Investigation of Hydraulic Processes Within an Aeroengine Bearing Chamber

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***Abstract*—It's describe the investigations results of processes in the electrically driven oil system at a facility with a simulator of a gas turbine engine oil chamber. A physical model of processes in the oil chamber is proposed, and its mathematical model is developed. The mathematical model is verified by computational studies.**

***Keywords*—oil system, electric motor-driven pump, mathematical model**

I. Introduction

Tests of the demonstration electrically driven oil system (DEOS) showed that if the working medium in the units of oil system is a two-phase mixture, then a number of complex processes arise that require in-depth research, including processes in the oil chamber (OC) [1].

As a rule, the literature describes the composition and functions of the oil system, as well as characteristics of its components – breathers, heat exchangers, pumps [2, 3, 4]. There are a few studies on the working process in individual components of the system. For instance, two-phase mixture flow in a cylindrical chamber with a rotating shaft simulating the gas turbine engine oil sump is experimentally investigated in [5]. This study, as well as work [6], is aimed at assessing the possibility to use software packages of applied fluid dynamics (ANSYS Fluent, etc.) for calculations of oil chambers. The analysed flow is not typical for oil chambers in gas turbine engine (GTE), because water is used as a liquid phase, air inflows from atmosphere through a hole at the top the cylindrical chamber, the two-phase mixture is drained from the chamber by gravity and not by a pump.

This article is devoted to the creation of a mathematical and physical model of the processes occurring in the oil chamber of the GTE rotor support. For this, the results of tests of the oil system with electrically driven supply and scavenge gear pumps in the installation with the oil chamber simulator are taken as the basis [7].

II. DEOS Test Results

The principal scheme of DEOS and bench stand with a simulator of GTE oil chamber is shown in Fig. 1. The rotor of bearings is driven by electric motor through a multiplier. The oil from oil tank 7 is fed through the oil filter 10 to two nozzles 11 and to the bearings 3 by feed pump 9. The oil chamber 1 is separated from pre-oil chambers by baffles with sealing 4. Air with excess pressure is supplied into pre-oil chamber to prevent the oil overflow from the oil chamber into pre-oil chamber through the seal of rotor. Oil and air are mixed in oil chamber. Thus the oil-air mixture is formed consisting of the gas emulsions of higher density in upper parts and lower density in the bottom, which is pumped by pumps 8 through a heat exchanger 6 in oil tank 7. Oil tank provides a separation of the air from the oil and brings it into the atmosphere. A throttle valve 5 is installed after pumps. Closing of throttle valve simulates pressure losses in engine's oil system from pumps to oil system.

The visualization of mixture flow through the optically transparent tubes 14 at the scavenge pump's 8 inlet and outlet is carried out during the test. Sensors with a transmission frequency of 1000 Hz are used for measuring the pressure. Information from the pressure sensors is registered to obtain the spectra of pressure fluctuations in the digital analyzer of dynamic processes MIC-300M by "Measure". Changing the color of two-phase mixture at its flow is used for visual estimation of flow dispersion.

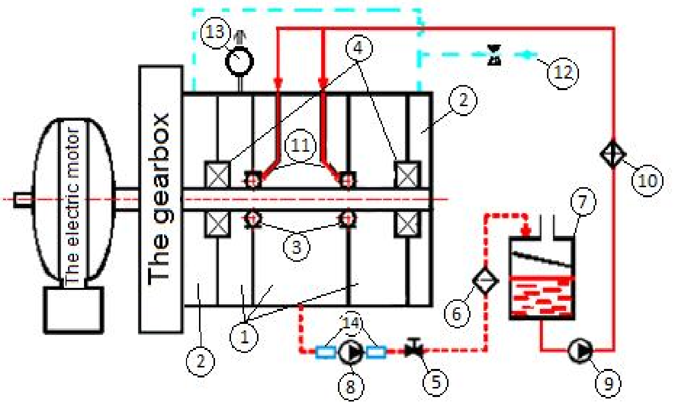

Fig. 1. Principle scheme of DEOS

1 – oil chamber; 2 – pre-oil chambers; 3 – bearings; 4 – seals; 5 – throttle valve; 6 – heat exchanger; 7 – oil tank; 8 – scavenge pump; 9 – feed pump; 10 – oil filter; 11 – nozzles; 12 – air supply; 13 – breather; 14 –transparent tubes.

The streams: – oil; – oil-air mixture; – air supply; – air discharge.

The MS-8P aviation mineral oil is used in tests; overpressure in the OC is between 0.01 and 0.03 MPa; pressure at the supply pump outlet is between 0.3 and 0.5 MPa; oil flow rate in the supply line is between 10 and 20 l/min and in the scavenge line - <60 l/min; mixture temperature varies between 20 and 70°C, volumetric gas content is between 0.2 and 0.5, rotational speed of the bearings in the OC changes within 4000-12000 rpm.

The analysis of the DEOS tests according to data presented in [7] and shown in Fig. 2 in the form of time records of the excess pressure at the OC top point, P_{oc_up}, and absolute pressure at the bottom point, P_{oc_bot}, and their spectra shows a considerable difference both in composition and amplitudes of harmonics along the OC height.

The mean value of pressure vibration amplitudes at the OC top point is about 0.0025 bar, the vibration records have a noisy character, and the pressure spectrum is characterized as "white noise" (Fig. 2a).This is an evidence of a random nature of the processes in the OC upper part due to the fact that there is a two-phase mixture with a low density as a result of a high content of air bubbles as compared with the OC bottom part. The bubbles in the mixture tend to coalesce due to effect of gravity forces on the oil film of bubbles.

A denser two-phase mixture is formed at the OC bottom. Processes with high vibration amplitudes take place in this part, as evidenced by time records of pressures and their spectra at frequencies higher than 10 Hz (Fig. 2b). In this case, the mean value of pressure vibration amplitudes at the OC bottom point is about 0.012 bar, that is not less than 5 times higher than the amplitude at the top point. A polyharmonic character of vibrations with summation of many frequencies is observed in time records of P_{oc_bot}.

As known, the gas-liquid emulsion is a homogeneous dispersion fluid consisting of two immiscible components. If air bubbles in the liquid phase (oil) in suspension state are contained in this fluid, this is an oil-air mixture. If oil droplets in the gas phase (air) in a suspension state are contained in this fluid, this is an air-oil mixture. These definitions are used below.

A spectral analysis of the pressure records in the oil chamber and flow visualization of the working medium at the inlet and outlet of scavenge pump showed that:

- The oil-air mixture is formed in the lower part of oil chamber, and the air-oil mixture is formed in the upper part. The air-oil mixture is removed from the chamber by a breather and can partially enter the pumping-out path.
- The oil-air mixture flows from oil chamber, and the mixture color changes when the pressure in the pumping-out path changes.
- If pump the air-oil mixture, then its structural sustainability is saved with local expansion and compression of the flow.
- The air-oil inclusions (bubbles) occur at the scavenge pump outlet only if they are present at the pump inlet.
- The bubbles speed in the outlet pipe of scavenge pump is higher than the two-phase mixture speed. They move and smoothly displace the mixture in front of them, without breaking the flow along the radius.

Based on these findings, it can be assumed that the process of dispersed mixture generation in the oil chamber is the same as the process of oil emulsion generation. Dispersion of one phase (air) in another phase (oil) takes place with formation of an adhesive (adsorption) stabilizing film (oil) on dispersed particles (air bubbles). This film prevents coalescence and stratification of the mixture. In this case, pumped flow of oil and air and to a lesser extent rotating rolling elements of the bearing, that providing hydrodynamic dispersion of air in oil, act as emulsifiers. Surface active substances (polar molecules of additives), which participate in the creation surface tension forces at the oil-air boundary, act as a stabilizing film. The resultant fine-dispersed oil-air mixture is a continuous elastic medium (conditionally called as "porous sponge") consisting of a number of immiscible bubbles moving with the same speed and covered with an oil film.

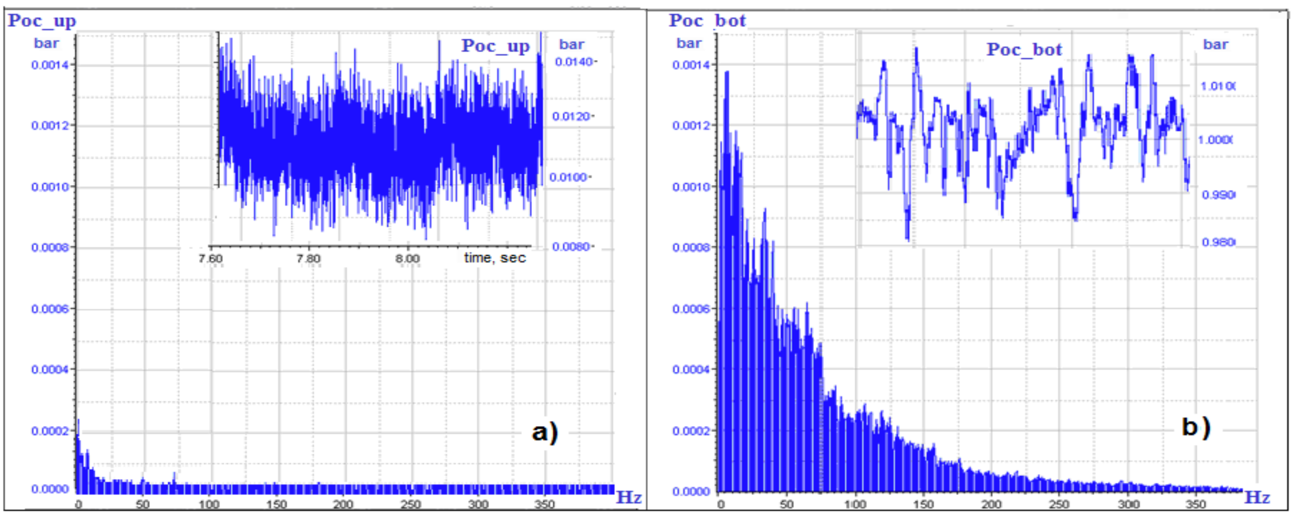

Fig. 2. Time records and spectra of pressure at the top (a) and bottom (b) points

Under action of Archimedes' buoyant force, bubbles of larger sizes emerge at the OC top in the form of bubbles covered with oil film. Under action of gravity, the film thickness decreases, and the film breaks down to form oil droplets with different sizes. At the same time, a part of the droplets coagulates and forms liquid oil while other droplets remain in air released from the bubble and form air-oil mixture (emulsion). The granulometric composition of oil droplets in the mixture is determined by processes of oil droplets generation in the oil chamber, film rupture, etc.

Surface tension forces at the "oil-air" boundary are the key mechanism in formation of a fine-dispersed oil-air mixture (emulsion) that outflows the bearing oil chambers into the pumping-out line.

An additional factor confirming the process of air and oil dispersion is the experiment with a special defoaming additive (PMS-200A) injection in the oil tank that reduces oil foaming by 90%. Analysis of test results shows that the additive decreases the pressure vibration amplitude by 23-40%,and power consumed by the pump decreases (as estimated from an active component of electric drive power) [7].

The additive in oil speeds up oil deaeration, i.e. accelerates the process of air release from oil in the OC, and, consequently, results in changes in the gas mass content along the OC height. Additionally, there is an increase in amount of air inflowing the OC top part and a decrease in amount of air incoming the bottom part.

As a result of this process, the air-oil mixture flowing out of the oil chamber has a lower value of gas mass content; sizes of air bubbles in the OC are slightly increased due to a decrease in surface tension forces at the oil-air boundary.

In literature, for example [11], the term "dissolved" air in liquid is widely used, that means the presence of air in oil in the form of micro-bubbles not interacting with each other. The bubbles reside in oil in this state due to the presence of surface tension forces at the oil-air boundary that interfere with the Archimedes' buoyant force. These forces decrease with a decrease in oil viscosity. Due to saturation, motionless mineral oil under standard atmospheric conditions contains up to 7-10 vol.% of dispersed ("dissolved") air [11].

III. Physical Model of Processes in the Oil Chamber

The process of dispersed fluid formation in the OC is multivariable. It can be presented as a result of distribution of liquid oil (incoming from rolling elements of the bearing) and air (incoming from the rotor-casing clearance) among different zones in the OC: Zone 1 - above the rotor, Zone 2 – to the side of the rotor, and Zone 3 - under the rotor (Fig. 3). Oil film can be formed on the OC walls with thickness about 3...5% of volume [5]. Air-oil mixture (AOM) is formed in the emersion zone (Zone 1), oil-air mixture (OAM) - in the pumping-out zone (Zone 3); oil and air inflowing the OC at T_o and T_a, respectively, are mixed and dispersed in Zone 2. The resultant air-oil mixture under action of the Archimedes' force rises up to the top of the OC at an increasing u_{AOM} rate of rise, and air-oil mixture is pumped out from the OC by a scavenge pump at u_{OAM} rate.

Similar but less severe processes are observed in oil tanks used to supply oil to the inlet of the oil system supply pump. As shown in [2], air bubbles incoming the oil tank together with oil-air mixture pumped out of the supports are not all floating up to the over-oil space of the tank. Smaller bubbles are entrained by oil and outflow into the supply line.

Volume of zones changes with time of operation. It is assumed that the volume of dispersion zone, V_{dis}, is constant; the volume of pumping-out zone, V_{OAM}, is equal to the volume of air-oil mixture in the OC; and the volume of emersion zone, V_{AOM}, can be found from the equation: $V_{OC}=V_{AOM}+V_{dis}+V_{OAM}$, where V_{OC} – volume of the OC. In this case we can derive:

$$V_{AOM} = V_{OC} - V_{dis} - V_{OAM}\,,\; V_{AOM} \geq 0 \tag{1}$$

In addition to pressure and temperature of the mixture and sizes of bubbles, specific parameters of the physical process in the oil chamber are the following:

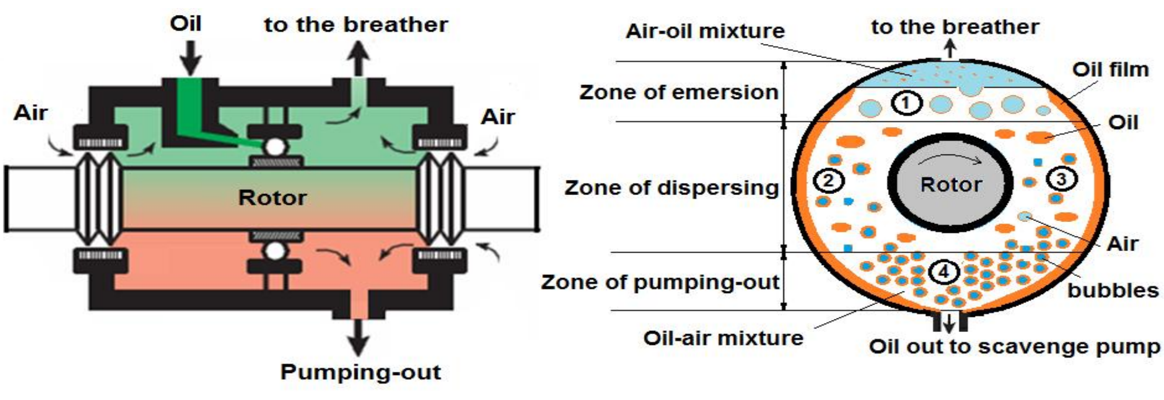

Fig. 3. Schematic diagram of the flow distribution in the oil chamber

- λ_o is the separation coefficient of the oil entering the OC into two parts: one part enters to the pumping-out zone, and the other - the emersion zone with a coefficient $(1–\lambda_o)$;
- λ_a is the separation coefficient of the air entering the OC into two parts: one part enters to the pumping-out zone, and the other - the emersion zone with a coefficient $(1–\lambda_a)$;
- Δt_{dis} – dispersion time of air bubbles into oil;
- Δt_{OAM} – residence time of oil-air mixture in the OC pumping-out zone;
- Δt_{fl} – floating up time for bubbles of air-oil mixture in the OC emersion zone.

The value of λ_a depends on many factors: OAM volume; temperature of the adsorption stabilizing oil film, T_{film}; the OC design; etc. The dependence is proposed for to determine the coefficient of air separation λ_a:

$$\lambda_a = f(\overline{V}_{mix}) \cdot f(\overline{T}_{film}) = (k_0 - k_1\overline{V}_{mix}) \cdot (k_2\overline{T}_{film}),\quad 0 \le \lambda_a \le 1 \tag{2}$$

where: $\overline{V}_{mix} = V_{OAM}/V_{OC}$ – relative volume of OAM equal to the ratio of the current volume of mixture to total volume of the OC; $\overline{T}_{film} = T_{o\text{-}a}/T_{base}$ – relative temperature of the adsorption stabilizing film equal to the ratio of the mass-average temperature of inflowing oil and air, $T_{o\text{-}a}$, to their base temperature, T_{base} ($T_{base} = 293$ K); k_0, k_1, k_2 – approximation coefficients; $T_{o\text{-}a} = (T_oG_o + T_aG_a) / (G_o + G_a)$.

Equation (2) illustrates the fact that the fuller the OC is filled with OAM, the greater is the air amount entering to the emersion zone – $f(\overline{V}_{mix})$; and the higher is the temperature of inflowing oil and air, the less is influence of surface tension forces and the greater is the number of air bubbles entering the emersion zone – $f(\overline{T}_{film})$.

According to DEOS experimental studies, k_2 coefficient is taken equal to 1; values of k_0 and k_1 can be found from the following conditions: $\lambda_a = 1$ at $\overline{V}_{mix} = 0.1$, $\lambda_a = 0.1$ at $\overline{V}_{mix} = 0.9$. With account of limitations imposed on values of $\overline{V}_{mix}$ and $\overline{T}_{film}$ used in tests, we get:

$$\lambda_a = (1.04 - 1.051\overline{V}_{mix}) \cdot \overline{T}_{film},\quad 0 \le \lambda_a \le 1,\ 0.1 \le \overline{V}_{mix} \le 0.9,\ 1 \le \overline{T}_{film} \le 1.07 \tag{2a}$$

The time of dispersion Δt_{dis} can be determined by the transition process of mixture formation in the volume of dispersion zone V_{dis}. It is accepted that this process is aperiodic with the time constant for the formation of dispersed mixture τ_{dis} equal to the ratio of dispersion volume V_{dis} to the total volume of air Q_a and oil Q_o flows entering to oil cavity:

$$\tau_{dis} = V_{dis} / (Q_a + Q_o) \tag{3}$$

Floating up time of the mixture, Δt_{fl}, is found as time of mixture transit through the V_{AOM} volume at u_{fl} velocity derived from the Stokes equation for bubbles emersion (floating up) [9]:

$$\Delta t_{fl} = V_{AOM} / (F_{OC}u_{fl}), \tag{4}$$

$$u_{fl} = (2\rho_o g r^2) / (9\mu_o) \tag{5}$$

where: ρ_o, μ_o — oil density and dynamic viscosity; g – free-fall acceleration; r – bubble radius.

Residence time of the oil-air mixture in the pumping-out zone, Δt_{OAM}, is found as time of mixture transit through V_{OAM} volume at u_{OAM} velocity:

$$\Delta t_{OAM} = V_{OAM} / (F_{OC}u_{OAM}), \tag{6}$$

$$u_{OAM} = u_{pipe}F_{pipe} / F_{OAM} \tag{7}$$

where: F_{OAM} – equivalent cross-sectional area of the OC in the pumping-out zone; F_{pipe} and u_{pipe} – cross-sectional area of the oil-air mixture pumping-out pipeline and flow velocity in it.

Mixture flow velocity in (7) is determined from the condition of continuity of oil-air mixture flow in the pumping-out zone and in the pumping-out pipeline at the OC outlet.

Equations of the mathematical model for the oil chamber should provide calculations of the pressure, temperature and mass (volume) gas content of the working medium at the outlets from the oil chamber. To solve the equations of this module, besides the geometrical dimensions, the following parameters must be known (calculated in other modules): flows of air, G_a, and oil, G_o, entering into the oil chamber, their temperatures T_a and T_o, also flows discharging into the breather, G_{br}, and the pumping-out line, G_{OC}.

To calculate air and oil flows at the outlet of the dispersion zone ($G_{d.o}$, $G_{d.a}$), we use a differential equation of a lag element with a time constant that is equal to a time constant of a disperse mixture formation, τ_{dis}.

$$\tau_{dis}\frac{\mathrm{d}G_{d.o}}{\mathrm{d}t} = G_o - G_{d.o}, \tag{8}$$

$$\tau_{dis}\frac{\mathrm{d}G_{d.a}}{\mathrm{d}t} = G_a - G_{d.a} \tag{9}$$

After the dispersion process, $G_{d.o}$ and $G_{d.a}$ flows are distributed within the OC volume in accordance with λ_o and λ_a coefficients. A layer of oil-air mixture, $G_{d.OAM}$, is formed at the bottom of the dispersion zone (Fig. 3) consisting of oil and air incoming it and equal to $\lambda_o \cdot G_{d.o}$ and $\lambda_a \cdot G_{d.a}$; a layer of air-oil mixture, $G_{d.AOM}$, is formed in the top part where amount of oil and air are respectively equal to $(1 - \lambda_o) \cdot G_{d.o}$ and $(1 - \lambda_a) \cdot G_{d.a}$:

$$G_{d.OAM} = \lambda_o G_{d.o} + \lambda_a G_{d.a}, \quad (10)$$

$$G_{d.AOM} = (1-\lambda_o)G_{d.o} + (1-\lambda_a)G_{d.a} \quad (11)$$

The mass gas content $x_{d.OAM}$ and $x_{d.AOM}$ come from the dispersion zone into the OAM and AOM layers, respectively. They can be calculated from the ratios for a homogeneous mixture:

$$\chi_{d.OAM} = \lambda_a G_{d.a} / G_{d.OAM}, \quad (12)$$

$$\chi_{d.AOM} = (1-\lambda_a)G_{d.a} / G_{d.AOM} \quad (13)$$

The volume of oil-air mixture, $V_{d.OAM}$, in the OAM layer can be calculated by dividing the mass of this mixture by its density, $\rho_{d.OAM}$. The mass of mixture is a product of the mixture flow rate, $G_{d.OAM}$, and the step of numerical integration of the OC system equations, Δt_{int}.

$$V_{d.OAM} = G_{d.OAM} \Delta t_{\text{int}} / \rho_{d.OAM}, \quad (14)$$

$$\frac{1}{\rho_{d.OAM}} = \frac{(1-\chi_{d.OAM})}{\rho_o} + \frac{\chi_{d.OAM}}{\rho_a} \quad (15)$$

where: $\rho_o = f(T_{mix})$, $\rho_a = P_{OC\_up}/R_a/T_{mix}$ – partial values of oil and air densities; P_{OC_up} – pressure in the OC upper part; R_a – air gas constant; T_{mix} – mixture temperature.

The layers move from the bottom point of the emersion zone upwards at u_{fl} velocity and downwards - from the upper point of the pumping-out zone at u_{OAM} pumping-out velocity. After Δt_{OAM} and Δt_{AOM}, the layers reach the upper and lower points of V_{AOM} and V_{OAM} volumes, respectively.

Movement of layers is described by an equation with transportation lag. For such parameters as mass flow rate, G_{AOM}, and gas content in air-oil mixture, x_{AOM}, at the OC top point, we have:

$$G_{AOM} = V_{d.AOM}(t_i - \Delta t_{fl}), \quad (16)$$

$$\chi_{OAM} = \chi_{d.OAM}(t_i - \Delta t_{fl}) \quad (17)$$

and such parameters at the OC bottom point as volume of OAM layer, V_{OAM}, and gas content, x_{OAM}, can be found as:

$$V_{OAM} = V_{d.OAM}(t_i - \Delta t_{OAM}), \quad (18)$$

$$\chi_{AOM} = \chi_{d.AOM}(t_i - \Delta t_{OAM}) \quad (19)$$

Local values of oil-air mixture homogeneous density, ρ_{OAM}, and air-oil mixture homogeneous density, ρ_{AOM}, at the inlets of pumping-out pipeline and breathing systems can be calculated based on local gas content at the final points of mixture movement as follows:

$$\frac{1}{\rho_{OAM}} = \frac{(1-\chi_{OAM})}{\rho_o} + \frac{\chi_{OAM}}{\rho_a}, \quad (20)$$

$$\frac{1}{\rho_{AOM}} = \frac{(1-\chi_{AOM})}{\rho_o} + \frac{\chi_{AOM}}{\rho_a} \quad (21)$$

The volume occupied by oil-air mixture, V_{OAM}, is calculated by the formula:

$$V_{OAM} = \sum_{i=1}^{n} V_{i.OAM} \le (V_{OC} - V_{dis}), \quad n = \Delta t_{OAM} / \Delta t_{\text{int}} \quad (22)$$

Mixture pressure in the emersion zone is calculated from the mass flow balance: the zone receives air-oil mixture flow, G_{AOM}, and discharges flows into a breather, G_{br}, and a pumping-out line, G_{OC}. With account of the mixture compressibility in the OC, we have:

$$c_{mix} \frac{\mathrm{d}P_{OC\_up}}{\mathrm{d}t} = G_{AOM} - G_{br} - G_{OC} \frac{\rho_a}{\rho_{OAM}} \quad (23)$$

where: $c_{mix} = V_{OC}/a^2_{mix}$ – compressibility coefficient; a_{mix} – sonic speed in mixture.

Pressure at the OC bottom point is equal to pressure in the emersion zone plus hydrostatic pressure head of oil-air mixture found from the height of mixture column in the pumping-out zone, h_{OAM}, and a mean density of the oil-air mixture between the layers at the start and end points of the pumping-out zone – $\rho_{d.OAM}$ and ρ_{OAM}:

$$P_{OC\_bot} = P_{OC\_up} + 0.5(\rho_{d.OAM} + \rho_{OAM}) h_{OAM} g \quad (24)$$

Oil-air mixture temperature, T_{mix}, is assumed to be the same within the total volume of the oil chamber. With account the fact that the specific heat of the mixture, Cp_{mix}, is equal to the sum of products of specific heats of oil, Cp_o, and air, Cp_a, by their mass fractions, we get:

$$M_{OAM} Cp_{mix} \frac{\mathrm{d}T_{mix}}{\mathrm{d}t} = Cp_o G_o T_o + Cp_a G_a T_a + + \Sigma Q_b - Cp_{mix}(G_{br} - G_{OC}) T_{mix} \quad (25)$$

where: $Cp_{mix} = Cp_o(1 - x_{\mathrm{OAM}}) + Cp_a\, x_{\mathrm{OAM}}$, ΣQ_b- heat release in the bearing and from the OC body.

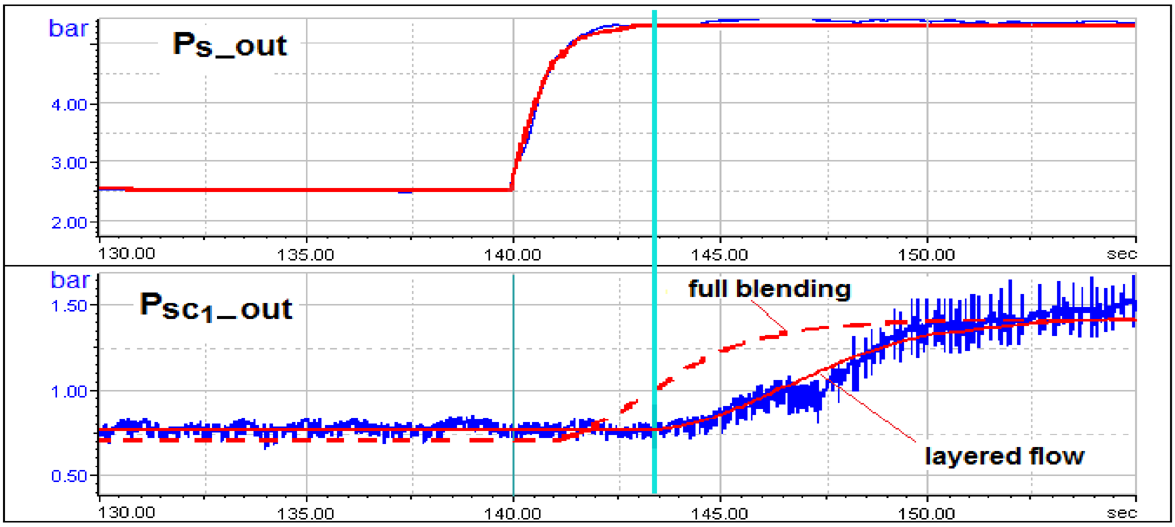

Fig. 4. Calculated and experimental data for transient processes in the oil system flow passage depending on changes in the delivery rate of the supply pump (calculations – red color)

The system of equations (1-25) used in the OC mathematical model makes it possible to find pressure, temperature and mass (volume) gas content of the working medium at the outlets from the oil chamber. These equations complement the earlier developed mathematical model of the oil system, where the oil chamber is described as an acoustic capacitance with oil-air mixing within the total volume without separation into air-oil and oil-air mixtures [10].

Fig. 4 shows calculated and experimental data for transient processes in the oil system when the delivery rate of the supply pump changes from 10 l/min to 20 l/min in the initial version of the OC mathematical model (dotted line) and in the model with a layered flow of oil-air and air-oil mixtures (solid lines). The following distribution of volumes in the OC is used: the emersion zone – 25%, dispersion zone – 15%, pumping-out zone – 60%.

The OC mathematical model with the working fluid separation into oil-air and air-oil mixtures illustrates the experimental fact of a delay in increase in parameters in the pumping-out line: the experiment shows ~3.2-s delay and the calculation – 3.1 s (instead of 1.8 s for the model with complete air-oil mixing). A revealed acceptable convergence of calculated and experimental transient processes is the evidence of validity of the proposed physico-mathematical model for the oil chamber.

IV. Conclusions

The mathematical model of hydraulic processes in the oil chamber is proposed on the basis of the oil and air dispersion process. It is characterized by the value of time constant for the formation of dispersed medium and its separation into the oil-air and the air-oil mixtures, which are layered flows at different rates. To describe these processes, mathematical tools are used in the form of transportation delay equations, first-order differential equations and algebraic dependences that provide an adequate accuracy of the convergence of numerical and experimental transient processes.

The results can be used for hydraulic calculations of the pipeline network of lubrication systems and its components in the design.

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