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THE APPROACH TO NUMERICAL SIMULATION OF THE SPATIAL MOVEMENT OF FLUID WITH THE FORMATION OF FREE GAS INCLUSIONS IN PROPELLANT TANK UNDER SPACE FLIGHT CONDITIONS

The space propulsion systems ensure several start-ups and shutdowns of main liquid-propellant rocket engines under microgravity conditions for the spacecraft program movements and reorientation control. During the passive flight of the space stage (after its main engine shutdown), the liquid propellant in the tanks continues to move by inertia in microgravity away from the propellant management device as much as possible. In this case, the pressurization gas is displaced to the propellant management device, which creates the potential danger of gas entering the engine inlet in quantities unacceptable for the reliable engine restart. In this regard, determining the parameters of fluid movement in propellant tanks in microgravity conditions is an urgent problem that needs to be solved in the design period of liquid propulsion systems. We have developed an approach to the theoretical computation of the parameters of the motion of the 'gas — fluid' system in the propellant tanks of modern space stages in microgravity conditions. The approach is based on the use of the finite element method, the Volume of Fluid method and modern computer tools for finite-element analysis (Computer Aided Engineering — CAE systems). For the passive leg of the launch vehicle space flight, we performed mathematical modeling of the spatial movement of liquid propellant and forming free gas inclusions and determined the parameters of movement and shape of the free surface of the liquid in the tank as well as the location of gas inclusions.

The numerical simulation of the fluid movement in an experimental sample of a spherical shape tank was performed with regard to the movement conditions in the SE Yuzhnoye Design Bureau 'Drop tower' for studying space objects in microgravity. The motion parameters of the 'gas — fluid' interface obtained as a result of mathematical modeling are in satisfactory agreement with the experimental data obtained.

The use of the developed approach will significantly reduce the amount of experimental testing of the designed space stages.

Keywords: *space launch vehicle, microgravity, engine restart, flight passive leg, spatial movement of liquid propellant, free gas inclusions, finite element method, Volume of Fluid method, propellant management device.*

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INTRODUCTION

The operability of main propulsion systems of launch vehicles (LV) space stages directly depends on the reliability of several liquid rocket engines (LRE) start-up — shutdowns necessary for the implementation of program motions and orientation control of the LV in space [5]. During the launch vehicle space flight, after the main engine shutdown, the liquid propellant moves by inertia to the propellant tank's upper bottom, moving as far as possible from the propellant management device (PMD). According to the fact of releasing PMD volume from the liquid propellant and filling it with pressurization gas in microgravity conditions, there is a threat of propellant discontinuity. The motion of a critical volume of pressurization gas to the engine inlet leads to cavitation failure in the LRE pumps and to the engine start-up failure. Design issues for the implementation of a reliable engine restart are based on the accumulation of liquid propellant certain mass at the outlet of the tank. This propellant mass must be sufficient to carry out the start-up even in cases when the vector of the total mass forces acting on the liquid propellant has a direction opposite to the direction of liquid motion from the tank inlet to the engine [8].

Space stage propellant tanks, in some cases, are containers of a complex spatial configuration with thin and smooth walls, which are under pressurization gas pressure [e.g., 4, 5, 8]. The complex and unpredictable features of liquid propellant motion in propellant tanks in microgravity conditions define the increased level of requirements for the design and functional characteristics of PMD (as a rule, well-proven capillary accumulators and mesh phase separators are used as such devices [8, 10, 13]). For excluding the possibility of gas entering the engine during a restart, it is necessary to predict the behavior of the 'gas — fluid' dynamic system on the stage of the space stage LRE design. This dynamic system describes the motion of fluid and gas in the tank during various LV program flight motions in microgravity conditions. The processes occurring in this dynamic system are the subject of many-sided experimental and theoretical investigations [e.g., 1, 2, 4, 6, 8, 20].

In [2, 4], the influence of the flight conditions of the LV space stage on the development of liquid propellant oscillations in tanks and the operability of PMD at various time intervals of the LV space stage flight was studied in cases when the filling level of the tanks is higher than the installation level of mesh phase separators.

In [20], for the flight conditions of the CZ-3A LV, the numerical modeling of the liquid fuel motion in the space stage fuel tank was carried out. Also, in this paper, the influence of the Rayleigh-Taylor instability on the fluid dynamics in the tank was studied. The process of liquid fuel reorientation in the tank volume is considered for two cases: when the interface between the 'gas — fluid' media is initially a flat surface and when this surface is curved. It is shown that these two different initial conditions for the 'gas-fluid' interface in the tank lead to the implementation of two different fluid flow modes.

In [1], the results of the Ariane 5 upper stage flight with a cryogenic propellant engine were analyzed. As a part of the analysis, the flight data were studied in detail to study the influence of various factors (including thermodynamic ones) on the behavior of liquid propellant during flight. The data from sensors of various types installed inside the propellant tanks made it possible to compare experimental data of the propellant position in the tanks and the results of the theoretical studies obtained using the CFD method and the special software designed to evaluate the propellant thermodynamic condition.

In [6], the behavior of liquid propellant and its free surface was investigated in conditions of reduced or almost zero gravity. For evaluating the dynamic behavior of liquid propellant, the propellant tank model of the Orion service module was built. Orion service module included propellant management devices and mass sensors. Flight data and data from ground experiments were used to test numerical models of propellant dynamics in tanks. On the basis of the developed models, the configurations of liquid propellant in microgravity conditions (at different levels of tank filling) were calculated. The propellant sedimentation time was evaluated for various docking maneuvers.

The propellant sedimentation process in the LV space stage oxidizer tank using two low-thrust engines before restarting the main engine was studied in [16]. The authors have developed a computational-experimental method for calculating the required propellant sedimentation time. This computational-experimental method combines experimental testing and numerical simulation of propellant sedimentation. Using this method makes it possible to carry out the necessary research (propellant sedimentation) with the required accuracy and to reduce the amount of testing significantly.

Despite the progress in studying the dynamics of 'gas — fluid' media in LV tanks, a number of unsolved problems remain. These problems are topical in the LV space stages design. In particular, nowadays, there is no approach for calculating the gas content of liquid propellant and the location of free gas bubbles in the liquid propellant of the LV space stage tanks (i.e., the 'gas — fluid' interface in the region of the propellant tanks) before main LRE start-up. Such evaluations are necessary for calculating the required operating time of low-thrust engines of a space LRE (for the aim of propellant sedimentation before main LRE start-up). These evaluations can increase the efficiency of PMD, taking into account the possibility of experimental testing of in-tank processes with reproduction of the required microgravity conditions limited by the technical characteristics of special 'Drop towers' [10, 20].

The aim of this paper is to develop an approach to the numerical calculation of the motion parameters of the 'gas — fluid' interface of the propellant tanks of modern LV space stages in microgravity conditions (i.e., in the period from the main space stage LRE shutdown until the LV control system command to main LRE start-up).

1. THE MODELING OF THE MOTION PROCESS OF THE GAS — FLUID INTERFACE IN MICROGRAVITY CONDITIONS USING THE VOLUME OF FLUID (VOF) METHOD AND FEATURES OF MODERN FINITE ELEMENT ANALYSIS SYSTEMS (COMPUTER AIDED ENGINEERING, CAE-SYSTEMS)

According to the proposed approach, mathematical modeling of hydrodynamic processes in the space propellant tanks of the main LRE feeding system is carried out by the finite element method. It allows us to take into account the design features of propellant tanks and hydraulic feedlines in mathematical modeling of the motion process of propellant components to the main LRE inlet in microgravity conditions [2].

Taking into account the fact that space stage tanks, as a rule, are symmetrical by the stage longitudinal axis, space stage tanks' geometric models can be considered as flat sections of the tanks. Then, accordingly, the mathematical model of the axisymmetric outflow of propellant components from space stage tanks is studied.

For modeling hydrodynamic processes in the propellant tanks of the main engine feeding system (propulsion system), the Volume of Fluid (VOF) method was used. This method allows taking into account the complex topology of flows. The implementation of VOF analysis in the proposed approach was carried out using modern issues of finite element analysis (CAE-systems) [9]. The CSF (continuous surface force) method is used to describe the motion interface between gas and fluid relative to the tank walls.

The developed model, describing the unsteady flow of an incompressible fluid with a deformable free surface in the considering tank, included the continuity equations, moment equations, and motion equations of the fluid free surface. These equations are written using function C. This function C describes the fluid fraction in the calculated volume of a finite element in the tank finite element model with fluid. These equations are written in a general form as follows [7]:

– continuity equations

$$\nabla V = 0 , \tag{1}$$

– fluid momentum equation

$$\frac{\partial}{\partial t}(\rho V) + \rho(V \cdot \nabla)V = -\nabla p + \mu \nabla^2 V + F_s + \rho a_z , \tag{2}$$

– motion equations of fluid free surface

$$\frac{\partial C}{\partial t} + V \cdot \nabla C = 0 , \tag{3}$$

where ∇ is Hamilton operator, V is the fluid velocity, p, ρ, μ, F_s are the pressure, density, viscosity, and surface tension of the fluid, respectively, a_z is the longitudinal acceleration of the LV space stage.

The function C in equation (3) can take the following values: $C = 0$ is in the case of the absence of fluid filling in the finite element volume, $C = 1$ is in the case of complete filling of finite element volume with fluid, and $0 < C < 1$ is for intermediate states.

In the context of VOF and CSF methods [9], the surface tension force of a fluid F_s is determined from the equation:

$$F_s = \sigma k \nabla C\,, \qquad (4)$$

where k is the average curvature of the ‘fluid — gas’ interface at the research point, σ is surface tension coefficient, calculated from experiment for a specific pair of ‘fluid — solid’.

2. NUMERICAL CALCULATION OF THE MOTION PARAMETERS OF THE ‘GAS — FLUID’ INTERFACE IN THE REGIONS OF THE MODERN LV SPACE STAGE FEEDING SYSTEM PROPELLANT TANKS DURING MAIN LRE START-UP

The LV space stage feeding system is designed to fill the reserves of propellant components in the stage propellant tanks and supply them to the propulsion system feedlines. This feeding system is one of the main structural and functional systems of the space stage. The propellant tanks included in the propulsion system are the thin-walled containers with structurally complex PMD for ensuring the continuity of liquid propellants. These PMDs, designed to maintain the propellant components without free gas bubbles, are placed at the inlet to the engine feedlines for the limits permissible for the operability of the start-up engine [5, 8].

Predicting the location of liquid propellant (i.e., the ‘gas — fluid’ interface in the propellant tanks regions) in the passive flight leg of the LV space stage is necessary for calculating the propellant sedimentation time after the implementation of various program motions of the LV space stage. Also, this prediction helps to carry out the reliable main LRE start-up. In addition, due to the irregular distribution of local path pressure losses during the motion of liquid in different parts of the feeding system from the liquid free surface in the tank to the inlet into the propellant feedline of the main LRE, under certain modes of stage LRE start-up in microgravity conditions, there may be a breakthrough of a certain volume of pressurization gas under the tank PMD and in the LRE propellant feedlines.

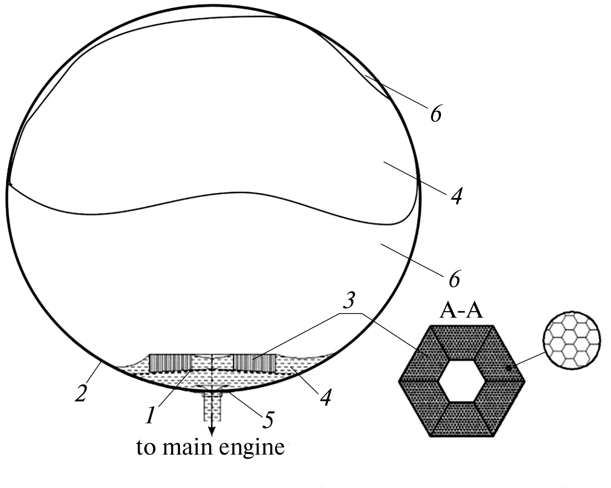

Figure 1. Schematic diagram of the propellant tank of the main LV space engine propellant feeding system: *1* is the mesh phase separator, *2* is a tank wall, *3* is the honeycomb capillary accumulator, *4* is a liquid propellant, *5* is PMD (plate), *6* is a pressurization gas

A typical schematic diagram of the propellant tank of the LV space stage main engine feeding system is shown in Fig. 1. In the figure, the number *4* indicates the position of liquid propellant immediately before the main LRE start-up.The capillary stabilizer (mesh phase separator, *1* in Fig. 1) in the presented LV space stage feeding system is made on the basis of a plain weave mesh. The capillary honeycomb propellant accumulator (*3* in Fig. 1) ensures that the part of the propellant component above the capillary stabilizer is in contact with it in an amount sufficient to orientation control system engines’ operation and stabilization of the space stage in the passive flight period. This prevents gas from motion under the capillary stabilizer when the component is rated from the tank. During the period of main engine operation, the capillary honeycomb accumulator is filled with a liquid propellant.

The proposed approach for calculating the motion parameters of the ‘gas — fluid’ interface in the regions of the propellant tanks of the modern LV space stages feeding system is based on modeling the motion parameters of the ‘gas — fluid’ interface in the propellant tanks regions for calculation the location of liquid propellant. In this case, numerical modeling is carried out taking into account the surface tension forces and propellant wettability, the resistance forces to the motion of liquid propellant, the design features of the propellant tank (geometry and composing of PMD), and capillary effects in the accumulator.

The resistance forces to the motion of liquid propellant and the pressure loss forces are irregularly distributed in the tank over the volumes of the flow part of the accumulators, the mesh phase separator (see Fig. 1), the subgrid space, and PMD in the conditions of the complex architecture of the intra-tank space. These forces make a decisive influence on the emerging fields of liquid propellant velocities and pressures during the propellant motion to the tank PMD in the process of main engine start-up.

For mathematical modeling of the tank depletion process (see the equations system (1)—(4)), the 'two-dimensional fluid' elements with coefficients K of local pressure losses are used to describe the propellant component motion in the accumulator through the phase separator grid, in the sub-grid space of the tank, and in the flow part of the PMD. The coefficients K are determined with the use of experimental data by the expression:

$$K = \frac{\Delta P}{\rho V^2 \Delta l},$$

where ΔP is the fluid pressure loss in the researched flow region, V is the steady fluid velocity, Δl is the length of the fluid path along the streamline with the acting resistance force to the fluid motion.

The resistance force to the fluid motion in the capillary accumulator was calculated by the formula [11, 14]:

$$F_{res} = a_* \cdot \sqrt[4]{\frac{\rho \sigma^3}{a_z}} \cdot V \cdot \Pi,$$

where Π is the accumulator cell perimeter, a_* is empirical coefficient ($a_* = 0.182$).

Local pressure losses on the grid of the grid phase separator were calculated using the hydraulic resistance coefficient of the grid ξ. The value of hydraulic resistance coefficient of the grid was obtained experimentally [3, 17]:

$$\xi = \alpha + \beta / \mathrm{Re},$$

where α, β are the values of empirical coefficients, Re is the Reynolds number.

3. AN EXAMPLE OF THE NUMERICAL IMPLEMENTATION OF THE DEVELOPED APPROACH TO CALCULATING THE PARAMETERS OF LIQUID PROPELLANT MOTION IN A PROPELLANT TANK IN MICROGRAVITY CONDITIONS, INVESTIGATED EXPERIMENTALLY IN A 'DROP TOWER'

For an experimental investigation of the liquid motion in the LV space stage tanks in low gravity conditions, the possibilities are widely used, which are provided by the research laboratory complexes of the so-called 'Drop tower' [6, 15, 19] including the laboratory and the 'Drop tower' for theoretical investigations performed by Yuzhnoye State Design Office [16].

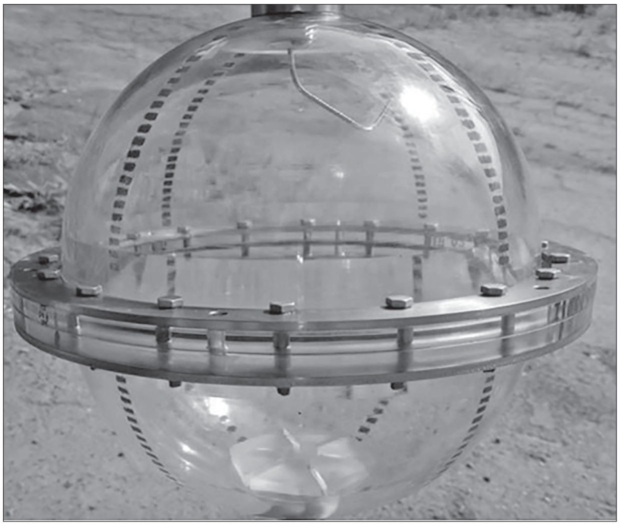

Figure 2. General view of the investigated structure of the tank with liquid filling [18]

In the experiment, the test container was a tank of a spherical shape on a scale of 1:12 (Fig. 2). For modeling the external conditions acting on the liquid in the model tanks, the so-called kinematic model was used (Fig. 3). This kinematic model for investigating the behavior of the liquid medium in the model tank in microgravity conditions is widely used. The kinematic model includes: a frame, gas jet system, optical device system, control and measurement system, technological feedlines and refueling system, overflow control system, a drainage system of the model tank, and a balloon of a gas jet system. The gas jet system is designed to create model longitudinal accelerations after breaking the connection between the kinematic model and the platform and includes a cylinder filled with high-pressure gas (from 100 to 150 bar), a control solenoid valve, and two jet nozzles that ensure the creation of thrust directed along the longitudinal kinematic model axis in the direction of gravitational forces action.

Figure 4 shows one of the versions of the dependence of longitudinal acceleration on time, realized during tests in a 'Drop tower' [18].

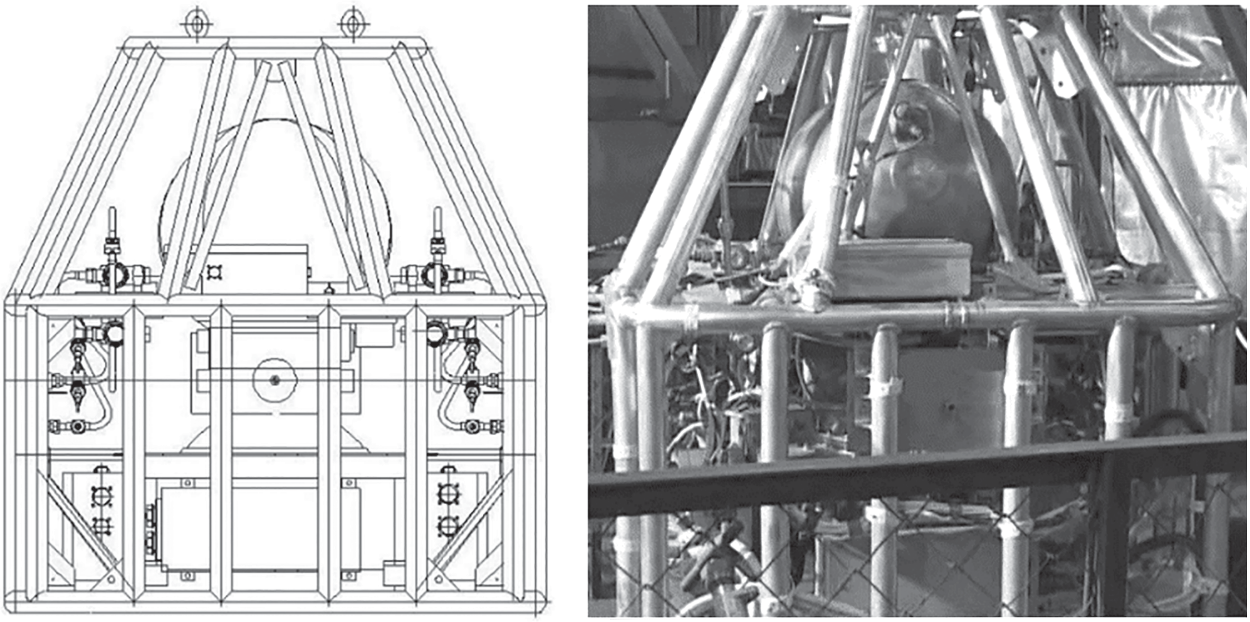

Figure 3. Composed scheme and photo of the kinematic model

The obtained dependences of the longitudinal model acceleration a_z on time can be divided into three characteristic periods (Fig. 4):

– from 0 to 0.38 s is the period of free fall after the action of the suspension lock of the kinematic model;

– from 0.38 to 0.51 s is the period of the electropneumatic valves opening and the set of thrust by the gas jet system;

– from 0.51 to 2.3 s is the period of longitudinal acceleration decrease due to the reduction of gas jet system thrust and the increase of the aerodynamic resistance.

For verifying the developed approach, the results of an experimental investigation of the fluid motion in a model tank when it falls in the 'Drop tower', given in [6], were used. A spherical tank ($D = 15$ cm; $V_{\text{liquid filling}} = 0.3$ dm^3) made of acrylic plastic was used as a test tank in the experiment. PMDs were not installed in the test tanks. Chladone 113 liquid (ethane series chladone) was used as a model fluid, having a surface tension coefficient $\sigma = 17.2\times10^{-3}$ N/m, density $\rho = 1564$ kg/m^3, viscosity $\mu = 4.7\times10^{-4}$ kg/m s. The temperature in the tank was assumed to be constant and equal to 20 °C. The deformation of the tank walls was not taken into account. The acceleration of the tank a_z (see Fig. 4) in the 'Drop tower' was directed along the longitudinal axis of the tank from the upper bottom to the PMD located in the lower region of the tank.

Numerical modeling of fluid motion in the tank, taking into account the deformation of the fluid free surface (see Fig. 5, 6), was carried out using the finite element analysis by the ANSYS (FLOTRAN CFD and ANSYS FLUENT) [9]. To analyze the motion of liquid propellant in the tank under microgravity conditions, the series of event times were considered that characterize this process: the event of $T_0 = 0.001$ s is the period of the fluid location at the bottom, the beginning of motion in microgravity conditions (Fig. 5, *a*, *b*); the event of $T_1 = 1.13$ s is the period of motion in microgravity conditions (Fig. 5, *c*, *d*); the event of $T_2 = 1.23$ s is the period of the 'connection' of a flow rate of 0.15 dm^3/s (Fig. 5, *e*, *f*); the event of $T_3 = 1.7$ s is the period of falling of the 'gas — fluid' boundary (Fig. 5, *g*, *h*); the event of $T_4 = 2.3$ s is the period of cut-off (Fig. 5, *i*, *j*). The areas occupied by fluid and gas are indicated in figures by numbers *1* and *2*, respectively.

It can be seen from the figures that the modeling results are in qualitative agreement with the experimental results.

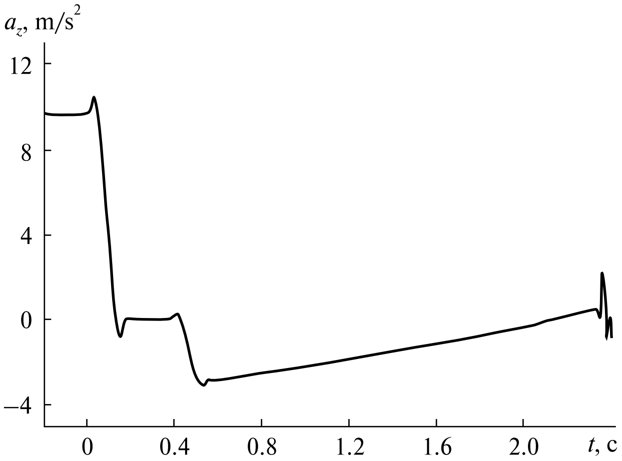

Figure 4. The dependence of the longitudinal acceleration of the kinematic model on time

The figures illustrate the process of liquid propellant motion in the studied tank in microgravity conditions created in the 'Drop tower'. Fig. 5, *b*, *d*, *f*, *h*, and *j* show the results of numerical modeling, Fig. 5, *a*, *c*, *e*, *g*, and *i* demonstrate the photo of the 'gas — fluid' interface in the tank, obtained as a result of the experiment.

Fig. 6, *c*, *f*, *g*, and j show the calculated distributions of velocities (V) in the nodes of the finite elements of the liquid propellant and gas in the tank along its longitudinal section for the events of 1.13, 1.23, 1.7, 2.3 s (taking into account the flow rate of 0.15 dm^3/s for 1.23 s).

From Fig. 6, *c* and *f*, it follows that the maximum values of the velocities are located near the upper bottom of the tank as a result of the fact that intensive wetting occurs and the greatest surface tension forces are present in this area.

From Fig. 6, *g* and *j*, it follows that the maximum velocity increases to 0.5 m/s and is located near the slot on the lower tank bottom. This speed value corresponds to the local liquid propellant loss realized during these time events.

For evaluating the operability of the PMD in the tank [12], it is necessary to know the values of the propellant flow rates (Fig. 6).

In addition, Fig. 6, *g* and *j* show that high velocities correspond to fluid drops that slide from the upper bottom of the tank and move in the gas bubble in the

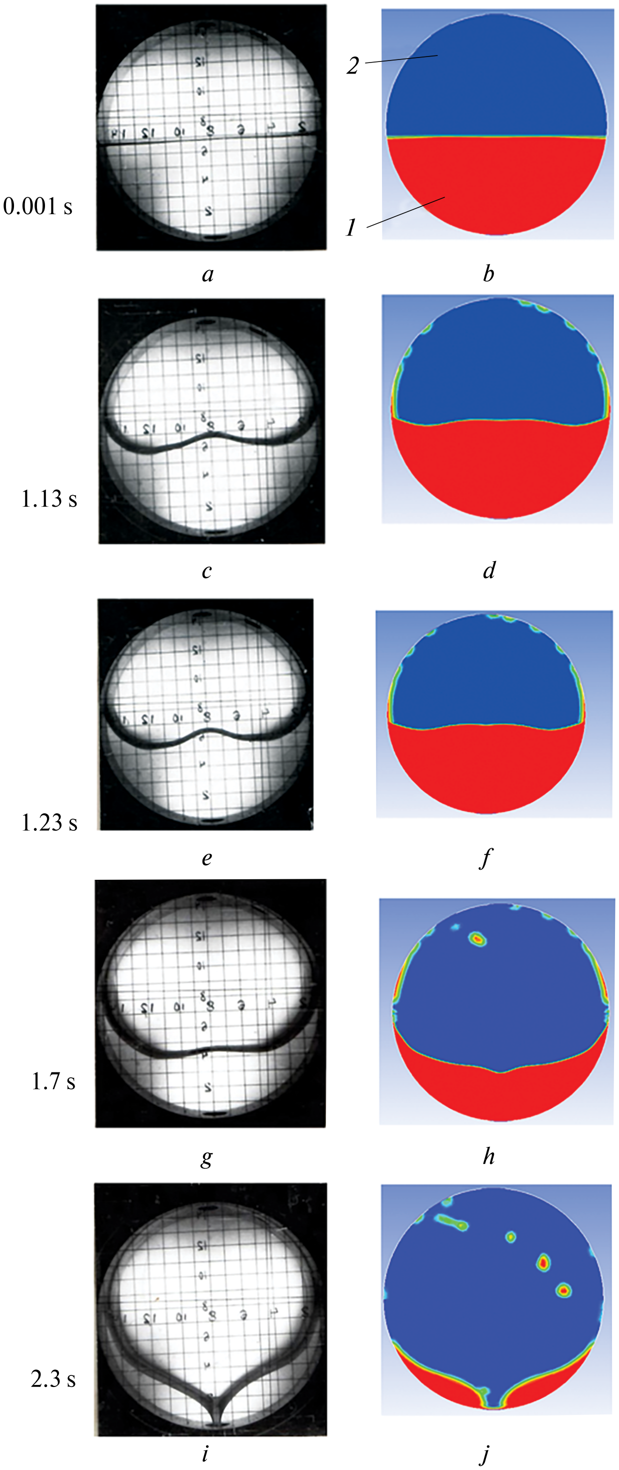

Figure 5. Motion of the 'gas — fluid' interface in the region of the model tank in microgravity conditions created in the 'Drop tower' for the events T_0 = 0.001 s, T_1 = 1.13 s, T_2 = = 1.23 s, T_3 = 1.7 s, T_4 = 2.3 s

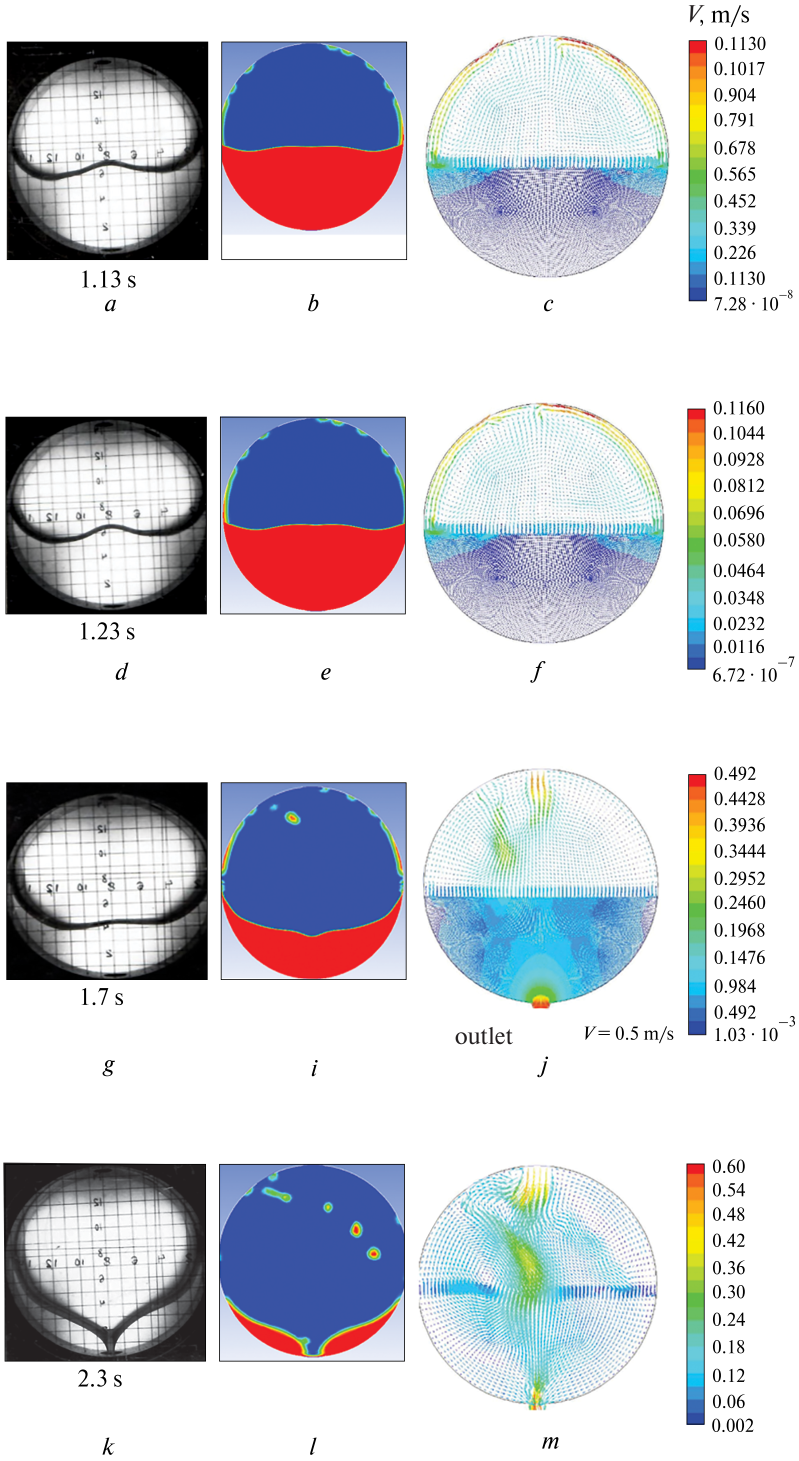

Figure 6. Calculated distributions of velocities (V) in the nodes of finite elements of liquid propellant and gas in the tank along its longitudinal section for events $T_1 = 1.13$ s, $T_2 = 1.23$ s, $T_3 = 1.7$ s, $T_4 = 2.3$ s

center of the tank. The effect of these drops (Fig. 6, *f* and *i* show the drops contours and significant speed values of the drops) must be taken into account for calculating the number of gas bubbles in the feedline.

4. DISCUSSION

Taking into account the issues of the 'behavior' of a cryogenic liquid in microgravity conditions ('zero' contact angle of the liquid propellant surface with the walls, a significantly small value $\sigma = 17.2\times10^{-3}$ H/m of the surface tension coefficient) for the nature of the chladone motion in the test tank the value of the contact angle acquires significance (the shape of the interface between the gas and fluid media on the tank walls depends on it), as well as the surface tension forces, which form the surface of the liquid medium in the gas cavity of the tank.

Analyzing the results of the chladone motion experiment (with the acceleration of the model tank a_z, see Fig. 4), the characteristic features of the motion of the interface between the liquid propellant and air environments can be marked:

1. The acceleration caused by gravitational forces is extremely small. The 'picture' of motion is defined by the most dominant surface tension forces formed by the physical properties of the liquid propellant, such as the surface tension coefficient. The motion of liquid propellant is also caused by capillary effects, which depend on the liquid propellant properties, for example, the contact angle of the liquid propellant surface and the tank walls.

2. For a small contact angle, intensive wetting of the tank wall surfaces by the liquid occurs. The shapes of the interface in the experiment and in the numerical model for intensive wetting are shown in Fig. 5, *a—f*. The maximum values of velocities in the liquid propellant, defined by the action of surface tension forces on the upper tank bottom for intensive walls wetting, are shown in Fig. 6, *c* and *f*.

3. The action of surface tension forces significantly exceeds the forces associated with microgravity (by 100 times, see period 1 in Fig. 4). This leads to the motion of the liquid located at the lower bottom of the tank in the direction of the upper tank bottom in the tangential direction to the interface surface. This conclusion follows from the time variations of the interface shown in Fig. 5, *a—e*. In addition, the velocities in the liquid propellant, defined by the action of surface tension forces and directed tangentially to the interface, are shown in Fig. 6, *c* and *f*.

4. In the 'tank-fluid pressurization gas' system, intensive wetting of the tank structure by the liquid fuel surface and the action of surface tension forces are considered, leading to the movement of liquid to the upper bottom of the tank with wetting of the tank structure (as it can be seen from the results of the experiment shown in Fig. 5, *a —h*). In this case, a gas cavity is formed in the middle of the tank. This cavity can be dangerous for the infiltration of free gas bubbles in unacceptable quantities to the LRE feeding system feedline. The process of moving of gas cavity to the tank bottom during the motion of liquid from the tank is shown in Fig. 5, *i*.

5. In this case, in the experiment, there were no PMDs at the lower tank bottom, presented in standard tanks of space upper stages. It is known that the presence of PMD can significantly reduce the value of gas bubbles entering the feedline during engine start-up. As shown in [12], for a different, for example, conical, shape of the tank with PMD in the form of grids or plates, the shape of the interface may be different, but the danger of gas bubbles infiltration the engine inlet remains.

In addition, from the obtained conclusions about the nature of fluid motion in the tank in microgravity conditions, we can additionally make the following remarks on the method of a physical experiment that are important for further research:

1. For an experiment in the 'Drop tower' to study, liquid (water, helium, or chladone) has a surface tension coefficient, which decreases with increasing temperature and is practically independent of pressure. This fact belongs to all liquids and cryogenic propellant components. It is necessary to take this fact into account for appropriate experiment processing and using the surface tension coefficient corresponding to the actual temperature.

2. The value of surface tension is affected by various reasons. The slightest impurities in the liquid change the surface tension greatly, reducing it in most cases. For performing practical calculations, this fact has to be taken into account. In particular, for calculating the surface tension coefficient, only pure liquids should be used. Surface tension can be significantly

reduced with the help of surfactants, which include detergents.

3. For calculating the surface tension coefficient and the contact angle, it is necessary to take into account not only the substances but also the contacting gas medium and the solid wall medium.

5. CONCLUSIONS

We propose the numerical approach to evaluate the motion parameters of the ‘gas — fluid’ interface in the volume of the propellant tanks for modern LV space stages in microgravity conditions (during the time interval from the moment the main space stage LRE shutdown to the moment the LRE start-up command). This approach takes into account the design features of the propellant tank and the thermodynamic characteristics of the interface between two phases of the ‘gas — fluid’ medium in equilibrium state and the tank design during LV programmed stage motion in space. According to the proposed approach, numerical modeling of hydrodynamic processes in the propellant tank is carried out using the Volume of Fluid method (VOF), taking into account the surface tension forces and propellant wettability, the forces of resistance to the liquid propellant motion, and the design features of the propellant tank. VOF analysis is performed using modern finite element analysis systems’ features and CAE-systems. The CSF method is used to describe the motion of the interface between gas and liquid relative to the tank walls.

The approach was tested based on the analysis of experimental and calculated data from rthe study of the physical model of fluid motion in a model tank in low gravity conditions in the ‘Drop tower’ for theoretical investigations performed in the Yuzhnoye State Design Office. There is a satisfactory agreement between the experimental and calculated data, i.e., the positions of the ‘gas — fluid’ interface in different time events of physical model motion in the ‘Drop tower’. In conclusion, the proposed approach can be used for theoretical prediction of the operability of LV space stage propulsion systems in conditions of multiple start-ups — shutdowns and LV program motion of the stage during its reorientation in space.

REFERENCES

1. Behruzi Ph., Michaelis M., Khimeche G. (2006). Behavior of the Cryogenic Propellant Tanks during the First Flight of the Ariane 5 ESC-A Upper Stage. 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Sacramento, California, AIAA 2006-5052. 9-12 July 2006. 10 p.
2. Bloha I. D., Zavoloka A. N., Nikolayev A. D., Sviridenko N. F. (2005). Influence of longitudinal vibrations of the upper stage of the launch vehicle on the operability of propellant management device (PMD) for ensuring the continuity of fuel components in the propulsion engine feeding system. *Technical mechanics*, № 2, 65—74 [in Russian].
3. Davydov S. A. (2004). *Calculation of the coefficient of infiltration of a submerged liquid jet through a woven metal mesh*. System design and analysis of the characteristics of aerospace technology: digest of sciences papers. Dnipropetrovsk, Edition V., 13—21 [in Russian].
4. Ducret E., Le Moullec L., Spencer B., Balaam P. (1992). Propellant management device studies, computational methods and neutral buoyancy tests. *AIAA 28th Joint Propulsion Conference and Exhibi.*, 92—3611.
5. Igdalov I. M., Kuchma L. D., Polyakov N. V., Sheptun Yu. D. (2004). *Rocket as a control object*. Dnepropetrovsk: ART-Press, 544 p. [in Russian].
6. I*nvestigation of Propellant Sloshing and Zero Gravity Equilibrium for the Orion Service Module Propellant Tanks* (2009). Final report. Microgravity University. Systems Engineering Educational Discovery. Kenosha, 22 p.
7. Hirt C. W., Nichols B. D. (1981). Volume of fluid (VOF) method for the dynamics of free boundaries. *J. Computational Phys.*, № 39 (1), 201—225.
8. Kashanov O. E., Degtyarev O. V., Pylypenko O. V., Zavoloka O. M., Nikolayev O. D., Sviridenko M. F. Ensuring operating efficiency of ilv space stages propellant feeding systems in different operating conditions. IAC-15-D.2.3, 66th Astronautical Congress International, 8832—8838. URL: http://toc.proceedings.com/29485webtoc.pdf (Last accessed: 13.06.2022).
9. Kohnke P. (2001). Ansys, Inc. Theory Manual 001369. Twelfth Edition. Canonsburg: SAS IP, Inc. 1266 p.
10. Kozlov A. A., Novikov V. N., Solovyov E. V. (1988). *Power feeding and control systems for liquid rocket propulsion systems*. M.: Engineering, 352 p. [in Russian].

11. Mikishev G. N., Churilov G. A. (1986). *Influence of surface tension and contact angle on liquid oscillations in vessels*. Spacecraft dynamics and space exploration. M.: Engineering, 164—175 [in Russian].
12. Pilipenko O. V., Degtyarev A. V., Zavoloka A. N., Kashanov A. E., Nikolayev A. D., Sviridenko N. F., Bashliy I. D. (2014). Determination of parameters of gas-liquid structures forming in propellant components during start-up of the space stage main engine with low filling levels of its tanks. *Technical mechanics*, № 4, 3—13. URL: http://dspace.nbuv.gov.ua/handle/123456789/88500 [in Russian].
13. Pilipenko O. V., Zavoloka A. N., Nikolayev A. D., Sviridenko N. F. (2006). The operability of propellant management device (PMD) for ensuring the continuity of fuel components in the feeding system of the main propulsion system of space stages of launch vehicles Digest scientific papers «Aero-gaso-dynamics: problems and prospects», № 2, 88—100 [in Russian].
14. Pozdnyshev N. O. *Development the capillary devices of launch vehicle tanks and peculiarities of hydrodynamic processes simulation occurring in them*. IAC-14-A2.2.3. URL: http://toc.proceedings.com/25520webtoc.pdf (Last accessed: 13.06.2022).
15. Salzman J. A., Masica W. J., Lacovic R. F. (1973). *Low-gravity reorientation in a scale-model Centaur liquid-hydrogen tank*. NASA TN D-7168. URL: https://ntrs.nasa.gov/search.jsp?R=19730007525 (Last accessed: 13.06.2022).
16. Sedykh I. V., Nazarenko D. S., Minai A. N., Babiychuk Ya. O. (2019). Experimental determination of the fuel sedimentation time in a spherical tank before restarting the main engine. *System design and analysis of the characteristics of aerospace technology*. **27**, 136—144. URL: https://www.dnu.dp.ua/docs/zbirniki/ftf/program_5e4456e3895d7.pdf (Last accessed: 13.06.2022).
17. Sichevoi A. V., Davydov S. A., Gorelova K. V. (2010). Coefficient of dynamic loading of grid devices for ensuring fuel continuity. *System design and analysis of the characteristics of aerospace technology: digest of sciences papers*. Dnipropetrovsk, Edition X., 106—113 [in Russian].
18. Siedykh I. V. (2021). *Selection of design parameters for inertial factors for ensuring the stability of propellant in the*: Candidate's thesis. Dnipro, 210 p. [in Russian].
19. The Bremen Drop Tower. URL: https://www.zarm.uni-bremen.de/en/drop-tower/team.html (Last accessed: 13.06.2022).
20. Zhang-Guo Li, Qiu-Sheng Liu, Rong Liu, Wei Hu, Xin-Yu Deng (2009). Influence of Rayleigh—Taylor instability on liquid propellant reorientation in a low-gravity environment. *Chinese Phys. Soc. and IOP Publ. Ltd.*, **26**, № 11, 114701-1—114701-4.

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ПІДХІД ДО ЧИСЕЛЬНОГО МОДЕЛЮВАННЯ ПРОСТОРОВОГО РУХУ РІДИНИ З ФОРМУВАННЯМ ВІЛЬНИХ ГАЗОВИХ ВКЛЮЧЕНЬ У ПАЛИВНОМУ БАКУ В УМОВАХ КОСМІЧНОГО ПОЛЬОТУ

Маршові двигунні установки космічних ступенів ракет-носіїв в умовах мікрогравітації забезпечують проведення кількох запусків — зупинок рідинних ракетних двигунів, необхідних для реалізації програмних переміщень і контролю орієнтації космічного апарату у просторі. Під час пасивного польоту космічного ступеня (після зупинки його маршового двигуна) рідке паливо у баках продовжує рух в умовах мікрогравітації за інерцією, максимально віддаляючись від внутрішньобакових забірних пристроїв. При цьому газ наддуву витісняється до забірного пристрою, що створює потенційну можливість проникнення газу на вхід у двигун у кількостях, неприпустимих для надійної реалізації повторного запуску двигуна. У зв'язку з цим визначення параметрів руху рідини у паливних баках в умовах мікрогравітації є актуальною задачею, яка вимагає вирішення при проєктуванні рідинних ракетних двигунних установок. Розроблено підхід до теоретичного визначення параметрів руху границі поділу середовищ «газ — рідина» у порожнинах паливних баків сучасних космічних ступенів рідинних РН в умовах мікрогравітації. Підхід базується на використанні методу скінченних елементів, методу об'єму рідини та сучасних комп'ютерних засобів скінченно-елементного аналізу (CAE-систем). Для умов пасивної ділянки польоту космічного ступеня РН виконано математичне моделювання просторового руху рідкого палива і вільних газових включень, що формуються, на основі якого визначено параметри руху і форми вільної поверхні рідини у баку, місце розташування газових включень.

Щодо умов руху експериментального зразка паливного бака з рідиною в «кидковій вежі» ДП «КБ «Південне», призначеної для вивчення об'єктів космічної техніки в умовах мікрогравітації, виконано чисельне моделювання руху рідини у баку сфероподібної форми. Отримані в результаті математичного моделювання значення параметрів руху рідини та границі поділу середовищ «газ — рідина» задовільно узгоджуються з отриманими експериментальними даними.

Використання розробленого підходу дозволить значно скоротити обсяг експериментального відпрацювання космічних ступенів РН, що проєктуються.

Ключові слова: рідинна ракета-носій, мікрогравітація, повторний запуск двигуна, пасивна ділянка польоту, просторовий рух рідкого палива, вільні газові включення до рідини, метод скінченних елементів, метод об'єму рідини, внутрішньобакові забірні пристрої.