Досліджуються процеси в замкненому об'ємі шестеренного насоса, який утворюється внаслідок особливостей геометрії евольвентного зачеплення, які властиві насосам даного типу. В рідині, що знаходиться в замкненому об'ємі, при обертанні шестерень виникає ряд складних гідродинамічних процесів. Внаслідок зміни величини замкненого об'єму відбувається компресія рідини, а також розрідження. При зниженні тиску в рідині нижче рівня тиску насиченої пари в ній виникає кавітація. Крім того, внаслідок обертання шестерень виникає вихровий рух рідини, що призводить до появи вихорів, в центрі яких відбувається зниження тиску, тобто вихори є потенційними зародками кавітації. Високошвидкісна відеофіксація дозволила детально розглянути процес виникнення та росту кавітаційних явищ в замкненому об'ємі, дослідити динаміку деформації кавітаційної бульбашки та каверни, що утворюються в замкненому об'ємі.

За результатами обробки отриманих під час досліджень кінограм були отримані залежності, що показують характер зміни розміру кавітаційної бульбашки та каверни. Отримані залежності мають нелінійний характер та точку екстремуму. Екстремум на графіку за часом спостерігається після розкриття замкненого об'єму, тобто потрібен деякий час (близько 0,3 мс) для зростання тиску в міжзубній западині. Причому екстремум спостерігається майже одночасно, як для деформації каверни, так і для деформації окремої бульбашки. Радіус бульбашки в рідині залежить від окремих факторів, а саме, властивостей рідини та значення тиску, для розрахунку якого можна скористатися наведеними у роботі залежностями відповідно до умов виникнення кавітації

Ключові слова: шестеренний насос, замкнений об'єм, вихор, відеофіксація, кавітація, кавітаційна бульбашка

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RESEARCH INTO CAVITATION PROCESSES IN THE TRAPPED VOLUME OF THE GEAR PUMP

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1. Introduction

Gear pumps are widely used in the systems of hydraulic machinery and hydroautomatics, lubrication, equipment for chemical industry. This is due to the relative simplicity of the design and manufacturing, high reliability, low sensitivity to the purity of the working fluid, high mass and size characteristics, the capacity to create high pressure. Modern pumps can deliver pressures up to 32 MPa, the flow rate of up to 0.1 m^3/s, and work with fluids with a viscosity of up to 10,000 Pa·s.

The principle of gear pump operation, as well as many studies into its properties and characteristics, have shown that at its operation a series of hydrodynamic phenomena occur in its cavities. The working fluid compression occurs, there are the phenomena of cavitation and vortex formation. These processes can have a negative effect on the liquid pumped by the pump, as well as on the elements of the pump design [1, 2].

When the pressure in the fluid decreases below the level of saturated vapour pressure, cavitation occurs in it. In addition, due to the rotation of gears, there is the vortex motion of the fluid, which leads to the emergence of vortices in whose centres the pressure reduces; in other words, they are the potential embryos of cavitation. Similar processes are observed in all gear pumps, but for some of them of particular importance is the non-stop operation. Thus, the failures of pumps used in search-and-rescue equipment during fire extinguishing activities may lead to fatal consequences. Thus, there is a need to investigate the process of occurrence and dynamics of the deformation of cavitation bubbles in a trapped volume of the pump. The efficiency of the system for generating water jets that are employed by firemen and rescuers can be assessed by applying the exergy method for analysis of complex technical systems. The specified analysis will contribute to the improvement of systems for generating water jets from fire-fighting vehicles and systems for automated fire extinguishing, whose elements include the gear pumps.

2. Literature review and problem statement

One of the promising methods to study hydrodynamic processes is the visualization that became possible following the development of the appropriate modern registering equipment. The visualization study into the operation of the gear pump [3] detected the emergence of cavitation phenomena in the trapped volume and the impact of operating parameters of the pump on them.

Note that probably the most important parameter of the gear pump, its maximum flow rate, essentially depends on the gap between gear engagement and the lateral gap [4]. The influence of geometrical parameters of the pump design on its performance was studied using a three-dimensional numerical simulation of the gear pump. Characteristics of internal flow are represented relative to the internal peak of pressure, local cavitation, and pressure pulsation at the inlet. However, there is no indication of the causes underlying the emergence of cavitation phenomena in the trapped volume.

Cavitation may exert significant influence on the work of pump components, especially for devices with forced displacement. Different models that describe the properties of flows are applied to study cavitation effects. The problem of predicting the effects of cavitation is considered in the study [5], which reports a comparison of the measured and simulated instantaneous internal spatial pressures, as well as flow rates at the inlet. The model proposed is compared to results obtained using classical models of flow properties, which do not make it possible to accurately predict the effects of cavitation.

The procedures that are applicable for modelling the phenomena of the performance of the motion of non-Newtonian viscoelastic fluids in pumps make it possible to improve results of designing the gear pumps [6]. The authors describe the technique for modelling pumps that operate with the non-Newtonian liquids. Specifically, the flow of fluid through cracks between the teeth of the gears; there is a comparison between modelling results and experimental data on liquids that have different characteristics of viscosity. However, there remain the insufficiently studied issues on deriving the dependences that characterize the size and change in the emerging cavitation bubbles.

An effective technique to assess the volumetric efficiency of a high-pressure pump is the application of numerical methods and experimental verification. Authors of paper [7], in order to predict cavitation phenomena in the region of a clutch of the pump, built a 3D model for studying the dynamics of fluid motion. The analysis made it possible to detect the areas of cavitation, especially at a high speed of rotation of pump gears. However, the authors did not detect the nature of deformation of cavitation zones at a change in the magnitude of the trapped volume of the intertooth chamber of the pump.

In addition to the purely theoretical methods and the application of simulation software, the process of fluid flow in a pump with external engagement can be investigated using experimental methods of study. Actually, the experimental methods help visualize the motion of fluid in the pump [8] with the aim of further improvement efficiency of its operation.

The process of tracking the origin of cavitation processes can be implemented by means of visualizing the flow of fluid using a high-speed video recording of the working process of the pump with a lid made of transparent material [3, 9]. Thus, the employment of a given technique can enable an analysis of the process of occurrence of a cavitation bubble, its growth and collapse, as well as obtain calculation dependencies that make it possible to find a relation between the size of cavitation bubbles and pressure in the surrounding liquid. One way or another, the cavitation processes influence the efficiency of pumps application and their hydromechanical and exergy patterns. The body of research into a given problem [10, 11] was aimed at developing practical recommendations in the field of application of the results obtained for the needs of modern rescue and fire-fighting means and equipment.

Because cavitation and the related phenomena have a significant impact on the operation of hydraulic systems and their characteristics, it is an important task to investigate the emergence of cavitation during operation of the gear pump. The essence of the problem is the lack of reliable data on the occurrence of cavitation in a trapped volume of the gear pump, on the size of emerging cavities, and on their impact on the pump operation.

3. The aim and objectives of the study

The aim of this study is to investigate the mechanism underlying the occurrence of cavitation phenomena in a trapped volume of the gear pump and to explore the dynamics of deformation of cavitation bubbles.

To accomplish the aim, the following tasks have been set:

– to visualize flow in the gear pump with external engagement and to acquire the sequence of frames to detect the emergence of cavitation zones in it;

– to analyze the acquired sequence of frames in order to derive dependencies that characterize the deformation of cavitation bubbles and cavities;

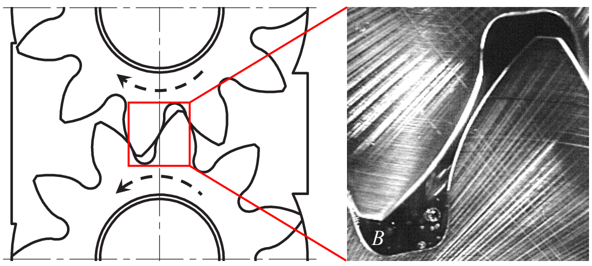
– to study existing procedures for calculating the cavitation phenomena and to derive dependencies for the calculation of the size of cavitation bubbles and their change over time.

4. Methods for studying the process of emergence and growth of cavitation phenomena in gear pumps

The basis of this paper was the use of high-speed video recording (10,000 frames per second), which allowed us to identify the point of origin and the dynamics of growth of cavitation bubbles. As a result, it was found that there were several phases of the cavitation phenomena. The images shown below were acquired at the frequency of pump rotation of 500 rpm, the pressure in the discharge line was 0.52 MPa, and the pressure in the suction line was equal to that in the atmosphere. The working fluid was the hydraulic oil of type HLP68, the temperature of the fluid was 27 °C; in this case, the viscosity was 130 cSt (liquid density is 868 kg/m^3). Parameters of the toothed gear used in the examined pump are: diameter of tops of the gear teeth is 69.4 mm, the diameter of the gear cavities is 45.4 mm, the number of teeth is 11.

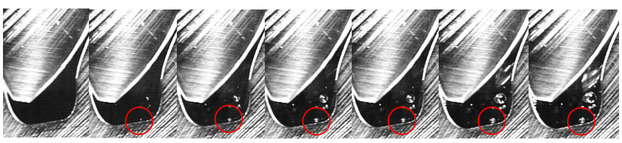
In this research, we studied processes in a trapped volume of the pump (Fig. 1, *a*), and specifically in the intertooth chamber 2 (Fig. 1, *b*), where one observes vortex formation and the cavitation phenomena in the process of pump operation. These processes are discussed in detail based on the sequences of frames (Fig. 2–4).

In a fluid that is confined to the trapped volume, the growth of its magnitude leads to the emergence of separate cavitation bubbles (Fig. 2), whose size increases according to the growth in magnitude of the trapped volume and the reduction of pressure in it.



a *b*

Fig. 1. Determining the examined region of the pump and the processes observed in it: *a* — the examined region of the pump (arrows indicate the direction of gear rotation); *b* — the flow of fluid between parts of the trapped volume: A — intertooth chamber 1; B — intertooth chamber 2



a *b* *c* *d* *e* *f* *g*

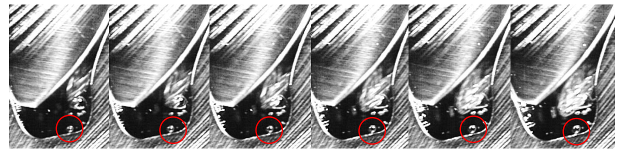
Fig. 2. Formation of cavitation bubbles in a trapped volume of the pump (time between frames is 0.1 ms): *a* — trapped volume without signs of cavitation; *b* — emergence of cavitation bubbles; *c*–*e* — growth of a cavitation bubble with the growth of the trapped volume; *f* — emergence of cavity as a result of the flow of fluid; *g* — growth of cavity

Along with this (starting from the time of 0.4 ms from the emergence of cavitation phenomena), one observes in the trapped volume the flow of fluid from the upper part of the trapped volume to the bottom part. The result of the flow of fluid through a narrow gap between the teeth of gears from a intertooth chamber A to chamber B (Fig. 1, *b*) is a decrease in pressure. A cavity appears whose size is greater than the cavitation bubbles formed because of the increased trapped volume.

To determine the size of the bubble and the cavity, we measured the region's area on the sequences of frames, which corresponds to the bubble and the cavity. The region in the image that corresponds to the trapped volume is dark, while the emerging bubbles and cavities are light enough to clearly define the boundaries of the desired shape. We determined the area using the GIMP 2.8.14 graphics editor, by determining the area of the selected shape in pixels. Next, knowing the size of the gear teeth, and by having similarly identified their dimensions in the sequence of frames in pixels, one can determine the size of bubbles and cavities.

We registered a time-dependent change in the size of a single cavitation bubble (highlighted in the red circle in Fig. 2) and the total area of bubbles and cavities that emerge in a trapped volume during pump operation.

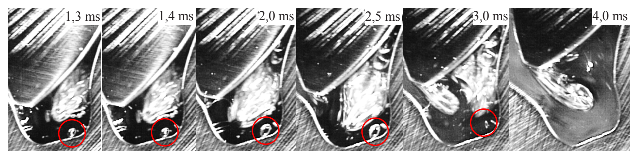
Note that the rotation of pump gears results in an increase in the magnitude of the trapped volume and, as a consequence, in the reduction in pressure and an increase in the magnitude of emerging bubbles and cavities (Fig. 3).



a *b* *c* *d* *e* *f*

Fig. 3. An increase in the size of cavitation bubbles in the trapped volume of the pump (time between frames is 0.1 ms): *a*–*f* — the growth of a cavitation bubble and cavity at the rotation of gears, due to the increased trapped volume

Upon opening the trapped volume, we observed the flow of fluid from a suction chamber into the open intertooth cavity (Fig. 4).



a *b* *c* *d* *e* *f*

Fig. 4. The opening of the trapped volume and collapse of the formed cavitation bubbles and cavities: *a*, *b* — an increase in the magnitude of the trapped volume; c — the opening of the trapped volume; *d*–*f* — emergence and growth of the second cavitation region, the collapse of the cavity and the cavitation bubble

In this case, there occurred the detachment of flow and the formation of a cavity at the top of the tooth, the result of which is the formation of a vortex. We also observed the collapse of a separate bubble and cavity that occurred as a result of the drop in pressure in the intertooth gap.

The research conducted allowed us to determine the law of change in the formed cavity and a separate cavitation bubble. The change in the size of a bubble (circled in Fig. 1) is shown in Fig. 5. One can see that the dependence is non-linear in nature. The video recording shows that the bubble acquires its maximum size after the opening of the trapped volume and collapses when the intertooth cavity is filled and pressure in it is levelled with pressure in the suction chamber.

A similar pattern is observed for the cavity, formed as a result of the flow of fluid through the intertooth gap. A change in size is nonlinear in character and has the point of an extremum (Fig. 6). The size of a cavity reaches the maximum value after the opening of the trapped volume. This is followed by the collapse of the cavity.

The cavity that emerges as a result of the flow detachment from the top of the tooth has a smaller area; the character of change in the magnitude of the cavity is shown in Fig. 6 (curve 2). Cavity growth was driven by the increased flow rate of fluid that enters the intertooth cavity of the growing intertooth space. This is followed by a decrease in a cavity in the suction chamber. The result of fluid motion implies that the cavity turns into a vortex that fades in the suction chamber.

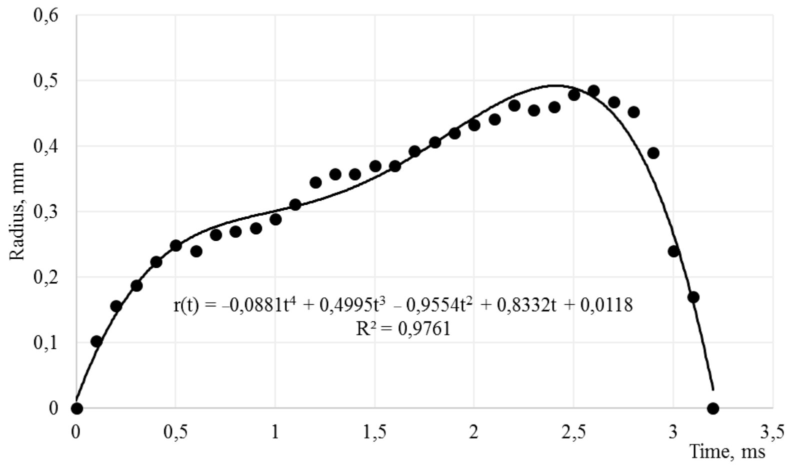


Fig. 5. A change in the radius of a bubble in the trapped volume of the gear pump

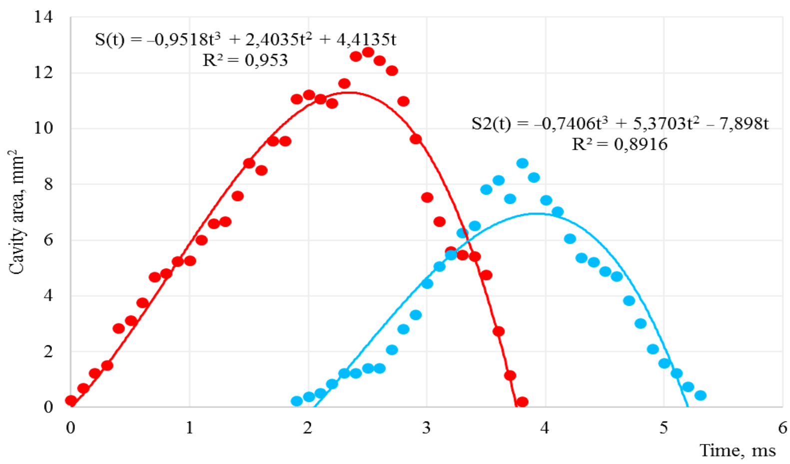


Fig. 6. Time-dependent change in the size of cavities that emerge in a trapped volume: 1 – change in the area of the first cavity and approximation; 2 – change in the area of the second cavity and approximation

The result of the analysis is the derived mathematical dependence that describes the dynamics of a cavitation bubble

$$r(t)=-0{,}0881t^4+0{,}4995t^3-$$
$$-0{,}9554t^2+0{,}8332t+0{,}0118,$$

where $r(t)$ is a change in the radius of the bubble; t is the time. In this case, the accuracy of approximation R^2=0.9761.

Dependences for the area of the emerging cavities were derived similarly:

$$S(t)=-0{,}9518t^3+2{,}4035t^2+4{,}4135t$$

and

$$S_2(t)=-0{,}7456t^3+5{,}4249t^2-8{,}0899t+0{,}2131,$$

where $S(t)$, $S_2(t)$ is a change in the cavity area; t is the time. The accuracy of approximation R^2=0.953 and R^2=0.8916, respectively.

The fluid pressure in the environment where a bubble forms can be derived from the formula [12]:

$$p_{env}=p_0\frac{R_0^3}{R^3}+p_s\left(1-\frac{R_0^3}{R^3}\right)+2\sigma\left(\frac{R_0^2}{R^3}-\frac{1}{R}\right), \qquad (1)$$

where R is the radius of the bubble, p_s is the pressure of saturated vapour. The index "0" accompanies the magnitudes corresponding to the initial value for the development of a bubble; σ is the surface tension coefficient.

Using equation (1), possible to find the value for the critical radius of a bubble and for the ambient pressure

$$R_{cr}=\sqrt{3}R_0\sqrt{\frac{R_0}{2\sigma}\cdot\left(p_0-p_s+\frac{2\sigma}{R_0}\right)}=$$
$$=\sqrt{3}R_0\sqrt{\frac{R_0}{2\sigma}p_{r0}}=\frac{4\sigma}{3(p_{cr}-p_s)},$$

$$\left(p_{env}\right)_{cr}=-\frac{2}{3\sqrt{3}}\left(\frac{2\sigma}{R_0}\right)\sqrt{\frac{2\sigma}{R_0}\frac{1}{p_{r0}}}=p_s\frac{2}{3}\frac{2\sigma}{R_{cr}}. \qquad (2)$$

Equation (2) shows that the important role is taken by the forces of surface tension σ.

To track the deformation of a bubble in perfect and viscous fluids, it is necessary to state the conditions for a change in the radius of bubbles. For a perfect fluid, such an equation can be represented in the following form

$$R\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2=\frac{p_0+p_s}{\rho}, \qquad (3)$$

where ρ is the density of the fluid.

A solution to equation (3) can be obtained at the following initial conditions when t=0, R=R_0 and $\left(\frac{dR}{dt}\right)_{t=0}=0$. We shall then obtain for the first and second derivatives

$$\left(\frac{dR}{dt}\right)^2=\frac{2}{3}\frac{p+p_s}{\rho}\left(1-\frac{R_0^3}{R^3}\right);$$

$$\left(\frac{d^2R}{dt^2}\right)^2=\frac{p+p_s}{\rho}\frac{R_0^3}{R^4}. \qquad (4)$$

The results obtained indicate a rapid change in speed at the onset of motion and during the enlargement of a sphere. We can write for a viscous liquid

$$\frac{p-p_0}{\rho}=\frac{1}{r}\left[R^2\frac{d^2R}{dt^2}+2R\left(\frac{dR}{dt}\right)^2\right]\frac{1}{2}\frac{R^4}{r^4}\left(\frac{dR}{dt}\right)^2. \qquad (5)$$

A special feature of equation (5) is that it does not contain terms that characterize the viscosity of the examined fluid. However, note that the influence of viscosity is associated with the boundary conditions.

With respect to viscosity for a Newtonian fluid, equation (5), which describes a change in the radius of a bubble, can be recorded as

$$\frac{p-p_0}{\rho}=R\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2+\frac{4\mu}{\rho R}\frac{dR}{dt}. \qquad (6)$$

Thus, by applying formulae (2), (6), one can determine the critical radius of a bubble and the dynamics of change in radius taking the viscosity and density of the fluid into consideration.

5. Results of research into the mechanism of cavitation phenomena in the gear pump

Based on the visualization of flow, we managed to monitor the process of forming a cavitation zone, starting with the formation of a single bubble and up to the process of its collapse. The presented graphical dependences of a given process demonstrate both the speed of a bubble formation and the conditions that are observed in the process of collapse, that is, the critical pressure. In the shown charts, this moment is characterized by a maximum of dependence r(t) (Fig. 5). At a given extremum, determining the radius of a bubble and the maximum pressure can be performed based on known formulae (4) and (5), which take into consideration the properties of the examined environment (viscosity, density).

Given that the process of bubble nucleation and their formation is observed throughout the entire trapped volume, there forms a cavity whose change in size over time is described by chart 1 (Fig. 6). A change in the area takes place in such a way that the extreme value is observed at the moment following the opening of the trapped volume, after which there is a decrease in its size, that is, the collapse of the cavity. Curve 2 in Fig. 6 illustrates a change in the size of the second cavity that emerges after opening the trapped volume as a result of vortex formation and rarefaction behind a tooth in the flow that occurs as a result of filling the intertooth cavity. Changing the size of a given cavity is similar to the preceding one.

This result, which is related to the moment of formation and collapse of bubbles and cavities, is extremely important because it can characterize the time and the region when and where pump gears may break down.

Based on the data acquired in line with a given procedure, we plotted charts and constructed mathematical dependences that make it possible to track the dynamics of cavitation phenomena. The derived dependences are non-linear, with points of an extremum, which are defined by the moment when a trapped volume is opened. The collapse of bubbles and reduction in the size of cavities occur at a certain delay (0.1–0.3 milliseconds) after opening the trapped volume, which can be explained by the time required to fill the intertooth cavity with a fluid from the suction chamber.

6. Discussion of results of studying the cavitation processes in a trapped volume of the gear pump

In a liquid confined to the trapped volume, at an increase in its magnitude, there emerge separate cavitation bubbles (Fig. 2) whose size increases according to the growth in magnitude of the trapped volume and reduction of pressure in it. Along with this, starting from the time of 0.4 ms from the emergence of cavitation phenomena, one observes, in the trapped volume, the flow of fluid from the upper part of the trapped volume to the bottom part. The result of the flow of fluid through a narrow gap between the teeth of gears from a intertooth chamber A to chamber B (Fig. 1, *b*) is the decreased pressure.

The research conducted allowed us to detect cavitation zones that emerge in the gear pump, specifically in the trapped volume. Thus, it has become possible to confirm theoretical assumptions about the emergence of cavitation in the pump. It was observed that one of the causes for the formation of a cavity is the flow of fluid through a gap between the teeth of the gears that connect parts of the trapped volume. In the process of gear rotation, the size of cavities changes, which causes the flow at a high rate; the regions of low pressure are created. An additional cause of cavitation is an increase in the magnitude of the trapped volume, followed by the further rarefaction of fluid inside it.

This result, which is related to the moment of formation and collapse of bubbles and cavities, is extremely important because it can characterize the time and the region when and where pump gears may break down.

The benefit of this study is the detailed patterns of flow in a trapped volume of the gear pump, acquired using a high-speed video recording, which made it possible to identify the regions of emergence and to investigate the mechanism of emergence of cavitation in a trapped volume of the gear pump. In addition, the characteristics of the trapped volume, obtained by visualization, refine, to a certain extent, existing ideas about the performance of fluid and the pump operation.

As an example, paper [13] constructed a mathematical model for the formation of a trapped volume and its shape, which made it possible to determine the shape and characteristic of the trapped volume for different moments of mutual arrangement of gears. However, the reported results of mathematical and geometrical modelling had some differences. Given this, in order to elucidate the issue on the size and deformation of a trapped volume, there was a necessity for visualization, which is described in this article. In addition, data from modelling did not provide for a possibility to identify and describe the phenomenon of cavitation.

Results of the study conducted are applicable for the Newtonian liquids, which include oil that was used during our experiment. For the non-Newtonian fluids, the process of cavitation could prove to be more complex, which would require testing and conduct additional studies. In addition, the purpose of further research is to investigate effects of the working fluid temperature, the speed of pump gears rotation, and the suction pressure, on cavitation processes.

The gear pumps that were examined in this work can operate with a variety of fluids. Some of them are susceptible to the cavitation impact; they consequently may change their physical, chemical and rheological properties. Therefore, studying the conditions for the emergence of cavitation phenomena and their development would make it possible choose rational modes of pump operation, namely the frequency of gear rotation, the pressure in the suction chamber, the temperature of the working fluid. Based on the data obtained, one can conclude about the intensity of the cavitation phenomena that emerge in a trapped volume.

However, the process of flow visualization in the gear pump is associated with the difficulty to ensure the strength of the pump casing, which should be made from a transparent material when registering the patterns of flow at a working pressure above 1 MPa.

7. Conclusions

1. The result of visualization research into flow has confirmed the emergence of cavitation zones in the trapped volume of the gear pump. It was established that cavitation zones are caused by the flow of a fluid through a narrow gap between the gears (for the examined model, it is approximately 0.3 mm), and by an increase in the trapped volume. In addition, there is the emergence of a vortex and a cavity while opening the trapped volume.

2. By processing the sequences of frames acquired in the course of this study, we determined dimensions of the emerging cavitation phenomena and the nature of their change over time. The maximum radius of a bubble was 0.5 mm, and the maximum area occupied by a cavity was 13 mm^2. It was established that the moment when cavitation bubbles and cavities acquire their maximum size is observed in about 0.3 milliseconds after its opening.

3. A traditional method for calculating the cavitation process is the method for determining the critical pressure and critical radius of emerging bubbles based on a Rayleigh equation, which makes it possible to take into account the effect of viscosity and density of the fluid on the collapse bubbles. By processing experimental data using the software package Microsoft Excel, we derived dependences that characterize the dynamics of a cavitation bubble and cavity, with an approximation probability, which is characterized by the magnitude of determination factor $R_2 \approx 0.95$; which allowed us to propose a mathematical notation of the process of cavitation in a trapped volume.

References

1. Grivnin Yu. A., Zubrilov S. P. Kavitaciya na poverhnosti tverdyh tel. Leningrad: Sudostroenie, 1985. 124 p.
2. Fedotkin I. M., Gulyi I. S. Kavitaciya. Kavitacionnaya tekhnika i tekhnologiya, ih ispol'zovanie v promyshlennosti. Kyiv: Poligrafkniga, 1997.
3. Visualisation research of the flow processes in the outlet chamber-outlet bridge-inlet chamber zone of the gear pumps / Stryczek J., Antoniak P., Jakhno O., Kostyuk D., Kryuchkov A., Belov G., Rodionov L. // Archives of Civil and Mechanical Engineering. 2015. Vol. 15, Issue 1. P. 95–108. doi: https://doi.org/10.1016/j.acme.2014.02.010
4. Numerical simulation of three-dimensional external gear pump using immersed solid method / Yoon Y., Park B.-H., Shim J., Han Y.-O., Hong B.-J., Yun S.-H. // Applied Thermal Engineering. 2017. Vol. 118. P. 539–550. doi: https://doi.org/10.1016/j.applthermaleng.2017.03.014
5. Zhou J., Vacca A., Casoli P. A novel approach for predicting the operation of external gear pumps under cavitating conditions // Simulation Modelling Practice and Theory. 2014. Vol. 45. P. 35–49. doi: https://doi.org/10.1016/j.simpat.2014.03.009
6. Rituraj F., Vacca A. External gear pumps operating with non-Newtonian fluids: Modelling and experimental validation // Mechanical Systems and Signal Processing. 2018. Vol. 106. P. 284–302. doi: https://doi.org/10.1016/j.ymssp.2017.12.042
7. Frosina E., Senatore A., Rigosi M. Study of a High-Pressure External Gear Pump with a Computational Fluid Dynamic Modeling Approach // Energies. 2017. Vol. 10, Issue 8. P. 1113. doi: https://doi.org/10.3390/en10081113
8. Ertürk N. Experimental Study of the Flow in an External Gear Pump by Time-Resolved Particle Image Velocimetry. University of Rovira, Tarragona Spain, 2008. 12 p.
9. Stryczek J., Kostiuk D. V., Yakhno O. M. Flows Features in the Internal Channels of Involute External Gear Pumps // Naukovi visti Natsionalnoho tekhnichnoho universytetu Ukrainy "Kyivskyi politekhnichnyi instytut". 2014. Issue 1. P. 64–70.
10. Stas' S. V., Shkarabura N. G., Yahno O. M. Eksergeticheskiy analiz struynyh potokov // Visnyk Kremenchutskoho Derzhavnoho politekhnichnoho universytetu imeni Mykhaila Ostrohradskoho. 2008. Issue 2 (49). P. 114–119.
11. Destabilization of stream in a channel with the length-varying flow rate / Yahno O. M., Seminskaya N. V., Kolesnikov D. V., Stas' S. V. // Eastern-European Journal of Enterprise Technologies. 2014. Vol. 3, Issue 7 (69). P. 45–49. doi: https://doi.org/10.15587/1729-4061.2014.24658
12. Pernik A. D. Problemy kavitacii. Leningrad: Sudostroenie, 1988. 438 p.
13. Shesterennye nasosy s asimmetrichnoy liniey zacepleniya shesteren (teoriya, konstrukciya i raschet): monografiya / Kuleshkov Yu. V., Chernovol M. I., Bevz O. V., Titov Yu. A. Kirovograd, 2009. 243 p.