Increase of Refueling Systems Efficiency of Rocket Launching Sites by Utilization of Cold Energy of Cryogen

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Abstract. An important point in the use of cryogenic substances is their storage and transportation taking into account their phase state. Cryogenic substances can be used in liquid, gaseous and solid state. In all cases, it is possible to utilize the cold energy potential of the cryogen, either to reject heat from the cooling object during its regasification, or to obtain mechanical work and / or electricity. Therefore, the actual task is to improve the efficiency of rocket launching sites by using cold energy of cryogenic substances.

1. Introduction

The implementation of flight to outer space in addition to creating spacecraft and rocket requires solving many complex scientific and technical problems in preparation for the launch. A complex of such problems include production, transportation to the launching site, storage with minimal losses of cryogenic components of rocket fuel and liquefied process gases, as well as refueling fuel tanks of carrier rockets and booster blocks.

The idea of using the cold energy of cryogenic liquids has recently become more widespread [1-5]. This is primarily due to the increasing volumes of production of cryogenic substances, as well as the general trend of energy saving and the energy potential existing in the cryogen in the form of previously used energy for its liquefaction.

The main advantage of using gases in the cryogenic-liquefied state is the convenience of their storage, as well as transportation and consumption (including motor fuel for vehicles). At one of the steps of its application gasification is performed – transformation from the liquid state into the gaseous one via environmental heat supply. It is recognized, that the use of environmental heat is not an energy consuming process. However it is worth considering, that for LNG liquefaction some substantial energy was spent earlier (about 1kW·h of power per 1 kg of LNG).

The rapid development of the economy, industry and transport in the last 25-60 years, associated with scientific and technological progress, led to a serious increase in energy consumption and, as a result, increase of consumption of hydrocarbon fuels. The most promising fuel is cryogenic fuel - LNG, consisting mainly of methane, which allows to solve the problems of shortage of hydrocarbon fuel. The volumes of production, transportation and consumption of this gas are growing at a rapid pace every year. A study by the International Energy Agency shows that the volume of international trade in liquefied natural gas will reach 40% of total natural gas production in 2020, and the annual
growth rate will be 2% - 3%. LNG consumption will increase to 10% in China, moreover, LNG imports will grow by more than 3 times [6-7].

The estimated loss of cold energy in the cryogenic systems of rocket launching sites shows that the total value of the power of cold energy losses is about 9 MW. The total available work with the use of this energy in the effective cycle of the heat engine will be 156 MW · h.

Low temperatures of cryogenic liquids cause inevitable heat inflows from the environment, which in combination with small heat values of phase transitions, as well as a small range of existence in the liquid state, and they lead to a continuous change in their parameters, enhance the possibility of phase transitions and cryogen losses.

In this connection, the development of methods for the calculation, design and testing of storage systems and transportation of cryogen at launching sites using its cold energy to generate additional energy and improve operational efficiency is an urgent task.

2. Reservoir with cryogenic filling and calculation of its working processes

As shown above, thermal compressing is the most effective way of cold energy storing of cryogen [5]. Therefore, one of the most important elements in power plants using cold energy are cryogenic reservoirs. Particular interest is the tank of high pressure, in which the cryogen can be filled, regasified and accumulate energy of pressure. Such tank can be a reservoir with cryogenic filling (Figure 1)[5,8].

![Figure 1. The structural design of the reservoir with cryogenic filling](image.png)

A feature of this tank is that it can be charged with both a gases and a cryogen. In the case of refueling reservoir with cryogenic filling (RCF) with a gases it works as a normal high-pressure tank, and in the case of filling with a cryogenic component equal in mass, gasification takes place already inside the reservoir, which allows refueling the RCF at lower pressures. The internal thermos volume for the cryogenic component prevents thermal shocks and softens the conditions for thermocyclic strength of the structure.

3. Physico-mathematical model of the processes in RCF

The behavior of the working fluid in the RCF is considered when the liquid phase of the cryogenic substance is discharged from the thermos volume, taking into account the heat inflow from the environment.

After filling of cryogen into the internal (thermos) volume of the RCF (Fig. 2) with heat inflow from outside, the behavior of the liquid and gas in the gas cavity may be different. The physical processes in such a system are difficult to predict, and they will depend not only on the design of the reservoir, but also on the initial state of the tank and the external conditions. In the case of evaporation of a liquid and its inflow into the gas cavity, the heat supplied to the gas is determined by the difference between \(dQ_c\) and \(dQ_l\). It is obvious that for a stationary process of heat transfer by heat conduction \(dQ_c = dQ_l = dl_c\). In the case of a quasistationary (in the time interval \(\Delta t\)) process during
the inflow of cold mass $dm_x$ part of heat $dQ_c$ will be spent on changing the internal energy of the incoming mass of gas $dm_x$.

$$dQ_c - dQ_l = dU_x.$$  

(1)

This process is similar to that considered by V.P. Isachenko [5] in the problem of the thermal conductivity of a porous wall with a stationary transit flow of liquid through the pores. In this case it is legitimate to make the same assumptions that the temperature of the main and newly incoming gas at the coordinate $r$ is the same, and the heat transfer can be represented as the thermal conductivity of the main gas and the heat exchange between it and the incoming gas masses $dm_{xr}$.

The change in the internal energy of the newly supplied mass of gas into each gas layer $dm_{xr}$ is defined as:

$$du_{xr} = dm_{xr} C_V r dr,$$

where $m_x = \int_m^m m_x(r) dr$.  

(2)

Here the definition of the distribution $m_{xr} = f(r)$, by analytical way is also very difficult and not accurate. Therefore, calculations were performed using real table values of the thermophysical properties of the working substance (nitrogen), which showed that the mass $dm_x$ entered in the gas cavity is distributed in each gas layer by volume $dV = 2\pi r dr$ almost equally.

![Figure 2. Scheme for the formulation of the problem and the development of processes for calculating algorithm in RCF](image)

So $dU_x$ is determined by the integral sum $du_x$ on all layers.

Taking into account the foregoing, the mass-weighted average value of the gas temperature in the gas cavity will correspond to the arithmetic mean value:

$$\bar{t} = \frac{t_c + t_l}{2}.$$  

(3)

Up to an average temperature level $\bar{t}$ the incoming mass of cold gas $dm_x$ is heated and the change in its internal energy as a part of the change in the internal energy of the whole mass of gas in the cavity will be:

$$\Delta U_x = dm_x (C_V \bar{t} - C_V t_l),$$  

(4)

where values $C_V$ are taken at appropriate values $t$.

Thus, for a considered point in time at a given linear gas temperature distribution along the radius it is possible to determine $dQ_c$ and $dU_x \approx \Delta U_x$.

The equation of energy for a gas cavity with an external heat input and the flow of a mass of gas from the liquid cavity of the tank will be:

$$dQ_{amb} + dQ_c - dQ_l + i_x \cdot dm_x + ig \cdot dm_g = dU_x,$$

(5)
where \(dQ_c - dQ_l\) is heat which is equal to the difference of the input and output heat flow and it goes to \(dU_x\), such

\[
dQ_c - dQ_l = dU_x, \tag{6}
\]

\(dU\) – change of internal energy of gas in the cavity due to external heat and incoming cold gas mass.

Thus, \(dU\) as the total differential can be defined as follows:

\[
dU = C_v \cdot m \cdot dT + C_v \cdot T \cdot dm_x, \tag{7}
\]

where \(m\) and \(T\) respectively, the mass and the gas temperature in the gas cavity.

Substituting (6) into (5) gives the following equation:

\[
dQ_{\text{opt}} + dU_x + i_x \cdot dm_x + i_r \cdot dm_r = dU \tag{8}
\]

or taking into account (7):

\[
dQ_{\text{amb}} + dU_x + i_x \cdot dm_x + i_g \cdot dm_g = C_v \cdot m \cdot dT + C_v \cdot T \cdot dm_x. \tag{9}
\]

4. Algorithm for calculating the parameters in RCF with the liquid phase rate flow of the cryogen

Based on the above ratios, an algorithm was developed and a calculation program was compiled.

The first stage of the work consisted in setting up a "block of auxiliary procedures," in which variables were placed. Determination of it can be made through analytic relationships and two-parameter functions.

After that, a number of parameters were set, such as: the outer and inner diameters of reservoir, the length of reservoir, the initial pressure in reservoir, the initial temperature of reservoir wall, etc.

Next - the implementation of the cycle, which includes:

- first initialization of all cycle variables; check conditions for continuation of a cycle or exit from it, depending on the chosen "cyclicity" operator; execution of the sequence of operations in the cycle - the body of the cycle; updating cycle variables after each iteration

At the beginning of each cycle, the cyclicity condition are checked, taking as a basis the data obtained as a result of the previous iteration, the program updates the variables and initializes them as first ones for the subsequent cycle, or completes the calculation by redirecting to the output form and plotting.

Also during the calculation:

- the time \(\Delta t\) was chosen as the step; the temperature and mass of the gas, as well as its specific volume in the gas cavity, the pressure, the wall temperature of the tank, the temperature of the liquid and the total volume realised from the liquid in the thermos are calculated twice during one iteration at the beginning of the cycle \([j]\) and at \([j+1]\); the value of the wall temperature is determined on the basis of the loss of enthalpy of the reservoir wall, and is refined from the change in internal energy in the gas cavity by the inflows of low-temperature vapors \(dm_h\) from thermos; the gas temperature at the beginning of the first iteration at \(j = 0\) assumes the average value between the wall temperature of the tank and the charged liquid, then at the end of the cycle, it recalculates after mixing with the incoming portion of the low-temperature gas from the thermos. The obtained value of the gas temperature will be taken for \(T_g\) at new calculation step; the pressure at the end of the cycle is determined by the two-parameter function of the specific gas volume \(v_{gg}\) and the adjusted values of the gas temperature \(T_{gg}\); the fluid temperature is refined according to the reference data in accordance with the pressure values in the new step; the refined value of each of the parameters or their value at the end of the cycle (after the time elapses) is taken as the initial value of the variable in the next cycle.

Based on the above algorithm, a program was written in the integrated software development environment – Embarcadero DelphiXE 5 under Windows 8.

5. Cryogenic pump-gasifier with RCF and power plant for obtaining additional energy

In the future, the use of a cryogen in the energy complex is necessary to carry out its gasification. During this process, the heat exchanger uses heat of the environment or specially supplied heat in the
gasifier. To reduce the gasification time, as well as to generate additional energy, this work propose to use a cryogenic pump-gasifier (Fig. 3).

The cryogenic pump-gasifier consists of two circuits: a gasification circuit and an additional energy generating circuit (steam power plant).

The device is operated as follows:

From RCF 1, when the valve 2 is open, the cryogen enters the gasification circuit. Passing through the plunger pump 3, the pressure of the cryogen increases, and it enters the heat exchanger-evaporator 4, takes heat from the working substance of additional energy generating circuit, and returns to RCF 1.

Work of additional energy generating circuit is carried out as follows. The working substance enters the heat exchanger-condenser 4, where it gives heat to the cryogen, and then it enters the pump 5. The pump 5 compresses the working fluid, as a result of which it is heated, and enters the heat exchanger-evaporator 6, in which it is completely gasified. The obtained gas enters the turbine 7, where the heat is converted into mechanical work, and then into electrical energy by means of an electric generator 8. The generated electric energy is stored in the battery 9. Electric energy is used to drive the plunger pump 3 and it goes to the electric consumers.

This system can work on various cryogens: nitrogen, oxygen, hydrogen, methane, helium. All these gases can be used for purging pipelines both for their cooling down, and for warming up, as well as for fuel.

Table 1. Estimation of the efficiency of the use of different working substances in the circuit for obtaining additional energy

|        | Renkin cycle | Briton cycle |
|--------|--------------|--------------|
|        | q1, kJ/kg    | q2, kJ/kg    | l, kJ/kg    | G, kg/s   | W, kW | ηt, % | q1, kJ/kg | q2, kJ/kg | ln, kJ/kg | G, kg/s | W, kW | ηt, % |
| Methane| 755          | 490          | 265         | 0,28      | 74,2   | 0,35  | 329      | 280      | 46        | 0,5    | 23    | 0,15  |
| Argon  | 156          | 125          | 31          | 0,88      | 27,3   | 0,2   | 77       | 63       | 20,4      | 2,37   | 48,4  | 0,18  |
| Ethane | 800          | 535          | 265         | 0,29      | 76,9   | 0,33  | 239      | 215      | 33,2      | 0,55   | 18,3  | 0,1   |
| Krypton| 141.5        | 98           | 43,5        | 1,32      | 57,4   | 0,31  | -        | -        | -         | -      | -     | -     |
| Neon   | -            | -            | -           | -         | -      | -     | 146      | 118      | 35,2      | 1,23   | 43,3  | 0,19  |

In the circuit for obtaining additional energy, it is possible to use power plants operating in the Rankine or Brighton cycle. On the basis of known calculation methods, the feasibility of such a solution was estimated for different working substances suitable for operating in such temperature regimes.

The general expression for the thermal efficiency of the cycle is

$$\eta_t = \frac{l_c}{q_1} = 1 - \frac{q_2}{q_1}$$

(10)

where $l_c$ – specific cycle work $q_1$ – amount of heat supplied to the working substance, $q_2$ - amount of heat rejected from the working substance.

The power produced by the turbine can be defined as

$$W = l_c \cdot G$$

(11)

where $G$ – consumption of working substance in the circuit for obtaining additional energy.

An estimate of the amount of additional electric energy that can be obtained is given in Table 1. Analysis of the calculation shows that it is most effective to use steam power plants operating in the Rankine cycle on methane or ethane.

Thus, the proposed technical solution will allow to reduce the gasification time of LNG in a reservoir, to obtain a high-pressure gas, and also to use cold energy of cryogenic substance to generate electric energy necessary for driving a plunger pump, as well as for another electrical consumers.

6. Cryogenic system for fuel cooling at launching sites of a rocket based on the RCF
Based on the methodology for calculating the processes occurring in the RCF, with the help of the developed program at the level of a numerical experiment, calculations of the main thermophysical parameters of the working fluid in the RCF, which is part of the fuel cooling system on the launching site, were performed.

In the liquid nitrogen filling system of the launching site [9-10], the fuel cooling mode is performed by supplying liquid nitrogen from the reservoir when nitrogen gas is supplied under pressure from the nitrogen gas storage. It is proposed in this system to use RCF as a pressure accumulator for nitrogen (Figure 4).

The change in the parameters in the tanks is shown in Figures 5 - 6.

In this case, the RCF refueling takes place with liquid nitrogen, which allows filling RCF at lower pressures, and its gasification takes place already inside the reservoir, allowing to obtain high-pressure gaseous nitrogen in RCF, which is part of the fuel cooling system at the launching site.

7. Conclusions

As a result of the theoretical studies, methodology and technique for the calculation, design and testing of RCF with a liquid phase flowrate of a cryogen has been developed.

The following results and conclusions were obtained:

1. A structural design of cryogenic pump-gasifier with RCF and power plant for obtaining additional energy is proposed;
2. Structural design of powerplants for obtaining additional electric energy at spacer rocket launching sites are proposed;
3. A physico-mathematical model of the processes in the RCF with a liquid phase flow rate of the cryogen was developed;
4. The calculation of the energy characteristics of power plants operating on the Rankine cycle and the Brighton cycle, which are part of the cryogenic pump-gasifier, is made and allows to increase its efficiency was made.
5. Analysis of calculations showed that the most efficient is a cryogenic pump-gasifier using a power plant operating on the Rankine cycle with the following working substances: methane (0.35% efficiency, the power produced by the turbine is is 74.2 kW) and ethane (efficiency 0.33 %, the power produced by the turbine is 76,9 kW).
6. The algorithm is developed, as well as the calculation program in the integrated software development environment – Embarcadero Delphi XE 5 for modeling thermophysical processes.

Figure 3. Cryogenic pump-gasifier

1 – RCF, 2 – valve, 3 – plunger pump, 4 – heat exchanger-evaporator, 5 – pump, 6 – heat exchanger-evaporator, 7 – turbine, 8 – electric generator, 9 – battery
Figure 4. Cryogenic system for fuel cooling at launching sites of a rocket based on the RCF: 1 - fuel reservoir; 2 - RCF, filled with liquid nitrogen; 3 - heat exchanger; 4 - barboter of nitrogen gas; 5 - gas reducer; 6 - pump; 7 - support armature; 8 - air heater; 9 - compressor; 10 - filter; 11 - fuel tank

Figure 5. Change in the parameters in the spherical reservoir used to cool the fuel in the launching site (RCF volume is 448 m³, the volume of the thermos container is 120 m³, the outer diameter is 9.5 m, wall thickness is 0.5 m, refueling weight is 88.3 tons of nitrogen, refueling temperature is 84 K, filling pressure is 0.2 MPa, consumption of liquid nitrogen is 2 kg/s)

Figure 6. Change in the mass of fluid and heat flows from the environment to the wall of a spherical RCF used to cool the fuel in the launching site (RCF volume is 448 m³, the volume of the thermos is 120 m³, the outer diameter is 9.5 m, the wall thickness is 0.5 m, refueling weight is 88.3 tons of nitrogen, filling temperature is 84 K, filling pressure is 0.2 MPa, consumption of liquid nitrogen is 2 kg/s)

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