

## THE EFFECT OF OIL FOAMING ON GAS TURBINE ENGINE OIL SYSTEM

L.S. Yanovskiy, A.I. Gulienko, V.M. Ezhov, A.A. Molokanov  
Central Institute of Aviation Motors  
Moscow, Russia

### Abstract

The paper represents a result of experimental researches of foaming properties of Russian and foreign lubricating oils' for aviation gas turbine engines (GTE). The experimental researches of the foam formation and flow by laboratory methods and bench facility (simulating a GTE) are shown. The conducted tests have demonstrated the dependence between increased oil foaming and characteristics of electric pumps of oil system and GTE fuming.

### Nomenclature

$Q_p$  - volumetric flow rate of feed pump, l/min  
 $n_p$  - rotation frequency of electric drive shaft of oil pump, Hz  
 $\alpha_p$  - calculated volumetric air content in oil-air mixture  
 $\alpha_n$  - real volumetric air content in oil-air mixture  
 $K_p$  - ratio of oil-air mixture flow rate pumped from oil chamber to flow rate pumped into oil chamber  
 $a$  - sound velocity, m/s  
 $P$  - pressure, bar

### Pressure indexes

$m$  - feed pump inlet  
 $p$  - feed pump outlet  
 $s$  - scavenge pump outlet  
 $o$  - oil chamber, bar

### Abbreviations

GTE - Gas turbine engine  
DELOS - Demo electric lubricating oil system  
ALF - Average level of foaming for oils from fuming engines

### Introduction

The rigid requirements are proposed for aviation oils to ensure a reliable

operation of gas turbine engines in a wide range of temperatures. Oils should have high lubricating and protective properties, low corrosion activity, minimal deposits, evaporation and foaming, also should be secure in operation, non-toxic and compatible with the constructional materials [1-3].

The aviation oil foaming is one of the most important factors influencing to the safety. The deterioration of oil operating properties with an increased tendency to foaming is due to increased air content in this oil during an engine operation. It can lead to a breach of the aviation GTE normal operation: heat sink worsening, overheating of friction units, accelerating of oil oxidation, reducing of friction parts lubricating efficiency, stopping electric drives of oil pumps [4].

Also recently the cases of helicopter engines fuming are raised (Fig. 1). This fuming is caused by hitting of oil into the engine exhaust nozzle, which could be due to increased oil foaming. A breather of GTE oil system cannot separate the oil-air mixture that formed at pumping out of the oil from rotor supports of engine. As a result the foam surplus through the breather flows to exhaust nozzle. Under these conditions the oil dispersed in exhaust gases with a temperature about 400 °C then evaporates resulting in fume exhaust from the engine.



Fig. 1. The helicopter engines fuming

Antifoaming additives are injected into the oil to improve the

operational properties, however, these additives deteriorate the oil deaeration. The reason is a difference between the surface tension of oil and additives, the last of which are concentrated on the surface of air bubbles in oil. It reduces the surface tension between the air and liquid phase. Based on the Laplace equation, the reduction of surface tension at the "air-oil" boundary reduces the size of bubbles [5]. According to the Stokes equation the lift speed of bubbles is proportional to square of radius, therefore, the lift speed of small bubbles is reduced [6]. Besides an additive have a higher density and influence to the lift speed of bubbles.

Fig. 2 shows the curves of air content in the oil for the stage of air passing and for the stage of oil settling [6]. At the stage of air passing (under the dynamic conditions) the oil with an antifoaming organosiloxane additives uses a less air, i.e. the foaming is lesser. But the velocity of air secretion from this oil is also lesser during the settling, so the deaeration is worse. It is clearly that the bubbles colliding with each other become larger and rises faster to the surface in dynamic mode [7, 8].

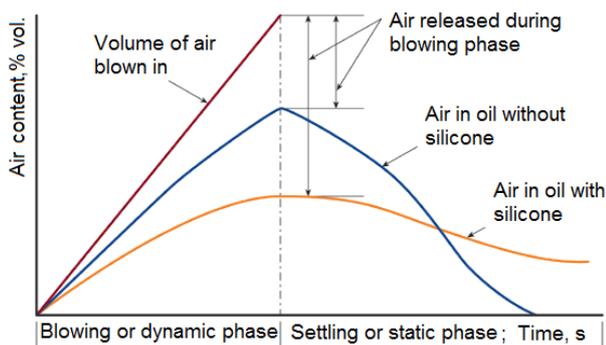


Fig. 2. Effects of organosiloxane additive on air content in oil during and after air passing

From the published papers [1-8] it is very difficult to clearly identify how will change the characteristics of GTE oil system with an introduction of antifoaming additives in oil.

The foaming of oils during engine operation depends on oil properties

and other factors: operation mode, temperature, impurities presence, type of constructional materials, degree of oxidation, intensity of aeration, mixing, etc. In addition into the oil may fall a lubricants based on molybdenum disulfide and organosiloxane fluid which significantly influences to foaming of oils and operation characteristics of GTE oil system [9].

Further the results of foaming estimation received by the standard method are difficult to interpret. For example, the column height of foam is 20 mm at 25 °C and 40 mm at 95 °C – is a lot or not? Does it mean that if the column height of foam is higher at 95 °C, the oil foaming in GTE oil system at 95°C will be higher also? We have difficulty to compare a foaming properties of two different oils if we use its determination according to the GOST 21058-75 at 25°C, 95°C and 25°C: for the first oil the foam column height is 40 mm, 10 mm and 20 mm, and for the second one – 20 mm, 10 mm and 40 mm. Is it possible to determine which foaming properties of oils' are better? To answer these questions it is necessary to investigate the dependences of foam formation properties from the temperature, the air flow and other factors.

The tasks of this work are:

1. Investigate the influence of air flow, temperature, oxidation time and the concentration of lubricants based on organosiloxane fluid and molybdenum disulfide on oils foaming with a purpose of establishing the dependence between oils foaming and GTE fuming.
2. Evaluate the parameters of oil system of demo electric lubricating oil system (DELLOS) of GTE at changing of oil foaming properties.

### The method of oil foaming determination

In Russia the main method of controlling the aviation oil foaming is the standard method GOST 21058-75. The dried air is passed through the oil sample in a thermostatic column. Definitions of the foaming parameters: the height and the column destruction time of foam – are

performed successively at 25°C, 95°C and 25°C again with a fixed air mass flow rate of 0.2 kg/cm<sup>3</sup> (Fig. 3). The last determination at 25°C is fundamentally different from the first two in the fact that oil sample is bubbled previously by gas and is kept at temperature of 95°C. This method is used for the quality control of aviation oils.

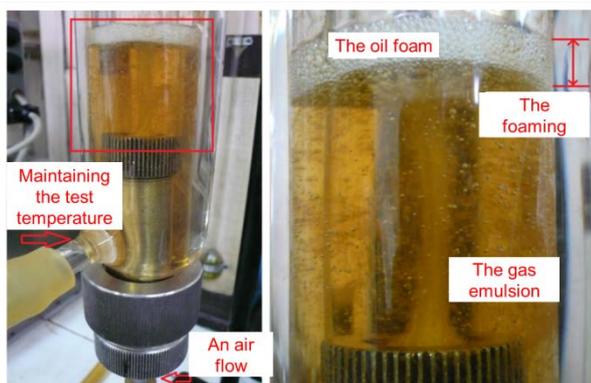


Fig. 3. The visualization of oil foaming

The authors have introduced changes in the GOST 21058-75 method for a comparative estimation of foam formation properties. The determination of foaming is carried out in the temperature range with step of 10 °, the sample preparation is regulated, and parallel and consistent definitions are conducted, the kinetics of foam development and destruction are studied, the impact of air flow and time of oil oxidation are estimated. The foaming and foam stability of oils are expressed in the percents relative to the base: foaming and foam stability of the Russian LZ-240 oil, oxidized during 50 hours at 200°C with additional lubricants, determined at 25°C - which is average for oils with a fuming engines.

The sample preparation consists in the following. Before testing the sample was mixed intensively for the uniform distribution of all substances in a volume, heating up to 110°C, holding at this temperature and then cooling to the test temperature. The heating reduces the oil viscosity in 10 times for normalizing the sample before test. Preheating and following cooling up to test temperature simulates the

oil-air mixture supply from the friction unit through a heat exchanger in the oil tank for bringing the experiment to operation conditions [10]. The effect of such samples preparation is seen in Fig. 4 at determining of the foaming of TN-98 oil and B-3V oil from fuming engines. For these oils at 25°C the increased foaming was determined after sample preparation only.

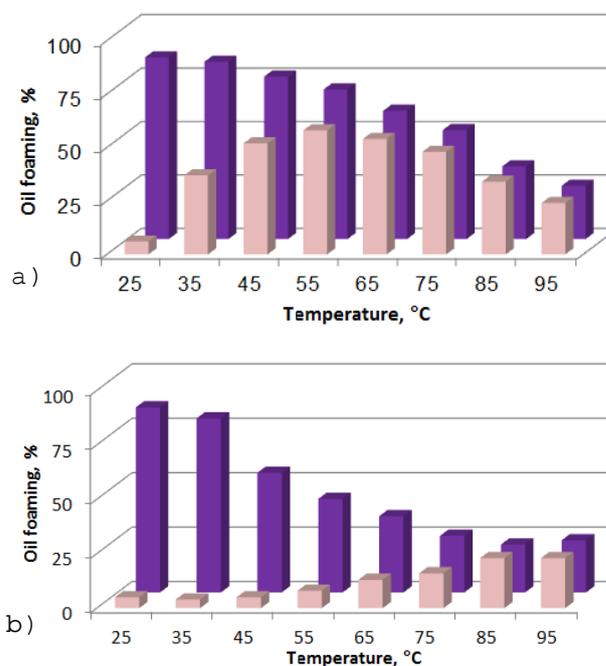


Fig. 4. Sample preparation effect on foaming of oils: a) TN-98; b) B-3V.

- no preparation;  
 - with preparation

Taken together it allows to determine the potential level of oil foaming at GTE operation.

### The experimental results of oil foaming

Russian and foreign lubricating oils: LZ-240, B-3V, TN-98, Royco 899 and others - are used in GTE. These oils have different operational and foaming properties.

Obviously overestimated foaming is set for only one of these oils from the fuming engines by the standard method estimation of oils. The opposite results are obtained for other remaining oils samples (which didn't have excessive foaming in standard method evaluation) from fuming engines due to the method proposed by authors.

It is set an increased foaming of these oils (Fig. 5).

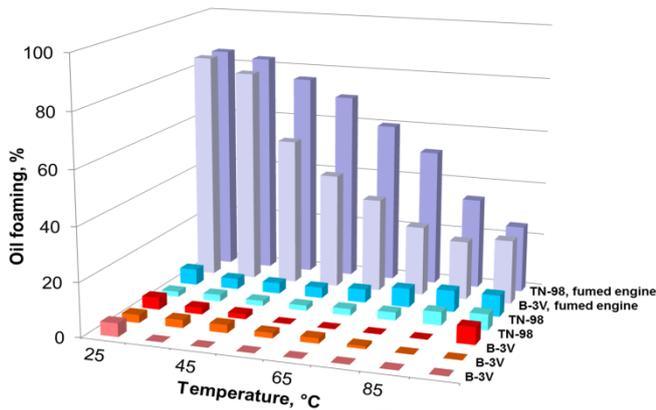


Fig. 5. Foaming of oils from fuming and non-fuming engines

As noted before the lubricant of high viscosity can get into the oil during GTE operation. Fig. 6 shows the oils foaming for GTE with adding the 0.005% wt. of lubricant based on organosiloxane fluid and molybdenum disulfide (and without this lubricant to compare). The presence of such negligible amount of lubricant in oil increases the oil foaming significantly.

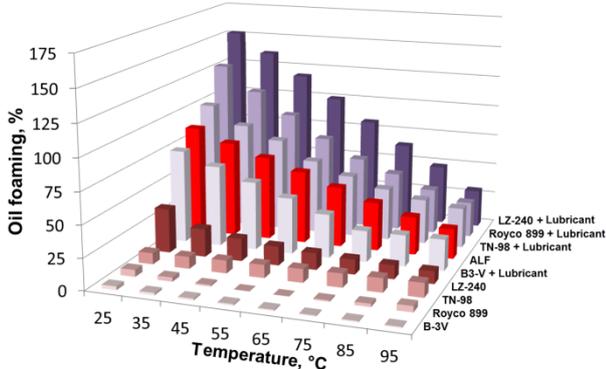
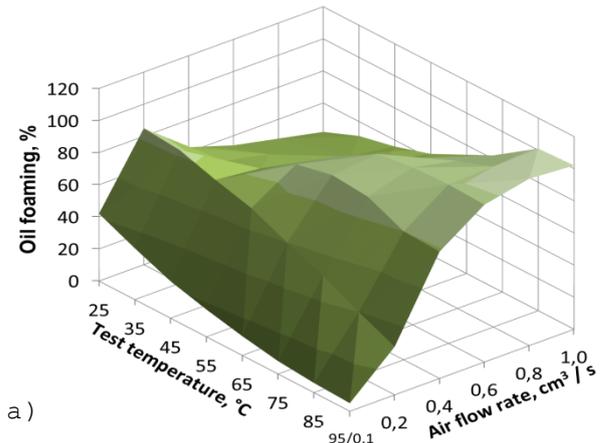
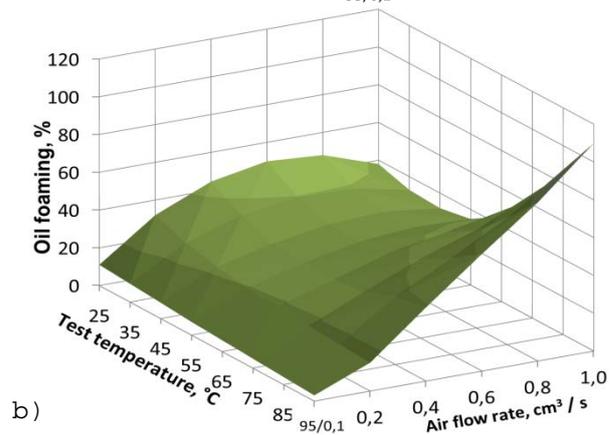


Fig. 6. Oils foaming after lubricant addition. Air flow rate  $0.2 \text{ cm}^3/\text{s}$ , oxidation time 30 hours; ALF - average level of foaming for oils from fuming engines

Two modes of foam formation have been determined during the research of air flow and test temperature influence to the foam column height for a synthetic (45 hours operating time) and petroleum (non-working) oils (Fig. 7): static and dynamic.



a)



b)

Fig. 7. Foam formation properties of oil vs. temperature and air flow. Oil: a) MS-8P; b) TN-98

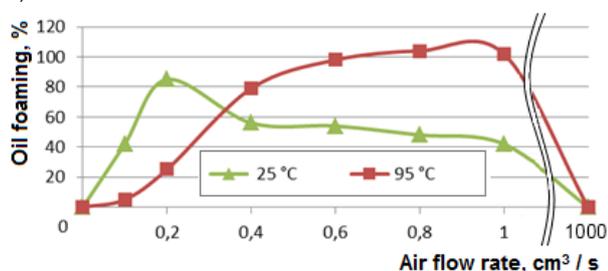
1. The static mode is realized at air flow  $0.2 \text{ cm}^3/\text{s}$  or less that corresponds to low Reynolds numbers. There is a gradual increase of foam without breaking the foam body by air stream in this mode. With air flow increasing the growth of foam column is due to increase a number of bubbles, and their size varies slightly. As a temperature increases the foam column height is decrease. The surface tension and solution density are determined the bubbles size in this mode. The surfactants' type and concentration effects on formation rate of adsorption layers and the stability of formed foam [7].

2. The dynamic mode is realized at air flow more than  $0.2 \text{ cm}^3/\text{s}$ . In mode of foam formation the bubbles size and properties are strongly depended from volumetric of air velocity. The column height of foam is increased at temperature increasing. This is due to increasing of bubbles size. After achieving a certain critical flow

rate the air begins to leave the pore of dispersing device by continuous stream. Then a stream splits into separate bubbles. Turbulent flow and viscosity of solution have a significant influence on the bubbles size in this mode, and lower influence - surface tension [8].

The column height of foam has extreme dependence from air flow (Fig. 8). The column height of foam is small at low flow rate, when flow rate increases it increases too, but at significant flow increasing the foam is disappears. The air flow passing through the oil prevents a foam formation on its surface and the oil becomes like a boiling liquid.

a)



b)

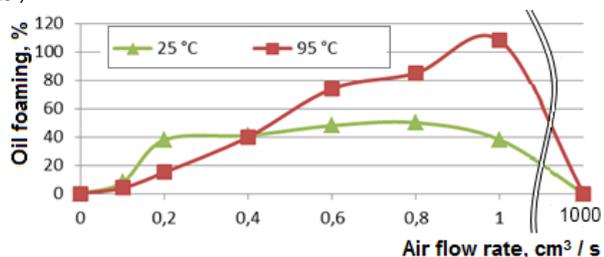


Fig. 8. Oil foaming vs. air flow. Oil: a) MS-8P; b) TN-98

The air in oils can be in dispersed and dissolved states and according to its have different effects on operational properties of oils. Solubility of air in oils varies within 7-10% at 20°C [11]. During operation a content of dispersed air in oil may rise significantly. This is confirmed by laboratory experiment: the volume of oil-air mixture is increased immediately by 15-20% when passing the air of 1000 ml/s through the petroleum MS-8P oil and increased up to 50% after 10-15 minutes (Fig. 9).

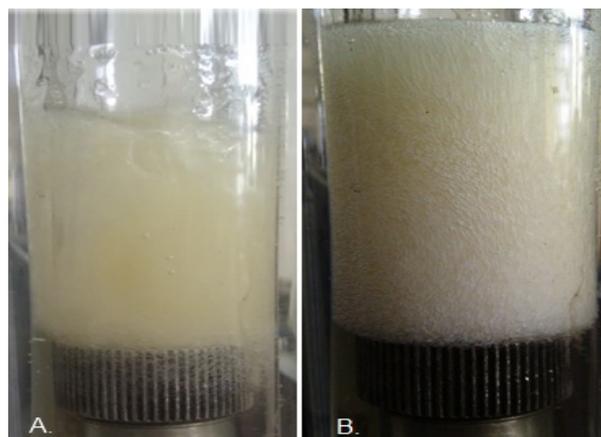


Fig. 9. The air involvement into oil during air passing. The sample volume 25 ml, air flow rate 1000 cm³/s. A - the test beginning. B - after 10-15 min of passing air

Decrease of oil foaming can be achieved by injection of organosiloxane as an antifoam additive (Fig. 10). If this additive is in a small concentrations the main operational properties of oil remain within the requirements of specification of oil. It allows recommend the introduction of such additive in oils for reduce a GTE fuming.

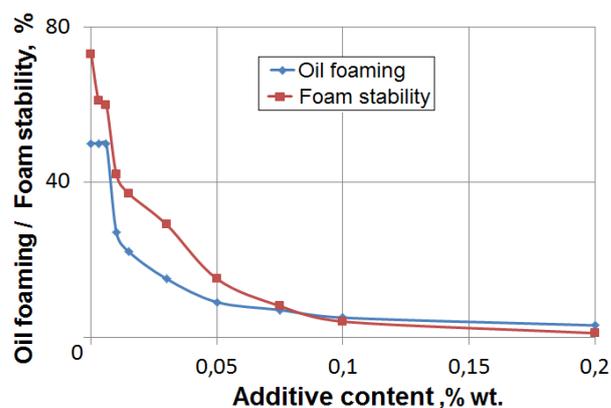


Fig. 10. MS-8P oil foaming properties vs. organosiloxane concentration

#### The effect of oil foaming on electric lubricating system characteristics

GTE with electric drive pumps of lubricating system are one of the promising engines [12]. For their development a physical research of oil-air flows is necessary to perform.

Experimental researches were carried out by authors on the demo electric

lubricating oil system (DELOS) with electric scavenge and feed gear pumps with variable rotating speed [13]. Experiments have shown the complexity of the hydro- and gas-dynamic processes which affecting on characteristics and performance of DELOS: a rise of oil-air mixture foaming, an excitement of polyharmonic pressure fluctuations, an exceeding the power of gear pumps on calculated values when oil-air mixture pumping etc. There is observed a shutdown of electric drive pumps (worst deaeration properties) at change of air content in oil.

The principal scheme of DELOS and bench stand with a simulator of GTE oil chamber is shown in Fig. 11. The rotor of bearings is driven by electric motor through a multiplier. The oil from oil tank 7 is fed through the oil filter 6 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 (Fig. 11). The camera Sony HDV-FX7 was used to visualize, video record was conducted with frequency of 25 frames per second and 100 frames/sec (slow shutter) at shutter speed of 1/6000 sec. 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.

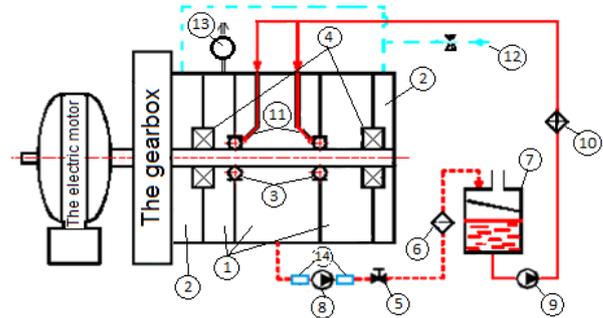


Fig. 11. Principle scheme of DELOS: 1 - oil chamber (OC); 2 - pre-oil chambers; 3 - bearings; 4 - seals; 5 - throttle valve; 6 - heat exchanger; 7 - oil tank; 8 - scavenge pump; 9 - feed pump; 10 - oil filter; 11 - nozzles; 12 - air supply; 13 - breather; 14 - transparent tubes. The streams: — - oil; ..... - oil-air mixture; - - - - - air supply; ——— - air discharge.

The research of characteristics was conducted at triple change of oil supply by feed pump, the supply ratio between scavenge pump to feed pump varies from 2 to 4. The rotation frequency of oil chamber's bearings was varied in the range of 4,000-12,000 rpm. Tests were conducted with MS-8P oil without antifoaming additives.

Air volume fraction (evaluated by calculation method) in oil-air mixture was increased from 0.40 to 0.55, that led to the excitation of polyharmonic oscillations of system parameters (pressure, air content, etc.), increasing the pumps power to critical values and disable their electric drives.

Fig. 12 shows the transient processes in DELOS during 18 minutes at operation mode with fixed rotation frequency of pumps and bearings. On the steady mode by hydraulic and thermal parameter's of the system comes out in about 80 seconds. The main parameter's values at the 2nd minute: feed pump flow rate  $Q_r=17.5$  l/min and feed pump outlet pressure  $P_p=4.2$  bar.

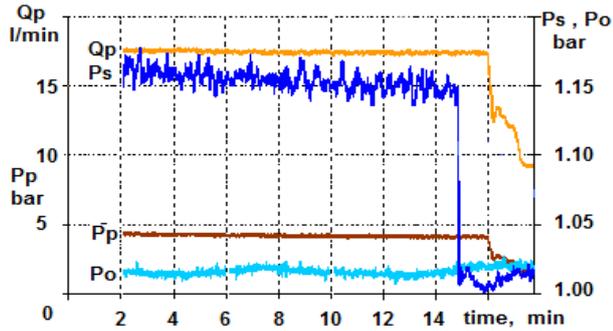


Fig. 12. The DELOS transient processes in mode with fixed rotation frequency of pumps

A smooth decrease the pressure of feed ( $P_p$ ) and scavenge ( $P_s$ ) pumps takes place starting from fifth minute at fixed volumetric feeding of feed pump  $Q_p$ . After this time a sharp (in 0.5 s) pressure drop  $P_s$  after scavenge pump to the pressure  $P_o$  in oil chamber takes place. The pressure drop is caused by disconnecting the electric drive of pump due to exceeding of admissible current value.

Video record of oil-air mixture flows at the pump inlet and outlet in combination with spectral analysis of records showed that the pumps are transferred a fine dispersed mixture. Slow reduction of pressure after pump indicates a smooth increase of the volumetric air content in mixture before the electric drive disconnection.

The fact of fine dispersed mixture flow is also confirmed by the low sound velocity in the mixture. It was determined by the analysis of the temporary records of pressure. The transition process at disconnecting the pump's electric drive is shown at the top of Fig. 13. At that the damped oscillations are observed on the pipeline natural frequency of 2.4 Hz due to hydraulic shock. The length of single pipeline from the oil tank to the pump inlet is 2.5 m. There is an "open-closed" acoustic system and its natural frequency in Hz is equal to the sound velocity in the mixture divided on four lengths of pipe. The sound velocity in mixture should be equal to  $2.4 \cdot 4 \cdot 2.5 = 24$  m/s for the oscillation frequency of 2.4 Hz. Such low sound velocity can be realized in fine dispersed two-phase mixture

which has a characteristics of homogeneous medium [14]. The value of volumetric air content appropriated to this sound velocity is 0.55. Fig. 13 shows the sound velocity in the homogeneous two-phase mixture vs. volumetric air content and shows the experimental point for operation conditions of DELOS.

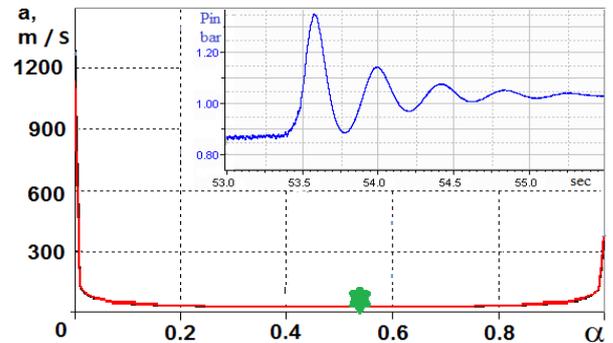


Fig. 13. The sound velocity in oil-air mixture vs. volumetric air content

The lubricating systems are usually includes a gear pump (volumetric type). The mixture flow rate in hydraulic net is determined by flow characteristic of the pump  $Q_r = f(n_p)$  which expressed the dependence of the volumetric flow rate at the pump output (input)  $Q_n$  from rotation frequency of its shaft (Fig. 14, b). It is choosing taking into account the condition of providing the required pumping of oil-air mixture with a calculated air content ( $\alpha_p$ ) value with a given pump rotation frequency. On another rotation frequency the volumetric flow rate value will correspond to flow rate pump characteristics. This specificity of pump operation caused by its design in which a pump pair of gears is pumping from the input to output the volume equaled to the volume of gears teeth cavities in the suction zone (Fig. 14, a).

The volumetric flow rate at the outlet (inlet) of pump at current rotation frequency characterizes its traffic capacity.

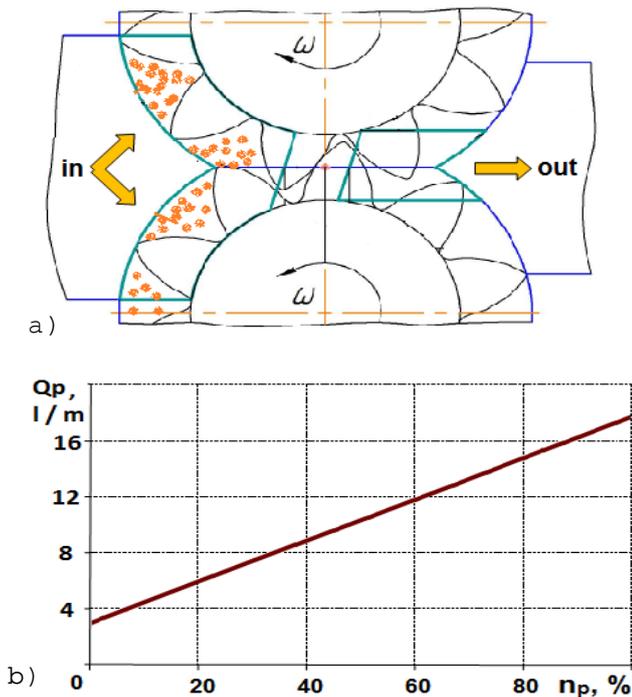


Fig. 14. Scheme (a) and flow rate characteristics (b) of gear pump

Real volumetric air content of the mixture at pump inlet ( $\alpha_n$ ) can be changed at fixed rotation frequency of gear pump. At the same time the visualization of a flow show us a possible options:

I. Real volumetric air content of the mixture at the inlet of the pump is equal to calculated value ( $\alpha_n = \alpha_p$ ), in that case the oil-air mixture is pumping without flow transformation.

II. Real volumetric air content is lower than calculated value ( $\alpha_n < \alpha_p$ ).

In this case a mixture with higher density is supplied to the pump inlet. As well as the carrying capacity of the pump is a higher, there is an evacuation effect of the pump's inlet pipe. As a result the pressure at the pump inlet is reduced and the volumetric air content is increased. The process occurs until the equilibrium state will be ensured. The interruption of flow continuity happens at certain value of the pressure and it begins to gravity flowing to the pump inlet. Decomposed stream with fine dispersed flow in the bottom of horizontal pipe is realized.

III. Real volumetric air content higher than calculated value ( $\alpha_n > \alpha_p$ ).

At this mode the carrying capacity of gear pump is lower than the flow rate arriving at inlet and the effect of pump locking is realized. At first there is a pulsating mixture flow in hydraulic circuit with the pump and then the aperiodic instability occurs under a certain high value of air content. It leads to a gradual increase of pump power. Since the power of pump's electric drive is limited, then the pump is shutdown due to current exceeding in the power windings of electric motor.

Instability of a two-phase mixture flow is associated with the formation of density waves (kinematic waves) into hydraulic tract, which propagated with the velocity of flow. When  $\alpha_n > \alpha_p$  the mixture can't be pumped from the inlet to the outlet and is collecting at the pump inlet. It leads to the pressure increasing and, consequently, the reduction of bubbles size in the mixture, increasing its density and decreasing of volume. The pump circulates the portion of mixture with higher density, which leads to a pressure drop at the inlet, the density reduction, pump blocking etc. This repeating process of density change leads to the appearance a pulsating flow with polyharmonic pressure fluctuations in the hydraulic tract of lubricating system, a changing of flow rate and volumetric air content in the oil chamber. The excitement of pulsating flow reduces the breather system efficiency and the oil-air mixture begins enter into the environment. This leads to GTE fuming under its operation.

Increased oil foaming can be one of the possible causes of the mixture formation with large volumetric air content. In this regard special tests with the addition of antifoaming additive in MS-8P oil are conducted which reduced the oil foaming at 90%.

Comparison of DELOS characteristics under operation with MS-8P oil showed that the adding of antifoaming additives:

- decreases the pressure fluctuation at 23-40%;
- there is a harmonics shift from the frequency of 110 Hz to 80 Hz in pressures Ps;
- decreases of power consumption by the pump during the operation on the dispersed mixture (power measurement of the electric drive shaft was carried by Fluke 41B).

Improvement of flow conditions as the reducing of oscillation amplitudes means an increasing of the number of small bubbles in oil. The frequencies in the range of 80-110 Hz are caused by weight of the liquid phase participating in the formation of oscillation period. So at their pulsed nature the bubble size reduction leads to increasing of the current mass and hence reducing the oscillation frequency.

Influence of additives on the pump power is illustrated in Fig. 15 which shows the change in the electric drive power of the pump depending on the coefficient  $K_p$ . The last one is the ratio of flow rate from the oil chamber to flow into the chamber. During the tests the changing of  $K_p$  was conducted by increasing the rotation frequency of scavenge pump at a fixed frequency of feed pump. At such technology the volumetric air content increases with growth of  $K_p$  at the scavenge pump inlet, which leads to an increasing of their consumed power.

As can be seen from the Fig. 15 there is an positive effect of the additive, but it decreases with increasing of volumetric air content of mixture (increasing  $K_p$ ) and it disappears at  $K_p=4$ . This fact confirms the shutdown of electric drive.

The workspace of  $K_p$  changing in GTE is in the range 2-3, and the influence of additives is significantly. The power consumed by the pump is reduced in 2 times under  $K_p = 2$ .

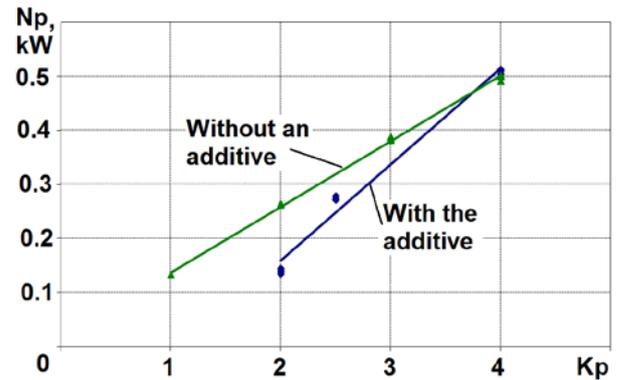


Fig. 15. Pump power vs.  $K_p$  with and without additive

Thereby testing of DELOS at the gear pumps operation with fixed rotation frequency establishes the reason of air saturation increasing of the oil in lubricating system. It is caused by changes in the oil properties during operation at its contact with air. Pump operation in the locking mode does not ensure the pumping of oil-air mixture from the pump inlet to outlet in full volume, and its excess falls into breather system of GTE and then into the environment.

### Conclusions

1. The standard method of determining the foam formation properties of aviation oils is improved. The changes in the GOST 21058-75 standard method proposed by authors allows to determine the potential foaming of oils in terms that are more closed to GTE operation conditions.
2. It is shown that the increased foaming of oils is the cause of engines fuming during their operation.
3. During operation of aviation GTE some lubricants may hit in the oil, which even a small amount (0.005% wt.) rapidly increase oil foaming.
4. The dependences of aviation oils foaming from air flow and temperature are determined. There are found two foam formation modes and established a relations of foam column's height and destruction time for these modes.
5. Bench tests of demo electric lubricating oil system with antifoaming additive have shown that

the additive reduces the power consumed by the pumps and improves the performance of GTE lubricating system.

### **Acknowledgement**

The authors gratefully acknowledge Dr. V.I. Babkin for the useful suggestions provided during the research. The work was carried out with a support of Russian Foundation for Basic Research № 15-01-03073.

### **References**

1. Yanovskiy L.S., Dubovkin N.F., Galimov F.M. etc. Aviation Chemmotology Basic Engineering. Kazan: Kazan University Press, 2005. – 714 p. (in Russian)
2. Yanovskiy L.S., Yezhov V.M., Molokanov A.A. Aviation Oils Admission Methodology for Using in Aviation in Russia and Abroad // Engine – 2012. – № 2. – pp. 20-22. (in Russian)
3. Kirishi E.L., Popov V.G., Yanovskiy L.S. Lubricants Quality Influence on an Aircraft Gas Turbine Engines Performance. Moscow: MATI, 2008. – P. 102. (in Russian)
4. Claxton P.D. Aeration of Petroleum Based Steam Turbine Oils // Tribology. – 1972. – February. – pp. 8-13.
5. Duncanson M. Effects of Physical and Chemical Properties on Foam in Lubricating Oils // Lubrication Engineering. – 2003. – № 5. – pp. 9-13.
6. Fowle T.I. Aeration in Lubricating Oils // Tribology International. – 1981. – № 6. – pp. 151-157.
7. Kruglyakov P.M., Ekserova D.R. Foam and Foam Films. – M.: Chemistry, 1990. – P. 432. (in Russian)
8. Stevenson P. Foam Engineering. Fundamentals and Applications. New Zealand: A John Wiley & Sons, Ltd, 2012. – P. 536
9. Anisimov I.G., Badushtova K.M., Bnatov S.A. etc., edited by Shkol'nikov V.M. Fuels, Lubricants, Technical Liquids. Assortment and Application. – Moscow: Techninform, 1999. – P. 596. (in Russian)
10. Bashta T.M. Engineering Hydraulics // Moscow: Engineering, 1971. – P. 672. (in Russian)
11. Rahmankulov D.L., Dolmatov L.V., Olkov P.L., Agliullin A.H. Commodity of Petroleum Products. Volume 3. Motor Oils. Moscow: Inter, 2006. – P. 312. (in Russian)
12. Kargopoltsev V.A., Pogosyan M.A., Babkin V.I. etc. Aircraft Power Installations Based on Electrochemical Generators // Materials of the Russian Conference with international participation «Fuel Cells and Power Installations Based on Them». – Russia, Chernogolovka: Institute of Physics of Solid Objects (Russian Academy of Sciences). – 2013. – pp. 74-75. (in Russian)
13. Gurevich O., Gulienko A., Schurovskiy U. Demonstration Systems of the «Electric» Gas Turbine Engine. – Russia, St. Petersburg: 29<sup>th</sup> Congress ICAS. – September, – 2014, – P. 6.
14. Wallis G.B. One-Dimensional Two-Phase Flow. McGraw-Hill Book Company. –1969. – P. 408.