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Use of the Low-Potential Heat for Heating Helium in Rocket-Carrier Tank Pressurisation Systems

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Abstract. The energy efficiency of new technical developments is a critical issue. It should be noted that today the focus in this issue has seen a major shift to the maximum use of renewable energy sources. The purpose of this research is to reduce the weight of helium heat exchangers of the fuel tank pressurisation systems in modern rocket propulsion systems that use fuel components like liquid oxygen and kerosene-type fuel. This is the first time that the question has been raised about the possibility and advisability of increasing the temperature of helium at the heat exchanger inlet without the use of additional resources. The paper addresses the use of the waste ("low-potential") heat and "industrial wastes" present in propulsion systems. Basic laws of complex heat exchange and the retrospective review of applicable heat exchanger structures are applied as a research methodology. Two sources of low-potential heat are identified that have been previously used in the rocket engine building in an inconsistent and piecemeal manner to obtain and heat the pressurisation working fluid. These are the rammed-air pressurisation during the motion of the rocket carrier in the atmosphere, and the tank pressurisation as a result of boiling of the top layer of oxidiser which is on the saturation line. This is the first time that the advisability has been substantiated of increasing the temperature of the working fluid at the heat exchanger inlet, first of all due to the use of the low-potential heat. This is also the first time that unemployed sources of low-potential heat and "industrial wastes" are found in modern deep throttling propulsion systems. These are the high-boiling-point fuel in the tank, behind the high-pressure pump, at the exit of the combustion chamber cooling duct, and also the fuel tank structures, and the engine plume. A possibility is proved, and an advisability demonstrated of their implementation to increase the efficiency of pressurisation system heat exchangers. This is the first time that the methodology of combustion chamber cooling analysis has been proposed to be adopted for the heating of heat exchanger by the engine plume. This is the first time that a classification of waste heat sources has been developed which can be used to increase the pressurisation working fluid temperature. The identified reserves help to increase the efficiency of the helium heat exchangers of the tank pressurisation systems in the propulsion systems

Keywords: rocket engines, high-boiling-point fuel, heat exchanger inlet temperature, sources, low-potential heat

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INTRODUCTION

Heat exchangers have been long and widely used in the technological processes in the mining, oil refining, automotive, aeronautical, petrochemical, chemical, nuclear, aerospace industries, in the agricultural sector, energy industry, public services. Suffice it to list their special names – steam generators, furnaces, cooling towers, water heater, evaporators, condensers, etc. As we can see, field of their application is very large. The rocket engine building is not an exclusion. The world's first ballistic rocket, the V-2, already had a heat exchanger for heating the pressurisation working fluid prior to feeding to the liquid oxygen tank.

In the context of the world economy globalisation, intensive fighting against climate change, greenhouse gas emission, the energy efficiency of new technical developments is a critical issue. It should be noted that today the focus in this issue has seen a major shift to the maximum use of renewable energy sources [1]. Therefore the urgency of the research aimed to reduce the energy consumption, expand the use of low-potential heat of the environment, is not in doubt.

Present-day rocket propulsion systems are widely using the liquid oxygen (LOX) and kerosene-type fuel (RP-1). Suffice it to list well known RC such as Zenith, Antares, Atlas-V, Falcon-9, Electron, Alfa, Angara, Cyclon-4M, Soyuz-5. The tank pressurisation systems with these components use hot helium as a pressurisation work fluid. Main reason why these systems are widely used, is that their design is simple. However, modern helium pneumatic systems are second most expensive parts of RC after liquid-propellant rocket engine (LPRE) [2]. That is why, it makes sense to foremost explore ways to improve the most expensive parts of rocket complex with most common fuel components.

Let us focus on the heat exchanger in the most common configuration of the hot helium system of oxygen tank pressurisation (Fig. 1). This will be useful for us in further researches.

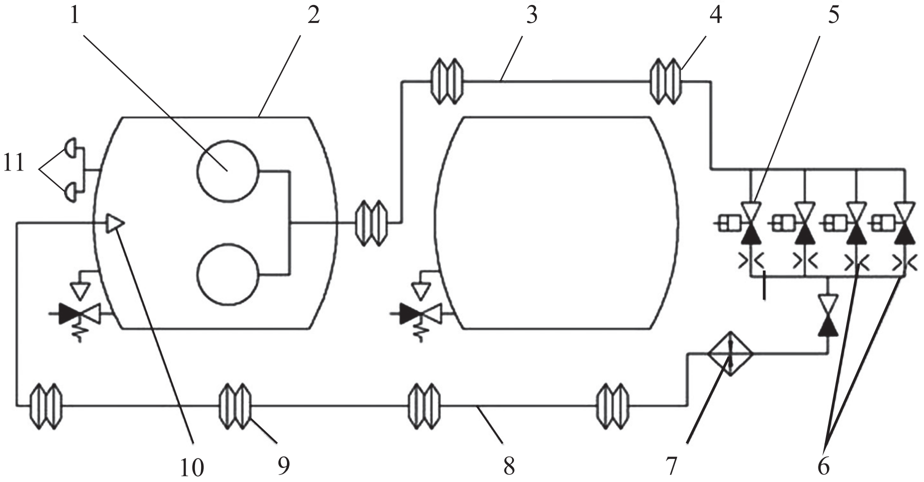

***Figure 1**. Schematic of hot gas bottle system of the oxidiser tank pressurisation:*
1 – helium bottles; 2 – liquid oxygen tank; 3, 8 – pipelines; 4, 9 – temperature compensators; 5 – elements of automatic control; 6 – orifices; 7 – heat exchanger ; 10 – tank pressurisation gas supply device; 11 – tank gas pressure switch unit

As we can see in the schematic above, the system contains helium high-pressure bottles 1 that are installed in LOX tank 2. This is a common configuration. By imparting cryogenic temperature to helium, the configuration allows to reduce almost two times the number of helium bottles. The bottles are connected through pipelines 3 with temperature compensators 4 by means of automatic control elements 5 to flow-metering orifices 6 and heat exchanger 7 of the engine that is placed in the tail compartment. The heat exchanger uses the coolant from the engine turbine, in this case, the oxidising generator gas. Hot helium is then fed, loosing the temperature, by pipeline 8 with temperature compensators 9 to the upper part of oxidiser tank 2. The gas passes into the free tank volume through a special gas supply device 10.

The rocket engine building may appear to be far from the use of renewable source of energy. However, under conditions of increased competition in the market of launch services [3], it is a time to deal with these possible sources. The purpose of the research is to:

– reduce the weight of heat exchangers of the fuel tank pressurisation systems in modern rocket propulsion systems in the ways that are unconventional for this technology;

– reduce the use of hydrocarbon fuel combustion products as a coolant in heat exchangers.

This is the first time that the issue has been addressed of finding and substantiating reasonable ways to employ the waste low-potential heat and the "industrial wastes" that are present in the rocket carrier (RC), foremost for increasing the heat exchanger inlet temperature of helium.

The objectives of the research are to:

– identify drawbacks of applicable heat exchangers of the fuel tank pressurisation systems in modern rocket propulsion systems on the basis of critical retrospective review of their structures, configurations of modern rocket engines, and achievements of heat engineering;

– audit possible unemployed heat energy sources on board of RC that designers have previously missed;

– substantiate most promised and technologically simple ways to use low potential heat for the improvement of heat exchanger characteristics, using the example of rocket propulsion systems;

– classify the sources of low potential heat and "industrial wastes" identified on board of and near to RC.

FEATURES OF ROCKET ENGINE HEAT EXCHANGERS

Rocket engine heat exchangers have a number of specific features that distinguish them significantly from their counterparts from other branches of technology. These features arise from peculiarities of their operation. The operation time of rocket heat exchangers is very short, just 120÷600 s. They are expendable, as a rule. The are manufactured 2-3 times a year, very rarely, 4-5 times. Liquid oxygen kerosene engines use oxidative or reductive generator gas from the turbine as a coolant. Such oxidative gas has a temperature of 620÷640 K, a pressure of 26÷28 MPa. The reductive generator gas from the turbine has a temperature of 820÷950 K, pressure is 1÷28 MPa, depending on the configuration of the engine.

Modern rocket engines are deeply and often throttled during the flight. This is a demand of time. During the throttling, the coolant consumption and temperature goes down significantly (for the configuration with afterburning of oxidative gas). A pronounced transient mode of operation of the heat exchanger is implemented. It should be understood that almost all officially accepted most accurate heat exchanger design methods are established for steady heat exchange conditions.

The first heat exchangers in the engines were of shell-and-tube type. They functioned with a low pressure of the coolant. A notable example is the heat exchanger [4] of the RD-107 engine of the Soyuz-2 rocket carrier stage 1 (Fig. 2).

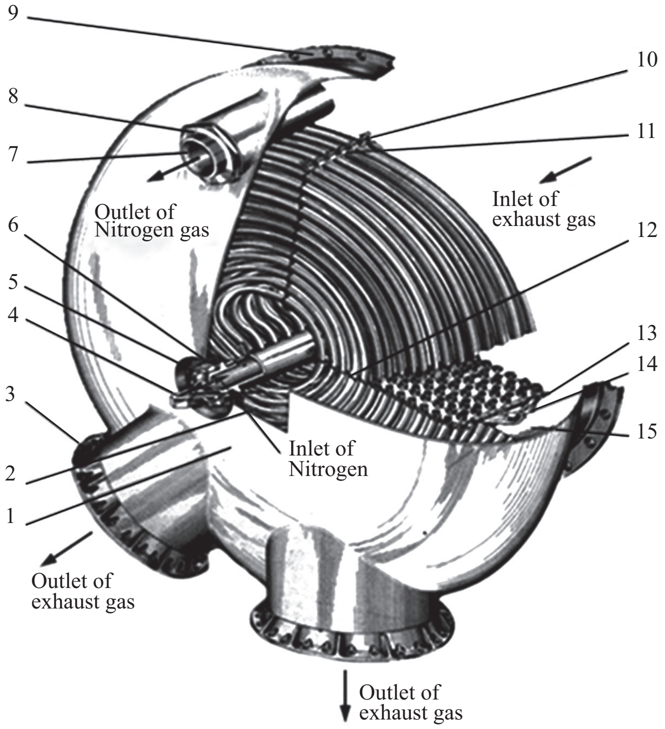

***Figure 2**. Section view of the RD-107 shell-and-tube heat exchanger:*
1 – casing; 2 – coil manifold; 3, 9 – flanges of exhaust gas outlet and Nitrogen gas outlet respectively; 4 – liquid nitrogen inlet connection; 5, 8 – nuts; 6 – paronite gasket; 7 – Nitrogen gas outlet connection; 10 – wire; 11 – plate; 12 – locking wire; 13 – clip; 14 – screw; 15 – bracket

The transition of engines to the configuration with afterburning of oxidative generator gas (high pressure) contributed to appearance of the contemporary cylinder heat exchanger. It was successfully used in the propulsion systems of two stages of all Zenith rocket carrier modifications, in four units of the first stage of the Energia rocket carrier. The coolant duct in the heat exchanger alternate with the duct of helium. The heat exchange surfaces of the helium duct walls are formed by the ribbing with direct channels. The finning in the generator gas ducts helped to intensify the heat exchange process by implementing the vortex flow.

A modern plate-fin heat exchanger [4] is used in the RD-191 deep-throttling engine (the Angara rocket carrier) (Fig. 3). This is the first heat exchanger that uses oxidative generator gas from the gas generator as a coolant. The reason for that is to give meaning to the helium pressurisation system under deep throttling conditions of the propulsion system. In this case the whole range of problems relating to the combustion of materials in the high-pressure oxidative gas environment extend to the heat exchanger. The need of such decisions is far from clear-cut.

It is important to emphasise that this is the use limit of the engine generator gas heat. This is the hottest gas on-board the rocket carrier. It is also important to reflect the problems arising in the course of optimisation of this heat exchanger. There is nowhere except in the rocket engine that such a unique coolant with fast varying parameters can be obtained. Since the optimisation of the heat exchanger is carried out without the engine, as a matter of course, the optimisation is very rough. We have to include large spreads in its basic parameters.

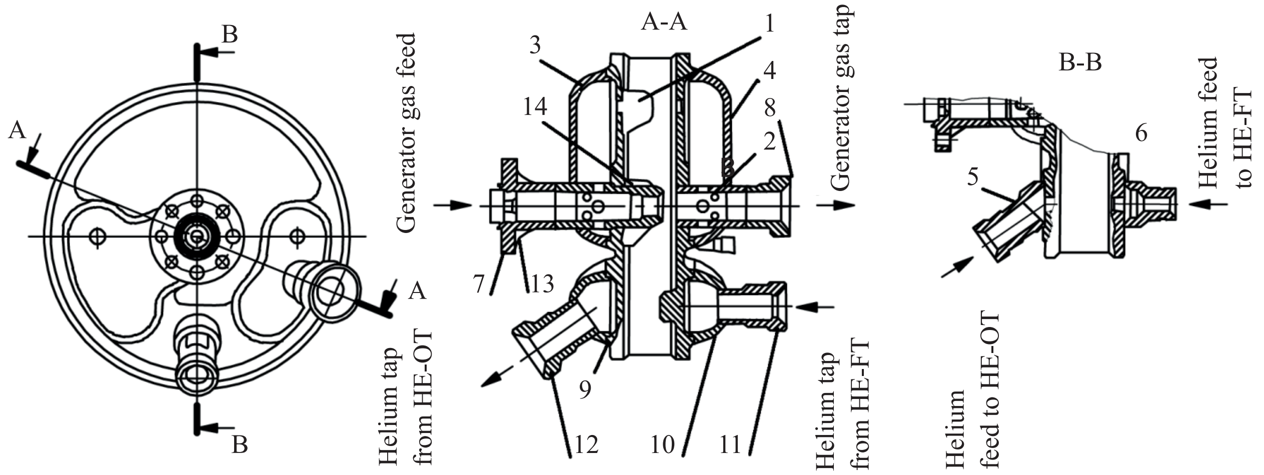

***Figure 3**. The RD-191 plate-fine heat exchanger (first stage of the Angara rocket carrier):*
1 – wall brazed package; 2 – central bushing; 3 – generator gas feeding manifold; 4 – generator gas tapping manifold; 5, 6 – helium feed; 7 – generator gas feeding flange; 8 – generator gas tapping connection; 9, 10 – helium tapping manifolds; 11, 12 – HELIUM tapping connections; 13 – washer; 14 – bypass hole

It is important to emphasise that the final purpose of the tank pressurisation system of which the heat exchanger is a structural part, is not to form a record heat exchanger but provide required pressure in the ullage with less resources and with the required reliability. The gas pressure in the ullage depends on a number of factors. The temperature of helium at the tank inlet is just one of multiple affecting factors, more precisely, the temperature of the working fluid at the ullage inlet and not at the heat exchanger exhaust. Figure 4 illustrates these significantly varying temperatures.

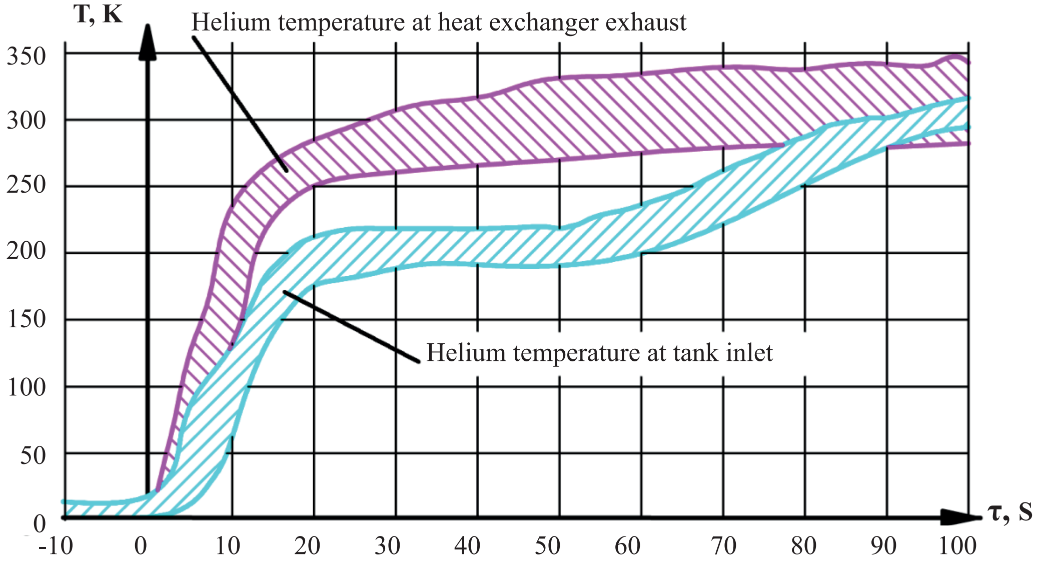

***Figure 4**. Helium temperature at the heat exchanger exhaust and the oxidiser tank inlet (full-scale data)*

As an example, in the first stage of the medium class rocket carrier, the length of hot pressurisation lines (40x1 mm from stainless steel) from the heat exchanger to the tank inlet makes up about 40m. At approx.50th second of the flight, the difference between helium temperature at the heat exchanger exhaust and at the tank inlet makes up approx.100K (more than 20%). Actual contribution of means and time spent on improvement of the heat exchanger, to the pressurisation system parameters can only be assessed if taken together with other factors by applying complex method of mathematical modelling of innertank processes.

It is surprising that such enormous reserves, that effectively lie on the surface, remain out of sight of the researchers. They are not addressed in the technical literature. This situation is probably due to the fact that the heat exchanger is developed by engine designers following the Requirement specification, but the required gas pressure in the tank is a responsibility of another team of specialists. A tight schedule for the development of any new rocket complex prevents from finding the integrated solution of the problem, but the next new complex will be developed in the country in 20÷30 years at best, by other specialists. The situation repeats itself.

Because of existing breakdown of responsibilities, it would be meaningful to solve the problem within the framework of the Requirement specification for the development of the heat exchanger. The specification dictates the limit on the weight and space of the heat exchanger, the temperature of helium at the heat exchanger exhaust (with the spreads) with prescribed helium consumption, the helium pressure losses in the heat exchanger duct with prescribed consumption and temperature, minimum temperature of helium at the heat exchanger inlet. Therefore, we concretise the task of the research – to develop the recommendations for the design of the helium heat exchanger of the RC pressurisation systems, to substantiate the ways that could reduce the weight of heat exchangers and make their development significantly easier.

THE TRADITIONAL WAYS TO IMPROVE THE EFFICIENCY OF HEAT EXCHANGERS

Let's try to analyse the assigned problem by the following areas of activity. The first area of activity represents the works aimed at the intensification of the heat exchange in the heat exchanger by means of various turbulators. The second area of activity represents the researches working to increase the efficiency of heat exchangers by means of circuit solutions.

The latest paper [5] addresses the architectures of recuperative heat exchangers of rocket propulsion systems. They are used in the fuel tank pressurisation systems of US rocket carriers. It is shown that the heat exchange efficiency in a pathway with inter-channel coolant transpiration through the porous mesh metal is higher than when compared to other heat exchange pathways. It has been established that the pathway efficiency is particularly high at low Reynolds numbers in the range of $1 \cdot 10^3 \div 5 \cdot 10^4$ the efficiency increases when the path of the coolant movement through the porous mesh metal decreases, and the porous mesh metal thermal conductivity increases. A conclusion is made that it makes sense to increase the heat exchange efficiency by developing the heat exchange surface rather than the by increasing the coolant movement speed.

In a number of works by A.A. Khalatov, e.g., [6], the efficiency of the dimpled surface of heat exchange is proved, which allows the turbulisation of the laminar sublayer of the flow boundary layer. It is the laminar sublayer that determines the rate of heat flow taken from the surface. Recommendations are developed for the distribution and geometry of the dimples. The parameters, at which the heat transfer grows faster than the pressure loss along the pathway, are shown.

For industrial shell-and-tube heat exchangers, the paper [7] addresses the effect of baffles on the increase in heat transfer efficiency. It is shown that the increase of the path of the coolant movement with simultaneous flow turbulisation gives a positive effect. However, this goes along with increasing the dimensions of the device, the pressure loss along the length of duct. As is known, the dimensionless heat-transfer coefficient Nu (Nu_{sm} for a smooth wall) is proportional to the Re number to the power of 0.8, and the aerodynamic drag Δp to a power close to:

$$Nu_{sm} = 0.021 \cdot Re^{0.8} \cdot Pr^{0.8} \tag{1}$$

$$\Delta p = \xi \cdot \frac{Re^2 \cdot \mu}{2 \cdot d^3 \cdot \rho} \cdot l \tag{2}$$

where Pr – Prandtl number; ξ – coefficient of friction; μ, ρ – coefficient of dynamic viscosity and coolant density respectively; l, d – length and diameter of the duct respectively.

The paper [8] also addresses the efficiency improvement of industrial water-heating shell-and-tube heat exchangers. The problem is solved by means of coarse surface finishing (artificial roughness) and riffling. It is recommended to make ribbing on the outer surface. These solutions also lead to increasing pressure losses along the ducts of the coolant and the working fluid. It is known that the thermal hydraulic efficiency of ducts with artificial roughness:

$$E = \frac{Nu}{Nu_{sm} \cdot \left(\frac{\xi}{\xi_{sm}}\right)^{\frac{1}{3}}} \tag{3}$$

barely reaches 1, and only at small values of Re numbers tends to 1.2.

The paper [9] addresses, by means of mathematical modelling, the effects of the helical baffle size and tilt angle on the flow swirl and two ways of interrupting the flow swirl in shell-and-tube heat exchangers. Recommendations for considered conditions are given.

The paper [10] brings light on the effects of circular fins in shell-and-tube heat exchangers on the increase in heat-transfer coefficients. It is shown that, under considered conditions, circular fins can lead to an improvement of the heat exchanger efficiency by ~ 8%.

A special case is the patent [11], which shows the way to significantly improving the efficiency of the helium propellant heat exchanger. This technology does not complicate the design of the latter, but greatly simplifies its experimental development. The exhaust products of the most common solid-fuel gas generators are proposed to be used as a heat carrier, e.g., based on sodium azide (used in automobile airbags). The use of a high temperature of the coolant helps to obtain a final high temperature of helium and minimise helium pressure losses in the heat exchanger ducts. At the same time, it is not linked to the engine, and it is logical to locate it in the intertank compartment of the rocket carrier. This significantly reduces the length of the pressurisation ducts, and, consequently, their total resistance. This solution allows the helium bottles to be more completely emptied.

A retrospective analysis of the studies on the improvement of the efficiency of the heat exchangers shows that almost all known studies are aimed at enhancing the heat transfer in the heat exchanger. The effect of various boundary layer turbulators such as dimples, artificial roughness, circular fins, helical baffles, porous mesh metal is discussed.

Surprisingly, the authors were not able to find any scientific paper on the possibility of increasing the working fluid temperature at the inlet of pressurisation system heat exchangers, though the results of such works could contribute to the reduction of the required heating value of the working fluid:

$$\Delta Q = mc_p\Delta T \qquad (4)$$

where $\Delta T = T_{out} - T_{in}$; m – weight of pressurisation working fluid fed through the heat exchanger, c_p – average working fluid heat capacity at temperatures within the range of T_{in} to T_{out}.

And this, giving other conditions being equal, will help to reduce the weight of the heat exchanger and the required consumption of the coolant. Moreover, the issues of searching and further using the low-potential heat have never been addressed in a targeted manner during the design of rocket heat exchangers.

It is also important to note that the transport of thermal energy, which is produced with such difficulty in the heat exchanger, to the consumer with minimal losses also remains beyond the attention of researchers. As Figure 4 shows, the helium temperature losses on the way from the heat exchanger to the oxidiser tank inlet of the medium-class RC. They make up at least 20%. So is it reasonable to spend resources, complicate the development and design of the heat exchanger in order to increase the heat exchange by 7%?

This gives grounds to affirm that the research, the first devoted to the ways of increasing the temperature of the working fluid at the rocket heat exchanger inlet, is useful. This will help to reduce the temperature difference by which the helium shall be heated. This solution, giving other conditions being equal, shall help to reduce the weight of the heat exchanger, what is extremely important for the rocket carrier. For example, a 10 kg weight reduction of heat exchanger at stage I of the Zenith rocket carrier makes it possible to increase the weight of the satellite by ~ 2.5 kg. The orbital insertion of 1 kg of the satellite costs the Customer today at least $20,000.

SEARCH FOR ATTEMPTS TO USE HEAT WITHOUT BURNING FUEL

If you look closely, from the modern perspective at the generally accepted classification of heat sources [1], the following interesting facts can be stated. For the first time, waste heat (the authors will conventionally call it low potential in the future) was used in rocket technology already on the first V-2 rocket. In the pressurisation system of the fuel tank (it was the upper one on the stage) in the atmospheric phase of the flight, a high-speed air pressure was used. At supersonic flight speed, the deceleration temperature of the air entering the tank was significantly higher than fuel temperature and tank structure. In this case, the required gas pressure in the tank was provided reasonably enough. It can be assumed that outboard rammed air performs the functions of a heat exchanger here.

It is necessary to note one more peculiar pressurisation system, in which the low potential heat of the oxidiser is used unambiguously. We are talking about the so-called “self-pressurisation” boiling of the upper layer of fuel in the tank, due to which the required gas pressure in it was maintained. In the second phase of the flight of the American intercontinental ballistic missiles Atlas-D, Titan-I, Titan-II, this maximally simple pressurisation system was implemented. It does not require any additional elements. The heat for boiling the upper layer of oxidiser was not supplied from the outside, but was taken from the oxidiser itself. The oxidiser itself can be considered a heat exchanger. This is the standard of design simplicity and reliability. Unfortunately, this system was not used due to the complexity of measuring the level with discrete float-type systems in a boiling bed. At present, this problem has been solved by the Dnieper school of pressurisation systems.

In the mid-seventies, when designing the Zenith and Energia rocket carriers, the students of the Dnieper scientific school carried out work to abandon the “generally accepted” hot helium system for pressurising the fuel tanks of the listed rocket carriers. The newly patented so-called "supercold" pressurisation was introduced. In the new system, helium from cylinders immersed in liquid oxygen is introduced into the fuel tank by the shortest way through the intertank bay. Its temperature at the tank inlet is in the range of 90÷60 K. As a result, the pressurisation system became ~ 30% lighter, the volume of experimental development decreased significantly, and its complexity and cost, due to the absence of a heat exchanger, also decreased significantly.

In this system, helium, with the help of a special input device, takes heat from the upper layers of the fuel, the weight of which is tens of tons, and from the tank structure, the weight of which is measured in tons. According to modern views, this can be considered the use of low potential heat. Except for the first seconds of operation of the pressurisation system, when the fuel level is at the outlet section of the input devices, the heat exchange of the pressurisation gas with the boundary surfaces proceeds according to the laws of natural convection, which is not particularly effective. The authors are not aware of any works aimed at heat transfer enhancement for these conditions. It is reasonable to carry them out.

By now, the supercold pressurisation system has been implemented in addition to Zenith rocket carrier, Energia rocket carrier, Atlas-III rocket carrier, and Atlas-V rocket carrier. An improved supercold system is used at stage I of the Antares rocket carrier [12], and is considered in the draft designs of Mayak, Cyclone-1M, and Cyclone-4M rocket carriers.

In work [13], it was proposed for the first time to use such a powerful heat source as a rocket engine plume for heating helium. It can be safely attributed to the typical "industrial wastes". Schematically, this is achieved by placing a simplified heat exchanger (some channels with helium) behind the bottom protection. In this case, a purely evaluative mathematical modelling of helium heating was carried out. As the total heat flux to the channels, the known value of the heat flux at the bottom protection for the F-1 engine of the Saturn-V rocket carrier first stage was used. This value is equal to 272 kJ / (m^{2}sec) [14]. It was obtained during ground tests of the engine. Apparently, this is the minimum value of the heat flux from the main engine plume. The fact is that the F-1 engine is the only one of its kind, in which the plume is shielded by reducing generator gas with soot, which is discharged tangentially at the turbine outlet into the engine nozzle (Fig. 5).

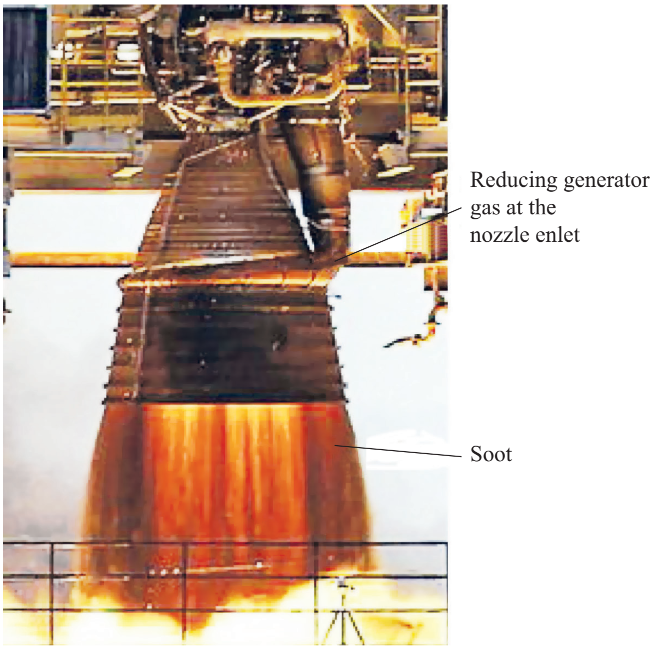

Figure 5*. Stage I of Saturn-V rocket carrier*

Source*: [15]*

The results of calculations on the dependences made by M. Mikheev [16] for complex heat transfer showed the following. Placing a heat exchanger made of chromium-nickel steels behind the bottom protection will bring it into a plastic condition already by 10÷12 s of engine operation, i.e. unserviceability. It is concluded that there is an excess heat flow behind the bottom shield and the need to take measures to reduce the specified heat flow. Modern shielding materials (marbled glass), which reduce heat fluxes, have been proposed.

In authors' opinion, more accurate modelling can be carried out with the following approach to the problem. One can notice an analogy in the physical processes occurring in the combustion chamber of a rocket engine and behind the bottom shield. In both cases, radiant heat fluxes and convective movement of combustion products act on the cooled walls. This makes it possible to take advantage of a well-developed methodology for calculating the cooling of the engine combustion chamber. It will be necessary to additionally take into account the decreasing density of the medium with respect to the flight time behind the bottom shield and some uneven heat supply to the channels with helium.

Thus, the previously expressed emotional judgment that rocket engine technology is far from using low potential heat is untenable. The pioneers of rocket engine technology, not spoiled by their narrow specialisation and stereotypes, used widely the waste heat and industrial wastes. At the same time, small masterpieces were created in rocket propulsion systems.

As shown above, implemented methods of using waste low potential heat are known for fuel tank pressurisation. Let's try to find a solution to the problem in relation to a tank with liquid oxygen. The situation is more complicated here, because helium in cylinders and liquid oxygen in a tank have approximately the same temperature. And it is problematic to use a heat pump in flight conditions in such a situation.

Let's pay attention to the "cold" pressurisation line 3 (Fig. 1), which runs along the fuel tank (its nominal temperature is 258 K) from its outer side and enters the "warm" engine compartment. Figure 6 shows the change in helium temperature at RD-171 LPRE heat exchanger inlet over the time of its operation. As you can see from the diagram, helium temperature changes in a very interesting way. At the time the pressurisation system starts operation, the temperature is equal to 270 K, after fifteen seconds it gradually drops to 110 K, then steadily increases and by the end of the start it reaches 160 K. Thus, the authors are convinced that, without applying any special efforts, without spending additional energy, helium from cylinders with a temperature of 90÷60 K before entering the heat exchanger can heat up "spontaneously" by ~ 100 K. Such temperature change should induce active action.

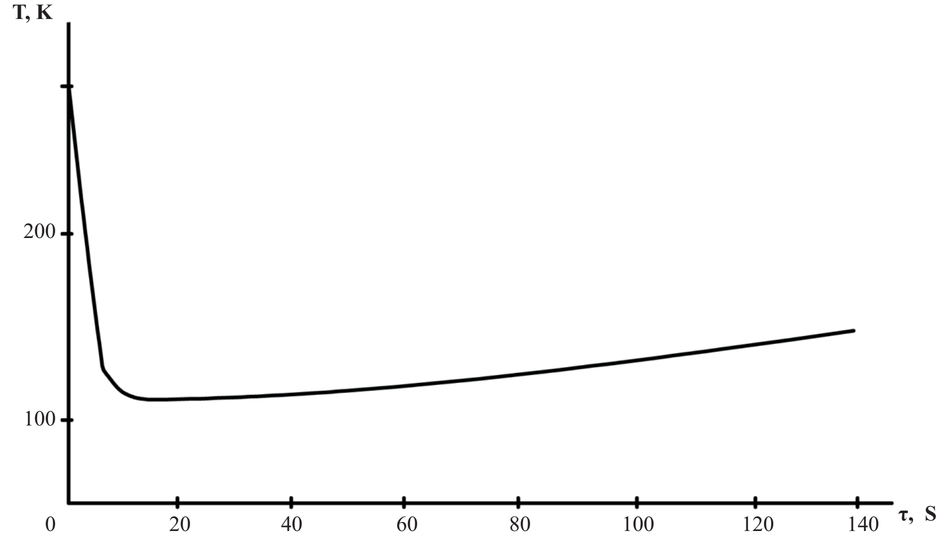

Figure 6. *Helium temperature at heat exchanger inlet according to the operation time of the pressurisation system*

Naturally, a question arises: What if you make a purposeful effort? Let's try to find a solution and answer this question.

If the "cold" pressurisation line passed through the fuel, then it would take much more heat from it (different heat capacities) than from the ambient air, the density of which sharply decreases as the rocket carrier is flying. There is no doubt about it. Therefore, the authors will consider the following option for obtaining low potential heat, the "cold" pressurisation line 3 (Fig. 1) is laid inside the fuel tank [17]. Mathematical modelling of helium heating in the pipeline is carried out using dependencies (1) and (2). With regard to RD-171 fuel tank, helium will be heated for at least 130K. The helium temperature can be further increased by turbulisation of the fuel flow on the outer wall of the pipeline (artificial roughness, dimples). In this case, the length of the pressurisation line (resistance) does not change. It should be noted that, depending on the needs, it is possible to heat helium almost to the temperature of the fuel in the tank, additionally making several turns of the line in the region of its lower bottom.

Further, the low potential heat of the fuel can also be supplied to the helium at the pump outlet, in which it heats up by 6÷12 K in any case and has a higher speed than the lowering of the fuel level in the tank.

Another drawback of the old classical helium heating model is realised with throttling of the liquid propellant rocket engine. As already noted, in this case, the flow rate and temperature of the oxidising generator gas drop sharply. Turbine exhaust temperature also decreases. The heating of helium in the heat exchanger is reduced. To maintain the required gas pressure in the tank with colder helium, it is necessary to increase its flow rate and reserves on rocket carrier board. This, in turn, significantly reduces the mass properties of rocket carriers.

Can this phenomenon be countered? Consider the following design model. The cooling component of fuel (kerosene) from the nozzle head of combustion chamber (the hottest cooling component) is used as a heat carrier. LPRE throttling in this case does not lead to such a sharp negative effect for the following reasons. So, when throttling, the ratio of the fuel components in the combustion chamber (temperature) practically does not change. Only the pressure in it decreases, and with it the heat flux into the wall of the combustion chamber decreases slightly. That is, the temperature of the proposed heat carrier will be more stable at different engine power ratings. It should also be noted that the heat capacity of kerosene is 2.9 times higher than that of the oxidising generator gas. All other things being equal, it can transfer more heat to helium. This is a vivid illustration of the use of industrial wastes in rocket engine technology.

Thus, the proposed simple model solutions significantly increase helium temperature at the heat exchanger inlet and stabilise the temperature of the heat carrier. Therefore, the design of the heat exchanger can ultimately be more compact. At the same time, the experimental development of it and pressurisation system is significantly simplified both for the nominal power rating and for the deep throttling.

For the fuel components: liquid oxygen and RP-1, the results obtained can be presented as follows (Fig. 7).

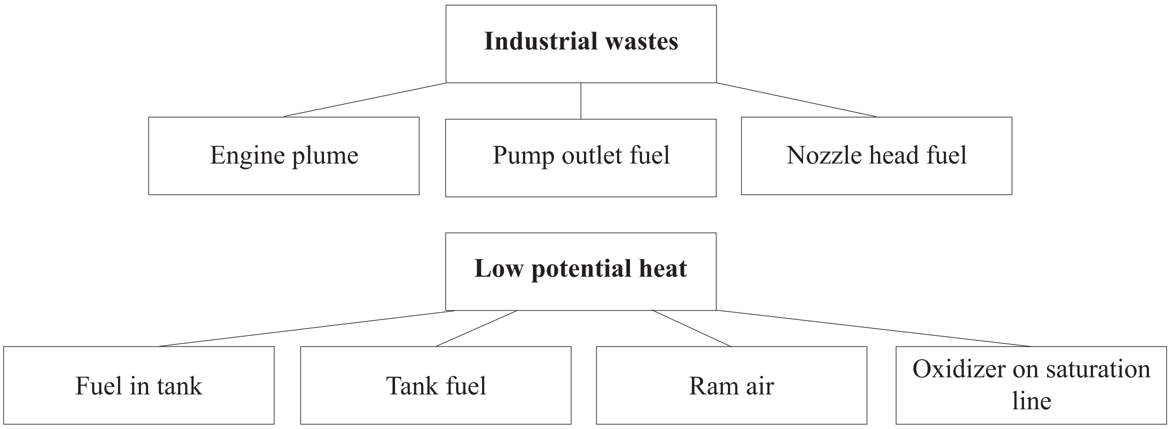

***Figure 7**. For the fuel components: liquid oxygen and RP-1, the results obtained can be presented as follows*

CONCLUSIONS

The conducted studies made it possible to substantiate a new direction for increasing the efficiency of helium heat exchangers for pressurising the fuel tanks of the propulsion systems of launch vehicles. It consists in attracting low-potential heat and "industrial waste" available in the LV. The basic laws of complex heat transfer and a retrospective analysis of the designs of the applied heat exchangers of the working fluid for pressurising fuel tanks are used.

The main results of these researches are as follows. Turbine exhaust gas was used as a heat carrier in all known engine heat exchangers. Only one design is known in which an oxidising generator gas is used, which is bled immediately at the gas generator outlet. This is the thermal limit for the use of oxidising generator gas. As the authors assume, this experience is unlikely to be followed due to the complexity of its implementation, especially during experimental testing.

The increase in the efficiency of engine heat exchangers proceeded mainly by the traditional way of improving the cooling paths, their designs (coplanar channels, interchannel transpiration, plate-finned structures, hole relief in the paths). No works aimed at investigating the possibilities of increasing the inlet temperature of the pressurised working fluid to heat exchangers have been found. Also, no works were noticed on the efficient transportation of thermal energy from the heat exchanger located in the engine compartment to the upper points of the fuel tanks.

A search has been made for attempts to use low potential heat in fuel tank pressurisation systems. It was found that such attempts were mainly at the dawn of the development of rocket technology. This is the pressurisation of the tanks by ram air in the atmospheric phase (V-2, R-14), the maintenance of the required gas pressure in the tanks due to the boiling of the upper layer of oxidiser (oxygen, nitrogen tetroxide) located on the saturation line (Atlas-D, Titan- 1, Titan-II). These attempts were of a fragmentary, unsystematic nature, and did not develop further.

In modern developments (rocket carriers: Zenith, Energia, Antares, Atlas-V), the low potential heat is partially used in the so-called supercold pressurisation of helium tanks with a hydrocarbon fuel such as kerosene. Helium of cryogenic temperature is injected in a special way into the free volume of the fuel tank, the weight of which is measured in tens of tons, removes heat from it and from the tank structure, the weight of which is measured in tons, and creates the required pressure. In this case, the temperature of the gas in the tank, with a competent input, by the time of engine shutdown, practically reaches the temperature of the fuel. This method of pressurisation is adopted in the preliminary designs of rocket carriers: Mayak, Cyclone-4M, Cyclone-1M.

From the standpoint of the achievements of thermal engineering, a search was carried out for previously unused low potential heat and industrial wastes in the propulsion systems of modern rocket carriers. Previously unused sources of low potential heat and industrial wastes were found and substantiated to improve the efficiency of heat exchangers for pressurisation systems of rocket carrier fuel tanks. They are the following: fuel in the tank, warmer fuel at the pump outlet, fuel from the nozzle head of the engine, engine plume. Realisation of the found possibilities of using waste heat makes it possible to significantly increase the efficiency of heat exchangers for pressurising tanks of propulsion systems, to reduce their weight and dimensions.

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REFERENCES

[1] Zakirov, D.G., & Rybin, A.A. (2015). *Use of low potential heat.* Moscow: Rusayns.

[2] Svetlichnyj, O., & Levchenko, D. (2019). Commercialization of space activities: Correlation of and public interest in the pursuit of outer space exploration. *Advanced Space Law,* 4. doi: 10.29202/asl/2019/4/8.

[3] Degtiarev, A.V., Kushnarev, A.P., & Popov, D.A. (2014). Ultra-small class space rocket. *Space technology. Missile Armament*, 1, 14-20.

[4] Klieva, O.G. (2008). *Development of unified compact plate-finned heat exchangers for liquid propellant rocket engines*. (Doctoral thesis, NPO Energomash named after Academician V. Glushko, Khimki, Russian Federation).

[5] Pelevin, F.V., Avraamov, N.I., & Semenov, P.Yu. (2014). Recuperative heat exchanger for pressurizing fuel tanks of a liquid-propellant rocket engine. *Bauman MSTU Engineering Bulletin*, 10, 50-60.

[6] Khalatov, A.A. (2012). Heat transfer and hydrodynamics in the fields of mass forces: A review of the work carried out at the IETP NAS of Ukraine. *Industrial Heat Engineering*, 34(2), 5-16.

[7] Zitek, P., & Valenta, V. (2015). Various methods to improve heat transfer in exchanger. *EPF Web of Conferences* 92, article number 02119. doi: 10.1051/epjconf/20159202119.

[8] Rajendra, Math, M.C., Sameer, S., & Rangu, P. (2016). Design of heat exchanger with effectiveness improvement techniques by using fins and inserts. *International Journal of Engineering Research & Technology (IJERT),* 5, 265-269.

[9] Mohan, K., Prakash, K., & Sathya Samy, C. (2016). Efficiency improvement in shell and tube heat exchanger using CFD tool. *International Journal of Innovative Research in Science, Engineering and Technology*, 5, 4128-4134.

[10] Srinivasana, K., Muthub, S., Devadasanc, S.R., & Sugumaran, C. (2014). Enhancing effectiveness of shell and tube heat exchanger through six sigma DMAIC phases. In *12th Global Congress on manufacturing and management, GCMM* (pp. 2064-2071). Vellore: Elsevier Procedia.

[11] Mitikov, Yu.O. (2014). The system of pressurizing the fuel tanks of the propulsion systems of rocket carriers. Patent 108414 Ukraine: IPC B64D 37/00/ – No. 201a201309167, 23.

[12] Shevchenko, B.O., Mitikov, Yu.O., & Logvinenko, A.I. (2002). Method for pressurizing a rocket fuel tank. Patent 51806 Ukraine: IPC B64D 37/00/ No. a200203979, 5.

[13] Mitikov, Yu.O., & Petrenko, R.M. (2015). Gas cylinder pressurization system of the fuel tank of the propulsion system. Patent 109481 Ukraine: IPC B64D 37/00, F02K 9/42/ No. a201313064, 9.

[14] What Made The Saturn V Rocket So Powerful? (2021). Retrieved from https://apollo11space.com/what-made-the-saturn-v-rocket-so-powerful.

[15] Saturn V. (2017). Retrieved from https://public-media.si-cdn.com/filer/3a/18/3a184293-b6ae-4089-9111-f4e54d462b22/09h_on2017_testing_6862846_orig_live.jpg.

[16] Mikheev, M.A., & Mikheeva, I.M. (1977). *Basics of heat transfer.* Moscow: Energy.

[17] Mitikov, Yu.O. (2020). Method of heating the helium of tank pressurization system of powerplant. Patent No. 121524 Ukraine: B 64D 37/34/ No. a201808948, 5.

Використання низькопотенційного тепла для нагріву гелію систем наддування баків ракет-носіїв

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Анотація. В даний час максимально гостро постає питання енергоефективності будь-яких нових технічних розробок. Особливо слід зазначити, що сьогодні акцент у цій проблемі істотно змістився у бік максимального використання відновлюваних джерел енергії. Метою досліджень є зниження маси гелієвих теплообмінників систем наддування паливних баків сучасних рухових установок ракет-носіїв, що використовують компоненти палива рідкий кисень і пальне типу гас. Вперше поставлено питання про можливість і доцільність підвищення температури гелію на вході в теплообмінник, насамперед, без використання додаткових ресурсів. Розглянуто залучення непрямого («низькопотенційного») тепла і «промислових стоків», що є у складі рухових установок. В якості методики досліджень використані основні закономірності складного теплообміну і ретроспективний аналіз конструкцій теплообмінників, що застосовуються. Виявлено два джерела «низькопотенційного» тепла, які раніше безсистемно і фрагментарно використовувалися в ракетному двигунобудуванні для отримання і нагрівання робочого тіла наддуву. Це наддув баків швидкісним натиском повітря під час руху ракети-носія в атмосфері, створення тиску в баку за рахунок кипіння в ньому верхнього шару окислювача, що знаходиться на лінії насичення. У даній статті вперше обґрунтовано доцільність підвищення температури робочого тіла на вході в теплообмінники, і в першу чергу, за рахунок використання низькопотенційного тепла. Вперше знайдені джерела низькопотенційного тепла, що раніше не використовуються, і «промислових стоків» у складі сучасних рухових установок глибокого дроселювання. Це висококипляче пальне: у баку, за насосом високого тиску, на виході з тракту охолодження камери згоряння. Також це конструкції паливних баків, факел двигуна. Доведено можливість та показано раціональність їх реалізації для підвищення ефективності теплообмінників систем наддуву. Вперше запропоновано запозичити методологію розрахунку охолодження камери згоряння двигуна для нагрівання теплообмінника факелом. Вперше розроблено класифікацію непридатних джерел тепла, придатних підвищення температури робочого тіла наддува. Розкриті резерви дають змогу підняти ефективність гелієвих теплообмінників систем наддуву баків рухових установок

Ключові слова: ракетні двигуни, висококипляче пальне, температура на вході в теплообмінники, джерела, низькопотенційне тепло