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THE PROBLEM OF THE TANK PRESSURIZATION WITH HYDROGEN PEROXIDE AND THE APPROACH TO ITS SOLUTION USING PRODUCTS OF ITS DECOMPOSITION

Aim. To find and confirm the possibility of hydrogen peroxide tank pressurization using high-temperature pressurization gas (~1100 K) with a high percentage of steam (up to 70 %) without its losses.

Research methods. Mathematical modeling of pressurization system parameters with the theory of mass transfer and thermodynamic of variable mass bodies have been used.

Results. The conducted research allowed us to find and confirm the possibility of using a new pressurization method with additional sources of heat and elaborate recommendations for its appliance during pressurization time.

Scientific novelty. The main processes have been determined, which prevent implementation of the efficient high-temperature pressurization system of the tank with the hydrogen peroxide using peroxide decomposition products. The main obstacle is the volume condensation of vapor in the free volume of the tank when heat exchange processes with boundary surfaces take place. For the first time, by means of theoretical calculations, the expediency and rationality of using the additional sources of heat such as high-temperature combustion product of solid-fuel gas generator based on sodium azide have been proved. Using of this additional source for the first 30 seconds of engine operation has been proved.

Practical value. Methodology of pressurization system parameters' calculation was supplemented with discovered thermodynamic relation, which allowed us to calculate the amount of vapor and take some measures to eliminate the condensation. Results of the research allowed the designation of the pressurization system for the highly concentrated hydrogen peroxide tank with a high value of length to diameter relation with its high-temperature decomposition products.

Keywords: high-test peroxide, pressurization system, condensation of the vapor, decomposition products, high temperature pressurization gas, saturated steam pressure.

Generalia praecedunt, specialia seguuntur

INTRODUCTION

Nowadays, the world's most popular satellite segment in terms of mass is only a few tens of kilograms. Medium-class launch vehicles (LV) may deliver tens and hundreds of such satellites into orbit per launch [16]. However, very often, it leads to the sacrifice of the orbit accuracy of each satellite. Moreover, logistical issues take place. Therefore, it is not surprising that today the interest in the ultra-light LV class has significantly increased. This particular LV class suits the best for the launching of satellites individually or in small homogeneous groups. However, the price for

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delivery of one kilogram of payload into orbit by ultra-light LV is significantly higher [4].

In order to eliminate this significant drawback, the most innovative decisions should be applied during the design process of such a launch vehicle. Also, all Cold War period technical stereotypes when some countries for different political reasons tried to reach space at any price should be abandoned.

THE AIM OF THE REASERCH

The purpose of this research is to find and confirm the simplest pressurizing method of tanks with hydrogen peroxide by its high-temperature decomposition products.

The tasks of the research are the following:

- Determination of reasons, which cause condensation of the vapor in the free volume of the tank during its pressurization with decomposition products of high-tense peroxide;
- Confirmation of the thermodynamic relation, which allows the exclusion of volume condensation of the vapor in the free volume of the tank;
- Confirmation of the way to provide conditions when found thermodynamic relation is fulfilled.

Methods of thermodynamic of variable mass bodies, heat exchange theory, and iteration calculation methods were used

LITERATURE REVIEW

It is believed that liquid oxygen (LOX) is the cheapest oxidizer. The fact of the matter is that it is true only for the factory manufacturing price. LOX attractiveness reduces if all additional systems which are necessary to make its usage possible are considered.

It is a well-known fact that the liquid-propellant rocket engine and helium pressurization systems are the most expensive parts of the launch vehicle [4]. That is why the design process of these LV systems should be the most careful and attentive.

It is not surprising that, nowadays, a significant increase of interest in the operation of rocket systems that run on widespread environmentally friendly storable propellants has been detected [1]. The most interesting propellant in this regard is highly concentrated hydrogen peroxide — kerosene or highly concentrated hydrogen peroxide — alcohol [15]. Currently, a number of companies are already developing an ultralight class launch vehicle based on the indicated propellant (Taimyr, Adler, Skyrora). Moreover, the European Space Agency has announced a tender for the development of a thruster that would run on hydrogen peroxide [5].

Until today, helium pressurization systems (PS) have found the most widespread use in the world for pressurizing propellant tanks. The reason for it is that no special research is necessary for them. Since 1966 after tragic failures of liquid-propellant missiles in the USA, the governments have chosen solid-propellant missiles as a main course of development. The financing of liquid-propellant propulsion systems almost had been ceased. In the Soviet Union, on the contrary, liquid-propellant missiles were chosen as a main course of development and, as a result, the famous missile R-36M, which is also known as “Satan”, was created. Gas-stored systems were not applied for the last two generations of Soviet missiles, which significantly simplified the design of the propulsion system and reduced the dry weight of the missile.

Further, due to the widespread use of helium PS, the impression of their reliability can be formed. However, this is far from the case [11]. Failures and accidents with the loss of payload due to the fault of helium systems over the past seven years in the world have occurred much more often than due to the failure of a much more complicated rocket engine.

Article [9] is devoted to the research of fragment acceleration modeling during the burst of the pressurized tank. Article [7] presents the modeling of mass and heat transfer during the pressurization of the tank with liquid hydrogen. Comparison between helium and evaporated hydrogen have been done.

Particular issues of the use of helium for pressurization have been considered in the technical (patent) literature. The process of gas pressure drops in a tank with an oxidizer which takes place after its prelaunch pressurization with helium, was studied in the article [8]. The article [17] is devoted to mathematical modeling of phase transitions in the system “cryogenic liquid-free volume of a tank with helium”. It is shown that the phase transition (boiling) has an insignificant effect on the pressure in the tank. The research [6] considers different conditions of hot helium entering into the free volume of the tank.

The conclusion was made that axial gas injection is more preferable to the commonly used radial injection. The failure factor of the system was determined (decrease of pressure in the tank).

It seems that the simplest way to a tank with hydrogen peroxide pressurization is by using its hot decomposition product. This idea seems to be the most obvious, but huge issues appear, such as the presence of steam (up to 70 % of mass) [3]. Due to thermodynamic expansion work *pdV*, heat exchange with the tank structure and propellant surface temperature of any hot pressurization gas drop immediately. Most of the water vapor condenses on relatively cold boundary surfaces. In this case, overheating of the aluminum supporting the upper bottom of the oxidizer tank may occur.

This is exactly what happened during the first in the world development of the first stage pressurization system for the RD-214 oxidizer tank which was powering the first stage of the Cosmos launch vehicle [12]. This pressurization system used the decomposition product of hydrogen peroxide. The issue with the upper bottom of the tank was solved by upgrading its design. A thin-walled steel false bottom was installed equidistantly to the main bottom with a minimum gap.

MATHEMATICAL MODELING AND ITS CONSEQUENCES

In accordance with the canons of thermodynamics, it is necessary to maintain the average mass temperature of the pressurization gas higher than the temperature of vaporous water pressure in the free volume of the tank. In other words, the partial pressure of water vapor in the free volume of the tank during operation of the liquid-propellant engine should be less than the pressure of saturated water vapor at the mass average temperature of the pressurization gas in the tank.

In our opinion, to achieve indicated state of the thermodynamic parameters in the tank, there are two simple ways [13]. The first way is to organize high-temperature prelaunch pressurization. The second way is to sustain pressure at the beginning of the propulsion system operation by means of additional high-temperature pressurization gas separately or in combination with decomposed hydrogen peroxide.

As an additional heat source, the most widespread sodium azide solid gas-generator was considered, which would generate almost pure nitrogen (≥98 % N_2) [14]. It is commonly used to inflate car airbags. Taking into account that no coolant is necessary for our purpose, this gas-generator is getting simpler. The combustion temperature of sodium azide with Fe_2O_3 as an oxidizer is about 1550 K and with WO_3 is about 1750 K. The pressure-fed propulsion system will be considered as the most complicated case (tank pressure is between 45 and 50 bar).

Mathematical simulation of internal tank processes was used as a basic one. It is based on the thermodynamics of variable mass. This simulation method allows determining pressure change in the tank depending on the mass flow rate of pressurization gas and change of the free volume [10]:

$$\frac{dp}{d\tau} = \frac{k-1}{V}\left[\dot{Q}_\Sigma + \sum_{i=1}^{n} I_i m_i - I_1 m_l - \right.$$

$$\left. - \frac{k_{av}}{k_{av}-1} p\dot{V} + \frac{\dot{k}Vp}{(k_{av}-1)^2} \right];$$

m_i and I_i — mass and enthalpy of the gases used for pressurization; m_l and I_l — mass and enthalpy of gas leakage. This term is relevant if the safety valve is triggered; p — current pressure in the tank; $\dot{V}$ — the volume flow rate of propellant; k_{av} — average heat capacity ratio of the pressurization gas may be determined as:

$$k_{av} = \frac{\sum m_i k_i}{\sum m_i},$$

Q_Σ — total heat flow from the gas, which may be determined as:

$$\dot{Q}_\Sigma = \dot{Q}_p + \dot{Q}_w + \dot{Q}_{con},$$

$\dot{Q}_p$ — heat flow from pressurization gas to the propellant; $\dot{Q}_w$ — heat flow from gas to the tank structure; $\dot{Q}_{con}$ — heat flow from volume condensation of the steam.

Heat losses to the boundary surfaces are determined from the dependences of stationary natural convection. These are generally accepted assumptions today.

In our case, when tank pressurization with decomposition product of hydrogen peroxide with 70 % of steam is being considered, the exact evaluation of the heat flow from the condensation process is the most relevant.

In order to make calculations possible, two fundamental assumptions were made:

1. All energy that is released during the condensation process heats pressurization gas in the free volume of the tank.

2. As soon as the pressure of saturated water vapor at the average temperature of the gas in the tank becomes higher than its partial pressure, the condensation process stops.

In this case, heat flow from the condensation process may be determined as the product of specific heat of condensation to the mass of condensed steam:

$$\dot{Q}_{con} = r(t)\cdot\dot{m}\,.$$

Taking into account the second assumption, the mass of condensed steam is an excessive mass in comparison with its boundary permissible mass, which may be determined as:

$$m_{con} = M_{\mathrm{H2O}i} - \frac{p_s(T)V}{R_{\mathrm{H2O}}T}\,,$$

$M_{\mathrm{H2O}i} = M_{\mathrm{H2O}i-1} + \dot{m}_{\mathrm{H2O}}$ is the amount of steam in the tank on the previous evaluation step; $\dot{m}_{\mathrm{H2O}}$ — the mass flow rate of steam for pressurization; $p_s(T)$ — saturated steam pressure, which is a function of temperature; V — current free volume in the tank; R_{H2O} — the gas constant of water vapor; T — the temperature of the pressurization gas in the tank.

It's evident that the condensation process has a negative role in the pressurization process. Firstly, this is a direct loss of pressurization gas which leads to the necessity of pressurization gas flow rate increase.

Secondly, the temperature of the upper layer of the propellant increases which causes an increase in saturated vapor pressure. Also, the necessity of the tank pressure increase appears in order to provide stable operation of the pumps.

Let's consider both ways of heat energy supply in a more detailed way:

- hot prelaunch pressurization;
- using of high-temperature solid-fuel gas-generator, which would pressurize the propellant tank in the initial moment. In this case, the task may be formulated as an optimization of the pre-launch pressurization temperature or operation time, the mass flow rate, and combustion temperature of the solid-fuel gas-generator, which would be sufficient to meet the necessary condition.

Let's consider a pressurization case when the propellant tank of a pressure-fed propulsion system is pressurized by means of a hydrogen peroxide decomposition product. The input data for mathematical simulation are presented in Table 1.

In this case, pre-launch pressurization is provided by nitrogen with ambient temperature, which is the simplest way. Analysis of the results of the mathematical simulation, which are presented in Figures 1 and 2, prove that the condensation process causes significant pressure drop at the initial moment of propulsion system operation. Based on these results, a conclusion can be made that the condensation process stops as soon as saturated steam pressure becomes lower than its partial pressure at the average gas temperature.

Let's conduct mathematical modeling of the case when pre-launch pressurization is performed using hot gas. It will help to increase the temperature inside the tank higher than the condensation temperature. Input data for the mathematical simulation is presented in Table 2. The results of mathematical modeling are presented in Figures 3 and 4.

Table 1. **Calculation of pressurization system with cold pre-launch pressurization**

Pressure after pre-launch pressurization, Pa	$45\cdot10^5$
Temperature after pre-launch pressurization, K	310
The mass flow rate of gas for pre-launch pressurization, $\mathrm{kg\cdot s^{-1}}$	0.22
Initial gas volume in the tank, l	80
Diameter of the tank, mm	750
The volume flow rate of propellant, $\mathrm{s^{-1}}$	8.36
Propellant temperature, K	293

Table 2. **Calculation of pressurization system with hot pre-launch pressurization**

Pressure after pre-launch pressurization, Pa	$45\cdot10^5$
Temperature after pre-launch pressurization, K	500
The mass flow rate of gas for pre-launch pressurization, $\mathrm{kg\cdot s^{-1}}$	0.22
Initial gas volume in the tank, l	80
Diameter of the tank, mm	750
The volume flow rate of propellant, $\mathrm{s^{-1}}$	8.36
Propellant temperature, K	293

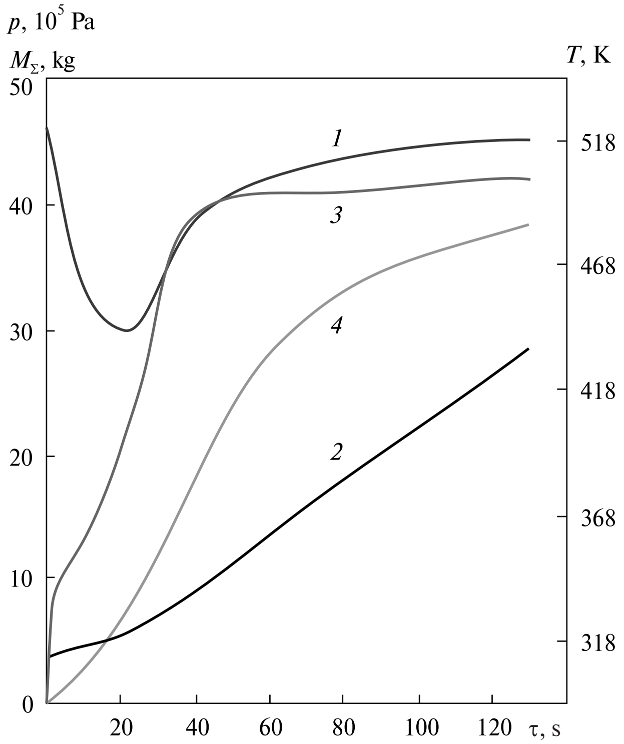

Fig. 1. Main parameters in the tank in case of pressurization with decomposed H_2O_2 and pre-launch pressurization with cold nitrogen: *1* — tank pressure, *2* — total mass of the gas in the tank, *3* — gas temperature on the tank, *4* — temperature of the dome

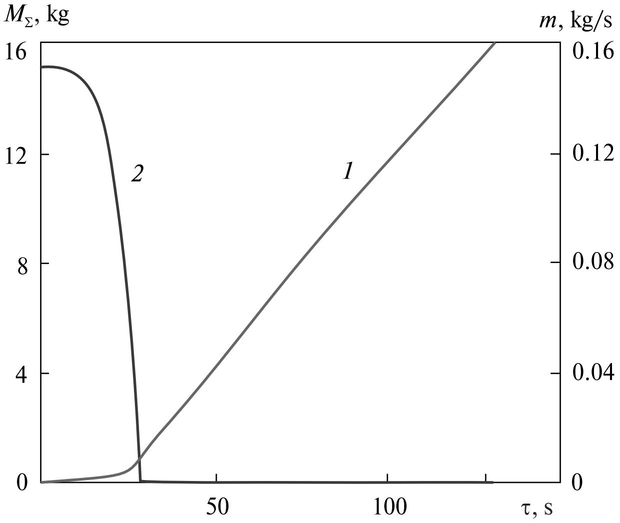

Fig. 2. Pressurization gas losses due to condensation and increase of steam mass in the tank: *1* — mass of the pressurization gas, *2* — loss of pressurization gas due to condensation

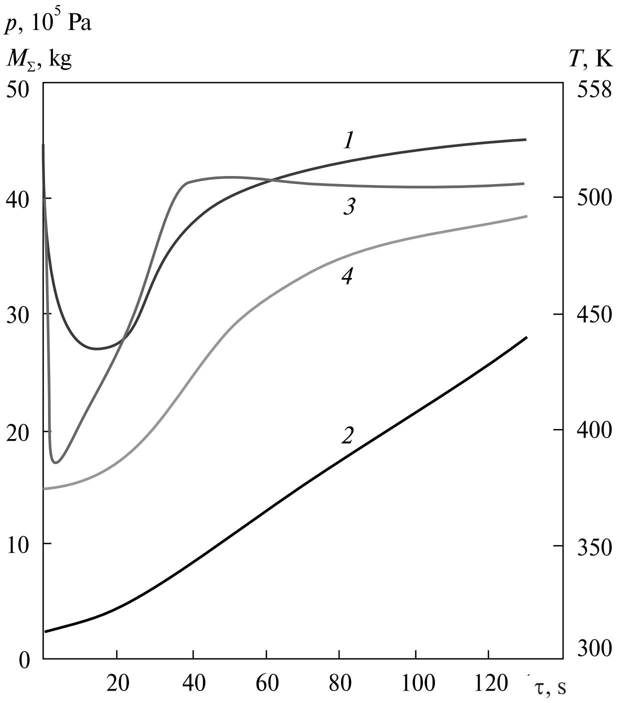

Fig. 3. Main parameters in the tank in case of pressurization with decomposed H_2O_2 and hot pre-launch pressurization: *1* — tank pressure, *2* — total mass of the gas in the tank, *3* — gas temperature on the tank, *4* — temperature of the dome

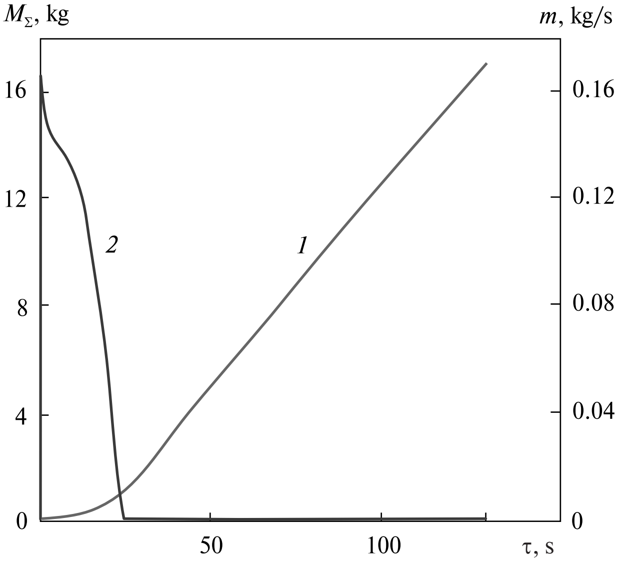

Fig. 4. Pressurization gas losses due to condensation and increase of steam mass in the tank: *1* — mass of the pressurization gas, *2* — loss of pressurization gas due to condensation

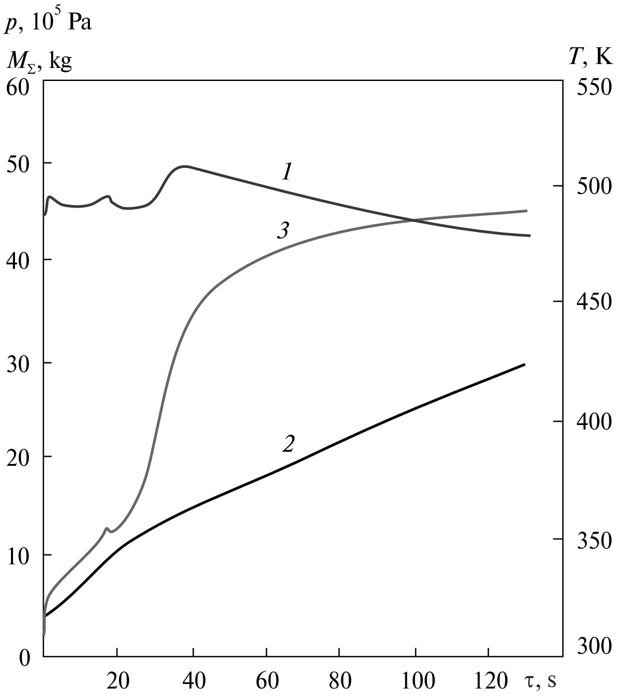

Fig. 5. Main parameters in the tank in case of hybrid pressurization system: *1* — tank pressure, *2* — total mass of the gas in the tank, *3* — gas temperature on the tank

Table 3. **Input data for hybrid pressurization system**

Pressure after pre-launch pressurization, bar	45
Temperature after pre-launch pressurization, K	310
The mass flow rate of gas for pre-launch pressurization, $kg \cdot s^{-1}$	0.18
Initial gas volume in the tank, l	80
Diameter of the tank, mm	750
The volume flow rate of propellant, s^{-1}	8.36
Propellant temperature, K	293

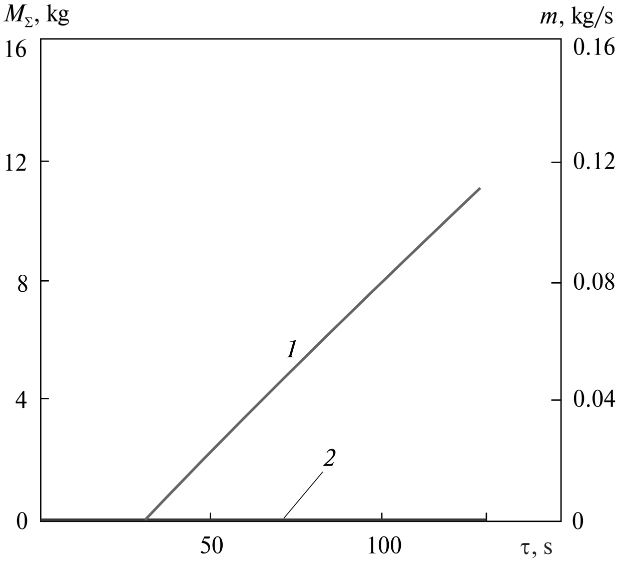

Fig. 6. Pressurization gas losses due to condensation and increase of steam mass in the tank: *1* — mass of the pressurization gas, *2* — loss of pressurization gas due to condensation

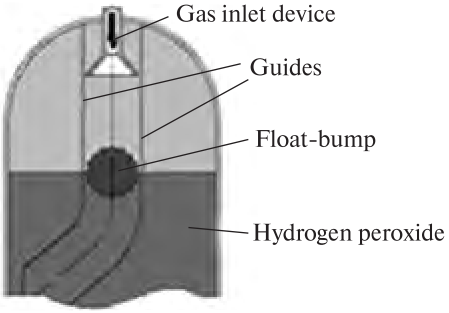

Fig. 7. Gas inlet device with float-bump

Mathematical modeling shows that hot pre-launch pressurization does not solve the issue of pressurization gas loss due to condensation. It is explained by the condensation of the steam on the fuel surface (the propellant level is close to the pressurization gas inlet). This circumstance gives the idea of hybrid pressurization system development when the tank will be pressurized by a solid-fuel gas-generator at the beginning of propulsion system operation. It will allow choosing the operational time of gas-generator, the mass flow rate, and combustion temperature, which would sustain tank pressure until the propellant level is far from the pressurization gas inlet.

Mathematical simulation of hybrid pressurization system has been conducted. The gas-generator with sodium azide fuel will sustain pressure during the first 30 seconds of operation. It will allow us to achieve the average temperature in the tank, which would exceed the temperature of saturated water vapor. In this case, the process of volume steam condensation will be eliminated. In Figure 5, data of the pressurization process with no condensation of steam is presented.

It must be admitted that sustaining pressure within the required range using a solid-fuel gas-generator with a constant mass flow rate is rather difficult. In order to increase the accuracy of pressure sustaining, two gas-generators are applied. The first one is with constant consumption of fuel, which is equal to 0.35 kg/s, and the second one is with a profiled charge, the flow rate of which varies smoothly from 0.3 to 0.23 kg/s.

In Figure 5, diagrams of the tank pressure, the average temperature, and the mass of pressurization gas are presented. In Figure 6, diagrams of steam mass in the tank and losses due to condensation are shown. Input data for mathematical simulation are presented in Table 3.

The analysis of the mathematical modeling shows that the issue of steam condensation may be successfully resolved. To do this, the tank pressure during the first 20—30 seconds of propulsion system operation should be sustained by the hot dry nitrogen. After that, the main pressurization system with decomposed hydrogen peroxide may start its operation. To prevent the condensation of steam on the cold propellant surface, the special inlet device with descending float-bump may be applied [2]. An example of such a device is presented in Figure 7.

CONCLUSION

Thermodynamic relation was found, which in relation to the pressurization process allows one to exclude the condensation of the vapor in the free volume of the tank. Both ways of heat energy supply, which allow keeping this thermodynamic relation fulfilled, have been proven.

The most complicated pressurization case of the pressure-fed propulsion system has been considered. Analysis of the conducted mathematical modeling allows us to make a conclusion that the issue of the tank with hydrogen peroxide pressurization by its decomposition products may be resolved in a way when no condensation process takes place.

It may be achieved by means of additional support of the pressurization system which would sustain the pressure with hot dry nitrogen (the combustion product of sodium azide fuel) during the first 20—30 seconds of propulsion system operation. The suggested system may be improved by means of hot pre-launch pressurization.

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ШЛЯХИ ВИРІШЕННЯ ПРОБЛЕМИ НАДДУВАННЯ БАКІВ З ПЕРЕКИСОМ ВОДНЮ ПРОДУКТАМИ ЙОГО РОЗКЛАДУ

Мета роботи — знаходження та обґрунтування способу використання високотемпературного робочого тіла (~1100 K) з великим вмістом водяної пари (до 70 %) без втрат робочого тіла наддування для паливного бака великої довжини з висококонцентрованим перекисом водню.

Методика. Для досліджень використовувався метод математичного моделювання параметрів системи наддування з використанням теорії масопереносу і термодинаміки тіл змінної маси.

Результати. Проведені дослідження дозволили знайти і обґрунтувати спосіб наддування баку з використанням додаткових джерел тепла і виробити рекомендації щодо часу їхнього використання.

Наукова новизна. Визначено основні процеси, які заважають впровадженню високоефективного способу наддування бака з висококонцентрованим перекисом водню продуктами її розкладу. У першу чергу це об'ємна конденсація водяної пари в баку після виконання термодинамічної роботи витискання палива і теплообмінних процесів з граничними поверхнями. Вперше розрахунково-теоретичним шляхом доведено доцільність і раціональність використання додаткових джерел тепла на прикладі високотемпературних продуктів згоряння твердопаливного газогенератора на основі азиду натрію. Обґрунтовано час використання цього тепла — перші 30 с роботи двигунної установки в умовах роботи першого ступеня ракети-носія.

Практичне значення. Базову методику розрахунку параметрів систем наддування доповнено термодинамічним співвідношенням, яке дозволяє розрахувати величину об'ємної конденсації і вжити відповідних заходів для її усунення. Отримані результати дозволяють спроєктувати систему наддування бака великої довжини з висококонцентрованим перекисом водню продуктами її розкладання.

Ключові слова: висококонцентрований перекис водню, система наддування, конденсація парів, продукти розкладання, високотемпературне робоче тіло, тиск насичених парів.