Розглянуто модернізацію системи заправки та термостатування рідким воднем паливного баку ракетиносія "Енергія" шляхом використання струминного охолоджувача рідини. Це дозволяє реалізувати замкнуту схему циркуляції рідкого водню при термостатуванні паливного бака та домогтися значного спрощення конструкції стенду та зниження його матеріаломісткості. Також забезпечується економія кріокомпонента в процесі заправки і термостатування

Ключові слова: рідкий водень, стартовий комплекс, випарне охолодження, струминний охолоджувач рідини

Рассмотрена модернизация системы заправки и термостатирования жидким водородом бака горючего ракеты-носителя "Энергия" путем использования струйного охладителя жидкости. Это позволяет реализовать замкнутую схему циркуляции жидкого водорода при термостатировании топливного бака и добиться значительного упрощения конструкции стенда и снижения его материалоемкости. Также обеспечивается экономия криокомпонента в процессе заправки и термостатирования

Ключевые слова: жидкий водород, стартовый комплекс, испарительное охлаждение, струйный охладитель жидкости

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LIQUID JET COOLER-BASED LIQUID HYDROGEN FUELING AND THERMOSTATING LAUNCH SYSTEM DEVELOPMENT

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1. Introduction

The long-term programs of outer space exploration implemented at present in the USA, Russian Federation and China imply conducting manned expeditions to the Moon and Mars. A necessary condition for the realization of these tasks is the creation of space carrier rockets (CR) of heavy and superheavy class, which use highly effective components of the fuel of liquid propellant rocket engines – liquid oxygen and hydrogen. This ecologically clean fuel makes it possible to ensure the best energy characteristics to the means of orbital injection, but it is characterized by the low temperature of storage and use. This causes significant heat gains in the systems of storage and fuelling of cryo-components and complicates heat removal in the process of fuelling and thermostating fuel tanks of the objects of rocket-space technology in preparation for the launch. At present, for providing the optimum temperature of cryogenic component supply to the tank, refrigeration plants are used, surface heat exchangers-recuperators, which use cryogenic liquid as the refrigerant that boils at reduced pressure or tanks for bubbling by gaseous helium. Cooling cryogenic liquid by the given methods is performed before the start of filling the fuel tank and in the case of the launch delay leads to unproductive expenditures in cryo-components and energy resources. An overall drawback in all these devices is the high magnitude of capital or operational expenditures. That is why the development of compact devices that make it possible to effectively perform the cooling of cryogenic liquids directly during filling the CR tank is of significant interest at present for the creation of new or modernization of the existing launching systems in the USA, Russian Federation and CPR.

2. Literature review and problem statement

The need of using the cryogenic components of rocket propellant in cosmonautics determined the emergence as early as in the 1950s of new direction in cryogenic technology, connected to the questions of large-capacity production, accumulation and storage of cryo-components, fuelling and thermostating of bench and onboard tanks. Studies on this topic were actively conducted in Germany, France, and Japan; however, leading designers of technologies for obvious reasons hailed from the USA and the USSR. The technical solutions developed in the USA were implemented in the programs “Apollo” and Space Shuttle. In the USSR, the result of research into this direction was the creation at the cosmodrome Baikonur of starting complexes for launching rocket-space system “Energy-Buran”.

Significant difference in approaches to the solution of the problem was observed at this stage [1]. Until recently, independent of the amount of the filled cryogenic component, at all ground-based starting complexes in the USA, cryogenic fuel and oxidizer have been stored at temperature not below than saturation temperature at normal pressure (that is, in the saturated or the so-called “boiling” state), and the formed vapors are discarded into surrounding space or are burned. During reverse countdown, the components are pumped over to the CR tanks, and in the case the launch cancels, they are returned back into the tanks of the starting complex. Insignificant differences are due to peculiarities of realization of these operations at different ground starting complexes. Analogous technologies are used as well at the cryogenic launching systems of the European Space Agency, Japan and China. The consequence of this is insufficient qualification of the American specialists when working with the supercooled propellant components [1–4], which could be the reason for explosion on September 1, 2016 at the cosmodrome Canaveral during preparation for the launch of rocket Falkon 9FT.

The system of storage and provision of temperature conditions for liquid hydrogen developed by the NASA specialists NASA inplies using cryogenic refrigeration plant of the Linde Cryogenics LR1620S type [5, 6]. Its refrigerating capacity is 850 W at temperature level 20 K, and minimum temperature level reaches 15 K. The tank capacity is 125 m^3. A surface heat-exchanger, which is characterized by low values of temperature head, built in the tank for storing the cryo-component, is used for heat exchange. The system provides storage of the cryogenic component without losses; however, this is achieved due to high capital and operational expenditures, which, given with low intensity of CR launches, proves to be economically disadvantageous.

The method of cooling the cryogenic component by bubbling with gaseous helium is examined in papers [7, 8]. The effect of temperature and specific expenditure of gaseous helium on the value of cooling cryogenic liquid was explored. The process of cooling is achieved in a tank for storing the component, as well as the above-described method of cooling with the aid of refrigeration plant. Thus the warming up of cryo-component is inevitable in the process of filling the CR fuel tank, which decreases effectiveness of the process of cooling. Results of the study demonstrated the necessity to cool gaseous helium before its introduction into the cooled liquid, which determines the need for using cryogenic refrigeration plants. Two schemes of using helium are examined – opened and closed. In the open scheme, the mixture of helium together with vapors of the cooled liquid is discarded to the drainage or to the afterburning (hydrogen), which leads to the irreversible losses of expensive helium. The closed scheme of the circulation of helium makes it possible to repeatedly use helium, but this can be realized due to the system, which makes it possible to divide helium and vapors of cryogenic liquid. Thus, the method of bubbling is also characterized by high capital and operational costs and it does not make it possible to operationally solve the problem of changing temperature of the cryogenic component supply.

In the USSR, they realized the filling of fuel tanks with liquid oxygen and hydrogen in the supercooled state. The concept of safety and reliability was the main concern in its development, realized through the use of only verified technical solutions and devices [2–4]. Its legitimacy was confirmed by successful start of the "Energy-Buran" rocket-space system in November 1988. However, from the point of view of effectiveness, this scheme of the starting complex is not optimum. The lack of reliable cryogenic pumps of required capacity determined the choice of a semiclosed scheme of motion of the component with the pressurized feed system. Surface heat exchangers are used for supercooling the components. That is why the creation of an alternative device for evaporative cooling of cryogenic liquids for the work in the structure of the system of filling and thermostating of CR tank is of practical interest. In this work, this is executed for the case of using a jet liquid cooler [9, 10] in the structure of the hydrogen system 17G24S of the starting complex for launching the "Energy" CR.

3. The purpose and objectives of the study

The purpose of this work is to design a system for filling and thermostating fuel tank of space carrier rocket with supercooled liquid hydrogen. For this purpose, as the heat-mass-transfer device, we used the jet liquid cooler (JCL) that was created at the Department of Aerospace Heat Engineering of the National Aerospace University "Kharkov Aviation Institute" named after N. E. Zhukovskiy (Ukraine). JCL is the device that provides for cooling the liquid at speed 400...500 K/s with the overall sizes and mass less by 30...100 times than those of the recuperator with the same thermal load.

To achieve the set goal, the following tasks were formulated:

– to substantiate the possibility and expediency of using jet liquid coolers in the systems of rapid cooling of cryogenic liquids of the starting complexes of space carrier rockets;

– to develop the procedure for the calculation of the thermostating process of fuel tank of a carrier rocket by the pressurized system of filling and thermostating, modernized by replacing traditional recuperative heat exchangers with the jet liquid cooler;

– to carry out calculation of the discharge characteristics of the fuel tank thermostating process with the use of the modernized pressurized system, which will make it possible to determine the range of workability of the system;

– to determine the useful effect from using JCL in the structure of the system for filling and thermostating of CR fuel tank CR with supercooled hydrogen.

4. Modernization of the system for filling and thermostating with the cooled hydrogen 17G24S with the use of a jet liquid cooler

In the course of implementation of the "Energy-Buran" program, at the cosmodrome Baikonur there was created a cryogenic complex, which was designated as the Universal complex stand-start (UCSS), intended for conducting the bench tests and launching the "Energy" CR. Structurally, UCSS includes three independent systems: hydrogen – 17G24S (Fig. 1), oxygen – 17G22S, and nitric – 17G85S [2–4]. The cryo-components are stored in the spherical reservoirs RS-1400/1,0 of volume 1400 m^3 at operating pressure 1,0 MPa. The reservoirs are located on the plots at a distance of 800 m from the line of launching pads, which provides for the safety of openly standing cryogenic reservoirs in case of explosion of a fully filled CR.

In the course of the filling operation, in reservoir 1, pressure 1,0 MPa is maintained. The main portion of LH flow is supplied to cooler 4, where, as a result of heat exchange with LH, which is boiling in the cooler reservoir at reduced pressure, it is cooled to intermediate temperature. Overcooling of LH to final temperature of 17,5...18 K is conducted in cooler 5, after which it is sent to fuel tank 9 of the carrier rocket "Energy". The second portion (to 10 %) is sent to cooler reservoirs 4 and 5. The third portion, the smallest, is used to maintain in the cooled form the thermostating pipleline (mainline, by which the cryo-component is returned to reservoir 1). Maintaining the required rarefaction in the intertube space (reservoir with boiling LH) of heat exchanger-coolers 4 and 5 is provided by the supersonic ejectors 7 and 8. The rarefaction in heat exchanger-cooler 4 is created with the help of single-step ejector 7, whereas in heat exchanger-cooler 5 – by two-step ejector 8. As the active flow in ejectors 7 and 8, gaseous nitrogen is used from the system 17G85S, which provides for the gas supply at pressure 1,0 MPa, temperature 323 K and consumption 120 t/h. The amount of filled LH is 104 t, consumption – 100 t/h.

Upon reaching the assigned level in CR tank, the filling is completed and the process of LH thermostating begins. This operation is conducted for obtaining the assigned average mass temperature and the LH density corresponding to it. The LH supply to CR tank at thermostating is performed by the filling pipeline, the discharge (return to emptied reservoir 1) – by the thermostating pipeline. As a result, the mixing of LH occurs, which makes it possible to aligh temperature by the height of tank and to ensure the assigned average mass temperature of the component in the tank without a change in the temperature of supplied product.

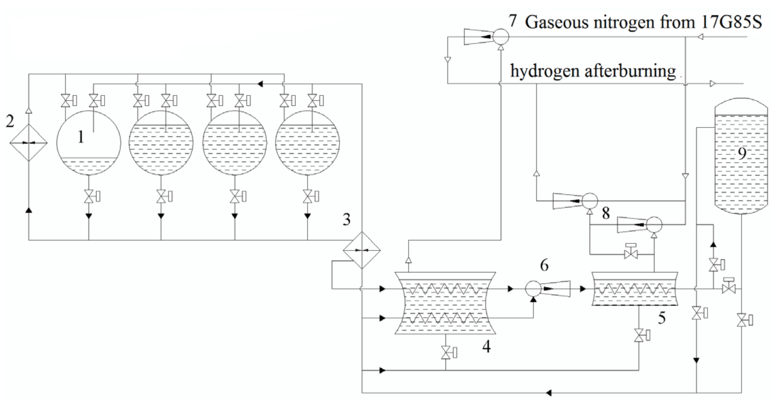

Fig. 1. Schematic of the system 17G24S for filling and thermostating the fuel tank of carrier rocket "Energy": 1 — reservoir RS-1400/1,0; 2 — heat exchanger-vaporizer of the system of reservoirs pressurized; 3 — recuperation heat exchanger; 4, 5 — cooler; 6 — jet pump; 7 — single-step ejector; 8 — two-step ejector; 9 — fuel tank of carrier rocket "Energy"

Circulation of LH at thermostating is achieved by jet pump 6, which uses LH as the active flow with mass flow rate 20 t/h, feed pressure 1 MPa and intermediate temperature, which is released from the heat exchanger of cooler 4. LH, poured from fuel tank 9 at temperature 19,5 K is used as follows. The main portion of the flow (50 t/h) after passing through heat exchanger of cooler 4 is sent to passive nozzle of jet pump 6. The pressure increment obtained in jet pump 6 makes it possible to compensate for the hydraulic losses of LH flow in heat exchanger-cooler 5 and to provide for the LH return, cooled to temperature 16 K, into fuel tank 9. The remaining "warm" LH (20 t/h) is consumed as follows. In order to provide cooling of LH flow, in the heat exchangers of coolers 4 and 5, about 8 t/h of LH is evaporated at the reduced pressure in the intertube space of the heat exchangers of coolers. Finally, unused remainder of the "warm" LH (12 t/h) returns to one of reservoirs 1, releasing its cooling capacity to the counterflow of additional supply of LH from reservoir 1 in recuperation heat exchanger 3.

An essential drawback in the system 17G24S is high material capacity and significant losses of LH, connected with it, for cooling when preparing for the filling. This is explained to a considerable degree by the choice of supply method of the cryo-component and by the length of pipelines, which is justified by the safety requirements, demanded of the system, as well as by the significant weight of heat exchangers.

The projects for modernization of the filling and thermostating system of fuel tank of CR "Energy" with cooled LH imply the creation, based on the existing element base of the system 17G24S, of the closed system of filling and thermostating, which uses as the heat-mass-transfer apparatus a jet liquid cooler (JCL) (Fig. 2) that makes it possible to realize evaporative cooling through reduction in the static, not total, pressure [5, 6]. Cooling a liquid in JCL occurs due to its partial evaporation, in particular, at the acceleration in the confusor-diffuser nozzle. The formed vapor-liquid flow is divided then into phases in the surface separator. Then the vapor is discarded through the vapor pipe, and pressure of the cooled liquid is restored in the diffuser.

The design of JCL is a box thin-walled structure with constant width of the flow area, which is the necessary condition for providing the uniformity of flow at the input to surface separator 2. For the purpose of provision of nonseparable uniform flow, the confusor part of the nozzle is fabricated according to the Vitoshinskiy profile. For the same purpose, the limitations are superimposed to the magnitude of opening angle of the nozzle diffuser part.

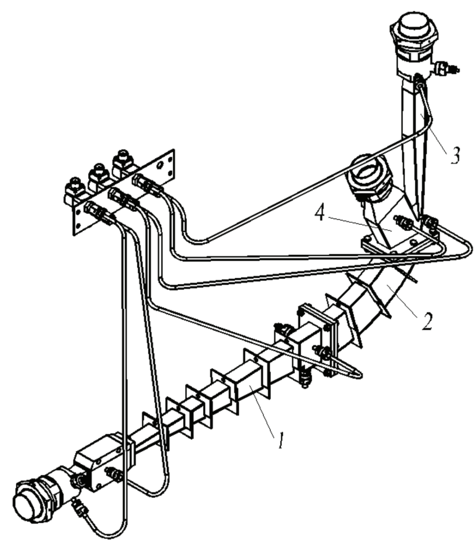

Fig. 2. Jet liquid cooler (JCL): 1 — confusor-diffuser nozzle; 2 — surface separator; 3 — diffuser, 4 — vapor pipe

The closed scheme of fuel tank thermostating implies maintaining the assigned average mass temperature of LH in the tank through the component circulation without returning a part of the overheated component to the idle tank for storing 1. In this case, consumption of the part of the component, used for the evaporative cooling of the recirculating flow, is compensated for by an equal amount of LH, supplied under pressure 1,0 MPa from reservoir 1.

The advantage of the modernized system is a significant simplification of the system, which is achieved by excluding from the structure of the system of heat exchanger-coolers 4 and 5, recuperative heat exchanger 3, return line of LH to reservoirs 1, as well as a considerable quantity of cryogenic pneumatically-controlled fittings. Insignificant amount, in comparison with the internal volume of heat exchanger-coolers 4 and 5, of LH, which is found in JCL at a time, makes it possible to draw it maximally closer to fuel tank 9, which minimizes both the preheating and hydraulic losses in the main supply line of LH cooled in JCL. The warming up of the filled LH between JCL and fuel tank is also minimized, as well as the warming up of recirculating flow between the tank and the jet pump.

A schematic of the system, modernized with the use of JCL, for filling and thermostating CR "Energy" with cooled

LH, based on the system 17G24S with the pressurized feed system, is shown in Fig. 3.

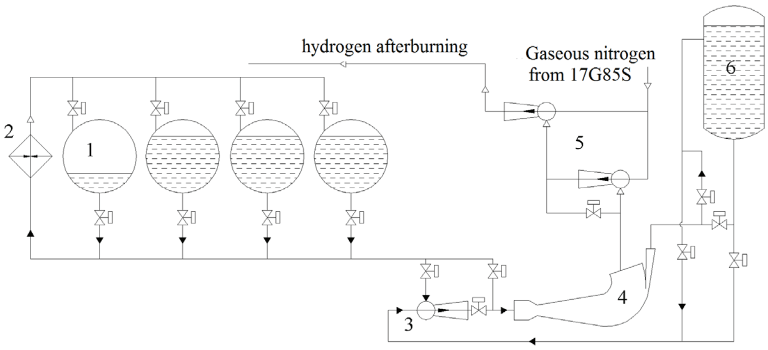

Fig. 3. Schematic of the modernized pressurized system 17G24S for filling and thermostating the fuel tank of carrier rocket "Energy" with cooled LH: 1 — reservoir RS-1400/1,0; 2 — heat exchanger-vaporizer of the system of reservoirs pressurized; 3 — jet pump; 4 — JCL; 5 — two-step ejector; 6 — fuel tank of carrier rocket "Energy"

The pressurized LH feed system with the use of JCL (Fig. 3) implies two operating modes – filling the fuel tank and its thermostating. During filling, the entire LH flow is sent directly from reservoir RS-1400/1,0 to the fuel tank. Since LH in reservoir 1 is kept at temperature 21,8 K, the LH flow cooling is accomplished in the process of filling. In this case, the compensation for LH heating is also achieved while in motion along the supply pipeline. The LH flow rate is determined by the boost pressure in reservoir 1 and by the JCL geometry. The cooled LH temperature at the output from the diffuser is regulated by changing the pressure at the JCL nozzle outout, performed with the aid of two-step ejector 5. Filling fuel tank 6 is achieved by supplying the supercooled component to the upper part of the tank, which makes it possible to provide the more uniform cooling of the tank design as well as temperature fields, uniform by height, in the liquid and steam filling of the tank to the moment of completing the filling [4]. The flow-rate control of the filled liquid is conducted by regulating boost pressure in reservoir 1 and, therefore, pressure at the JCL input.

With thermostating the CR fuel tank, the flow of heated LH, diverted from the tank, does not return to the vacated reservoir 1 but is directed in full to cool JCL in 4 with its subsequent returning to tank 6. In order to create the required pressure that provides for its return to the fuel tank, jet liquid pump 3 is used, whose passive nozzle accepts the recirculating flow from tank 6. The LH flow of high pressure is supplied to the active nozzle of jet pump 3 from reservoir 1. After the jet pump, the LH flow is directed to JCL input 4, where its cooling takes place. The cooling magnitude in JCL is determined by rarefaction at the JCL nozzle exit, which is created by the block of ejectors 5. The cooled flow from the JCL diffuser is sent to fuel tank 6.

Thermal capacity, diverted from the fuel tank, is determined by the consumption of recirculating LH and by a difference in temperatures of discharge and return of the component. A special feature of using JCL in the structure of the system is the limited possibility of changing the consumption depending on the pressure at the JCL output, which in turn depends on the expenditure of active flow in jet pump 3. Since, in the process of thermostating, the amount of component in the tank remains constant, then the flow rate of feeding LH from reservoir 1 and the consumption of vapor from the JCL vapor pipe, pumped out with the help of block of ejectors 6, must be equal.

Thus, the LH flow of high pressure from reservoir 1 makes it possible to compensate for both the LH flow hydraulic losses between the output from the jet pump and tank input 6 and the LH losses for the evaporative cooling in JCL 4. Since the supply of high pressure LH is conducted by the cryogenic pipeline of length exceeding 1 km, this unavoidably leads to additional losses of pressure and warming, which must be considered as the additional source of thermal energy supply.

In the course of developing the procedure for calculation of the thermostating process in the modernized system of filling and thermostating, the following assumptions were accepted:

– the process is stationary;

– only heat flows to fuel tank 6 and the cryogenic pipleline that connects reservoir 1 and jet pump 3 are considered; we disregard the heat flows to the remaining functional units of the system due to their insignificant influence;

– the losses of pressure at the LH flow are considered only for the cryogenic pipleline that connects reservoir 1 and jet pump 3; we also disregard hydrolosses in the remaining pipelines because of their insignificant influence on the results of calculations;

– calculation of the attainable parameters of jet pump 3 is carried out with the aid of the procedure, represented in [11];

– calculation of the attainable parameters of JCL 4 is performed with the aid of the procedure, represented in [10].

At the assigned temperature in the tank and the known heat capacity, stationary mode of thermostating can be realized in the modernized pressurized scheme by selecting pressure at the JCL nozzle exit section. Thermal and hydraulic problems are interconnected. A system of equations that describe stationary mode of thermostating takes the following form:

$$T_A = f_1(p_1, T_1, p_A, G_A); \quad (1)$$

$$p_A = f_2(p_1, T_1, T_A, G_A); \quad (2)$$

$$T_{JP} = f_3(p_A, T_A, G_A, p_T, T_{EX}, G_T); \quad (3)$$

$$p_{JP} = f_4(p_A, T_A, G_A, p_T, T_{EX}, G_T); \quad (4)$$

$$T_{IN} = f_5(p_{JP}, T_{JP}, p_{EVAP}); \quad (5)$$

$$p_{JCL} = f_6(p_{JP}, T_{JP}, p_{EVAP}); \quad (6)$$

$$G_{EVAP} = f_7(p_{JP}, T_{JP}, p_{EVAP}); \quad (7)$$

$$G_{JCL} = f_8(p_{JP}, T_{JP}); \quad (8)$$

$$G_{JCL} = G_A + G_T; \quad (9)$$

$$G_T = G_{JCL} - G_{EVAP}; \quad (10)$$

$$p_{JCL} \geq p_T; \quad (11)$$

$$N_T = G_T\left(i_L(p_T, T_{IN}) - i_L(p_T, T_{EX})\right). \quad (12)$$

Here:

– "1" designates the LH parameters in reservoir 1;

– "A" – parameters of high pressure LH at the input to active nozzle of liquid jet pump 3;

– "T" – parameters in thermostating fuel tank 6;

– "JP" – parameters at the output from jet pump 3;

– "JCL" – parameters at the output from diffuser of JCL 4;

– "EVAP" – parameters in vapor discharge manifold of JCL 4;

– T_{IN} – temperature of LH input to the thermostating system (temperature at the output from tank 6);

– T_{EX} – temperature of LH output from the thermostating system (temperature at the input to tank 6);

– G_T – LH consumption at the input to thermostating tank 1.

In the system of equations (1)–(12):

– functions f_1 and f_2 approximately describe thermal and hydraulic characteristics of the cryogenic pipleline that connects reservoir 1 and jet pump 3; we used empirical dependences of losses in pressure and heat flows on the mass consumption of cryogenic liquid in the following form:

$$p_A = p_1 - C_{PX} G_A^2,$$

$$i_L(p_A, T_A) = i_L(p_1, T_1) + \frac{C_{TX} C_L}{G_A},$$

where i is the specific enthalpy of parahydrogen; C_L is the mean heat capacity of liquid parahydrogen in the range of temperatures T_1–T_A; empirical coefficients for calculating the losses of pressure and heat flows

$$C_{PX} = \frac{\Delta p_0}{G_0^2},$$

$$C_{TX} = \Delta T_0 \, G_0$$

are obtained as a result of processing experimental data for the parahydrogen flowing in the system 17G24S. At the consumption of liquid parahydrogen G_0=50 kg/s, pressure losses Δp_0 reached 50 kPa, heating of liquid ΔT_0=0,8 K. During the motion of liquid parahydrogen, self-similar flow mode is realized in the pipleline, hence, for calculating pressure losses, we take quadratic dependence on velocity and, therefore, on the mass consumption of cryo-component;

– functions f_3 and f_4 are determined by the procedure for calculating the attainable parameters of jet pump 3 [11];

– functions f_5, f_6, f_7 and f_8 represent dependences of the JCL parameters, calculated with the help of procedure [10].

Condition (11) expresses the peculiarity of functioning of the JCL diffuser, connected with the position of the sealing-condensation jump depending on counterpressure after the diffuser.

A straight problem is solved when calculating the characteristics of jet pump 3 and JCL 6: the assigned geometry of flow part makes it possible to determine the attainable parameters of jet apparatuses, refined by using empirical coefficients.

When calculating the parameters of multiphase flows, we used a set of subprograms for the calculation of thermophysical properties coefficients of cryogenic liquids (parahydrogen and nitrogen) NIST REFPROP 8.0 that uses the Benedict-Webb-Rubin equation of state.

The Newton method, realized with the aid of the subprograms library IMSL in the FORTRAN 90 programming language, was used for solving the system of nonlinear transcendental equations (1)–(12).

To close the system of equations (1)–(12), it is necessary to assign the following parameters, which were obtained from [1–4]:

– temperature of the component, diverted to the thermostating system from the fuel tank of CR "Energy" T_{EX};

– pressure p_T in the fuel tank of CR "Energy";

– pressure at the JCL nozzle exit section (in vapor pipe) p_{EVAP};

– pressure p_1 and temperature T_1 in high pressure LH reservoir 1.

Pressure at the JCL nozzle exit section (in the vapor pipe) p_{EVAP} determines the cooled LH flow temperature, returned to the fuel tank of CR "Energy". A special feature of the work of both JCL and the jet liquid pump is a relatively narrow range of working expenditures, determined by the fixed geometry of the flow area of jet devices. That is why, when profiling JCL and the jet liquid pump, it is desirable to provide alignment of their pressure-consumption characteristics. An increase in the consumption of recirculating LH can be realized only through an increase in pressure at the JCL input, which, it turn, can be achieved only by increasing the rate of active flow in the jet liquid pump. However, there must also be observed the equality of consumption of the feeding flow of high pressure LH from the reservoir and the consumption of vapor, diverted from the JCL vapor pipe, since, at thermostating, it is unacceptable to change the amount of cryo-component, filled in the tank. As a result, the task of heat removal from the thermostatically controlled tank is solved mainly by changing the degree of cooling, which depends on the pressure at the JCL nozzle exit section p_{EVAP}. This control method has its specific boundaries as well. At large values of pressure p_{EVAP}, which correspond to low magnitudes of removed heat N_T, the LH pressure at the JCL output becomes insufficient for returning the component to the fuel tank. At low pressure at the JCL nozzle exit section, the larger thermal capacity N_T is removed, but the consumption of high pressure gaseous nitrogen in ejector system 5 becomes unacceptably large.

Underlying the program for calculating the static characteristic of the thermostating process of the modernized pressurized system (Fig. 3) is the following algorithm for calculation. The following data are assigned as the initial: pressure in the fuel tank p_T and temperature of discharge of "hot" LH from the fuel tank T_{EX}, pressure at the JCL nozzle exit section p_{EVAP}, pressure p_1 and temperature T_1 of high pressure LH in reservoir 1. Then pressure p_{JP} and T_{JP} at the JCL input are assigned in the first approximation. This makes it possible, at the known p_{EVAP}, to determine consumption of LH G_{JCL} through the JCL nozzle, pressure p_{JCL} and temperature T_{IN} at the JCL output, vapor consumption in the JCL vapor pipe G_{EVAP}. The feeding expenditure of LH from reservoir 1 G_A is taken as equal to the consumption of removed vapor G_{EVAP}. This makes it possible to determine parameters of the LH feeding flow at the input of active nozzle of the jet liquid pump (p_A and T_A) taking into account hydraulic losses and heat flows in the main line that connects reservoir 1 and the jet liquid pump. The known parameters at the input of active (p_A, T_A and G_A) and passive (p_T, T_{EX} and G_T) nozzle of the jet liquid pump allow us to determine the attainable parameters at the JCL output and at the input, respectively, which can be used for fulfilling the following approximation.

LH flow rate G_{JCL}, directed to the JCL input, is determined by the method of sequential approximations because, in the course of iterations, we also refine the magnitude of hydraulic losses and warming-up of the high pressure LH feeding. In this case, the flow parameters in all characteristic sections of the system are refined simultaneously. Then we calculate the magnitude of heat flows to the CR fuel tank, it is the same as thermal power of the thermostating system N_T.

The procedure for calculating the attainable parameters of gas jet ejector was used for the calculaton of consumption of gaseous nitrogen in ejector system 5 [11]. Initial data for the calculation (temperature, pressure and passive flow rate) were obtained from the solution of system of equations (1)–(12), but the problem was solved independently.

Fig. 4 displays LH consumption, which circulates in the thermostating system (G_T), and LH expenditures for cooling in JCL (G_{EVAP}) depending on pressure at the JCL nozzle exit section p_{NEX}. Calculation was performed at the fixed values of temperature T_T and pressure p_T in the CR fuel tank, as well as temperature T_1 and pressure p_1 in the reservoir RS-1400/1,0. We examined the use in the structure of the thermostating system of the JCL with flow area width b=25 mm (Fig. 4, *a*), b=40 mm (Fig. 4, *b*), as well as simultaneous use of two JCLs: b=25+40 mm (Fig. 4, *c*).

Fig. 5 displays thermal power of the thermostating system N_T and consumption (G_{EJ}) of high pressure gaseous nitrogen, used by ejector system 5, depending on the pressure at the JCL nozzle exit section p_{NEX}. Calculation was conducted at the same parameters of the working process and geometry of the JCL flow area, which are given for the values of temperature T_T and T_1, pressure p_T and p_1 represented in Fig. 4. We also assigned temperature T_{EJ} and pressure p_{EJ} of active flow of the ejector system.

It is obvious that the assigned thermal power can be removed only through a change in pressure at the nozzle exit section p_{NEX}, since the mass flow rate of cryogenic liquid in JCL (G_T) changes insignificantly – not exceeding 3 %. As a consequence, the assigned thermal power of the thermostating system with JCL can be provided for while operating either one of JCL or two JCLs simultaneously. On the other hand, we should note the limited, in comparison with the surface heat exchangers, possibility of regulating the cooling process via the vaccuuming of the JCL nozzle exit section. The left boundary of operating region is determined formally by the parameters of triple point of cryogenic working medium, actually – by operational characteristics of the ejector system, which creates rarefaction. This is explained by a disproportionate increase in the rate of active flow in the ejector at the increase in the degree of rarefaction.

Fig. 6, 7 display analogous dependences for G_T, G_{EVAP}, N_T and G_{EJ} depending on temperature T_T of LH removal from the CR tank. Calculation was performed at the same parameters in the reservoir RS-1400/1,0 and pressure p_T in the thermostatically controlled tank, as well as temperature T_{EJ} and pressure p_{EJ} of active flow of the ejector system. We registered as well pressure at the nozzle exit section p_{NEX}. Similar to the preceding case, we obtained analogous monotonic dependences. Of interest here is a significant increase in thermal power of the thermostating system, explained by an increase in the difference in temperatures when removing and returning the liquid hydrogen in the CR tank.

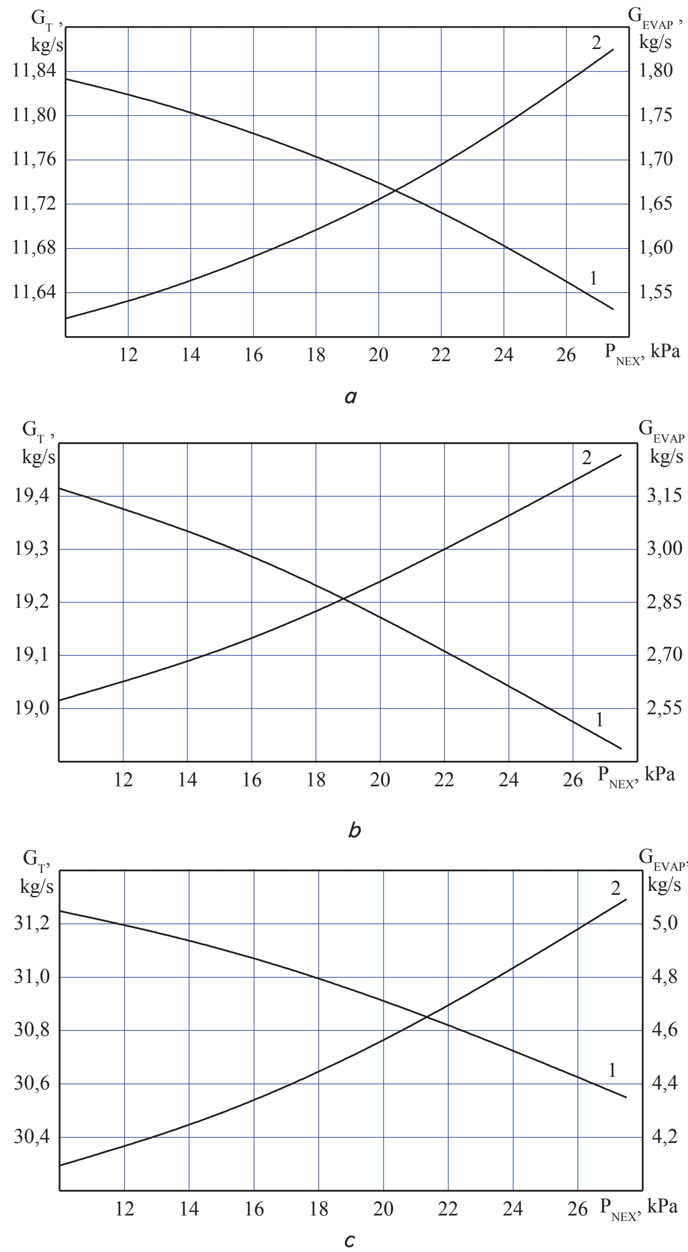

Fig. 4. Consumption characteristics of the thermostating process of the CR "Energy" LH tank with the help of the modernized pressurized filling and thermostating system: p_T=0,225 MPa; T_T=19,5 K; p_1=1,0 MPa; T_1=21,8 K; 1 – G_T; 2 – G_{EVAP}; *a* – b=25 mm; *b* – b=40 mm; *c* – b=25+40 mm

The right boundary of working region is connected to special features of the JCL working process. With an increase in pressure at the JCL nozzle exit section, the flow speed at the nozzle exit section decreases and, ultimately, the attainable pressure after the JCL diffuser. That is why, pressure at the nozzle exit section will correspond to the right boundary of the working zone, at which the estimated pressure after the JCL diffuser will not provide for returning the cooled liquid to the thermostatically controlled fuel tank. It should be noted that going beyond the right boundary of the working zone in reality does not lead to disrupting the JCL operation, since, in this case, the JCL diffuser reaches the pre-limit operating mode when a condensation jump leaves the diffuser throat. As a result, the flow pattern changes and volumetric steam content of the flow at the diffuser input, which leads to the increase in pressure after the diffuser, decreases consumption of the cooled liquid. In this case, the JCL parameters at the diffuser under the pre-limit operating mode cannot be calculated using the existing program for calculating the JCL characteristics.

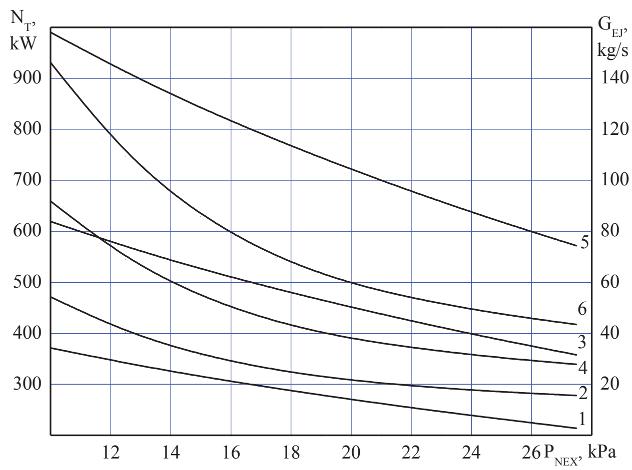

Fig. 5. Characteristics of the thermostating process of the CR "Energy" tank with the help of the modernized pressurized filling and thermostating system: p_T=0,225 MPa; T_T=19,5 K; p_1=1,0 MPa; T_1=21,8 K; p_{EJ}=1,0 MPa; T_{EJ}=323 K; 1, 3, 5 – N_T; 2, 4, 6 – G_{EJ}; 1, 2 – b=25 mm; 3, 4 – b=40 mm; 5, 6 – b=25+40 mm

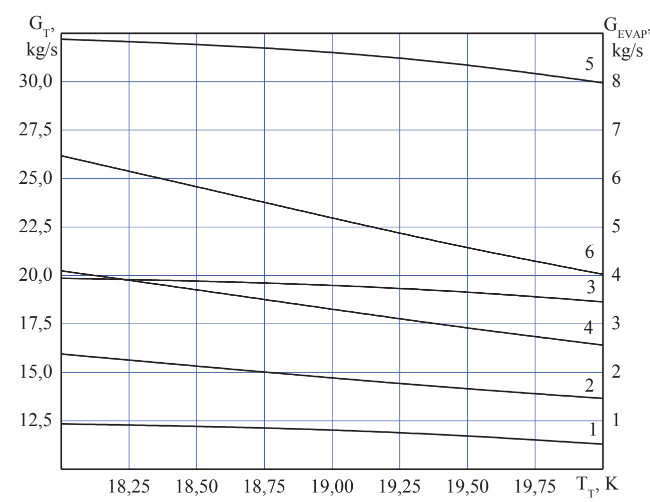

Fig. 6. Consumption characteristics of the thermostating process of the CR "Energy" LH tank with the help of the modernized pressurized filling and thermostating system: p_T=0,225 MPa; p_{EJ}=1,0 MPa; T_{EJ}=323 K; p_1=1,0 MPa; T_1=21,8 K; p_{NEX}=20 kPa; 1, 3, 5 – G_T; 2, 4, 6 – G_{EVAP}; 1,2 – b=25 mm; 3, 4 – b=40 mm; 5, 6 – b=25+40 mm

Let us compare consumption characteristics of the process of thermostating the base system 17G24S [2–4] and the modernized pressurized system. As the evaluation criterion, we accept the maximum period of thermostating the fuel tank of the CR "Energy" block 'C' after completing the filling. In the analysis, we examine the processes of cooling the system, filling and thermostating as it is. In this case, it is considered that four reservoirs RS-1400/1,0 contain 372 t of LH. For the regime of thermostating, we accept removal temperature of "warm" LH from the fuel tank T_T=19,5 K, refrigerating capacity of the system (thermal power, removed from the tank) N_T=720 kW. The LH consumption when filling the reservoirs RS-1400/1,0 was not considered since it must not change in modernizing the system. Decrease in the mass of reservoirs and, accordingly, consumption of the cryo-component for their cooling, is possible only when designing new structures with low operating pressure. Results of comparison are represented in Table 1.

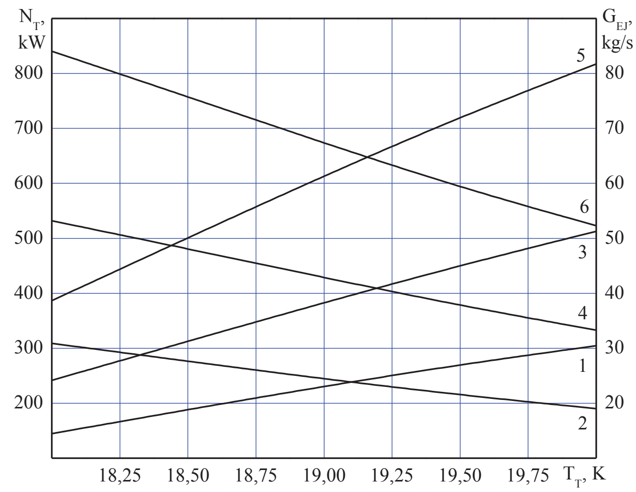

Fig. 7. Characteristics of the thermostating process of the CR "Energy" LH tank with the help of the modernized pressurized filling and thermostating system: p_T=0,225 MPa; P_{EJ}=1,0 MPa; T_{EJ} =323 K; p_1=1,0 MPa; T_1=21,8 K; p_{NEX}=20 kPa; 1, 3, 5 – N_T; 2, 4, 6 – G_{EJ}; 1,2 – b=25 mm; 3, 4 – b=40 mm; 5, 6 – b=25+40 mm

Table 1

LH consumption when performing the operations of cooling, filling and thermostating of the CR "Energy" fuel tank using the system 17G24S and the modernized pressurized system with the use of JCL

Parameters	System 17G24S	Modernized system
Total capacity of 4 reservoirs 1400/1,0, t	372	372
LH consumption for cooling the system's elements, t	27,4	6,8
LH consumption for filling the fuel tank, t	104	104
LH consumption for cooling at filling, t	8,32	14
High-pressure hydrogen, remaining in reservoirs upon completion of the work, t	32,27	32,27
LH expenditures for evaporation, t/h	10,73	16,42
Hot LH release, t/h	15,76	0
Attainable thermostating time, h	7,55	13,1

5. Discussion of results of numerical study of the filling and thermostating processes of CR fuel tank

When running LH cost analysis in the preparation for the CR launch, we should be looking at both the functioning peculiarities of starting complexes of analogous designation as whole and special features of using JCL. Thus, replacing the heat exchanger-coolers by using JCL and changing the scheme of the cryo-component flow from the semiclosed to the closed made it possible to decrease the LH consumption for cooling the structure before the operation of filling. On the other hand, specific consumption of LH in JCL is larger in comparison with the original system 17G24S because of the removal of small drops of the cooled liquid together with the removed vapor.

When considering these factors only, the use of JCL is expedient when the thermostating period does not exceed 2,5 hours.

If we examine the peculiarities of functioning of starting complexes (periodicity of launches, intervals between launches), then the benefits of JCL appear more obvious. The semiclosed thermostating circuit, applied in the original system 17G24S, implies returning a part of “warm” LH from the thermostatically controlled fuel tank to the reservoir RS-1400/1,0, vacated after the filling.

Theoretically, this part of LH consumption might be used for subsequent operations and it does not constitute irrecoverable losses. However, when returning, its additional preheating occurs during heat exchange with the high pressure LH counterflow in heat exchanger 3 (Fig. 1), as well as heat exchange with the environment. As a result, returned LH enters the reservoir in the overheated state, which makes its use without precooling impossible. To provide for the return to the reservoir, it is also necessary to lower pressures in it, because, by the point of completion the process of LH displacement from the reservoir, it still contains 8,07 t of gaseous hydrogen at temperature not below 25 K and pressure 1,0 MPa. Hydrogen through the drainage system is discarded into the atmosphere. Additional problems may as well occur in the course of repeated switching the system of cryogenic pneumo-valves, which is why repeated connection of reservoirs RS-1400/1,0 in the process of thermostating is not implied. Therefore, “warm” LH that remained after the filling and thermostating may be used for subsequent operations; however, it is not possible to prolong the fuel tank thermostating process using it. At the same time, insignificant portion of repeatedly used LH, with regard to the known peculiarities of its transportation and storage, as well as to relatively low degree of the launching equipment load, makes this particular process uneconomic. Thus, the modernized pressurized system of filling and thermostating based on JCL makes it possible to prolong the period of maintaining the starting complex ready for launch on by 73 %.

6. Conclusions

The possibility and expediency of using JCL is proven in the systems for rapid cooling of the cryogenic liquids of starting complexes of space carrier rockets.

We developed the procedure for calculating the process of thermostating by cooled hydrogen of the CR “Energy” fuel tank in the modernized pressurized system of filling and thermostating and obtained consumption characteristics of the thermostating process of the CR “Energy” fuel tank with the use of the modernized pressurized system: dependences are determined of the consumption of cryogenic liquids at the variation in temperature of the component removal from the thermostatically controlled tank in the interval 18–20 K, pressure at the JCL nozzle exit section in the interval 10–30 kPa and the removed thermal capacity to 1 MW.

We determined the useful effect from applying JCL in the structure of the system for filling and thermostating of the CR fuel tank by supercooled hydrogen, which manifests itself in LH saving or increasing the period of tank thermostating when preparing for launch by 73 % during standard filling with LH.

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