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# Ring-shaped fluorescence of mineral oil on the front edge of the choke coil

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**Abstract:** Hydraulic drive is a quite complicated technical system widely used in various industries: transport, agriculture, aviation, aerospace, robotics etc. During operation of the hydraulic actuators there are various modes and physical processes that occur in the working fluid to its devices. It is known that various processes like cavitation, degassing, erosion are observed in hydraulic drive devices, which are deeply studied and fully described in the literature. As follows from the analysis of the literature, the emergence of such a process as the light emission of a liquid in the form of flashes of light, the nature of which is ultrasound, is possible. The paper presents the material on the study of a rare and little-known phenomenon in the devices of hydraulic drives – the glow of the working fluid without ultrasound in it. To fill a certain gap in the study of the nature of the fluorescence of the working fluid, in particular, the fluorescence of mineral oil, the authors of this paper conducted an experimental study of cavitation processes in the transparent model of the hydraulic device – in the diaphragm choke coil.

## 1. Introduction

In the scientific and technical literature, two terms are widely used for fluid fluorescence, namely: “sonoluminescence” and “light emission”. The first term is directly connected with the ultrasound as the reason that causes the fluorescence of the liquid; the second provides a broader range of causes for the fluorescence of the liquid.

The first report on sonoluminescence in the fluid flow was published in 1933 by Marinesco and Trillat [1], and a little later (1934) Frenzel and Schultes found a weak fluorescence in the fluid that arose under the action of acoustic oscillations [2]. In 1964, Jarman and Taylor [3, 4] registered a weak luminescence of water in the zone of closure of cavitation cavities in the Venturi pipe. In his dissertation Peterson [5] in 1966 also noted light emission in the field of bubble closure in hydrodynamic cavitation.

At the moment, there is no single explanation of the phenomenon of light emission in science. Currently popular methods for solving hydrodynamic problems [6–10] imply the numerical solution of the Navier—Stokes equations (so-called CFD-methods). However, these methods have some significant drawbacks: high costs of machine and human time, relatively low accuracy, since the



results obtained by such methods are fundamentally discrete and do not provide the possibility to continuously study the physical quantities of interest to us. All this leads to the search for methods alternative to the above.

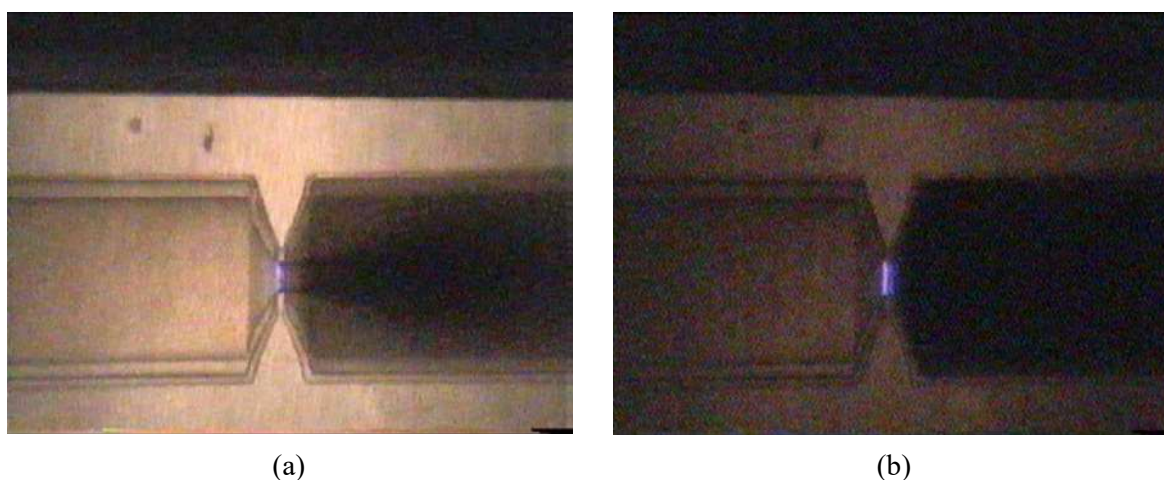
The authors of this paper have conducted a study of cavitation processes in a transparent model of the diaphragm choke coil. During the study of cavitation processes in the choke coil, a localized stable ring-shaped light emission in the blue part of the color spectrum was found at its entrance edge. The brightness of the light emission increased as the flow rate increased. Since at the time of detection of light emission in the literature there was no information about fluid fluorescence in the low pressure region, the task of conducting additional studies to determine the causes and nature of light emission in hydrodynamic cavitating flows of mineral oil in narrow slits was set.

## 2. Experimental study of the fluorescence process of mineral oil on the sharp inlet edge of choke coil

In hydraulic automation devices, various types of choke coil are widely used as shut-off and control elements: in diaphragm and cylindrical choke coils, the flow of the working fluid has a pronounced turbulent character, and in the compressed section, a high speed causes cavitation and the associated active release of undissolved air and steam bubbles. In the zone of high pressure bubbles are instantly closed, which causes erosion destruction of the material of the channel walls and active acoustic processes. Rapid closure of vapor-gas cavities, in accordance with the laws of thermodynamics, can cause a local temperature rise, as well as, under certain conditions, fluid fluorescence.

Research of the literature in the field of the theory of sonoluminescence [11] showed that it is possible to suppose the electrical and electrochemical nature of its appearance and existence, so the identification of the causes of light emission at the entrance edge of choke coil was the task of the study, the results of which are presented in this article.

In the 70-ies of the twentieth century A. I. Koldomasov discovered the fluorescence of distilled water in a narrow channel [12]. The nature of the fluorescence was explained by plasma discharges during water cavitation, but the cause of discharges and the source of plasma formation were unclear. Later (2007–2010) light emission was found in the study of cavitation in organic liquids flowing at high speed in narrow dielectric cracks [13-15]. Since 2004, studies of cavitation regimes of high-speed flow of highly purified deionized water in narrow profiled dielectric channels have been carried out in the Keldysh Center [16]. The detected bright fluorescence was localized in the region of the largest narrowing of the channel with a diameter of 1-2 mm at a distance of 2-3 mm from the entrance to the capillary of the Venturi pipe at a flow rate exceeding 40 MS-1. Fluorescence manifested itself in the form of sparks, galloping along the flow in the Central part of the channel.

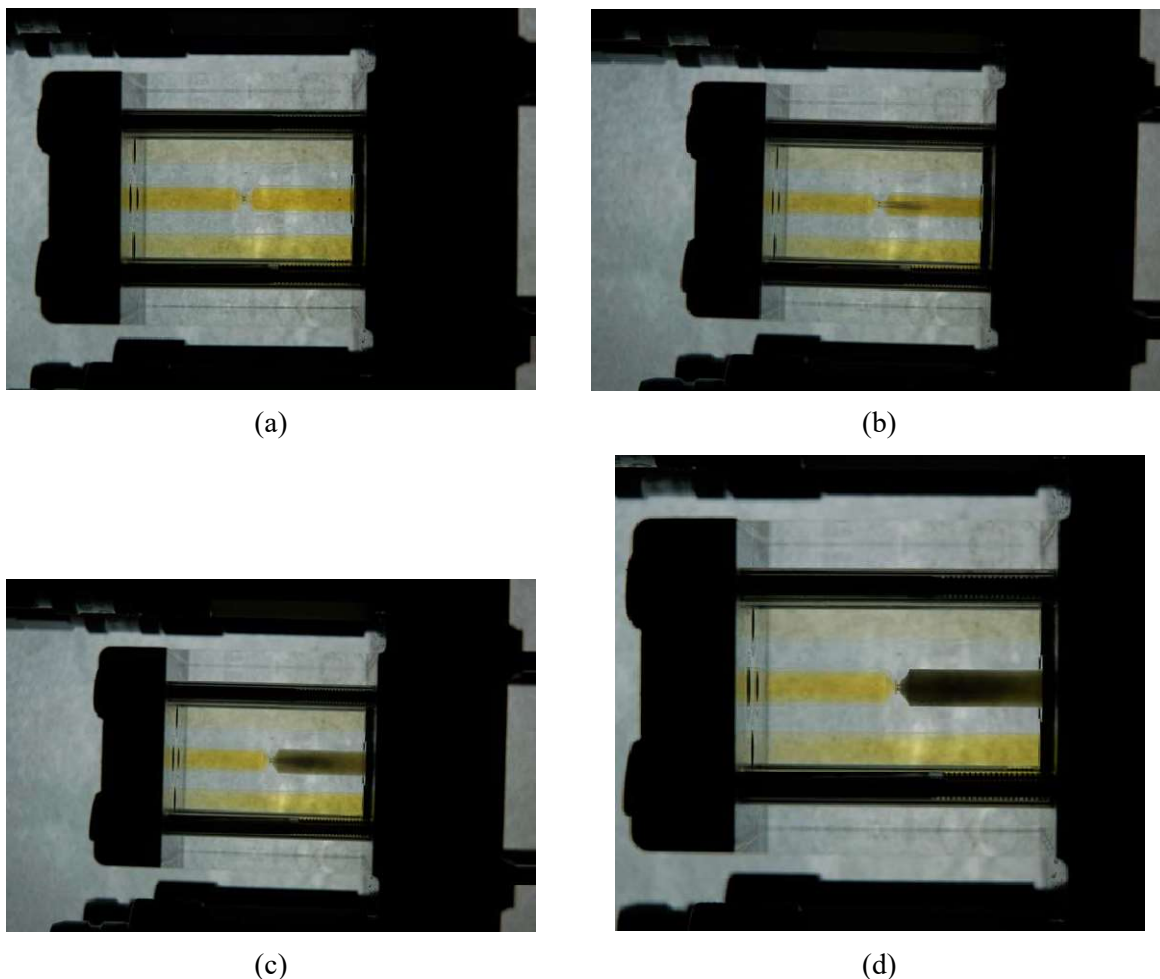


**Figure 1.**Light emission in the cavitating flow of mineral oil in the inlet section of choke coil: a) light emission in the choke coil inlet section; b) stable light emission in the input section of choke coil.

It follows from the above that the causes of light emission in liquids have not yet been identified in many cases. In this regard, this experimental study was aimed to study the process of light emission in the cavitating flow of mineral oil at the inlet edge of the diaphragm choke coil.

During the experimental study, in the flow of mineral oil at the inlet edge of the diaphragm choke coil, made of transparent organic glass, the authors found a bright light emission in the blue part of the spectrum (figure 1).

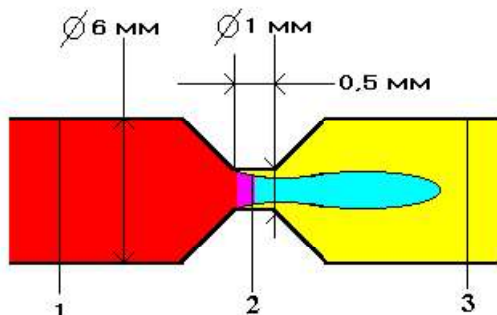
Fragments of video filming of the stages of development of the cavitation process in the diaphragm choke coil, recorded by a digital camera with shooting speeds of 50 and 2000 FPS, are shown in the photo (figure 2):



**Figure 2.** The development of the process of hydrodynamic cavitation: a) origin of the cavitation ring on the inlet edge of the choke coil; b) the appearance of a cavitation torch; c) the spread of the plume in the area of the allotment; d) supercavitation mode.

In the photo (figure 2) the whole process of hydrodynamic cavitation is observed, which begins with the origin of the ring at the inlet edge of the choke coil (figure 2a), then, as the velocity of the liquid increases, the ring turns into a cavitation torch (figure 2b), expanding (figure 2c), closes with the inner surface of the tap, which results in supercavitation mode (figure 2d). It should be noted that light emission occurs at the input sharp edge of the choke coil at the time of the cavitation ring, continues until the super-cavitation mode starts and stops at the developed super-cavitation (figure 2d). At the same time, the continuity of the fluid flow is maintained on the channel axis in the high pressure zone.

The beginning and end of the light emission process are determined by the pressure levels  $p_1$  in the inlet and  $p_3$  in the outlet of the choke coil, determining the pressure difference of the choke coil  $p_{cc} = p_1 - p_3$  and the speed in the compressed section (figure 3).



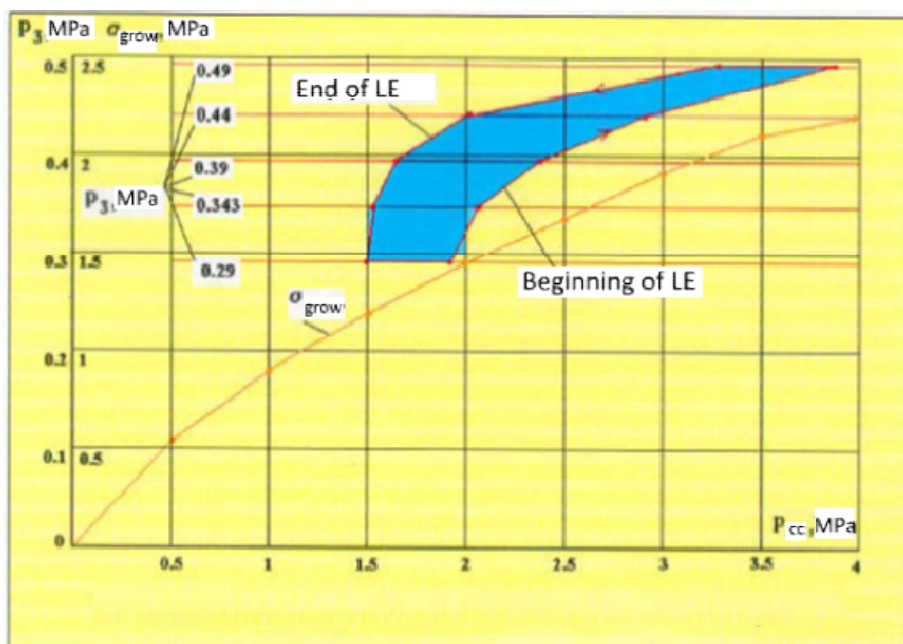
**Figure 3.** Flow structure and geometry of the diaphragm choke coil.

The solution of equations of Bernoulli for sections 1-2 and 1-3 in terms of continuity of fluid flow in the mode of origin of the cavitation ring and when the condition  $p_{2abc} = p_{ov}$ , where  $p_{ov}$  is the pressure of saturated oil vapor at a given temperature, determined the condition of the beginning of cavitation in the compressed section of choke coil:

$$p_1 - 5.43p_3 = 4.43 (p_{\text{at}} - p_{\text{ov}}). \quad (1)$$

The coefficients in the supply of equation (1) determining the cavitation start condition are obtained for the choke coil geometry shown in figure 3, and the compression ratio of the jet  $\varepsilon = 0.75$ . It should be noted that in the mineral oil heated to 50 °C light emission was not observed.

The graph (figure 4) presents the diagram of light emission (SI) origin and termination at the change of the pressure of the backwater  $p_3$  in the choke coil outlet and the pressure drop  $p_{cc}$  on the choke coil.



**Figure 4.** Influence of the backwater flow parameters on the light emission.



Horizontal sections of the diagram corresponding to the specified back pressure  $p_3$  in the outlet of the choke coil allow to determine pressure levels  $p_1$  in the inlet, at which the light emission begins and ends: for example, at the back pressure in the tap  $p_3 = 0.44$  MPa, light emission occurs when the pressure difference on the choke coil  $p_{cc} = 2.80$  MPa, that corresponds to the pressure in the inlet  $p_1 = 2.36$  MPa. Light emission stops when the pressure difference is equal to  $p_{cc} = 2.00$  MPa. It follows from the diagram that in the process of light emission there is a hysteresis. The digital increase in the photo of the glowing ring to the pixel level showed that in its conditional center of symmetry the color of light emission is pure white, remaining brightly blue on the periphery.

In this paper, the cavitation process in the flow of fresh mineral oil of the firm *SHELL* which has the viscosity  $\nu_{40} = 20$  sSt was initially investigated.

Cavitation in hydrodynamic flow of MGE10 mineral oil with viscosity  $\nu_{40} = 10$  sSt it was more intense, and light emission was not observed. Thus, we can assume the existence of dependence of light emission from the following factors: the properties of a basis of mineral oil, the pressure of the saturated vapor and its package structure of corrective additives.

In the course of long-term studies of the cavitating flow of mineral oil in the transparent model of diaphragm choke coil, the intensity of light emission decreased and after a certain time the light emission completely stopped. Replacement of spent mineral oil with fresh did not lead to the resumption of light emission.

In a new instance of the choke coil model of the previous geometry, light emission resumed in the same quality and at the same flow modes. This allows to make a conclusion about dependence of intensity of light emission from the sharpness of the leading edge of choke coil, is susceptible to dulling with abrasive wear of the material of the walls. A fragment of the experimental stand for the study of hydrodynamic processes in choke coil is shown in figure 5.



**Figure 5.** Experimental stand for the research of the characteristics of the choke coil.

Pressure drop in the choke coil  $\Delta p = p_1 - p_2$  was estimated taking into account hydraulic losses in high-speed flexible hose connectors and in the inlet and outlet channels of choke coil. Flow parameters in diaphragm choke coil are shown in figure 6. At the highest value of the pressure drop on the choke coil  $\Delta p = 4$  MPa the Reynolds number in the choke coil input section has reached the value  $Re = 3.5 \times 10^3$ ; this corresponded to the beginning of the turbulent regime of fluid motion, while the flow regime in the inlet and outlet corresponded to the laminar flow at Reynolds number  $Re = 500$ . The speed of movement of the liquid in the inlet, in the cross-section of choke coil and the compressed cross section of the flow received, respectively, the values  $V_1 = 1.9$  m/s;  $V_2 = 65$  m/s;  $V_{comp} = 100$  m/s.

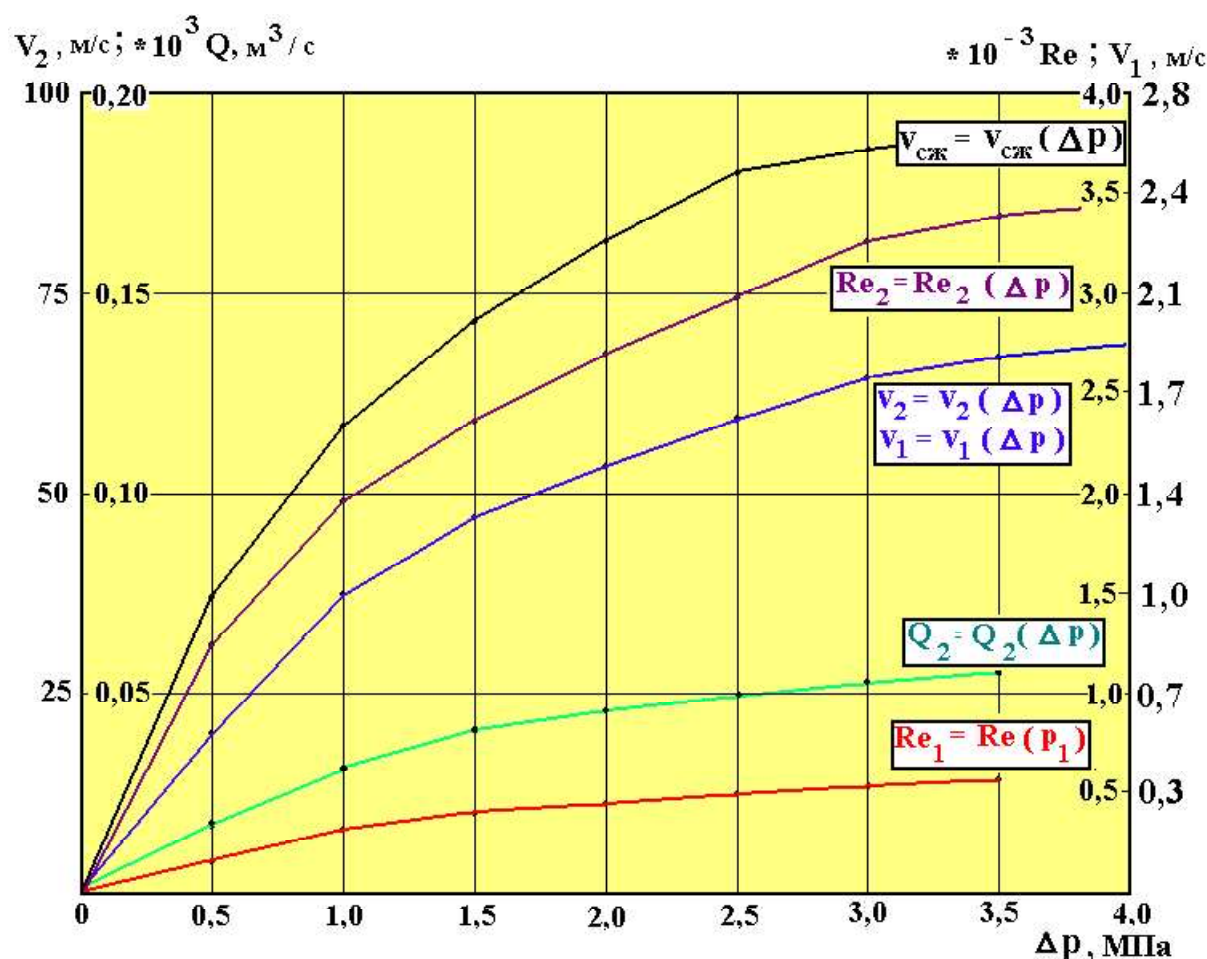


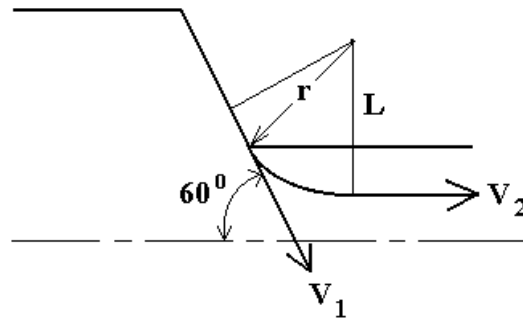
Figure 6. The parameters of the flow of mineral oil in a diaphragm choke coil.

Comparison of graphs in figure 4 and figure 6 shows that light emission occurs at fluid flow rates in a compressed section  $V_{comp} \geq 75$  m/s.

### 3. Physical and mechanical justification of the results of the experimental study

The results of the study of the hydrodynamic flow of mineral oil (a medium with dielectric properties) in narrow channels showed that electric charges and associated complex processes may form inside the flow, causing, in the presence of additional conditions, light emission in the compressed section of the flow, when it passes through the sharp entrance edge of the diaphragm choke coil [17]-[20].

Under certain conditions, light emission may occur in the flow, the nature of which is difficult to determine, but it is most likely that it is determined by electrical rather than thermal processes. The absence of melting of the sharp entrance edge in the model of diaphragm choke coil made of organic glass is not consistent with the stated versions of “plasma discharges” [12] and “spark discharges” and “plasma breakdown” [16]. Localization of light emission at the entrance sharp edge of the diaphragm choke coil in the compressed flow section, its absence in other sections of the turbulent flow, as well as the dependence of the light emission on the degree of sharpness of the entrance edge, necessitated the analysis of the dynamics of the process of bending peripheral streams flow conditionally sharp entrance edge diaphragm choke coil (figure 7).



**Figure 7.** The scheme of diffraction of the peripheral stream sharp edge of the input choke coil.

If we assume the uniformity of motion of the liquid particle in the area of the circumference of the peripheral jet of the sharp entrance edge of the choke coil along a curvilinear trajectory with a constant radius  $r$ , such movement can be considered as uniformly accelerated, with zero local acceleration  $\partial V/\partial t = 0$  and final values of convective accelerations  $\partial V/\partial S \neq 0$ , caused by a change in the direction of the velocity vector. In this case, the acceleration is directed to the center of the circle perpendicular to the velocity vector and is considered as a normal centripetal acceleration of the portable motion  $a_{cp} = V^2/r$ .

On a particle of liquid mass  $\Delta m$ , located on the peripheral stream and the envelope of the sharp edge, in the center of its mass acts the centrifugal force  $F_{cf}$ , determined by the pressure forces on the side of adjacent particles on the outside of the trajectory (supporting force), and the tensile forces on the part of the particles on the inside of the trajectory adhering to the solid wall (attracting force). It can be assumed that in the case of non-wettability of the wall with a liquid, the attracting force will be absent.

The volume of a droplet liquid particle of spherical shape with radius  $R$  is related to its mass and density  $\Delta W = \Delta m/\rho = 4\pi R^3/3$ . In this case, the radius  $R$  is defined by the expression

$$R = (3\Delta W/4\pi)^{1/3} = (3\Delta m/4\pi\rho)^{1/3}. \quad (2)$$

If we assume the modulo equality of the supporting and attracting forces, the resulting surface force acting on the plane diametrical cross section of the sphere with the area of

$$\Delta S = \pi R^2 = \pi(3\Delta m/4\pi\rho)^{2/3}, \quad (3)$$

will be determined by the equation

$$\Delta m V^2/r = 2\pi p(3\Delta m/4\pi\rho)^{2/3}. \quad (4)$$

Expressing from equation (4) the value of  $p$ , which is considered to be the intensity of the surface force in “Fluid Mechanics”, we obtain

$$p = \Delta m V^2/2\pi r(3\Delta m/4\pi\rho)^{2/3}. \quad (5)$$

The substitution of the average density of mineral oil  $\rho = 860 \text{ kg/m}^3$ , defines an expression for the numerical evaluation of the intensity of the surface force

$$p = 37\Delta m^{0.33} V^2/r. \quad (6)$$

In the expression (6) the mass  $\Delta m$  is not determined, so it is advisable to estimate the intensity of the surface force reduced to the mass  $\Delta m^{0.33}$ :

$$p/\Delta m^{0.33} = 37 V^2/r. \quad (7)$$

Table 1 presents the intensity of the reduced surface force, calculated in accordance with the equality of (7) for specific values of  $r$  and  $V$ .



**Table 1.** The intensity of the given surface forces

| $r = 0.5 \text{ mm}$ |                                  | $r = 0.1 \text{ mm}$ |                                  | $r = 0.1 \text{ mm}$ |                                  |
|----------------------|----------------------------------|----------------------|----------------------------------|----------------------|----------------------------------|
| $V, \text{ m/s}$     | $\Delta m^{0.33}, \text{ m/s}^2$ | $V, \text{ m/s}$     | $\Delta m^{0.33}, \text{ m/s}^2$ | $V, \text{ m/s}$     | $\Delta m^{0.33}, \text{ m/s}^2$ |
| 0.5                  | $9 \times 10^3$                  | 0.5                  | $18 \times 10^3$                 | 0.5                  | $90 \times 10^3$                 |
| 1                    | $3.7 \times 10^4$                | 1                    | $7.4 \times 10^3$                | 1                    | $37 \times 10^3$                 |
| 2                    | $1.48 \times 10^5$               | 2                    | $2.96 \times 10^5$               | 2                    | $14.8 \times 10^5$               |
| 5                    | $9.25 \times 10^5$               | 5                    | $18.5 \times 10^5$               | 5                    | $92.5 \times 10^5$               |
| 10                   | $3.7 \times 10^6$                | 10                   | $7.40 \times 10^6$               | 10                   | $37 \times 10^6$                 |
| 50                   | $9.25 \times 10^7$               | 50                   | $18.5 \times 10^7$               | 50                   | $92.5 \times 10^7$               |

The data in table 1 show that a mineral oil particle located on a peripheral jet, enveloping the sharp entrance edge of the choke coil, can be affected by a sufficiently large tensile force, which can cause light emission. Due to the speed of the processes, the liquid particle does not have time to turn into steam, which explains the localization of light emission in the pre-cavitation zone. According to equality (7) and table 1, the magnitude of the tensile force depends significantly on the sharpness of the inlet edge, which determines the compression ratio of the jet and the radius of curvature of the trajectory. For example, reducing the fillet radius of an edge from 1 mm to 0.05 mm increases the intensity of the reduced surface force by 20 times. This, to some extent, reveals the reason for the lack of light emission in the diaphragm choke coil, which in the process of long-term operation occurred dulling its sharp entrance edge due to abrasive wear. Quantitative assessment of the intensity of the tensile force gave the following results:

1)  $R = 0.1 \text{ mm}$ ;  $\Delta W = 4.2 \times 10^{-12} \text{ m}^3$ ;  $\rho = 860 \text{ kg/m}^3$ ;  $\nabla m = 0.36 \times 10^{-8} \text{ kg}$ ;  $\nabla m^{0.33} = 0.0016$ .

For  $r = 1 \text{ mm}$  and  $V = 50 \text{ m/s}$ :  $p = 152 \text{ kPa}$ ; for  $r = 0.5 \text{ mm}$  and  $V = 50 \text{ m/s}$ :  $p = 304 \text{ kPa}$ ;

2)  $R = 0.05 \text{ mm}$ ;  $\Delta W = 0.52 \times 10^{-12} \text{ m}^3$ ;  $\rho = 860 \text{ kg/m}^3$ ;  $\nabla m = 0.045 \times 10^{-8} \text{ kg}$ ;  $\nabla m^{0.33} = 0.00079$ .

For  $r = 1 \text{ mm}$  and  $V = 50 \text{ m/s}$ :  $p = 75 \text{ kPa}$ ; for  $r = 0.5 \text{ mm}$  and  $V = 50 \text{ m/s}$ :  $p = 150 \text{ kPa}$ .

The above flow characteristics in the diaphragm choke coil allow us to estimate the averaged velocity of the fluid in the compressed section and the intensity of the tensile force.

D. Bernoulli equation written for the input section of choke coil channel and the compressed section of the flow (its pre-cavitation zone) in the conditions of continuum preservation  $V_i \times A_i = \text{inv}$ , (where  $V_i$  is the speed averaged for the  $A_i$  flow cross section), determines the average value of the pressure in the compressed section of flow

$$p_2 = p_1 + \rho V_1^2 / 2 - (1 + \zeta_{\text{in}}) \times \rho V_2^2 / 2, \quad (8)$$

where

$\zeta_{\text{in}} = 0.05$  is the coefficient of hydraulic resistance of the input sharp edge choke coil;

$\rho = 860 \text{ kg/m}^3$  is the density of mineral oil.

After substitution of the value of the imperfect compression ratio of the jet  $\varepsilon = 0.65 \div 0.70$ , the equation (8) will take the form

$$p_2 = p_1 - 451 V_2^2. \quad (9)$$

The algebraic values of pressure  $p_2$  averaged over the flow cross-section obtained by the results of the experiment had a negative value, which indicates the presence of tensile stresses in the cross-section  $p_{\text{grow}} = -p_2$ .

The values of the tensile stresses averaged over the flow section calculated from the test results  $\sigma_{\text{grow}} = \sigma_{\text{grow}} (\Delta p)$ , where  $\Delta p = p_1 - p_3 = p_{\text{cc}}$  is the differential pressure on diaphragm choke coil;  $p_3$  is the pressure in the outlet of the choke coil, are shown in the graphs figure 4.

From the graph figure 6 it follows that

– the average velocity of the liquid in the compressed section reached the values  $V_{2\text{max}} = 100 \text{ m/s}$ ,

- the average value of the tensile force intensity (tensile stress)  $\sigma_{\text{grow max}} = 2.2$  MPa.
- tensile stress corresponding to the beginning of light emission in the input section of the choke coil lies within  $\sigma_{\text{grow}} = 1.4 \dots 2.2$  MPa and depends on the amount of pressure in the backwater choke coil.
- the light emission is terminated at lower values of tensile stress  $\sigma_{\text{grow}} = 1.1 \dots 2.0$  MPa, which indicates the presence of hysteresis effect in the process.

Taking into account that the input flow section is taken on the left edge of the cavitation ring, the pressure field along the flow section is inhomogeneous, and the tensile stress calculated from the Bernoulli equation  $\sigma_{\text{grow}}$  should be considered as averaging the pressure plot. The same factor can be explained by the influence of the back pressure  $p_3$  on the intensity and stability of light emission: the termination of light emission in the regime of intense supercavitation is due to a decrease in  $\sigma_{\text{grow}}$  in conditions of closure of the attached and moving cavitation areas.


The time required for the origin and closure of the moving cavity in the case where the main role is played by the inertia forces is a few milliseconds. In addition, the estimates of the tensile force intensity performed on the basis of the solution of the Bernoulli equation and the analysis of the dynamics of the process of envelope of the liquid particle of the sharp entrance edge of choke coil are quite correlated.

#### 4. Conclusions

The results of the analysis of processes in the flow of dielectric fluid and the results of the experiment on the study of the hydrodynamic flow of mineral oil in narrow channels allow us to reach the following main conclusions.

1. The presence of high tensile stresses in the liquid can cause light emission of sufficient intensity in the blue part of the color spectrum.
2. Light emission originates from and is localized in the zone of origin of cavitation caverns at the entrance edge of the diaphragm choke coil, where the absolute pressure is reduced, and not in the zone of closure of cavitation caverns, where the absolute pressure is much greater.
3. The intensity of light emission depends significantly on the absolute pressure in the zone of formation of vapor-gas cavities from cavitation nuclei, the flow rate determining the value of centripetal forces acting on the liquid particles located on the peripheral flow jets enveloping the sharp edge, as well as on the basis of mineral oil and the presence in it of a package of corrective additives.
4. The dependence of the light emission on the degree of sharpness of the input edge, necessitates the analysis of the dynamics of the process of envelope peripheral streams flow conditionally sharp entrance edge diaphragm choke coil.
5. It can be assumed that possible electrical processes in the flow of mineral oil in narrow slits can cause electrical erosion of the oil base and limiting the flow of the channel walls made of materials with a crystal structure, as well as “burning” of corrective additives. Electrical erosion of the channel walls made of amorphous material (organic glass) was not detected.

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