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M.V. Polyakov, S.A. Davudov, A.V. Davudova, K.V. Heti

Oles Honchar Dnipro National University

DESIGN PARAMETERS OF MESH PHASE DELIMETERS FOR ENSURING REPEATED STARTING OF SPACECRAFT IN THE CONDITIONS OF HEIGHTLESS

У статті наведено основні результати теоретичних і експериментальних досліджень проектних параметрів сітчастих розділювачів фаз, як основного засобу для забезпечення повторного запуску двигунів космічних літальних апаратів багатоцільового призначення в умовах практичної невагомості, які проводились в лабораторії гідродинаміки Дніпровського національного університету імені Олеся Гончара протягом останніх трьох десятиріч

Ключові слова: *паливні баки, ракетні двигуни, невагомість, космічний літальній апарат,сітчасті розділювачі фаз*

В статье приведены основные результаты теоретических и экспериментальных исследований проектных параметров сетчатых разделителей фаз, как основного устройства для обеспечения повторного запуска двигателей космических летательных аппаратов многоцелевого назначения в условиях практической невесомости, которые проводились в лаборатории гидродинамики Днепровского национального университета имени Олеся Гончара в течение последних трех десятилетий

Ключевые слова: *топливные баки, ракетные двигатели, невесомость, космический летательный аппарат, сетчатые разделители фаз*

The article presents the main results of theoretical and experimental studies of design parameters of mesh phase separators, as the main device for ensuring the re-launch of multi-purpose spacecraft engines under conditions of practical weightlessness, which were conducted in the laboratory of hydrodynamics of the Oles Honchar Dnipro National University during the last three decades

Keywords: *fuel tanks, rocket engines, weightlessness, spacecraft, mesh phase separators*

Introduction. Under the conditions of motion of a spacecraft (SC) along a passive trajectory section, components of a liquid rocket fuel are mixed with pressurized gas. At the same time it is impossible to guarantee the contact of the drainage hole with the gas phase, and the drain - with the fuel. As a result, the launch of a SC engine may be disrupted.

To solve this problem, it is proposed to use a variety of so-called means of ensuring the fuel continuity (MEFC). The effectiveness of controlling and controlling the position of the fluid in the flight conditions of an aircraft (AC) along the passive trajectory section is determined by the ability of the MEFC to ensure that the fluid is drained from the tank without gas inclusions at any desired time with a given flow rate and in the right quantity with a minimum amount of residues. The work of MEFC is complicated by external power influences that are both random in nature and provided for by the flight program.

Mechanical methods for phase separation (elastic bags, membranes, bellows), the use of inertial forces for pre-launch separation of liquid and gas phases, fuel gelling are widely known [1]. However, the most widely spread MEFC, whose work is based on the use of the capillary properties of the liquid.

The main advantage of capillary MEFC is the passive nature of their action, which does not require any additional energy costs for their functioning. In addition, they do not have moving parts, are compatible with any type of fuel, are insensitive to the ambient temperature, the number of launches of SC engines. Capillary MEFC easily adapts to the existing tank geometry.

The main disadvantage of capillary MEFC is an insignificant amount of capillary forces and, as a result, a decrease in the effectiveness of the functioning of a MEFC of this type with an increase in the intensity of external force effects.

There are various types of capillary MEFC [14]. In particular, "lobed" systems, perforated plates, blocks of metal discs with grooves etched on their surface, mesh phase separators, capillary pumps.

Among the above types of capillary MEFC, mesh phase separators (MPS) have the greatest versatility and adaptability. Net type MEFC can be used in a wide range of multidirectional external force effects, for tanks of relatively large volume, to ensure high levels of fuel consumption, for highly maneuverable multi-purpose SC. At present, dozens of various designs of the MEFC mesh type have been developed and are successfully functioning.

The purpose of research. Over the past thirty years, a variety of theoretical and experimental studies have been carried out at the hydrodynamics laboratory of the Oles Honchar Dnipro National University in the fuel supply system during the performance of a SC flight task. On the basis of these studies, engineering methods were developed for calculating the design parameters of the MPS to perform preliminary design of promising aircraft. The purpose of this work is to summarize the results already obtained, as well as to identify areas for further research on the features of the functioning of devices of this type.

The presentation of the main material. Mesh phase delimeters are woven metal nets with micron-sized cells. When a gas-liquid flow passes through them when the SC engine is started up from a state of weightlessness, the fuel passes through the MPS, and gas bubbles remain on its surface due to the action of capillary forces. As the fuel enters the combustion chambers of the engines and increases their thrust, gas bubbles move away from the MPS surface and a simply connected liquid-gas interface is generated in the tank.

The main design parameters of the MPS are their so-called static retention capacity (SRC) and dynamic retention capacity (DRC). SRC is the pressure drop on the surface of the MPS, at which gas bubbles start to break through the MPS cells. The dynamic holding capacity of the MPS is determined by the maximum amount of work that MPS of a single area is capable of accomplishing by slowing down the fluid flow at the stage of passing through its cells to the free surface of the liquid in the passive flight of the aircraft.

The highest level of SRC and DRC of MPS can be achieved, first of all, by reducing the size of the MPS cells. However, modern MPS manufacturing technologies do not allow cell sizes to be less than 10 microns. Therefore, studies of the MPS operability are aimed at a reasonable reduction in the requirements for the minimum allowable level of the spacecraft and SRC of MPS in the fuel supply system of a particular aircraft.

As gas bubbles are deposited on a mesh surface, this surface that is available for the passage of fuel decreases, and the pressure drop increases while maintaining the desired fuel consumption. When the pressure drop on the MPS surface equal to its SRC, the MPS will be impaired, i.e. breakthrough gas phase in the drain line. Therefore, the calculation of the actual pressure drops on the MPS at the stage of launching the engines of spacecraft in zero gravity conditions is of considerable practical interest at the stage of preliminary design.

The characteristics of the contact of gas bubbles with MPS were studied theoretically and experimentally. As a result of mathematical modeling, the following equation was obtained for calculating the deformation of the gas bubble on the surface of the MPS under the conditions of the launch of the propulsion system (PS) [15]:

$$\left(2(z^{/})^{2}-(z^{/})^{1/2}-(z^{/})^{-5/2}\right)=-Boz^{/}-We\frac{(R^{/})^{4}}{((R^{/})^{2}-(b^{/})^{2})^{2}} ,$$

where $z^{/}=\frac{z}{r_p}$ – the dimensionless length of the semiaxis of a bubble along an axis perpendicular to the MPS plane; $R^{/}=\frac{R}{r_p}$ – reduced dimensionless surface radius of MPS, through which fluid flows; $b^{/}=\frac{b}{r_p}$ – the dimensionless length of the semiaxis of the bubble along the surface of the MPS; $Bo=\frac{g\rho r_p^2}{\sigma}$ – Bond number; r_p – reduced bubble radius; $We = \frac{\rho V^2 r_p}{2\sigma}$ – Weber number; ρ – fluid density; σ – liquid surface tension coefficient; g – effective mass acceleration in the direction perpendicular to the surface of the MPS; V – average velocity of the liquid flow passing through MPS.

Experimental studies of this process were carried out at the facility, the scheme of which and the general view are shown in Figures 1 and 2, respectively. The cylindrical model 1 (Fig. 1), the centrifugal pump 7 and the connecting piping were filled with working fluid. Using the generator of gas bubbles 5, a bubble of a given volume was located under the mesh surface. The centrifugal pump 7 set in motion the fluid in the direction indicated by arrow in Fig. 1. The current pressure drop on the woven mesh 2 was recorded using a pressure gauge 8.

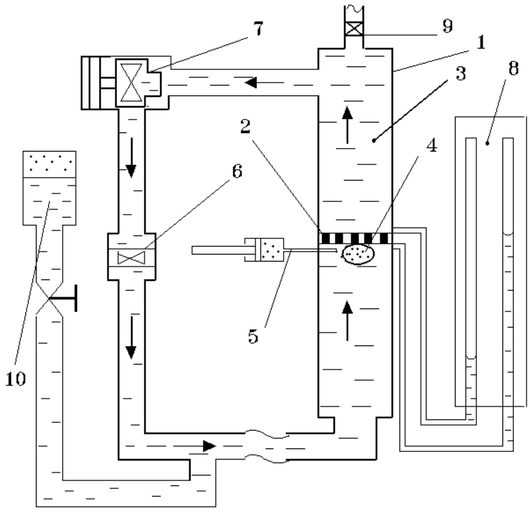

Fig. 1. Scheme of the experimental setup for studying the interaction of gas bubbles with MPS: 1 - a cylindrical model; 2 - frame with woven mesh; 3 - working fluid; 4 gas bubble; 5 - gas bubble generator; 6 - flow sensor; 7 - centrifugal pump; 8 - liquid manometer; 9- drainage fitting; 10 - filling-drain capacity.

Fig.2. General view of the experimental setup for the study of the interaction of gas bubbles with a mesh phase separator

As a result of comparing the experimental data with numerical calculations, the developed mathematical model was corrected by introducing an empirical coefficient that takes into account the peculiarities of the gas bubble contact with the MPS surface in the incoming liquid flow [16].

According to the results of the research, a technique was developed for the engineering calculation of the current pressure drop on the MPS surface during the deposition of gas bubbles on it depending on the average fluid flow rate, bubble size and physical properties of the fuel. Using this technique allows you to specify the minimum allowable level of the DRC of MPS for the successful launch of the remote control of spacecraft in zero gravity.

Directly related to the peculiarities of the contact of gas bubbles with the surface of the MPS is the question of the magnitude of the change in the current differential pressure on the MPS as a result of an abrupt change in fuel consumption characteristic of the stage of starting the remote control. The increase in pressure drop on the MPS, caused by the acceleration of the fuel flow, can lead to permanent deformation of the woven mesh, up to a mechanical rupture of the braiding wires.

The scheme and general view of the experimental setup (ES) for the study of the hydraulic resistance of the MPS in a non-stationary liquid flow are shown in Fig. 3 and 4, respectively. A metal ring with MPS 3 (Fig. 3) was installed inside a cylindrical model 2 filled with working fluid. The liquid was set in motion with the help of the consumable block 7. The current pressure drop was recorded by a system of strain gauges that were placed on a metal ring with MPS 3.

As a result of a theoretical analysis of this hydrodynamic process [11], as well as physical modeling [13], it was found that in a non-stationary liquid flow the pressure drop on the MPS Δp should be calculated using the formula [12]

$$\Delta p = (\alpha + \frac{\beta}{\text{Re}} + \frac{C}{Fr^{\lambda}})\frac{\rho V^2}{2},$$

where α, β, C and λ – empirical constants depending on the type of weaving MPS; $\text{Re} = \frac{V\,d_c}{\nu}$ – Reynolds number; $\text{Fr} = \frac{V^2}{a\,d_c}$ – Froude number; V – current fluid velocity; a – current fluid acceleration; d_c – hydraulic diameter of MPS cells; ν – fluid kinematic viscosity.

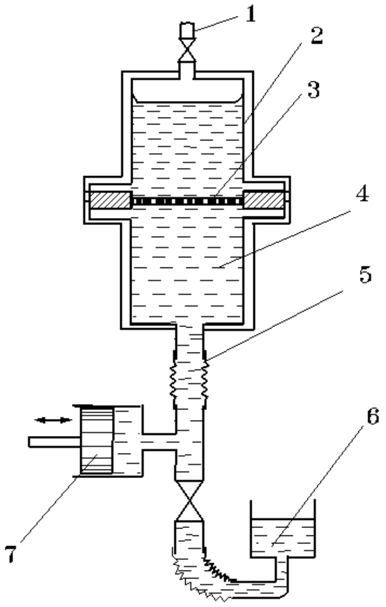

Fig.3. The experimental setup for the study of the hydraulic resistance of MPS in a non-stationary liquid flow: 1 - drainage fitting; 2 - cylindrical model; 3 - mesh phase separator; 4 - liquid; 5 - drain line; 6 - refueling capacity; 7 - consumable unit.

Fig.4. General view of the experimental setup for the study of the hydraulic resistance of mesh phase separators in non-stationary liquid flow

Net type of capillary MEFC, depending on the purpose and flight task of the spacecraft, may have a different design. However, a mandatory element of this design is a woven metal mesh, which is fixed on the perimeter to the supporting frame. This support frame perceives the main force action from the flow of fuel passing through the MPS. The woven mesh placed on the support frame must have the greatest possible elasticity, which is usually achieved by stretching the mesh before fastening it to the support. When an MPS is stretched, its internal structure inevitably changes, and, as a result, its performance as a phase separator. The results of studies of the relationship between the level of elasticity and the SRC of MPS are given below.

The experiments were carried out on the installation, the scheme of which and the general view are shown in Figs 5 and 6. The sample MPS 2 (Fig. 5) was fixed in clamping devices 3 and 4, and then stretched with screws 5 and 6. This tension was carried out in two mutually perpendicular directions (not shown in Fig. 5). The coefficient of elasticity was determined using the linear displacement meter MPS 7. The static holding capacity of the MPS at a given level of the coefficient of elasticity was determined using a differential pressure gauge 13.

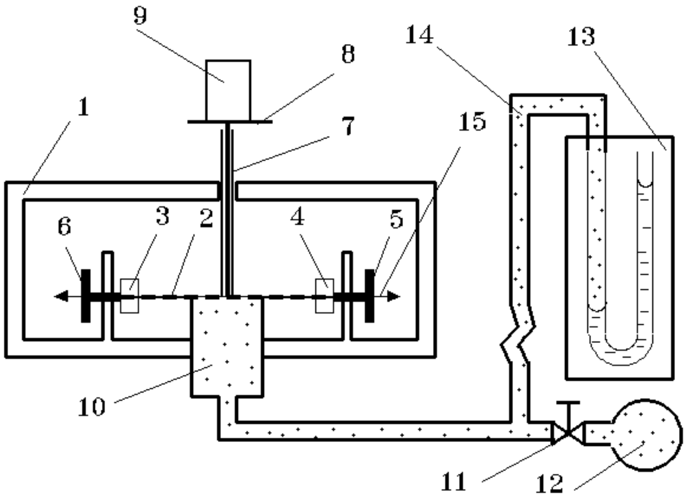

Fig.5. The experimantal scheme for investigation the influence of the coefficient of elasticity of the MPS on its SRC: 1 - supporting frame; 2 - MPS; 3,4 - clamping device; 5,6 - tensile screws;
7 - linear displacement meter MPS; 8 - loading table; 9 - cargo; 10 - pipe to create excess pressure on MPS; 11 - valve; 12 - overpressure tank; 13 - differential pressure gauge; 14 - pipeline;
15 - the direction of stretching.

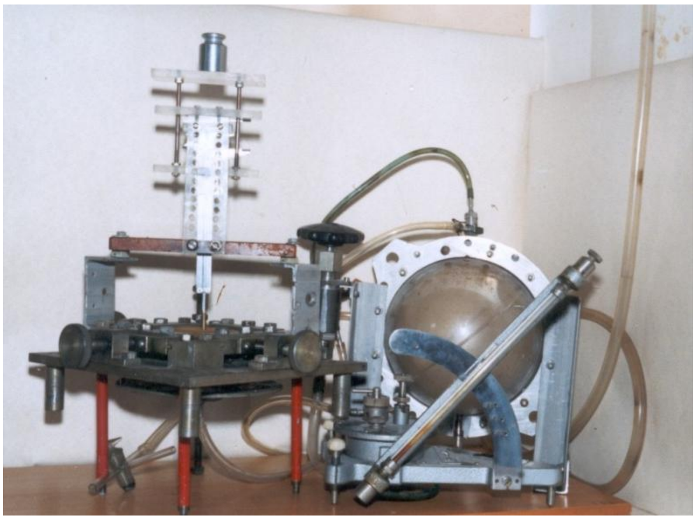

Fig.6. General view of experimantal scheme for investigation the influence of the coefficient of elasticity MPS on its SRC

As a result of the theoretical analysis [5], as well as taking into account the experimental studies carried out [9], the following relationship was obtained for calculating the reduction rate of the SRC of MPS K_c depending on its elasticity coefficient α_c:

$$K_c = \frac{a_0}{a_{\max} + d_0 \psi Q \bar{E} \alpha_c},$$

where $a_{\max} = \sqrt{(a_0^2 + (a_0 + d_0)^2)(1 + Q^* \bar{E} \bar{\alpha}_{\min})^2 - d^2} - d$ – side length of the MPS cell; a_0, d_0 – the length of the side of the cell MPS and the diameter of the wire weaving in the relaxed state, respectively; ψ – Poisson's ratio; Q – empirical coefficient; $\bar{E} = \frac{E}{E_c}$ – relative modulus of elasticity of the material of weaving mesh; E_c – Young's modulus of elasticity for steel; α_c – coefficient of elasticity of the MPS in the support window.

Under weightless conditions, under the action of external multidirectional power pulses of various origins, the fuel moves in the cavity of the SC tank. Gas bubbles are carried along with the fuel flow and collide with the surface of the MPS. When this occurs, the dynamic loading of MPS. When fuel moves, a part of it passes through the MPS, and another part passes over the surface of the MPS. Depending on the features of the separation of the fuel flow on the MPS, the level of its dynamic loading will change when it collides with a gas bubble.

In order to physically simulate the separation process of the MPS liquid flow, an engine system was developed, the circuit of which and the general view are shown in Fig.7 and 8, respectively [8]. The working fluid is driven by a centrifugal pump 5 (Fig. 7) and is directed to a tank model with MPS 1. In model 1, a submerged jet of fluid collides with MPS and subsequently the separated flow moves along two separate pipelines. After measuring the flow rate in these pipelines, the flows are again connected together. During the experiments, the types of MPS, the working fluid, and the flow rate of the fluid varied.

As a result of mathematical modeling [4], the following equation was proposed for calculating the separation coefficient of the liquid flow on the surface of the MPS k:

$$\alpha k^2 + \frac{1}{\mathrm{Re}}\left(\frac{\beta}{\bar{d}_c} + \frac{16}{\bar{l}^3} + \frac{16}{(\bar{L}_0 - \bar{t})^3}\right)k - \frac{16}{(\bar{L}_0 - \bar{t})^3 \mathrm{Re}} = 0,$$

where $k = \frac{Q^*}{Q}$; $\mathrm{Re} = \frac{r_c V}{\nu}$ – Reynolds number; $V = \frac{Q}{\pi r_c^2}$ – the speed of the liquid flow in contact with MPS; $\bar{d}_c = \frac{d_c}{r_c}$; $\bar{l}_c = \frac{l_c}{r_c}$; $\bar{L}_0 = \frac{L_0}{r_c}$; $\bar{t} = \frac{Vt}{r_c}$; d_c – hydraulic mesh radius; Q – total fluid flow; Q^* – fluid flow through the MPS surface; R – reduced surface radius MPS; r_c – the radius of the submerged jet of fluid at the point of exit from the pipeline; l_c – distance from MPS surface to tank wall; L_0 – distance from the exit point of the submerged jet of liquid over the MPS surface.

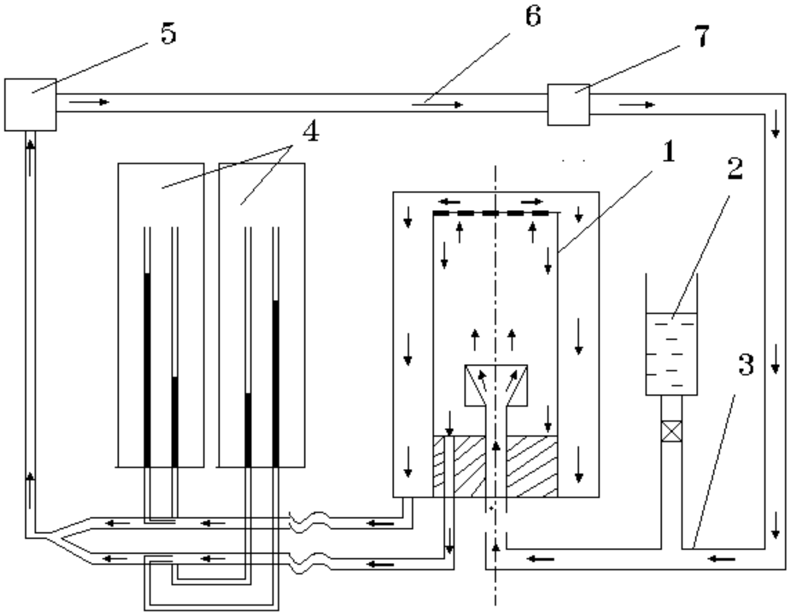

Fig.7. ES scheme for separation studies liquid flow MPS: 1 - tank model with MPS; 2 - filling and drainage tank; 3 - connecting pipelines; 4 - manometer; 5 - centrifugal pump; 6 - the direction of movement of the fluid; 7 - turbine flow sensor.

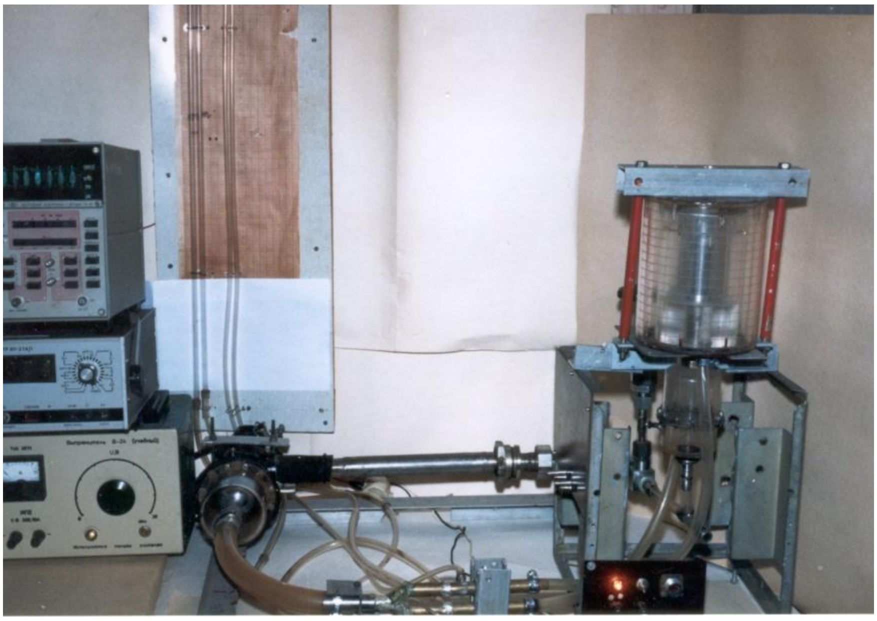

Fig. 8. General view of the ES on the study of the separation of the liquid flow MPS

In addition, studies were carried out to study the dynamics of the free surface of the liquid in the tank and the conditions for the breakthrough of the gas phase through the MPS under the action of an external power pulse. The scheme and general view of the ES for the physical modeling of this process are shown in Fig.9 and 10 [3].

The experimental setup is a movable unit 3 (Fig. 9) with a model 4 containing MPS and filled to a predetermined level with a working fluid. A backlight unit 6 and a video recording device 8 are installed on the movable unit. The movable unit moves with a given acceleration along the guides in the horizontal plane. During the experiments, the type of MPS, the working fluid, the filling level of the model with the working fluid, and the effective horizontal acceleration varied.

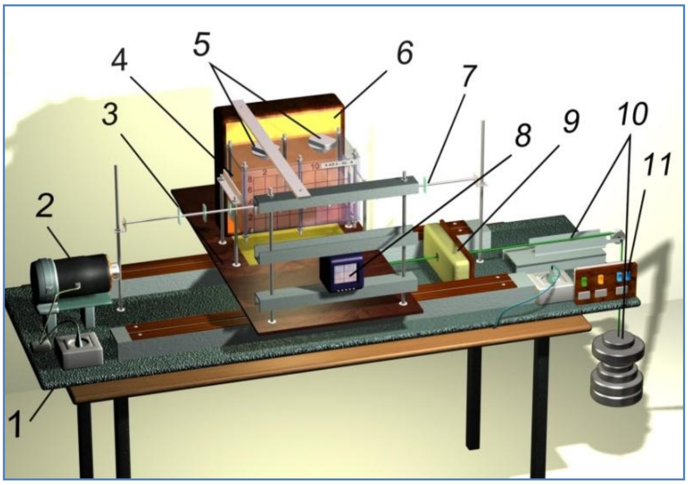

Fig.9. The ES scheme for the study of the reorientation of fuel in the tank under the action of an external power pulse: 1 - base plate with guides; 2 - electromagnet; 3 - mobile unit; 4 - model with MPS; 5 - fittings; 6 - backlight unit; 7 - device for fixing the current coordinate of the moving unit; 8 - video recorder; 9 - depreciation pad; 10 - unit for creating horizontal acceleration; 11 - control panel.

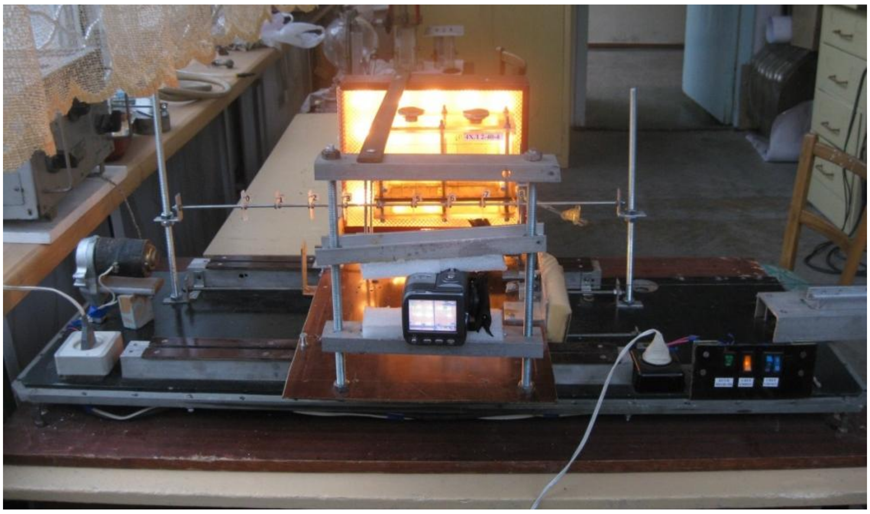

Fig.10. General view of the ES on the study of the dynamics of fuel in the tank under the action of an external power pulse

For the theoretical description of this process, the following system of differential equations was used [2]

$$\begin{cases} \frac{\partial \vec{V}}{\partial t} + \nabla\left(\frac{\vec{V}^2}{2}\right) = \vec{a}_0 + \vec{a}_I - \frac{1}{\rho}\nabla p, \\ \nabla \vec{V} = 0 \end{cases}$$

where $\vec{a}_0, \vec{a}_I$ – vectors of longitudinal and transverse mass accelerations, respectively; $\vec{V}$ – fluid velocity vector; p, ρ – pressure and fluid density, respectively.

To calculate the pressure field, the Poisson equation was used.

The calculation of the velocity field and pressures of a liquid volume with a free surface in a tank with MPS, making uniformly accelerated horizontal movement under normal gravity, was carried out numerically using the finite volume method. Comparison of the results of numerical calculations with experimental data showed satisfactory agreement.

When designing a grid-type of MEFC, it is assumed that during the entire flight time of a spacecraft, up to the full production of fuel, a breakthrough of the gas phase through the MPS does not occur. However, of considerable practical interest is the process of breaking through the gas phase through the MPS and the peculiarities of its functioning in the event of a violation of regular working conditions.

Interest in the functioning of the MPS after a breakthrough of the gas phase through them arises in situations when the conditions of the spacecraft operation allow limited penetration of the gas phase through the MPS. Some structures of the MPS provide on the way of the movement of fuel to the discharge line several MPS, through which pressurized gas will pass as tank is emptied [14].

An experimental study of the breakthrough of the gas phase through the MPS was carried out at the ES [10], whose diagram and general view are shown in Fig. 11 and 12, respectively. The tank model with MPS 1 (fig.11) is filled above the MPS level with the working fluid from the tank 9. After that, with the help of the consumable block 7, the free surface of the fluid moves towards the MPS and the gas breaks through the mesh surface. The current static pressure at the same time is fixed by the sensor 3, and the coordinate of the free surface is displaced by the displacement sensor 8. During the experiments, the working fluid, MPS and fluid flow varied.

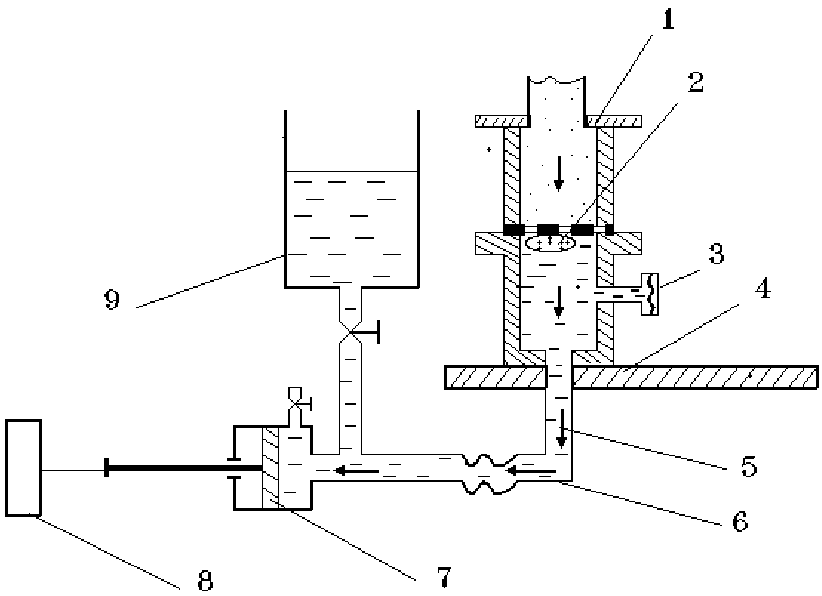

Fig.11. ES scheme for the study of gas phase breakthrough through MPS: 1 - tank model with MPS; 2 - gas bubble; 3 - pressure sensor; 4 - supporting platform; 5 - the direction of movement of the fluid; 6 - connecting pipeline; 7 - consumable unit; 8 - displacement sensor; 9 - filling-drain capacity.

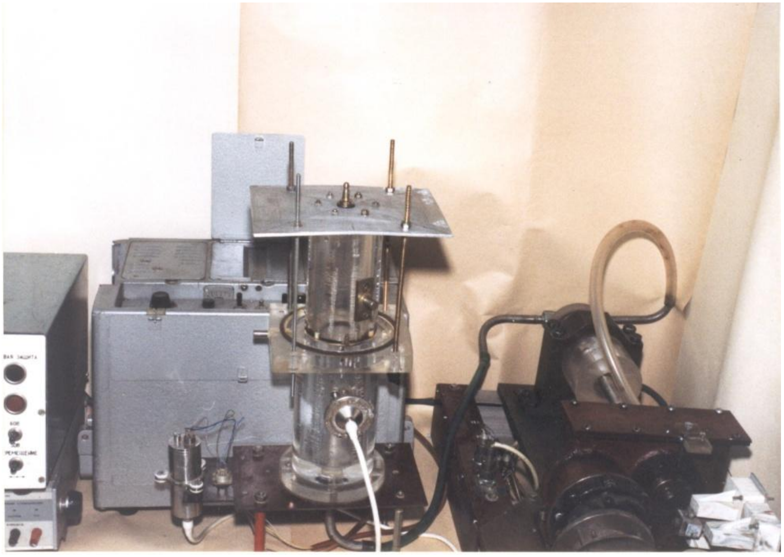

Fig.12. General view of the ES on the study of the breakthrough of the gas phase through the MPS

As a result of mathematical modeling [7] of this process, a calculation method [6] was developed, which allows, under the condition of introducing two empirical coefficients into the calculation equations, to adequately describe the real physical process.

Conclusions. The above results of studies of the functioning of the MPS in the system of fuel supply to the spacecraft make it possible to clarify the required values of the main design parameters of the MPS, first of all, SRC and DRC. Developed methods for calculating the values of pressure drop on MPS in the conditions of contact of its surface with gas bubbles, as well as changes in pressure drop when the remote control is turned on in conditions of weightlessness. In addition, a method was proposed for calculating the separation coefficient of the liquid flow of the MPS during inertial movement of fuel in the cavity of a spacecraft tank under the action of an external power pulse. The influence on the design parameters of the MPS features of their attachment to the support frame is investigated. Finally, the results of studies of the functioning of the MPS in the supercritical mode, ie, in the conditions of breakthrough of the gas phase through the cells of the MPS.

Despite the considerable variety of investigated MPS operating conditions in the spacesraft fuel supply system, these results still do not fully allow to optimize the design parameters of the MPS of promising spacesraft at the stage of preliminary design. The limitation of the maximum value of the SRC and DRC of the MPS, caused by the peculiarities of their manufacturing technology, requires conducting comprehensive studies of the operation of the MPS under vibrational and pulsed loading conditions. The lack of currently reliable methodologies for calculating the required level of MPS operability under these dynamic conditions leads to a significant overestimation of the requirements for the value of the main design parameters of these devices and, as a result, the narrowing of the scope of capillary MEFC of the mesh type.

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