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**K. M. SUKHYI**<sup>1</sup>, Rector, Doctor of Technical Sciences, Prof.,  
Corresponding Member of the National Academy of Sciences of Ukraine  
ORCID 0000-0002-4585-8268  
E-mail: ksukhyi@gmail.com

**S. M. VOIT**<sup>2</sup>, General Director, Doctor of Economics  
E-mail: umz@yuzhmash.com

**Yu. O. MITIKOV**<sup>1</sup>, Deputy Director of the Educational and Scientific Institute “Aerospace Institute”,  
Doctor of Technical Sciences, Prof.  
ORCID 0000-0002-4787-603X  
E-mail: mitikov2017@gmail.com

**S. V. SPIRKIN**<sup>2</sup>, Chief Designer  
E-mail sergiyspirkin@gmail.com

**I. V. SUKHA**<sup>1</sup>, Director of the Educational and Scientific Institute “Aerospace Institute”,  
Candidate of Technical Sciences, Associate Prof.  
ORCID 0000-0002-5579-2047  
E-mail: irinasuha3@gmail.com

<sup>1</sup> Ukrainian State University of Science and Technologies  
2, Lazariana Str., Dnipro, 49010 Ukraine

<sup>2</sup> State Enterprise “Production Association Yuzhny Machine-Building Plant named after O. M. Makarov”  
1, Kryvorizka Str., Dnipro, 49008 Ukraine

## **ASSESSMENT OF THE EFFICIENCY OF HOT HELIUM TANK PRESSURIZATION SYSTEMS FOR OXYGEN-PROPELLED ROCKET ENGINES**

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*For the first time, a study of the design has been conducted, and a detailed weight summary of the hot helium pressurization system for an oxidizer tank of the first stage of a launch vehicle (LV) has been presented; the propulsion system of this LV uses boiling oxygen — RG-1 as propellants. The oxidizing generator gas was considered as the heat exchanger heat carrier. The weight of this system was also evaluated for an alternative common heat carrier — reduced generator gas. A good correlation was shown between the obtained results and known data from other pressurization systems.*

*The efficiency of hot helium pressurization systems is demonstrated in the case of multiple reuses of the first stage of an LV. It is also reasonable to use it for the dual activation of the liquid rocket engine (LRE) of the second stage of an LV. In these cases, arising issues are solved using well-established, proven solutions. However, an analysis of technical literature shows that alternative solutions have not been thoroughly studied. In other cases, considering the high cost, structural complexity, actual low reliability, and lack of weight advantages, the use of hot helium pressurization systems is hardly justified. This primarily concerns LREs with afterburning of generator gas, where oxidizing gas is used as the coolant in the heat exchanger.*

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*It is also noted that it is necessary to provide helium reserves on board the LV and to introduce a gas pressure regulation system in the tank. This is due to the large variations in pressurization path resistance and helium temperatures after the heat exchanger at the design stage. The result is an increase in the calculated gas pressure in the tank, leading to an additional weight increase of 5–8 %. It is shown that helium reserves can be easily adjusted based on the results of the first flight tests, whereas reducing the thickness of the tank walls and the diameter of the hot pressurization pipelines with thermal compensators is extremely problematic.*

**Keywords:** *pressurization systems, propulsion systems, hot helium, boiling oxygen, system weight, efficiency, coolant.*

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## INTRODUCTION

Currently, a wide variety of pressurization systems (PS) for fuel tanks of intercontinental ballistic missiles (ICBMs) and launch vehicle (LV) propulsion systems (PrS) are known. Over the 85-year history of rocketry, various types of PS have been used, including steam (oxygen, nitrogen tetroxide), gas cylinder (nitrogen, air, helium), velocity head, liquid and solid propellant generators, decomposition of one of the components (hydrogen peroxide, UDMH), chemical, piston, polytropic PS, and others [3, 14]. An equally broad range of possibilities has been realized concerning the temperature of the working pressurization fluid at the tank inlet (from 70 K to 1300 K). This diversity is primarily related to ICBMs. Weight efficiency was one of the top priorities in design. During the Cold War, limitations were imposed by intergovernmental treaties on the number and launch mass of ICBMs, as well as modifications of launch silos.

As ICBMs evolved, so did their PS. They became increasingly reliable, lighter, structurally simpler, scientifically advanced, and technologically sophisticated, with minimal or no maintenance at launch. The pinnacle of this model range is the R-18M, better known as “Satan”. It was designed by specialists of the “Pivdenne” Design Bureau and manufactured at SE PA “Southern Machine-Building Plant” (Dnipro, Ukraine). It contains everything necessary for launch and flight, remaining operational for 25 years. Fig. 1 presents a conventional classification of known PS for both ICBMs and LV.

Liquid oxygen has found the widest application as an oxidizer for LV PrS. It is used both in its boiling and subcooled states. Hydrogen peroxide, a high-boiling oxidizer, is also gaining popularity [1]. However, its advantages — simplifying the PS structure, reducing maintenance, and significantly lowering weight — are not yet widely acknowledged in academic textbooks, resulting in its limited adoption. An

exception is engineers and scientists at Skyrora Ventures Limited (Ukraine, Scotland).

For pressurizing LV PS fuel tanks with liquid oxygen (hydrocarbon fuel RG-1), helium has become the most commonly used working fluid [16]. Over many years, no significant advancements in tank pressurization have been observed. This applies to both pre-launch and in-flight pressurization systems. Examples include PS of different purposes and different times — Atlas-D, Saturn-V, Zenit, KSLV-2, Falcon-9, Electron, Alpha, first stages of Energia, Antares, Cyclone-4M, and others. Structurally, they are all quite similar. Previously, steam PS were widely used, such as in the first stage of Saturn-V, the second stage of Kosmos, and two stages of the R-9A ICBM. Notably, ICBMs worldwide managed without helium pressurization.

Helium PS has been used in LV systems for over seventy years. Considerable experience has been accumulated in their design, construction, and operation, revealing both positive and negative aspects. In practice, their positive and negative qualities have been found out. Today, there should be no more unclear issues. Is it so in reality? What exactly constitutes the efficiency of helium systems, and in which cases are they justified? Do they simplify and clarify design, production, and operation, enhance reliability, or provide a better weight summary? In which cases is the use of helium PS justified? This paper attempts a conceptual review, not at the level of reliability statistics, which can be misleading, but based on real-world data and statistical evidence.

**Research Objective:** to attempt a systematic assessment of the efficiency components of helium PS for oxygen tanks, highlighting key advantages and disadvantages, presenting a detailed weight summary of a hot helium PS for an oxygen tank using a specific example, comparing the obtained results with known data, and evaluating their accuracy.

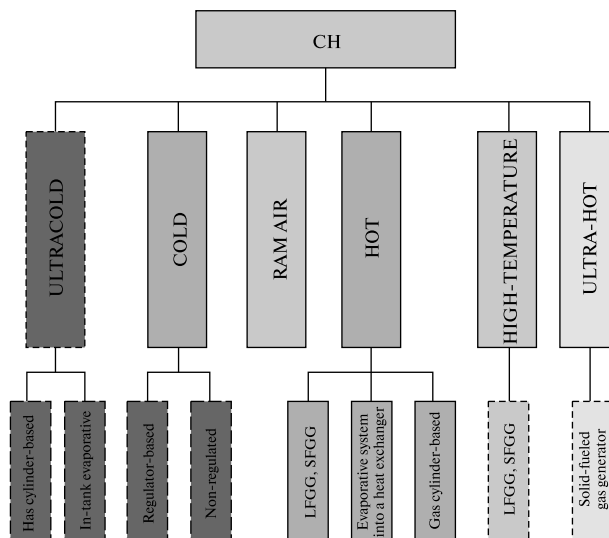
**Research Methods:** retrospective analysis, conceptual approach, comparative analysis.

## ANALYSIS OF PUBLICATIONS AND RESEARCH RESULTS

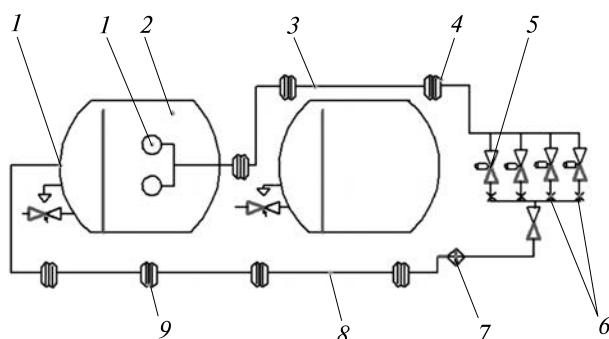
As is known, helium PS for LRE propellant tanks are among the most expensive, complex, and scientifically intensive components of the LV after the LRE itself [5, 23]. It would seem that the challenges of improving these systems should receive increased attention. However, this is far from the case. An analysis of scientific and technical literature reveals an almost complete absence of studies in this area. The only school that continues to work intensively is the Dni-pro PS school [8, 12, 13, 15], founded by Professor N. M. Belyaev in the early 60s of the last century.

We have been unable to find any scientific or technical literature that compares the most critical characteristics of hot helium PS with their steam or generator-based counterparts. Among the most important characteristics, we would include the complexity of the launch due to the presence of helium on board the LV, actual reliability, and design challenges. For example, the system for preparing and supplying cold helium at the Baikonur Cosmodrome for charging the PS cylinders of the Zenit LV has the following composition. It includes 1266 high-pressure cylinders (37.5–40.5 MPa), with a capacity of 500 liters each, more than 3,000 pneumatic automation units, and pipeline lengths totaling tens of kilometers [2]. The equipment is located deep underground in thermostabilized facilities. It must be regularly maintained and replaced when necessary per regulations, and the high-pressure vessels must also be inspected by state supervisory authorities [18]. It is evident that the liquid generator, solid-propellant, and polytropic PS do not require such a massive amount of expensive hardware.

Regarding the reliability of helium systems, widespread global use and long history of operation of helium pneumohydraulic systems may create the impression of their increased reliability. However, this is far from the case. Over the past twelve years, according to our calculations, there have been at least seven failures of helium systems [18]. Some of these failures have had significant consequences — explosions at launch, in-flight failures, and issues during astronaut transportation to the ISS. This list includes the Falcon-9 LV. All of these incidents occurred despite the full cycle of ground testing. It is surprising that while



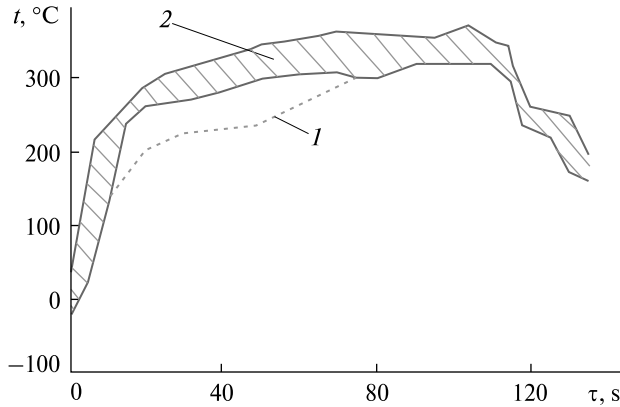
**Figure 1.** Classification of PS by working fluid temperature. Legend: LGG — liquid gas generator, SFGG — solid fuel gas generator, HE — heat exchanger



**Figure 2.** Fundamental diagram of a hot gas-cylinder PS for an oxidizer tank: 1 — helium cylinders, 2 — liquid oxygen tank, 3, 8 — pipelines, 4, 9 — thermal and technological compensators, 5 — automation units (EPV), 6 — metering washer, 7 — heat exchanger (HE), 10 — gas inlet

complex assemblies, such as LREs in Falcon-9, are duplicated, simple elements of helium PS that led to failures are not. It is also noteworthy that while LREs are an order of magnitude more complex than PS, they do not exhibit such an alarming failure rate.

Regarding the mathematical modeling of PS parameters to ensure accurate gas pressure maintenance in an oxygen tank during flight at the design stage, let us first consider the fundamental schematic of a regulated hot helium PS [17] using the example of the oxidizer tank of the first stage of the Zenit LV



**Figure 3.** Helium temperature after the heat exchanger (Fig. 2): 1 — temperature after the first test (8 cylinders), shaded area 2 — helium temperature range after five launches (6 cylinders)

(Fig. 2). As shown in the diagram, the system consists of high-pressure helium cylinders (1) (in our case, six with an internal volume of 132L each), located inside the liquid oxygen tank (2). The cylinders are connected via pipelines (3) with thermal compensators (4), automation units (5), and metering washers (6) to the engine’s heat exchanger (7), which is placed in the tail section. The heated helium then flows through the pipeline (8) with thermal and technological compensators (9) and enters the upper part of the oxidizer tank (2) through the gas inlet (10) for pressurization.

We assume that the required hot helium flow rate for tank pressurization to maintain the necessary pressure is known. Let us consider the most commonly used equation for calculating the gas flow rate through an orifice with an area  $f$  using gas dynamic functions:

$$\dot{m}_i = \frac{fm\mu q(\lambda)p}{\sqrt{zRT[1+m^2q^2(\lambda)\zeta_\Sigma]}}$$

where  $m$  is the gas dynamic function that accounts for the molecular weight of the gas in the cylinder (for helium, 2.28),  $\mu$  is the flow rate coefficient,  $q(\lambda)$  is the gas dynamic function,  $p$  is the pressurization gas pressure in the cylinder,  $z$  is the compressibility factor of the gas in the cylinder,  $R$  is the gas constant of the pressurization gas.

At the design stage, several parameters in the equation are not yet precisely defined. For example, the helium temperature after the heat exchanger (HE) in nominal mode is specified in the technical requirements with a deviation of up to 13 % ( $540 \pm 70$  K) [9]. During flight, it becomes clear only at the stage of flight tests (Fig. 3).

The helium path resistance in the HE is known at this stage only from the technical requirements —  $\Delta P \leq 15$  bar at a reference helium flow rate with a temperature of 90 K [9]. Based on the results of six launches, the helium pressure drop in the HE is presented in Table 1. Analysis of the obtained results indicates compliance with the technical requirements of the HE. At the same time, there is a significant variation in the pressure drop in the HE (up to ~5 times from launch to launch based on six test results).

The resistance of the entire pressurization path also has approximately the same variation. This occurs because the final diameters of the pipelines, the designs of the thermal compensators, the automation units, the actual lengths of the pipelines, the number of their bends, and the welds are not yet precisely known. The solution to this situation at the design stage is well known. It is necessary to account for gas reserves and introduce a pressure regulation system in the oxidizer tank. For example, for the PS of the oxidizer tank of the first stage of the Zenit LV, a helium reserve of about 20 % was adopted [19]. Ultimately, this increased the calculated strength pressure of the tank. For example, for the oxidizer tank, this equated to an additional weight of ~400 kg. Based on the

**Table 1.** Heat exchanger parameters based on test results

LV Launch No.	According to TR	1	2	3	4	5	6
Helium pressure drop in the HE, bar	$\leq 15$	5	10	3	5	2	2
Helium temperature after the HE, K	573	600	618	615	643	618	621

results of the first flight tests, the number of helium cylinders can be reasonably reduced without issue. This was promptly done on the Zenit LV. However, reducing the tank weight and decreasing the diameter of the hot pressurization pipeline with compensators is not so simple. This requires an expensive cycle of repeated tests with refinement of the equipment.

It is worth noting several studies, such as [20], that attempt to calculate the required gas pressure in the oxygen tank during flight, considering heat and mass transfer processes and gas movement in the free volume of the tank with an accuracy of 3–5 %. As is known, the current accuracy of maintaining the required thrust level of an LRE (component consumption from tanks) is  $\pm 3$  %. Given the above variations in some factors affecting gas pressure in the tank, such studies appear somewhat naïve. Once all precise initial data are available (following a series of flight tests), such calculations are no longer necessary.

In the studies we found on the mathematical modeling of steam and generator PS for oxygen tanks [11, 22], it is a priori stated that they are lighter and simpler than hot helium PS. Regarding simplicity, especially of solid-propellant PS, this assumption raises no doubts. However, no corresponding calculations or arguments supporting these conclusions are provided.

We found only one study on cold helium PS [24], which briefly outlines the weight efficiency loss compared to liquid and solid-propellant generator PS. Cold PS are systems that introduce gas into the tank at approximately the same temperature as the propellant component [3]. It is shown that in cylinders at normal temperature, for every 1 kg of helium used, there are 28 kg of “cylinder construction”. What exactly constitutes the “cylinder construction” is not explained. For liquid generator and solid-propellant PS, no more than 1 kg of construction corresponds to 1 kg of pressurization working fluid. Generator PS, especially solid-propellant ones, are structurally much simpler than helium gas-cylinder systems. This is indisputable. For solid-propellant PS (e.g., using pure nitrogen based on sodium azide), the advantage over helium PS increases when used in a PrS with nine autonomous LREs. Adjusting for differences in the efficiency of pressurization working fluids, this ratio should be corrected to  $\sim 7$  kg of construction.

Unfortunately, the study does not specify which helium PS schemes were considered (reducer-based or metering washer-based). It somewhat diminishes the value of the results obtained for engineering practice.

Some studies [6] cite helium’s low weight as a strong argument for the efficiency of helium PS. This is indeed true and indisputable.

## RESEARCH RESULTS

Now, let us move on to the primary objective of this work. We will examine the specific weight summary of a hot helium-regulated PS (with sequentially activated EPV 6, Fig. 2) for an oxygen tank in the first stage of the Zenit LV (Fig. 2). We specify the initial data. An oxidizing generator gas, after the turbine, with a nominal turbine temperature of  $\sim 650$  K, was used as the heat exchanger coolant. The helium temperature at the HE outlet in nominal mode is  $540 \pm 70$  K, as regulated by technical requirements. Over the LRE operation time, it is refined only at the stage of flight tests (as shown in Fig. 3). It is particularly noteworthy that one of the world’s best titanium alloys (VT6S) was used in the PS structure for the helium cylinders (six units) with an internal volume of 132 L and a weight of  $\sim 45$  kg. It strengthens almost twice at cryogenic temperatures. Manufacturer — SE PA “Southern Machine-Building Plant after O. M. Makarov”.

The weight analysis is done at the 110th second of the flight. This is due to the fact that beyond this time in the active flight phase, an additional PS operates in the oxidizer tank (in this case, a cold helium PS), which sequentially ensures non-cavitation work of the intake device and LRE pumps by raising the gas pressure in the tank by  $\sim 0.3$  bar. By this time, the primary hot PS cylinders are almost empty. All the weight summary components of the analysed PS are presented in Table 2. The analysis of the obtained results shows the following. The specific weight efficiency of the hot helium propellant tank pressurization system (PTPS) using oxygen and utilizing regenerative generator gas as a heat carrier in the thermal oxidizer is significantly higher than when using reducing generator gas. Generator-fed liquid and solid propellant PTPSs demonstrate good weight characteristics and considerably simpler designs. However, in cases where the engine is ignited twice

Table 2. The weight of the components of the hot helium PS at the 110th second of the flight with an oxidizing heat carrier

No.	PS weight components (reference to Fig. 2), kg	Component weight
1	Pressurization working fluid in the tank and pressurization cylinders at the 110th second of the flight: helium oxygen	80.5 ± 4 250 ± 60
2	Structural elements inside the tank (item 1, Fig. 2)	290
3	Gas inlet (item 10)	36
4	Structural elements outside the tank (items 3.4, 5.6, 8.9)	120
5	Cylinder filling system (not shown)	9
6	Tank reinforcement for pressurization paths (not shown)	30
7	Heat exchanger of the PrS	75
8	Residual helium in cylinders	30
9	External volume of cylinders, L Additional weight of the tank shell due to the cylinders	960 ~25
10	Total weight of the PS structure	615

and the first stage is reused multiple times, their application is hardly advisable.

It should also be noted that when using a reducing generator gas in the HE (LRE Merlin-1D), the weight summary of the helium PS will be noticeably better. We will attempt to estimate it further. However, it should be noted that in this case, the HE coolant path becomes contaminated with soot. This creates additional challenges for multiple reuses of the stage.

During 110 seconds of flight, ~51 kg of helium is consumed for pressurization from six cylinders. Thus, for every 1 kg of helium used for pressurization, a PS utilizing oxidizing gas after the turbine as the HE coolant accounts for ~12 kg of structure. Using the dependence of pressurization gas requirements on its temperature at the tank inlet for the first stage of an LV with oxygen [4], these requirements for a reducing generator gas as the HE coolant can be estimated at ~35 kg. In this case, the ratio of structural weight to helium for pressurization will be ~8 kg of structure per 1 kg of helium.

The obtained results and data from the study [24], recalculated considering gas constants, are presented in summary Table 3.

Regarding the advantages of hot helium PS, let us consider two of the most advanced and best LVs in their class that use these systems — Falcon 9 and Zenit. The use of these PS in Falcon 9 is justified

for two reasons. The first one is the second ignition of the main LRE in the second stage. During the pause between ignitions, the motion of liquid oxygen in the second-stage tank leads to the condensation of oxygen vapours in its free volume. With a steam PS, most of the introduced vapour would condense. The gas pressure in the tank would drop to the saturated vapour pressure at the average mass temperature of the liquid oxygen. With a helium PS, such a sharp drop in gas pressure does not occur. It happens due to a decrease in the gas temperature in the tank. Helium also plays a crucial role in reaching the required tank pressure for the second LRE ignition. A higher initial gas pressure level in the tank significantly simplifies subsequent pressure maintenance. If helium is available at the launch for the second stage, it is also practical to use it for the first stage. A similar situation occurs with the return section for the reusable first stage of an LV. The operation of multiple LREs during descent is easiest to support with helium. However, alternative solutions also exist, such as [7, 10, 21]. Another important factor in the development of Falcon 9 is that before the design phase I. Musk had resolved the issue of renting existing launch complexes where the entire helium infrastructure was already in place.

Regarding the Zenit LV, a decree by the Soviet Union's government required the first stage of Zenit

**Table 3. Structural weight of the considered PS per 1 kg of helium for tank pressurization**

No.	PS tank type	kg PS/kg He
1	Cold	28
2	Generator (liquid, solid-fuel) [19]	7
3	Hot with an oxidizing HE coolant	12
4	Hot PS with a reducing HE coolant, assessment	~8

LV to be maximally compatible with the first stage of the Energia LV. This stage was designed for up to ten reuses. Therefore, the pressurization working fluids needed to be clean. What is most important, in the event of an LRE failure in any of the blocks (four in the Energia LV), an emergency oxidizer dump is performed. For this reason, the liquid generator and evaporative PS, which rely on the resources of an operating LRE, were turned off for oxidizer expulsion. This led to the adoption of helium PS in the Zenit LV.

### CONCLUSIONS

For the first time, a detailed weight summary of a hot helium PS for an oxidizer tank has been conducted; its PrS uses oxygen — RG-1 as propellants. The oxidizing generator gas was considered as the HE coolant. The weight of this system was also evaluated for an alternative common coolant, reducing generator gas. A good correlation was shown between the obtained results and known data from other PS.

Approximately equal weight efficiency has been demonstrated for the hot helium pressurization sys-

tem (PTPS) with a reducing heat carrier and for the generator-fed liquid and solid propellant PTPS using oxygen.

The hot helium PTPS with an oxidizing heat carrier is significantly heavier under otherwise equal conditions.

Unless there are specific reasons for its use, such a system is hardly advisable.

The efficiency of hot helium PS is evident in the case of multiple reuses of the first stage of an LV. It is also reasonable to use it for the dual activation of the LRE of the second stage of an LV. In these cases, arising issues are solved using well-established, proven solutions. However, an analysis of technical literature shows that alternative solutions have not been deeply studied. In other cases, considering the high cost, structural complexity, actual low reliability, and lack of weight advantages, the use of hot helium PS is hardly justified. This primarily concerns LREs with afterburning of generator gas, where oxidizing gas is used as the coolant in the HE.

It is also necessary to note the need to provide helium reserves on board the LV and to introduce a gas pressure regulation system in the tank. This is due to the large variations in pressurization path resistance and helium temperatures after the HE at the design stage. The result is an increase in the calculated gas pressure in the tank, leading to an additional weight increase of 5—8 %. Helium reserves can be easily refined after the first flight tests, but reducing the tank wall thickness or the diameter of hot pressurization lines with thermal compensators is extremely challenging.

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К. М. Сухий<sup>1</sup>, ректор, д-р техн. наук, проф., член-кор. НАН України

E-mail: ksukhyu@gmail.com

С. М. Войт<sup>2</sup>, ген. дир., д-р екон. наук

E-mail: umz@yuzhmash.com

Ю. О. Мітків<sup>1</sup>, д-р техн. наук, проф.

E-mail: mitikov2017@gmail.com

С. В. Сніркін<sup>2</sup>, голов, конструктор

E-mail: sergiyspirkin@gmail.com

І. В. Суха<sup>1</sup>, дир. нав.-наук. ін-ту «Аерокосмічний інститут», канд. техн. наук, доцент

E-mail: irinasuha3@gmail.com

<sup>1</sup>Український державний університет науки і технологій

вул. Лазаряна 2, Дніпро, Україна, 49010

<sup>2</sup>ДП «ВО «Південний машинобудівний завод ім. О. М. Макарова»

вул. Криворізька 1, Дніпро, Україна, 49008

### ОЦІНКА ЕФЕКТИВНОСТІ ГАРЯЧИХ ГЕЛІЄВИХ СИСТЕМ НАДДУВАННЯ БАКІВ РУШІЙНИХ УСТАНОВОК З КИСНЕМ

Вперше проведено дослідження конструкції та наведено детальне вагове зведення гарячої гелієвої системи наддування бака окиснювача першого ступеня РН, рушійна установка якого використовує компоненти палива киплячий кисень — РГ-1. Як теплоносій теплообмінника розглядався окислювальний генераторний газ. Наведено оцінку ваги цієї системи для іншого поширеного теплоносія — відновного генераторного газу. Показано хорошу збіжність отриманих результатів з показниками інших відомих систем наддуву.

Показано ефективність гарячих гелієвих систем наддування при багаторазовому використанні першого ступеня РН. Також є сенс застосовувати їх при дворазовому включенні РРД другого ступеня РН. У цих випадках проблеми, що виникають, вирішуються відомими перевіреними способами. Водночас аналіз технічної літератури показує, що інші рішення глибоко й не опрацьовувалися. У інших випадках, враховуючи дорожнечу, конструктивну складність, фактичну низьку надійність, відсутність переваг по масі, використання гарячих гелієвих СН навряд чи доцільне. У першу чергу це стосується РРД з допалюванням генераторного газу, в яких у теплообміннику використовується як теплоносій окислювальний газ.

Також відзначено необхідність закладати запаси гелію на борту РН і вводити систему регулювання тиску газу в баку. Це пояснюється великими розкидами опору трактів наддування і температур гелію за теплообмінником на етапі проектування. Підсумок — підвищення розрахункового тиску газу в баку, що призводить до збільшення його маси на 5—8 %. Показано, що запаси гелію легко уточнюються за підсумками перших льотних випробувань, а зменшити товщину стінок бака чи діаметр гарячих магістралей наддування з температурними компенсаторами вкрай проблематично.

**Ключові слова:** системи наддування, рушійна установка, гарячий гелій, киплячий кисень, маса системи, ефективність, теплоносій.