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CHOICE OF THE OPTIMUM DESIGN OF LATERAL PMD USING THE CFD METHOD

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Abstract

Residues of propellant components in the power system of the propulsion system, at the end of the operation of the launch vehicle, to a large extent affect its energy characteristics. Propellant management devices (PMD), which are equipped with tanks of modern launch vehicles, provide a continuous supply of liquid propellant components from the tank to the propulsion system without disturbing the continuity of the flow and minimize of the residues of the propellant components. In the tank of a launch vehicle, the presence of a tunnel pipeline complicates, and in certain cases excludes the possibility of taking from the pole of the tank. In this case, the use of a lateral PMD allows solving the problem of propellant intake. The authors carried out a search and justification for the optimal design of the PMD using the example of the fuel tank of the first stage of the "Cyclone-4" launch vehicle, which is equipped with an PMD in the form of a profiled plate. The designs of the siphon and annular PMD are considered. An analytical calculation using empirical dependences, a physical experiment and numerical simulation of their main parameters was carried out. The result of the experimental and computational-analytical work was the determination of the most optimal variant of the PMD, which, according to several parameters, turned out to be a siphon PMD. The introduction of a more advanced siphon PMD into the design of the fuel tank of the "Cyclone-4" launch vehicle will improve the energy characteristics of the launch vehicle by increasing the weight of the output payload by 5.4 kg.

Introduction

The energy characteristics of modern launch vehicles are largely influenced by the residues of propellant components in tanks and highways at the end of the rocket stage. Residues propellant components are the amount of propellant in the power system of the propulsion system that cannot be produced due to violations of the requirements for continuity, pressure, propellant temperature at the inlet to the propulsion system, as well as due to the design features of the tank and the pipeline.

The PMD is an important element of the propellant tank, which provides a continuous supply of propellant components from the tank to the propulsion system without disturbing the continuity of the flow (without gas inclusions), that is, their maximum production.

In the process of designing propellant tanks and systems for supplying propellant components to propulsion systems, both for the lower stages [1, 2] and for space stages of launch vehicles [3, 4], choosing the most optimal type of PMD is important. This will further determine: the timing of the design of PMD; volume and duration of experimental development (physical and numerical) [5, 6]; the material and technical part necessary for experimental testing; the energy characteristics of the launch vehicle (due to the residues of propellant components) and, as a result, the total time and material and technical costs for the development of PMD and the launch vehicle as a whole [7, 8].

The main parameter that determines the efficiency of the PMD is the critical height of the dip in the level of the propellant component (H_{cr}) in static conditions. It represents the height of the liquid level in the tank, at which a breakthrough of the gas phase in the PMD occurs. The mass of unusable residues of propellant components directly depends on this value.

1. Statement of the problem

The presence of a tunnel pipeline in the fuel tanks of some launch vehicles, a small distance between the engine inlet and the bottom of the tank, the need for separate power supply of several engines from one tank to supply the propulsion system with propellant components complicate the possibility of taking propellant from the propellant tank.

The purpose of the research work given in this article is to search and select the optimal design of the PMD in the tank with the presence of a tunnel pipeline, which provides an increase in the energy characteristics of the launch vehicle.

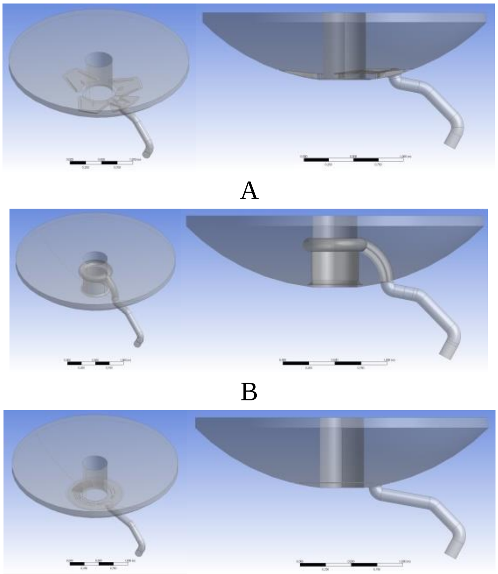
One of the common solutions for taking propellant from the tank in this case is the use of lateral PMD.

Lateral PMDs are characterized by an angle of location relative to the pole of the tank β (for central PMD, the angle $\beta = 0$). The presence of the angle β leads to an uneven level of gas breakthrough to the inlet to the pipeline and, as a result, a significant increase in the residuals propellant components, which adversely affects the energy characteristics of the launch vehicle [9, 10].

In a previous article by the authors [11], using the example of the fuel tank of the first stage of the "Cyclone-4" launch vehicle, equipped with lateral PMD in the form of a profiled plate (dish) to eliminate the disadvantages inherent in the lateral PMD, the authors considered the use instead of the lateral plate (dish) – siphon and annular PMD. For this, design work was carried out to determine their main geometric parameters (development of design schemes), and the calculation of H_{cr} was made, according to the method [12], which is based on empirical and semi-empirical dependencies, whose coefficients were obtained from the results of experimental testing of models, the design of which is most similar to the designed PMD.

After that, a comparative analysis of the change in the energy characteristics of the launch vehicle was carried out, depending on the chosen PMD design.

Structural schemes of the existing PMD launch vehicle "Cyclone-4" in the form of a fuel lateral plate (dish) and designed siphon and annular PMD are shown in Fig. 1, respectively. In more detail, the general parameters of the siphon and annular PMD, together with the basic principles of their design, were considered in the article [11].



A

B

C

Fig. 1. Structural schemes of the PMDs, in the fuel tank of the first stage of the "Cyclone-4" launch vehicle: (A) – lateral PMD in the fuel tank of the first stage of the "Cyclone-4"; (B) – siphon PMD; (C) – annular PMD

Based on the results of computational and analytical work, a comparative analysis of the operating parameters of the PMD under consideration was carried out.

The values of the critical height of the dip in the level of the propellant component and the residues of propellant components in the fuel tank with the presence of a tunnel pipeline during the implementation of various PMD schemes are given in Table 1 [11].

Table 1. The values of the critical height of the dip in the level of the propellant component and the corresponding value of the residues of the fuel component in the fuel tank

№	Parameter	H_{cr}, mm	M_{RC}^{stat}, kg	M_{RC}^{struc}, kg	M_{RC}^{total}, kg
1	Existing design of lateral plate (dish) PMD	147	94,8	–	94,8
2	Siphon PMD	40	8,69	22,91	31,6
3	Annular PMD	104	47,4	–	47,4

Table 1 uses the following designations:

H_{cr} – is the critical height of the dip in the level of the propellant component relative to the theoretical pole of the tank;

M_{RC}^{stat} – is the mass of the static hydraulic residues of the propellant component;

M_{RC}^{struc} – is the mass of the structural residues of the propellant component;

M_{RC}^{total} – is the total mass of the residues of the propellant component.

In the development of the design work given in the article [11], with the aim of a more perfect calculation of the operating parameters of PMD, the authors carried out:

– physical experiment to determine the residues of the propellant component for lateral PMD, on prototype construction;

– numerical simulation of hydrodynamic processes during the tank emptying and determination of the residues of the propellant component for lateral PMD using ANSYS Fluent;

– verification of numerical simulation based on the results of a physical experiment;

– numerical simulation of hydrodynamic processes during the tank emptying and determination of the residues of the propellant component for siphon and annular PMD;

– comparative analysis and determination of the optimal design of the PMD by the factor of influence of the obtained values of the residues of the propellant component on changes in the energy characteristics of the launch vehicle, based on the results of numerical simulation.

1.1. Physical experiment to determine the residues of the propellant component for the lateral PMD

A physical experiment to determine the static hydraulic residue component for the lateral PMD was carried out on the fuel tank prototype of the lateral PMD of scales M_1 1:1 and M_2 1:4 under gravity. As model fluids: M_1 1:1 – distilled water; M_2 1:4 – kerosene, were used.

The similarity of the hydrodynamic processes, occurring during the emptying of the propellant tank prototype in terrestrial conditions, to the processes occurring during the emptying of full-scale propellant tanks under space flight conditions, was ensured by the equality of the dimensionless complexes (numbers): Froude (Fr), Reynolds (Re), Struhal (St), and geometric similarity [13].

The prototype construction M_1 1:1 was the lower part of a regular fuel tank, together with a lateral PMD and a pipeline, at the end of which a photometric continuity sensor was installed. Before starting the experiment, the prototype construction was filled with a model liquid (water). The required value of the liquid flow rate during the experiment was provided due to the preliminary adjustment of the throttle mechanism of the cut-off valve. During the experiment, after detecting the presence of gas inclusions in the liquid flow with a continuity sensor, the residues of the propellant component were cut off and drained along the bypass line into the measuring container. Thanks to this, the values of the stats of the residues of the propellant component were determined.

The prototype construction of the M_2 1:4 fuel tank was the lower part of the standard fuel tank, made of transparent organic glass, together with the lateral PMD and a pipeline, at the end of which a photometric continuity sensor was installed. The prototype construction of the fuel tank was integrated into a kinematic model which included: control and measurement system; pneumo-hydro system; video measurement system.

Before starting the experiment, the prototype construction of the fuel tank was filled with a model liquid (kerosene). The required value of the liquid flow rate, during the experiment, was provided by creating the required pressure value in the prototype construction of the fuel tank. During the experiment, thanks to the appropriate sensors, the following were recorded: pressure in the prototype construction of the fuel tank, fluid flow, continuity of the liquid flow at the outlet of the pipeline, pressure in the drain tank, video recording of the process of draining the model liquid from the prototype construction of the fuel tank into the drain tank.

The calculation of the residues of the propellant component was carried out by the computer station of the control and measurement system due to the data obtained (fixed) during the experiment.

Fig. 2 shows photos of the equipment of the hydrodynamic stand.

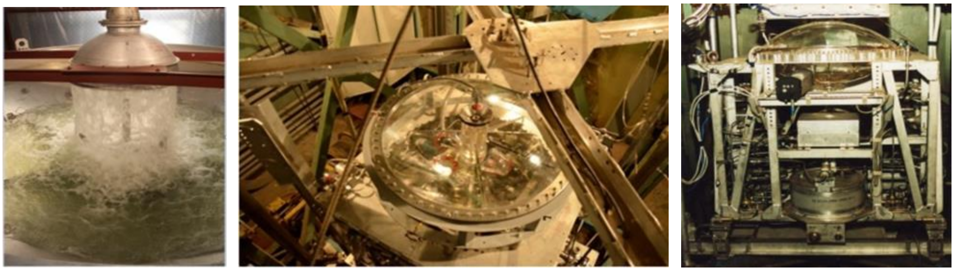

(A) *(B)* *(C)*

Fig. 2. Photos of the equipment of the hydrodynamic stand.:
(A) process of filling the prototype construction M_1 1:1 with a model liquid (water);.
(B) prototype construction of a fuel tank (top view) M_2 1:4; (C) general view of the kinematic model for hydrodynamic testing of a prototype construction of a fuel tank M_2 1: 4

The results of experiments to determine the mass of static hydraulic residues of the propellant components in prototype construction of M_1 1:1 and M_2 1:4 scales for lateral PMD, depending on the Froude number (Fr), recalculated for natural flight conditions of the launch vehicle, are shown in Fig. 3.

1.2. Numerical modeling of hydrodynamic processes during tank emptying and determination of the residues of the propellant component for lateral PMD

With the development of computer technology and numerical methods for solving differential equations of fluid motion, it became possible to replace the almost universal use of empirical dependencies with a more accurate computational experiment which PMD design engineers began to use very actively [14, 15, 16, 17, 18].

So, by the 90s of the XXth century in the USA, "Lockheed Martin" and "PMD Technology" companies completely formed and repeatedly tested a scientific and engineering approach to the development of PMD, which made it possible to expand the model range, optimize design parameters, reduce design time, and the cost of the final products. This approach was based entirely on the computational fluid dynamics (CFD) method. Over time, it has become a universally recognized engineering tool.

The key projects that confirmed the possibility of using numerical methods in the development of PMD were the missions of the SDO and JWST telescopes; space experimental platform NFIRE; research satellite MESSENGER.

At the same time, during the MESSENGER mission in orbit of Mercury, the developers carried out numerous calculations in CFD to optimize the sequence of turning on the sustainer engine to extract the residues of the propellant component that "stuck" to the tank baffles. CFD forecasts were very accurate, which once again confirmed the economic and scientific feasibility of using numerical simulation methods in the rocket and space industry.

In Europe, in the absence of an accessible database of the results of ground-based experimental testing of various PMD designs, the process of introducing numerical methods in the development of PMD has been slower.

It was boosted by the work on the "Space Shuttle" project with the United States in the late 1980s. During its implementation, large-scale studies were carried out using the EMTE research platform, which made it possible to obtain a good initial database. In the future, the European developers of PMD, extending and expanding the database, in the implementation of various projects, carried out both experiments and calculations by numerical methods.

In Ukraine, the engineers of Yuzhnoye State Design Office have started using numerical methods in the design of PMD since 2012, after acquiring a license for the ANSYS software package. As in the case of European engineers, the replenishment of the experimental data base necessary for the verification of numerical calculations went along with the work on the "Cyclone-4" launch vehicle project. And if at the first stages of work the design parameters of PMD were confirmed exclusively by the results of experiments on ground-based hydrodynamic stands and weightlessness stands, then at the final stages, the parallel use of numerical methods began. Numerical methods made it possible to reduce: the number of experimental designs that must be used, the required number of tests, the duration of the examinations, and, as the most important consequence, the overall material costs.

To solve the current problem, the simulation was carried out for a full-scale (natural) fuel tank and natural flight conditions of the "Cyclone-4" launch vehicle.

The process of solving the problem of numerical modelling of hydrodynamic processes when emptying the tank and determining the residues of the propellant component for lateral PMD in the ANSYS Fluent CFD software package consisted of the following steps: building a 3D model of the computational area of the fluid flow; constructing a computational grid; choosing the mathematical model of calculation; setting the properties of materials; setting initial and boundary conditions; setting solver parameters; calculating; visualization processing and analyzing calculation results.

The accuracy and reliability of the results of the numerical experiment depended on the correctness of the execution of each stage of the calculation.

During the numerical experiment, several simplifications and assumptions were made (mainly when constructing a 3D model), since it is practically impossible to consider all the factors that affect the behavior of the fluid under natural conditions of the launch vehicle flight.

Also, some deterioration in the accuracy of the numerical experiment was associated with the power of the available computer technology and the limitation of the time resource.

To carry out a numerical experiment, a 3D model of the computational domain of the fluid flow was built, i.e., the internal cavities of the full-scale (natural) tank bottom and the pipeline are modeled, not counting the wall thicknesses.

Based on the 3D model, a computational finite element mesh was created [19].

Later, in the ANSYS Fluent CFD module, after loading the computational grid, the numerical calculation was performed for natural conditions [20].

After the final settings in the Run Calculation section, the calculation was made and the results of the parameters of hydrodynamic processes during the emptying of the tank and the determination of the residues of the propellant component for the lateral PMD were obtained, which were displayed using the Results module.

Results of numerical modelling are shown in Fig. 5 and Table 2.

1.3. Verification of numerical simulation of hydrodynamic processes during tank emptying and determination of the residues of the propellant component for the lateral PMD based on the results of a physical experiment

The results of numerical simulation, as usual, are verified by the data of a physical experiment.

For a comparative analysis, the data of the physical experiment were plotted on the graph of the dependence of the mass of the propellant component residues on the Fr number (see Fig. 3) along with numerical simulation data and data from preliminary calculations using empirical dependencies (see Table 1) for lateral PMD.

The values of the numbers Fr and the mass of the residues of the propellant component in Fig. 3 are given for a full-scale (natural) propellant tank (together with a pipeline) and full-scale flight conditions of the launch vehicle when the gas phase enters the inlet to the propulsion system.

At the same time, since the calculated value of the residues of the propellant component for the lateral PMD (see Table 1) was obtained for the propellant tank without the pipeline, at the time the gas phase entered the pipeline, its value at the time the gas phase entered the inlet to the propulsion system (M_L'') will be equal to:

(1) $$M_L'' = M_{RC\,LPMD}^{total} + M_{pipelane}^{LPMD} - \tau' \cdot \overset{\bullet}{G}_{PS},$$

where:

$M_{RC\,LPMD}^{total}$ – is the total mass of the residues of the propellant component.

$M_{RC\,LPMD}^{total} = M_{RC}^{total}$, for lateral PMD (see Table 1);

$M_{pipelane}^{LPMD}$ – is the mass of the propellant component in the pipeline of the tank with the lateral PMD ($M_{pipelane}^{LPMD} = 10,67\ \text{kg}$);

τ' – is the time during which the gas phase moves from the entrance to the pipeline to the entrance to the propulsion system. Theoretically, this time depends on the configuration of the pipeline, the distance that the gas phase overcomes from the entrance to the pipeline to the entrance to the propulsion system, and the speed of it is movement. This time is ~ 0,3s.

$\overset{\bullet}{G}_{PS}$ – is the weight consumption of the propellant component for the propulsion system ($\overset{\bullet}{G}_{PS} = 38,57\ \text{kg/s}$).

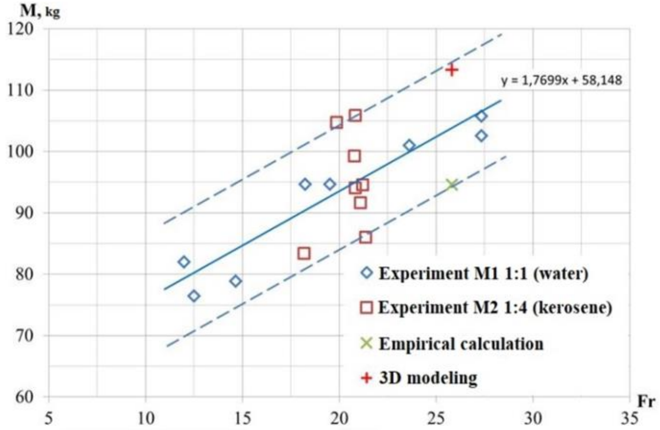
To more accurately take into account the mass of the propellant component, by which the total value of the residues of the propellant component will decrease during the movement of the gas phase from the inlet to the pipeline to the inlet to the propulsion system, we will replace the value of the multiplier ($\tau' \cdot \overset{\bullet}{G}_{PS}$) by the difference ($M_{T_D} - M_{T_C}$) in formula (1) (see Table 3). In this case, formula (1) will look like:

(2) $$M_L'' = M_{RC\,LPMD}^{total} + M_{pipelane}^{LPMD} - M_L',$$

where:

$$M_L^{'} = M_{T_D} - M_{T_C} . \tag{3}$$

For lateral PMD – $M_L^{'} = 10,91\,\text{kg}$.



—— *linearly approximated mean value of experimental data;*

▪▪▪▪▪▪ *scatter limits of experimental data values*

Fig. 3. Graph of the dependence of the mass of the residues of the propellant component, when the gas phase enters the inlet to the propulsion system on the number Fr

As we see from Fig. 3, the value of the residues of the propellant component for the lateral PMD obtained by numerical simulation is within the range of experimental data values. It has a deviation relative to the averaging line of the experimental data, equal to ~ 9% (average value of the residues of the propellant component approximated by the results of the experiment is 104 kg, at Fr=25,81) with a total deviation of the scatter of the values of the experimental data ~±12%.

This testifies to the observance of hydrodynamic similarity in 3D modelling and confirms the correctness of the fulfilment of the set tasks of the numerical experiment.

The simplifications and assumptions adopted during the numerical experiment, which affect the behaviour of the fluid during the full-scale (natural) conditions of the launch vehicle flight, and the need to degrade the accuracy based on the power of the available computing equipment and the limitation of the time resource, did not significantly affect the accuracy of the results, because they are confirmed by physical experiment data.

This makes it possible to use the obtained mathematical model for numerical simulation of hydrodynamic processes during tank emptying and determination of the residues of the propellant component for siphon and annular PMD.

1.4. Numerical modeling of hydrodynamic processes during tank emptying and determination of the residues of the propellant component for siphon and annular PMD

Numerical simulation was performed for a full-scale (natural) fuel tank of the 1st stage and natural flight conditions of the "Cyclone-4" launch vehicle, with alternative PMD options: siphon and annular.

For numerical simulation, a 3D model of the computational area of the fluid flow was built, that is, internal cavities were modelled full-scale (natural) tank bottom and pipeline, without taking wall thicknesses into account – for siphon and annular PMD.

Based on the 3D model, a computational finite element mesh was created [19].

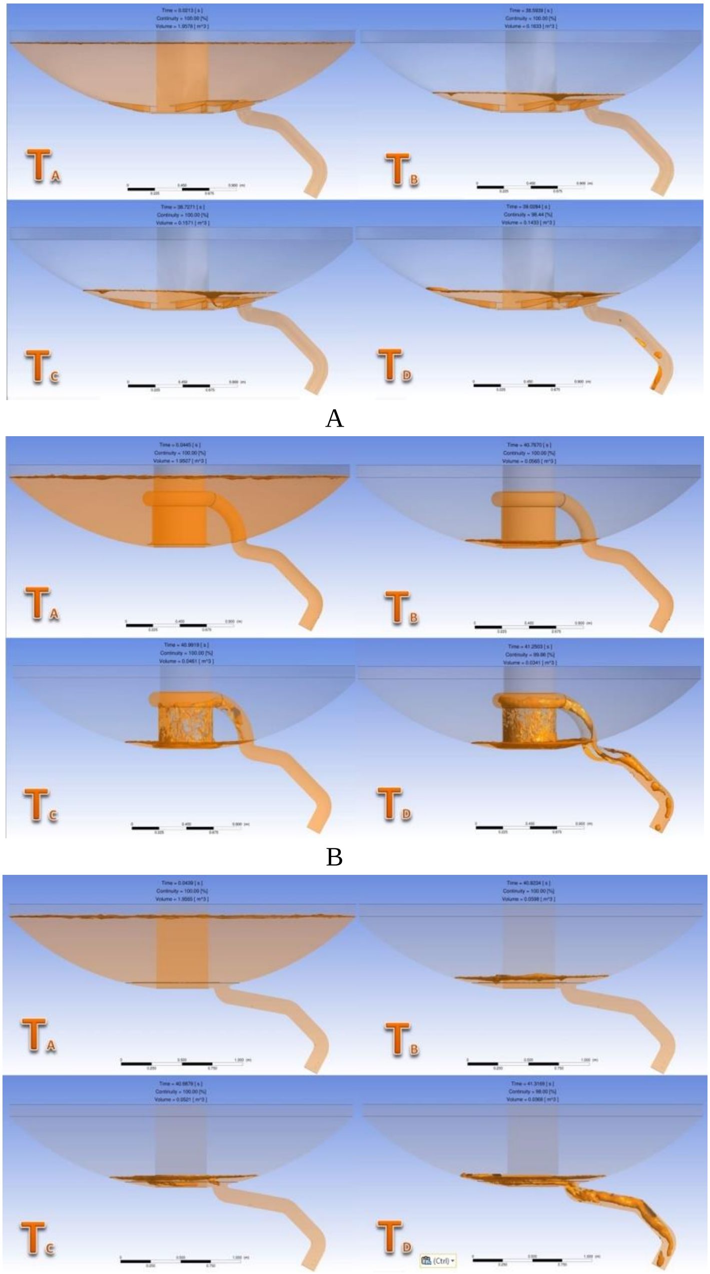
Later, in the ANSYS Fluent CFD module, after loading the computational grid, the settings were selected, and the initial and boundary conditions were set according to the methodology worked out for the lateral PMD (see section 1.2) [20].

After carrying out the calculations and obtaining the results of the parameters of hydrodynamic processes during emptying the tank and determining the residues of the propellant component for the siphon and annular PMD, they were visualized using the Results module.

Table 2 shows the values of the mass of the propellant component and the fluid continuity (at the end of the pipeline) in the propellant supply system of the propulsion system for 4-key moments (T_A, T_B, T_C, T_D) of emptying the propellant tank with a lateral, siphon and annular PMD.

Table 2. The value of the mass of the propellant component and the continuity of the liquid in the propellant supply system of the propulsion system for the lateral, siphon and annular PMD

<table>
<tr><th colspan="5">Lateral PMD</th></tr>
<tr><td>Parameter</td><td>T_A</td><td>T_B</td><td>T_C</td><td>T_D</td></tr>
<tr><td>Time, s</td><td>0,0213</td><td>38,5939</td><td>38,7271</td><td>39,0284</td></tr>
<tr><td>Continuity, %</td><td>100</td><td>100</td><td>100</td><td>98</td></tr>
<tr><td>Mass of the propellant component, kg</td><td>1547,64</td><td>129,09</td><td>124,19</td><td>113,28</td></tr>
<tr><th colspan="5">Siphon PMD</th></tr>
<tr><td>Parameter</td><td>T_A</td><td>T_B</td><td>T_C</td><td>T_D</td></tr>
<tr><td>Time, s</td><td>0,0445</td><td>40,7670</td><td>40,9919</td><td>41,2503</td></tr>
<tr><td>Continuity, %</td><td>100</td><td>100</td><td>100</td><td>99</td></tr>
<tr><td>Mass of the propellant component, kg</td><td>1542,03</td><td>46,24</td><td>36,44</td><td>26,96</td></tr>
<tr><th colspan="5">Annular PMD</th></tr>
<tr><td>Parameter</td><td>T_A</td><td>T_B</td><td>T_C</td><td>T_D</td></tr>
<tr><td>Time, s</td><td>0,0439</td><td>40,8234</td><td>40,9879</td><td>41,3169</td></tr>
<tr><td>Continuity, %</td><td>100</td><td>100</td><td>100</td><td>98</td></tr>
<tr><td>Mass of the propellant component, kg</td><td>1546,61</td><td>47,27</td><td>41,19</td><td>29,09</td></tr>
</table>



A

B

C

Fig. 4. Timing of the process of emptying the tank and determining the residues of the propellant component for 4-key moments the: (A) – lateral PMD; (B) – siphon PMD; (C) – annular PMD

Fig. 4 shows the timing of the process of emptying the tank and determining the residues of the propellant component for the lateral, siphon and annular PMD (respectively) for 4-key moments: T_A – the beginning of the emptying; T_B – immersion of the gas phase under the lateral/siphon/annular PMD; T_C – immersion of the gas phase to the entrance to the pipeline; T_D – immersion of the gas phase at the entrance to the propulsion system.

2. Analysis

Since the value of the hydraulic residues of the propellant components is determined for the power supply system of the propulsion system of the launch vehicle consisting of a fuel tank and a pipeline, then for a correct comparison and analysis of the results of analytical calculations, carried out without considering the pipeline, with the results of numerical simulation, in which the mathematical model of the calculation liquid flow area in the fuel tank and pipeline system – recalculations of the residues of the propellant components for the siphon and annular PMD should be carried out, which are shown in Table 1 according to the following formulas:

(4) $$M_S'' = M_{RC\,SPMD}^{total} + M_{pipelane}^{SPMD} - M_S',$$

where:

$M_{RC\,SPMD}^{total}$ – is the total mass of the residues of the propellant component.

$M_{RC\,SPMD}^{total} = M_{RC}^{total}$, for siphon PMD (see Table 1)

$M_{pipelane}^{SPMD}$ – is the mass of the propellant component in the pipeline of the tank with the siphon PMD ($M_{pipelane}^{SPMD} = 10,75\ \text{kg}$)

M_S' – is the mass of the propellant component, by which the total value of the residues of the propellant component will decrease during the time of gas phase immersion from the entrance to the pipeline to the entrance to the propulsion system for the siphon PMD.

For siphon PMD – $M_S' = 9,48\ \text{kg}$.

5) $$M_A'' = M_{RC\,APMD}^{total} + M_{pipelane}^{APMD} - M_A',$$

where:

$M_{RC\,APMD}^{total}$ – is the total mass of the residues of the propellant component.

$M_{RC\,APMD}^{total} = M_{RC}^{total}$, for annular PMD (see Table 1)

$M_{pipelane}^{APMD}$ – is the mass of the propellant component in the pipeline of the tank with the annular PMD ($M_{pipelane}^{APMD} = 12,09\ \text{kg}$)

M'_A – is the mass of the propellant component, by which the total value of the residues of the propellant component will decrease during the time of gas phase immersion from the entrance to the pipeline to the entrance to the propulsion system for the annular PMD.

For siphon PMD – $M'_A = 12{,}10$ kg .

The results of the calculated values of the static hydraulics of the residues of the propellant component determined for the power system of the propulsion system of the launch vehicle according to the formulas (2), (4), (5) (M''), the results of numerical simulation (M''_{CFD}) for all three variants of the PMD, and their average deviation from the calculated values (σ) are given in Table 3.

Table 3. Significance of static hydraulic of the residues of the propellant components

№	Parameter	M'', kg	M''_{CFD}, kg	σ, %	Change in payload mass $\Delta M''_{CFD}$, kg
1	Existing design of lateral plate PMD	94,56	113,28	20,8	0
2	Siphon PMD	32,87	26,96	18,0	+5,4
3	Annular PMD	47,48	29,09	38,7	+5,2

As we can see from Table 3, the results of numerical simulation have a significant deviation from the values of hydraulics of the residues of the propellant components calculated using the technique [12], based on empirical and semi-empirical dependencies, the coefficients of which were obtained from the results of experimental testing of the models, the design of which is most similar to the designed PMD. However, the data presented in section 1.3 indicate that the results of numerical simulation (for lateral PMD) have a deviation relative to the averaging line of experimental data equal to ~ 9% (the average approximated by the results of the experiment value of the residues of the propellant component is 104 kg, at Fr = 25,81) with a total deviation of the scatter of values experimental data ~ ± 12%.

This makes it possible to put forward a hypothesis that the developed method for numerical simulation of hydrodynamic processes during emptying the tank and determining the residues of the propellant components is valid, and the values of the residues of the propellant components for lateral, siphon and annular PMD obtained using it will be within the limits, no more ~ ± 15% than the average approximated value of the physical experiment.

The deviation of the residues of the propellant components value according to the result of numerical simulation of the annular PMD is 38,7 % due to the fact that the analytical method [12], according to which the previous value of the residues of the propellant components was calculated, equal to 47,48 kg, does not take into account the fact that, when emptying the tank with the annular PMD , due to its design features, the flow of fluid in the chute under the perforated plate can occur according to the "piston" principle. This is possible when the initial immersion of the gas phase under the plate occurs in its sector farthest from the pipeline, which can subsequently lead to the complete uniform emptying of the chute according to the "piston" principle. Partially, this effect is observed in the timing of the process of numerical simulation of emptying a tank with an annular PMD in Fig. 5 (T_B, T_C, T_D).

Thus, it can be concluded that of the residues of the propellant components' values obtained by numerical simulation fully reproduce the physical picture of emptying the tank and of the residues of the propellant components formation and are more reliable than the values obtained by analytical calculations.

It follows from Table 3 that the siphon PMD provides the smallest mass of the residues of the propellant component, both according to analytical and numerical calculations.

Based on the obtained values of the residues of the propellant component in the fuel tank for the considered variants of PMD, according to the methodology and recommendations given in [21], the change in the energy characteristics of the "Cyclone-4" launch vehicle was determined. For this, the change in the mass of the payload that can be launched by the launch vehicle into a reference orbit relative to the existing lateral PMD was estimated.

Table 3 also shows the values of the change in the mass of the output payload in the case of the introduction of a siphon and annular PMD, relative to the lateral one, according to the results of numerical simulation.

Conclusions

The results of the computational-analytical and experimental work have shown that of residues of the propellant component is the smallest when using the siphon PMD.

The main advantages of which are:

– reducing the average approximated by the results of a physical experiment, the value of the static hydraulics of the residues of the propellant component in the power system of the propulsion system of the launch vehicle "Cyclone-4", from 104 kg (for the existing lateral PMD), to 26,96 kg (the difference is $\Delta M = 77,04$ kg and is significant).

– ensuring a uniform decrease in the level of the fuel component in the tank;

– decreasing the dynamic component of the total balance, because of a decrease in H_{cr} due to the central selection of the fuel component;

– introducing a siphon PMD to power the steering propulsion system does not require refinement in the PMD fuel tank for the main propulsion system.

As a result, the introduction of a more advanced siphon PMD into the design of the fuel tank of the "Cyclone-4" launch vehicle instead of the lateral PMD will improve the energy characteristics of the launch vehicle by increasing the mass of the payload launched into the reference orbit by 5,4 kg.

As shown by the results of the work carried out, the use of numerical modeling methods (CFD methods) in the design work on development, optimization, and improvement, instead of the widespread use of empirical and semi-empirical dependencies, allows: getting more accurate results; reducing the number of prototype construction to be used; reducing the required number of tests; reducing the duration of experiments; reducing the total duration of computational and design and experimental work; reducing overall material and technical costs and, as a result, reducing the final cost of the development product, which will increase it is competitiveness.

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ИЗБОР НА ОПТИМАЛЕН ДИЗАЙН НА СТРАНИЧЕН PMD С ИЗПОЛЗВАНЕ НА МЕТОДА CFD

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Резюме

Остатъците от горивни компоненти в енергийната система на задвижващата система в края на експлоатацията на ракетата-носител влияят до голяма степен на нейните енергийни характеристики. Устройствата за управление на горивото (PMD), които са оборудвани с резервоари на съвременни ракети-носители, осигуряват непрекъснато подаване на компоненти на течно гориво

от резервоара към системата за задвижване, без да се нарушава непрекъснатостта на потока и минимизиране на остатъците от компонентите на горивото. В резервоара на ракета-носител наличието на тунелен тръбопровод затруднява, а в някои случаи и изключва възможността за вземане от полюса на резервоара. В този случай използването на страничен PMD позволява решаване на проблема с приема на гориво. Авторите извършиха търсене и обосновка на оптималната конструкция на PMD на примера на горивния резервоар на първата степен на ракетата-носител “Циклон-4”, който е оборудван с PMD под формата на профилна плоча. Разгледани са конструкциите на сифона и пръстеновидния PMD. Извършено е аналитично изчисление с помощта на емпирични зависимости, физичен експеримент и числена симулация на основните им параметри. Резултатът от експерименталната и изчислително-аналитичната работа беше определянето на най-оптималния вариант на PMD, който по няколко параметъра се оказа сифонен PMD. Въвеждането на по-усъвършенстван сифон PMD в конструкцията на горивния резервоар на ракетата-носител “Циклон-4” ще подобри енергийните характеристики на ракетата-носител чрез увеличаване на теглото на изходящия полезен товар с 5,4 kg.