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VISUALIZATION OF HYDRODYNAMIC PROCESSES IN A TWO-PIPE HYDRAULIC SHOCK ABSORBER IN THE STUDY OF THE CAVITATION TRANSFER PHENOMENON

The work processes that occur in the chambers of a double-tube hydraulic shock absorber during its operation are considered, such as the flow of working fluid through the piston valve, which is caused by the pressure difference between the working chambers. When the working fluid was flowing in the valve-throttle tract, in throttle operation, where only calibrated holes are used, hydrodynamic cavitation was poorly developed, which corresponds to a piston speed of about 0,25 m/s. It should be noted that when operating in a valve mode of operation, when the liquid flows through the open valves, at critical and close to critical operating modes of the hydraulic shock absorber, developed hydrodynamic cavitation occurs. In this regard, the operating characteristic changes, due to the occurrence of a two-phase flow, which is due to the presence of air, which leads to a decrease in the resistance force and a deterioration in the efficiency of vibration damping by a hydraulic shock absorber. To ensure the expansion of the range of effective operation, the operating modes were precise in which hydrodynamic cavitation occurs. One of the effective methods for fixing the occurrence of hydrodynamic cavitation is the visualization of working processes in the chambers of a hydraulic shock absorber. An experimental stand was developed and a prototype was manufactured made it possible to carry out the necessary experimental studies and establish the operating modes and the depth of the occurrence of cavitation. The study of the piston valve operation by visualizing the flow in the "rebound" mode made it possible to obtain the dependences of the flow rate on the Reynolds number and temperature, presented in the pressure range of 1–4 MPa. The experimental study also takes into account the change in the viscosity of the liquid in the temperature range from 20 °C to 50 °C. The results of the experimental study showed the weakest elements of the piston valve, and their analysis made it possible to determine the critical parameters at which hydrodynamic cavitation occurs in the shock absorber. Research in the future will make it possible to modernize the design of the valve-throttle tract to prevent the premature occurrence of hydrodynamic cavitation, taking into account changes in the viscosity of the working fluid and operating conditions. As a result of expanding the range of effective operation and the development of a control law for the conductivity of the throttles, taking into account cavitation phenomena and changes in the rheological properties of the hydraulic shock absorber fluid, it will be possible to develop a technical solution that will significantly improve the efficiency of vibration damping and stabilize its performance.

Keywords: hydraulic shock absorber, valve-throttle tract, cavitation phenomenon, flow visualization, diameter, oil viscosity.

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ВІЗУАЛІЗАЦІЯ ГІДРОДИНАМІЧНИХ ПРОЦЕСІВ У ДВОТРУБНОМУ ГІДРАВЛІЧНОМУ АМОРТИЗАТОРІ ПРИ ДОСЛІДЖЕННІ ЯВИЩА КАВІТАЦІЙНОГО ПЕРЕНОСУ

В статті розглянуто робочі процеси, які виникають в камерах двотрубного гідравлічного амортизатора під час його роботи, такі як потік робочої рідини через поршневий клапан, викликаний перепадом тисків між робочими камерами. При протіканні робочої рідини через клапанно-дросельний тракт в дросельному режимі роботи, де задіяні лише калібровані отвори, гідродинамічна кавітація проявлялася в нерозвиненій формі, що відповідає швидкості руху поршню приблизно 0,25 м/с. Слід відмітити, що при роботі в клапанному режимі, коли рідина перетікає через відкриті клапани у критичних та наближених до критичних режимах роботи гідравлічного амортизатора, виникає розвинена гідродинамічна кавітація. В зв'язку з цим виникає двофазний потік, який обумовлений наявністю повітря, що призводить до зниження зусилля опору та погіршення ефективності гасіння коливань гідравлічним амортизатором. Для забезпечення розширення діапазону ефективної роботи уточнено режими роботи при яких виникає гідродинамічна кавітація. Одним з ефективних методів фіксації виникнення гідродинамічної кавітації є візуалізація робочих процесів в камерах гідравлічного амортизатора. Розроблений експериментальний стенд та виготовлений дослідний зразок дозволили провести необхідні експериментальні дослідження та встановити режими роботи і глибину виникнення кавітації. Дослідження роботи поршневого клапана шляхом візуалізації потоку в режимі «відбій» дозволили отримати залежності коефіцієнта витрати від числа Рейнольдса та температури, представлені в діапазоні тисків 1–4 МПа. Експериментальне дослідження враховує і зміну в'язкості рідини в інтервалі температур від 20 °С до 50 °С. Результати експериментального дослідження показали найбільш слабкі елементи поршневого клапана, також їх аналіз дозволив визначити критичні параметри, при яких виникає гідродинамічна кавітація в амортизаторі. Дослідження в подальшому дозволять модернізувати конструкцію клапанно-дросельного тракту для запобігання передчасному виникненню гідродинамічної кавітації з врахуванням зміни в'язкості робочої рідини та умов експлуатації. В результаті розширення діапазону ефективної роботи та розробки закону керування провідністю дроселів з урахуванням кавітаційних явищ та зміни реологічних властивостей рідини гідравлічного амортизатору дозволить розробити технічне рішення, що дозволить стабілізувати робочу характеристику гідравлічного амортизатора.

Ключові слова: гідравлічний амортизатор, клапанно-дросельний тракт, явища кавітації, візуалізація потоку, діаметр, в'язкість мастила.

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ВИЗУАЛИЗАЦИЯ ГИДРОДИНАМИЧЕСКИХ ПРОЦЕССОВ В ДВУХТРУБНОМ ГИДРАВЛИЧЕСКОМ АМОРТИЗАТОРЕ ПРИ ИССЛЕДОВАНИИ ЯВЛЕНИЯ КАВИТАЦИОННОГО ПЕРЕНОСА

В статье рассмотрены рабочие процессы, возникающие в камерах двухтрубного гидравлического амортизатора во время его работы, такие как поток рабочей жидкости через поршневой клапан, который вызван перепадом давлений между рабочими камерами. При протекании рабочей жидкости в клапанно-дроссельном тракте в дроссельном режиме работы, где используются только калиброванные отверстия, гидродинамическая кавитация имела мало развитой характер, что соответствует скорости движения поршня примерно 0,25 м/с. Следует отметить, что при работе в клапанном режиме, когда жидкость перетекает через открытые клапаны при критических и приближенных к критическим режимах работы гидравлического амортизатора, возникает развитая гидродинамическая кавитация. В связи с этим возникает двухфазный поток, что обусловлено наличием воздуха, который приводит к снижению усилия сопротивления и ухудшению эффективности гашения колебаний гидравлическим амортизатором. Для обеспечения расширения диапазона эффективной работы были уточнены режимы работы, при которых возникает гидродинамическая кавитация. Одним из эффективных методов фиксации возникновения

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гидродинамической кавитации является визуализация рабочих процессов в камерах гидравлического амортизатора. Разработаный экспериментальный стенд и изготовленый опытный образец позволили провести необходимые экспериментальные исследования и установить режимы работы и глубину возникновения кавитации. Исследование работы поршневого клапана путем визуализации потока в режиме «отбой» позволили получить зависимости коэффициента расхода от числа Рейнольдса и температуры, представленные в диапазоне давлений 1–4 МПа. Экспериментальное исследование учитывает изменение вязкости жидкости в интервале температур от 20 °С до 50 °С. Результаты экспериментального исследования показали наиболее слабые элементы поршневого клапана, а также их анализ позволил определить критические параметры, при которых возникает гидродинамическая кавитация в амортизаторе. Исследования в дальнейшем позволят модернизировать конструкцию клапанно-дроссельного тракта для предотвращения преждевременного возникновения гидродинамической кавитации с учетом изменения вязкости рабочей жидкости и условий эксплуатации. В результате расширения диапазона эффективной работы и разработки закона управления проводимостью дросселей с учетом кавитационных явлений и изменения реологических свойств жидкости гидравлического амортизатора позволит разработать техническое решение, которое позволит стабилизировать рабочую характеристику гидравлического амортизатора.

Ключевые слова: гидравлический амортизатор, клапанно-дроссельный тракт, явления кавитации, визуализации потока, диаметр, вязкость масла.

Introduction. In machine building industry hydraulic shock absorbers are used for damping and minimizing oscillations in mechanical systems. Using of hydraulic dampers has become wider as result of their compact size, low costing and a little consumption of materials for design and manufacturing. Typical "twin - pipe" shock absorber has three chambers that are connected by channels through two valve-throttles groups: the piston valve and the base valve. The pressure difference in chambers is caused by resistance of the valve tracts. If fluid goes through tract on high speed, caused by high frequency of changing movement direction and magnitude of load value on piston rod, this means that flow is unstable and there's possibility of forming cavities in the flow and viscosity changes. Usually in calculations, flows are considered as continuous without cavitation and gas. However, these processes effect on damping characteristics [1, 2, 11–18]. It's necessary to study hydrodynamic processes in absorber for taking into account those specialties. To define circumstances of the flow interruption, throttling characteristic and to spectate processes in valve tract the sample for visualization was design and manufactured. Main aim of research is definition specialties of flow in the piston valve throttle tract on working modes and circumstances [3, 19, 20].

1.1. Objectives:

a) experimental researches of influence on the flow rate coefficient at piston valve tract due to viscosity changes;

b) defining the modes and circumstances of cavitation processes at the piston valve.

Visualization and study. Visualization had been made by using the sample that has transparent cylinder made of Plexiglas (Fig. 1).

Fitting of the cylinder and the piston valve of shock absorber was sized according to their real connection as it needs to form throttling apertures as well. Experiments were made with pressure at the inlet up to 4 MPa and flow rate up to 10^{-5} m^3/s. These quantities correspond to real values of damping processes in shock absorber work. The sample was connected to hydraulic system according to scheme (Fig. 2), hydraulic system is able to imitate working modes of shock absorber – compressing and return (rebound). Main parameters that were controlled: the pressure level at inlet, pressure difference at sample's inlet and outlet channels, flow rate and temperature at the outlet. The temperature of the working fluid was controlled in the apparatus using the aries reference thermocouple. Experimental studies were made for return mode using the "H-L" type working fluid. Shooting of processes in the sample of piston valve was made via camera at 120–1000 fps. Studies had been made to obtain data that describe structure and parameter specialties of the flow. Input values correspond to values on working modes of real hydraulic shock absorber.

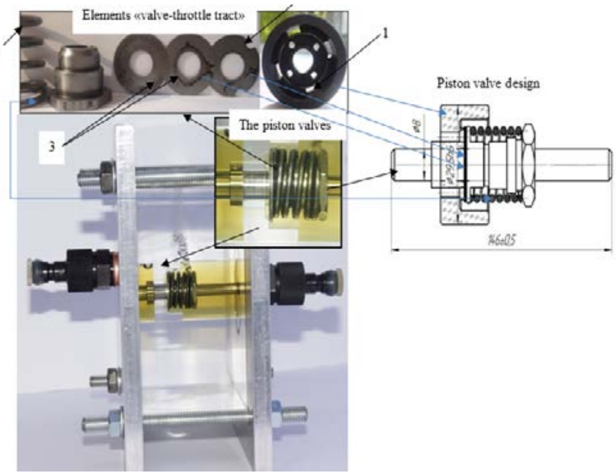


Fig. 1. Studying model (the sample) design:
1 – piston; 2 – rebound valve spring; 3 – rebound valve disc;
4 – by-pass valve disc

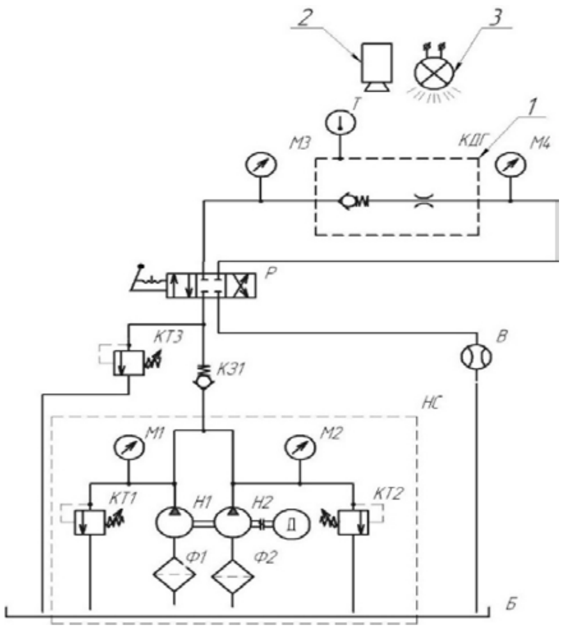


Fig. 2. Principal hydraulic diagram of experimental stand:
1 – the sample; 2 – high-speed camera; 3 – light source;
T – reference thermocouple

Construction parameters of 3D-model are same as for the sample, used in the experiment. Experiment was made via the sample of piston valve and hydraulic system, was done on didactic stand (Fig. 3).

The experimental research technique consisted of the following actions. Setting the required differential pressure on the apparatus, the temperature of the working fluid was controlled by a reference thermocouple and the volumetric flow rate was measured.

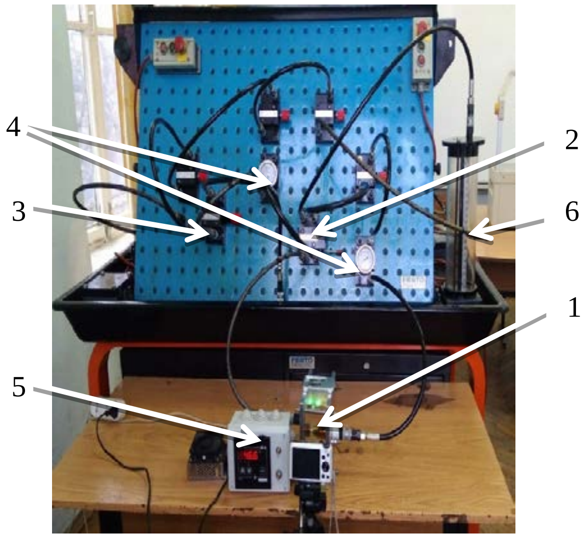


Fig. 3. Experimental stand. General view:
1 – the sample; 2 – directional valve; 3 – pressure relief valve;
4 – manometers at the inlet and outlet; 5 – temperature sensors;
6 – flow meter

The required number of temperature and flow measurements was calculated in the coordination of the design of the experiment. Obtained experimental data allows to define dependence of the flow rate coefficient of piston valve throttles on Reynolds numbers and kinematic viscosity (Fig. 4, *a*). The diagram shows that value of flow rate coefficient has been increased a twice (at $\mathrm{Re}_h = 300$) due to viscosity has been changes (from 0,00025 to 0,000035 m^2/s because of the fluid temperature increasing). Curve form $\mu = f(\mathrm{Re})$ can be explained by influence of complex changes of density, viscosity and aperture (defined by pressure difference) due to temperature (Fig. 4, *b*).

The kinematic viscosity was calculated for the "H-L" shock-absorbing working fluid, for changing the temperature of the working fluid in the range of +20 °C–+50 °C, with a density of 917 kg/m^3.

The viscosity of the working fluid was calculated using the nomogram for this type of oil [1, 9, 10] (where the temperature range corresponded to a specific viscosity value.) The change in viscosity was taken into account when determining the number Reynolds number, which is defined as

$$\mathrm{Re} = \frac{vd}{\vartheta} = \frac{\rho \vartheta d}{\mu} = \frac{Qd}{\vartheta A} \tag{1}$$

where ρ is the density of the fluid (SI units: kg/m^3); v is the flow speed (m/s); d is the diameter of the tube (m), μ is the dynamic viscosity of the fluid (Pa·s or N·s/m^2 or kg/(m·s)); ϑ is the kinematic viscosity of the fluid (m^2/s); A channel cross-sectional area (m^2); Q volumetric flow rate (m^3/s).

$$\vartheta = \mu / \rho. \tag{2}$$

In the general case, viscosity is non-linear in temperature and is described by the Frenkel-Andrade equation. The movement of fluid in the calibrated channels of the damper can be represented by the pulse flux density (the force of internal friction between two layers of gas (liquid), which is described by Newton's law into which we to express the Frenkel-Andrade law) [3, 5]:

$$I_L = -\mu \frac{du}{dx} = -Ce^{\frac{W}{kt}} \frac{du}{dx}, \tag{3}$$

where W – activation energy; kt – average energy of chaotic motion; C – coefficient depending on the intensity of oscillations, temperature, hopping; du/dx – the velocity gradient is the rate of change of velocity in the direction perpendicular to the direction of motion of the layers.

The Newtonian viscosity coefficient depends on temperature, pressure, and the type of substance: $\mu = f(\mathrm{T}, \mathrm{p}, \rho)$.

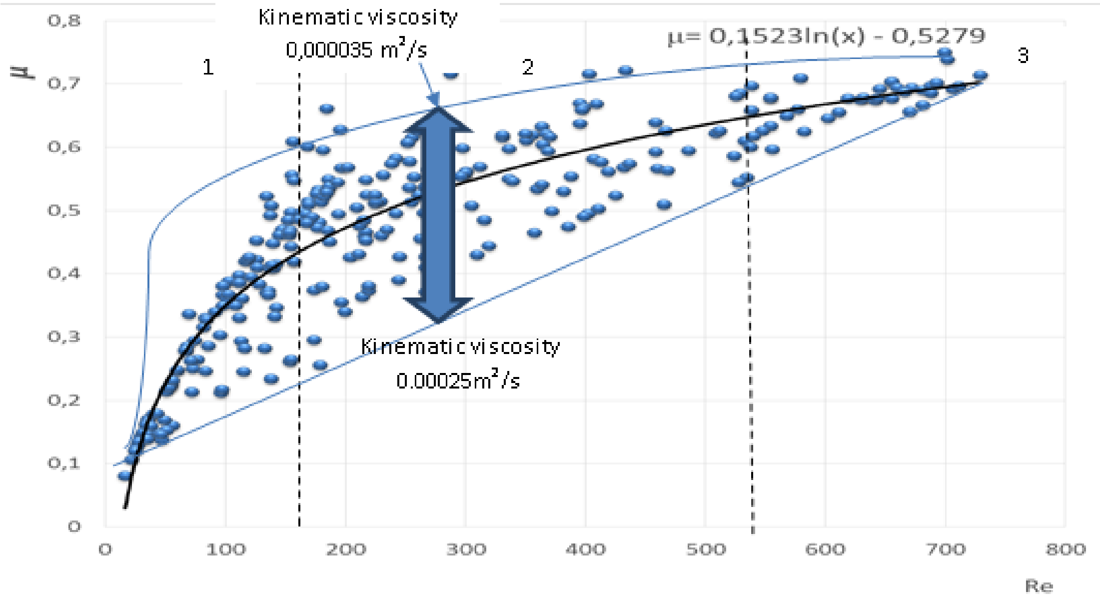
It is known that the analytical dependence of the dynamic viscosity on temperature according to the research of G. M. Panchenkov has the form:

$$\mu = 3\sqrt{6R} \cdot \sqrt{\frac{\omega_w^2}{N_0}} \cdot \rho^{\frac{4}{3}} \cdot M^{-\frac{5}{4}} \cdot T^{\frac{1}{2}} \times \\ \times e^{-\frac{\varepsilon}{RT}} \cdot \left(1 - e^{-\frac{\varepsilon}{RT}}\right)^2, \tag{4}$$

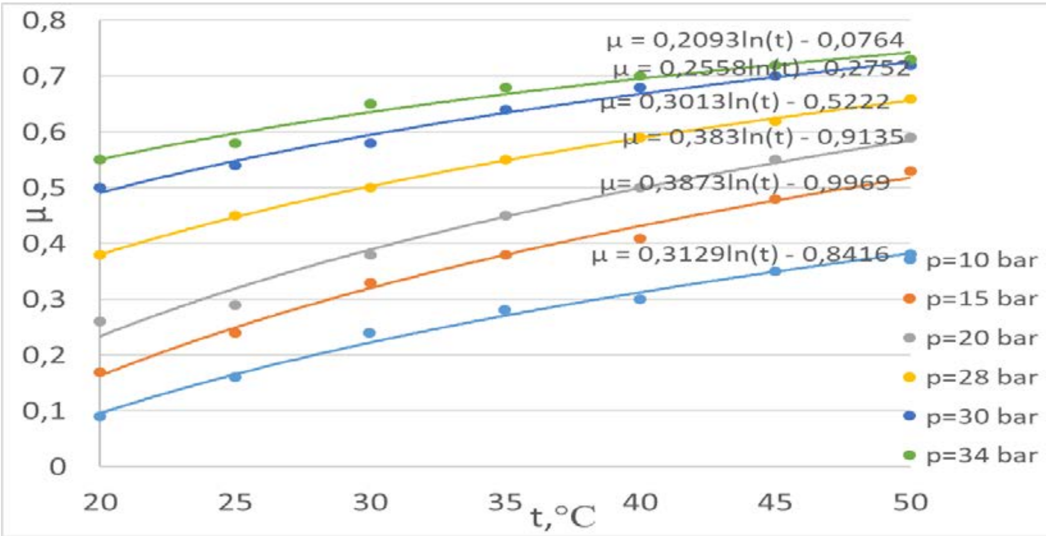
where R is the gas constant; ω_w – own volume of molecules in the calculation of 1 g-mol; N_0 – the number of molecules in a volume of 1 g-mol; M – molecular mass; ρ – density; ε – the binding energy of liquid molecules, is determined by the work that must be expended to move infinitely long distances from its original position (this work is equal to the latent heat of evaporation divided by half the coordinate number of the liquid).

Temperature influence on the flow in piston valve tract shows necessity of taking into account viscosity changes to increase calculation precision. Visualization showed possibility of the flow interruption because of cavitation (existed small bubbles in the flow) due to local areas with critical pressure, that corresponds to vapors pressure of the fluid (Fig. 5).

It means possibility of cavitation in shock absorbers, that have negative influence on damper characteristics. There are two cavitation types in the hydraulic shock absorber: volumetric cavitation in working chambers; and stream cavitation in the flow. In general, cavitation leads to negative processes, like as mechanical vibrations, noise, material erosion of working surfaces, pressure pulsations and sometimes has being accompanied with hydraulic luminescence [4, 9].



a



б

Fig. 4. The flow rate coefficient dependencies on Reynolds number and temperature of the piston valve tract: *a* – on Reynolds number; *б* – on temperature; 1 – laminar flow; 2 – intermittent flow; 3 – turbulent flow

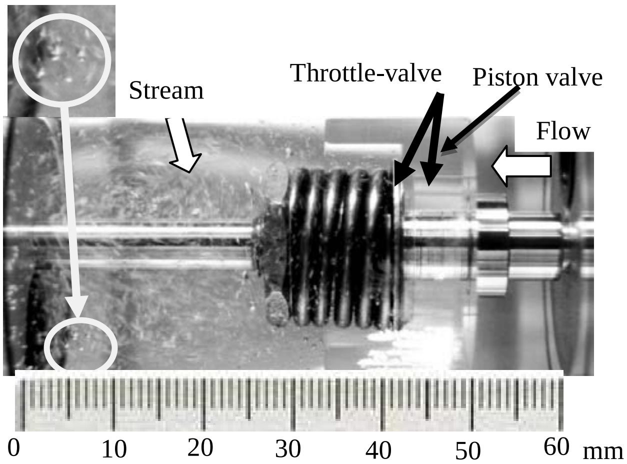


Fig. 5. Twin-phase flow in the piston valve sample Δp = 4 MPa, t = 20 °C, $Q = 7\cdot 10^{-5}$ m³/s, 200 fps

High value of pressure difference leads to increase flow velocity that occurs rising of bubbles concentration in the flow mand their volume growing. Gases in bubbles, as known, have high compressibility and their concentration at the tract outlet leads to change magnitude of pressure pulsation and its frequency.

Size of bubble 1 is calculated as [5]:

$$R_{ed} = \sqrt{3}R_0\sqrt{\frac{R_0}{2\sigma}\cdot\left(p_0 - p_H + \frac{2\sigma}{R_0}\right)} = \sqrt{3}R_0\sqrt{\frac{R_0}{2\sigma}pr_0} = \frac{4\sigma}{3\left(p_{ed} - p_H\right)} \qquad (5)$$

where R – bubble radius; p_H – vapors pressure, index 0 is for values that correspond to zero-stage of bubble evolution; σ – surface tension of the fluid. Volume of gases in bubbles depends on cavitation coefficient 2.

Critical parameters of the flow and depends between pressures height and velocity, that indicate the start of stream cavitation can be carried out [6].

Volume of gases in bubbles depends on cavitation coefficient. Critical parameters of the flow and depends between pressures height and velocity, that indicate the start of stream cavitation can be carried out [4]:

$$\chi = \frac{2\left(p_1 - p_2\right)}{\rho \cdot V_1^2} \tag{6}$$

where p_1 – pressure of flow, e. g. at the valve inlet; V_1 –velocity of flow, e. g. at the valve inlet; p_2 – vapors pressure; ρ – fluid density.

As known, in case of drowned bores the stream cavitation starts at the edge of bore when $\chi \leq 0{,}5$. Critical parameters, that indicate the start of volumetric cavitation, depend on throttle shape, fluid rupture strength, vapor volume in fluid, fluid viscosity and variables, as temperature, pressure and velocity [9, 10]. However, in experiment were spectated start of cavitation on the $\chi \sim 0{,}9$–1 (Fig. 6). For twin-pipe shock absorber, it is possible to prevent cavitation by increasing pressure of inertial gas in the reserve tube that also increase fluid pressure in general and by intensify cooling. That leads to change critical values of pressure and temperature for liquid, so the operating fluid temperature and vapors pressure will be lower than the critical values. That prevent foaming fluid also and make the damper characteristics more smoothly and stable.

The results showed that with an increase in temperature from 20 to 50 °C and a pressure drop of 1 MPa, the flow rate increased by 50 % for the "compression" mode.

Analytical processing of the experimental results made it possible to determine and evaluate the effect of kinematic viscosity for fluid on the damper resistance force in the range 0,000035–0,0001 m^2/s (Fig. 7). At the same time, when the temperature changes from +20 °C to + 50 °C, the damper resistance efforts changed almost 2 times, which is unacceptable and does not meet the standardization requirements.

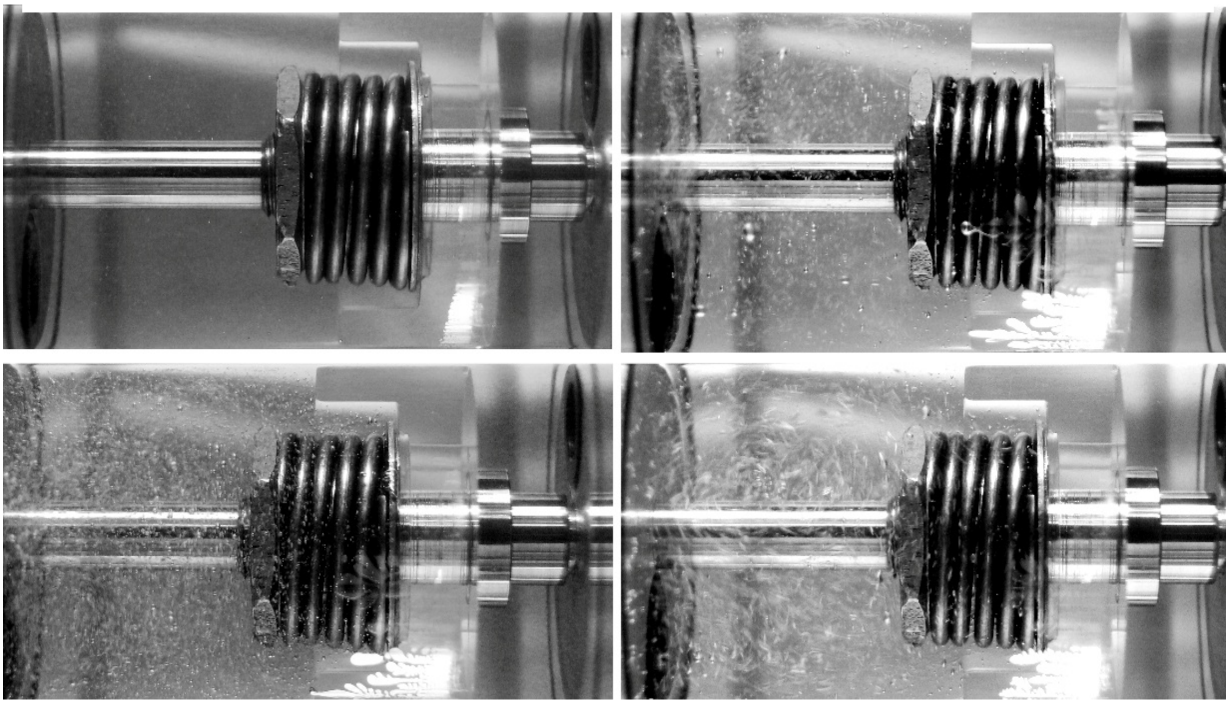
The results obtained allowed us to determine the mathematical function for determining the resistance force from the kinematic viscosity (Fig. 7).

Having analyzed the workflows in the damper, it is further was installed that the of transfer coefficients mainly have to should determine corrective action to form the damper characteristics.

The coefficients form and directly influence the pressure ripples in the working cavities of the following and form the nature of the ripple and the law of oscillation damping.

On the other hand, corrective actions of the working characteristic can be achieved by structuring the substance, changing the shape and concentration of molecules (particles) in a given direction, or using repulsive "clathrates" of heterogeneous «nanoscale» structures ("clathrate compounds") [20], which can be the main tool in the design and the development of intelligent designs with adaptive properties.

$\chi \geq 1{,}54$; Δp = 1 MPa; t = 40 °C; $Q = 1{,}5 \cdot 10^{-5}$ m^3/s $\chi \approx 0{,}9$; Δp = 1,9 MPa; t = 40 °C; $Q = 3 \cdot 10^{-5}$ m^3/s



$\chi = 0{,}7$; Δp = 3 MPa; t = 40 °C; $Q = 6 \cdot 10^{-5}$ m^3/s $\chi = 0{,}5$; Δp = 4 MPa; t = 40 °C; $Q = 7 \cdot 10^{-5}$ m^3/s

Fig. 6. Changes in the flow due to pressure changes at the inlet. Flow direction – from left to right (as at Fig. 5); Δp = 4 MPa; t = 20 °C; $Q = 7 \cdot 10^{-5}$ m^3/s; 200 fps

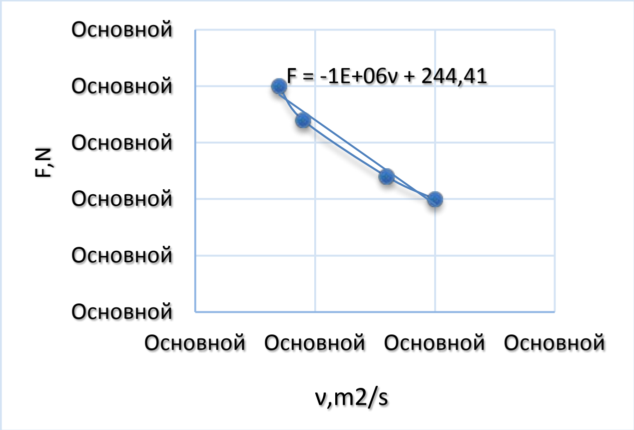


Fig. 7. Temperature characteristic of the damper dependence of the resistance of the damper force when the kinematic viscosity of the working fluid changes in the range of 0,000035–0,0001 m^2/s (Δp – 1 MPa; Q – 0,00001–0,00002 m^3/s)

Conclusions. It was carried out that the flow rate coefficient had been changed from 0,03 to 0,68 corresponding to viscosity decreasing from 0,00025 to 0,0000358 m^2/s. Spectated changes were studied during experiment in three flow modes: laminar, intermittent and turbulence. Also, was defined evolution of the twin-phase flow at pressure difference 1,9 MPa, greater or equal. Its characterized by spectating the bubble (diameter 0,01 to 1 mm) in the flow, after throttle aperture. As result of bubble presence in the flow there are decreasing of density, viscosity and modulus of elasticity. There is correlation among these parameters and temperature that effects on static, kinematic and dynamic damper characteristics. To find the solution for characteristics stabilization there are planning to precise calculations, forms and sizes of throttles and to define protection against cavitation and oxidative processes in shock absorbers.

Because of in-depth analysis of work processes, it established that the functional disadvantages of the damper include foaming, cavitation of the working fluid, pressure pulsations, and dependence of viscosity and density on temperature and inertia of the working fluid.

In-Depth knowledge of the phenomenon of transfer and accounting for transient operating modes in changing operating conditions may be the main criterion in the design of dampers with a stable operating characteristic.

It was also found that in accordance with the above approach, the damping problem in a hydraulic damper with a variable viscosity transfer coefficient was considered when the temperature changed from +20 °C to + 50 °C, the resistance of the damper was halved. That requires the use of a compensation unit – a "compensator" and an in-depth study of rheological models and properties of working fluids on a synthetic basis.

References

1. Morettini G, Bartolini N, Astolfi D, Scappaticci L, Becchetti M, Castellani F. Experimental diagnosis of cavitation for a hydraulic monotube shock absorber. *Diagnostyka*. 2016. Vol. 17, no. 3. P. 75–80.
2. Струтинський В. Б., Колот О. В. *Математичне моделювання стохастичних процесів у системах приводів*. Краматорськ: Тираж-51, 2005. 530 с.
3. *Control Valves. Cavitation in control valves. Technical information*. Frankfurt: Samson AG., 2003. 62 p.
4. d'Agostino L., Salvetti M. V., eds. *Fluid dynamics of cavitation and cavitating turbopumps. Courses and lectures*. NewYork: Springer-Verlag Wien, 2007. 351 p.
5. Batchelor G. K. *An Introduction to fluid dynamics*. Cambridge: Cambridge University Press, 2000. 615 p. doi:10.1017/CBO9780511800955
6. Bird R. B., Stewart W. E., Lightfoot E. N. *Transport Phenomena*. NewYork: John Wiley & Sons. 2002. 895 p.
7. Nochnichenko I. Uzunov O. Characteristics of throttles in hydraulic shock absorber considering temperature changes of fluid. *Mechanics and Advanced Technologies*. 2017. Vol. 2, no. 80. P. 39–44. doi: 10.20535/2521-1943.2017.80.109169
8. Nochnichenko I. V., Luhovskyi A. F., Jakhno O. M., Kostiuk D. V., Komada P., Kozbakova A. Experimental research of hydroluminescence in the cavitating flow of mineral oil. *Proc. SPIE 11176, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments. Vol. 1117615 (6 November 2019, Wilga)*. Wilga, 2019. P. 8. doi: 10.1117/12.2536946
9. Nochnichenko I., Jakhno O., Liberatskyi I. The character of the transfer phenomenon in the work processes of the hydraulic damper. *International scientific conference proceedings "Unitech 2019" (16–17 November 2019, Gabrovo)*. Gabrovo, 2019. P. 273–277.
10. Alsaydalani M. Influence of cavitation phenomenon on the hydraulic behavior of leaks in water distribution systems. *Journal of Water Supply: Research and Technology-Aqua*. 2017. Vol. 66, iss. 5. P. 327–339. doi: 10.2166/aqua.2017.013
11. An C. G., Cao Y., Zhang J. W. Cavitation and noise analysis of throttle hole in double cylinder hydraulic shock absorber. *Journal of Shanghai Jiaotong University*. 2018. Vol. 52, no. 3. P. 297–304.
12. Chao Q., Zhang J., Xu B. Effects of inclined cylinder ports on gaseous cavitation of high-speed electro-hydrostatic actuator pumps: a numerical study. *Engineering Applications of Computational Fluid Mechanics*. 2019. Vol. 13, no. 1. P. 245–253. doi: 10.1080/19942060.2019.1576545
13. Dong X. M., Yu J. Q., Yang M. J. Optimum design and experiment of MR damper considering temperature. *Vibration and Impact*. 2016. Vol. 35, no. 8. P. 54–59.
14. Faraj R., Holnickiszulc J., Knap L. Adaptive inertial shock-absorber. *Smart Materials & Structures*. 2016. Vol. 25, no. 3. P. 035031. doi: 10.1088/0964-1726/25/3/035031
15. Chen L., Wang R., Jiang H. Semi-Active Suspension and its Control System Based on Large Scale System Theory. *Chinese Journal of Mechanical Engineering*. 2008. Iss. 8. P. 97–101.
16. Li S., Lü Z. Technology Development of Cylindrical Fluid Drag Shock Absorber for Motor Vehicle. *Automobile Technology*. 2001. Vol. 8. P. 10–16.
17. Lü Z., Li S. Technical Status of Dynamic Simulation Analysis Developing for Hydraulic Telescopic Damper. *Journal of Qinghua University*. 2002. Vol. 11. P. 1532–1536.
18. Jiang H., Yang L. Q., Chen L. Simulation and Testing of Damping Characteristics of Hydraulic Shock Absorber for Front Macpherson Suspension. *Automotive Engineering*. 2007. Vol. 11. P. 970–974.
19. Zhao L., Wen G., Han X. An Investigation into the Optimal Control of Vehicle Semi-active Suspension Based on Magnetorheological Damper. *Automotive Engineering*. 2008. Vol. 6. P. 1–6.
20. Ночніченко І. В., Яхно О. М. Інформаційно-енергетичний підхід до вирішення задач гідродинаміки та механотроніки в процесах переносу енергії. *Mechanics and Advanced Technologies*. 2019. Vol. 3, no. 87. P. 38–48. doi: 10.20535/2521-1943.2020.88.195505

References (transliterated)

1. Morettini G, Bartolini N, Astolfi D, Scappaticci L, Becchetti M, Castellani F. Experimental diagnosis of cavitation for a hydraulic monotube shock absorber. *Diagnostyka*. 2016, vol. 17, no. 3, pp. 75–80.
2. Strutyns'kyy V. B., Kolot O. V. *Matematychne modelyuvannya stokhastychnykh protsesiv u systemakh pryvodiv* [Mathematical modeling of stochastic processes in drive systems]. Kramatorsk, Tyrazh-51 Publ., 2005. 530 p.
3. *Control Valves. Cavitation in control valves. Technical information*. Frankfurt, Samson AG Publ., 2003. 62 p.

4. d'Agostino L., Salvetti M. V., eds. *Fluid dynamics of cavitation and cavitating turbopumps. Courses and lectures.* NewYork, Springer-Verlag Wien Publ., 2007. 351 p.
5. Batchelor G. K. *An Introduction to fluid dynamics.* Cambridge, Cambridge University Press Publ., 2000. 615 p. doi:10.1017/ CBO9780511800955
6. Bird R. B., Stewart W. E., Lightfoot E. N. *Transport Phenomena.* NewYork, John Wiley & Sons Publ., 2002. 895 p.
7. Nochnichenko I. Uzunov O. Characteristics of throttles in hydraulic shock absorber considering temperature changes of fluid. *Mechanics and Advanced Technologies.* 2017, vol. 2, no. 80, pp. 39–44. doi: 10.20535/2521-1943.2017.80.109169
8. Nochnichenko I. V., Luhovskyi A. F., Jakhno O. M., Kostiuk D. V., Komada P., Kozbakova A. Experimental research of hydroluminescence in the cavitating flow of mineral oil. *Proc. SPIE 11176, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments. Vol. 1117615 (6 November 2019, Wilga).* Wilga, 2019, p. 8. doi: 10.1117/ 12.2536946
9. Nochnichenko I., Jakhno O., Liberatskyi I. The character of the transfer phenomenon in the work processes of the hydraulic damper. *International scientific conference proceedings "Unitech 2019" (16–17 November 2019, Gabrovo).* Gabrovo, 2019, pp. 273–277.
10. Alsaydalani M. O. A. Influence of cavitation phenomenon on the hydraulic behavior of leaks in water distribution systems. *Journal of Water Supply: Research and Technology-Aqua.* 2017, vol. 66, issue 5, pp. 327–339. doi: 10.2166/aqua.2017.013
11. An C. G., Cao Y., Zhang J. W. Cavitation and noise analysis of throttle hole in double cylinder hydraulic shock absorber. *Journal of Shanghai Jiaotong University*. 2018, vol. 52 , no. 3, pp. 297–304.
12. Chao Q., Zhang J., Xu B. Effects of inclined cylinder ports on gaseous cavitation of high-speed electro-hydrostatic actuator pumps: a numerical study. *Engineering Applications of Computational Fluid Mechanics.* 2019, vol. 13, no. 1, pp. 245–253. doi: 10.1080/ 19942060.2019.1576545
13. Dong X. M., Yu J. Q., Yang M. J. Optimum design and experiment of MR damper considering temperature. *Vibration and Impact*. 2016, vol. 35, no. 8, pp. 54–59.
14. Faraj R., Holnickiszulc J., Knap L. Adaptive inertial shock-absorber. *Smart Materials & Structures.* 2016, vol. 25, no. 3, p. 035031. doi: 10.1088/0964-1726/25/3/035031
15. Chen L., Wang R., Jiang H. Semi-Active Suspension and its Control System Based on Large Scale System Theory. *Chinese Journal of Mechanical Engineering*. 2008, issue 8, pp. 97–101.
16. Li S., Lü Z. Technology Development of Cylindrical Fluid Drag Shock Absorber for Motor Vehicle. *Automobile Technology*. 2001, vol. 8, pp. 10–16.
17. Lü Z., Li S. Technical Status of Dynamic Simulation Analysis Developing for Hydraulic Telescopic Damper. *Journal of Qinghua University*. 2002, vol. 11, pp. 1532–1536.
18. Jiang H., Yang L. Q., Chen L. Simulation and Testing of Damping Characteristics of Hydraulic Shock Absorber for Front Macpherson Suspension. *Automotive Engineering*. 2007, vol. 11, pp. 970–974.
19. Zhao L., Wen G., Han X. An Investigation into the Optimal Control of Vehicle Semi-active Suspension Based on Magnetorheological Damper. *Automotive Engineering*. 2008, vol. 6, pp. 1–6.
20. Nochnichenko I. V., Yakhno O. M. Informatsiyno-enerhetychnyy pidkhid do vyrishennya zadach hidrodynamiky ta mekhanotroniky v protsesakh perenosu enerhiyi [Information-energy approach to solving problems of hydrodynamics and mechanotronics in energy transfer processes]. *Mechanics and Advanced Technologies.* 2019, vol. 3, no. 87, pp. 38–48. doi: 10.20535/2521-1943.2020.88.195505

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