtained from ratio of steam and air molar masses.

Based on gas volumes \( V_g \) and \( m'_{a} \), we can calculate the mass of water \( (m_w) \) contained in oil as follows:

\[
m_w = V_g m'_{a}. \tag{3}
\]

As shown by calculations based on (2), when the pressure increases from atmospheric to \( P_2 = 1 \text{ MPa} \) or higher, the moisture content \( m'_{a} \) becomes negligible. The radius of droplets scattered within volume \( (R_d) \) will be determined by surface tension forces as follows:

\[
R_d = 2 \sigma_{s.t.} / P_2, \tag{4}
\]

where \( \sigma_{s.t.} \) is the surface tension.

Number of drops \( Z_d' \) in 1 m³ of oil is equal to

\[
Z_d' = m_w / m_d = \frac{V_g m'_{a}}{(4/3)\pi R_d^3 \rho_w}, \tag{5}
\]

where \( m_d \) is the mass of 1 drop of water and \( \rho_w \) is the density of water.

It is known that hydraulic oils contain air bubbles with average radii \( (R_{ab}) \) of about 27 \( \mu \text{m} \). During the compression of pressure fluid, the temperature of air inside the bubble rises to the value determined by (1).

The amount of heat that is wasted in heating the air in the bubble from temperature \( T_1 \) to temperature \( T_2 \)