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# FORMATION OF A MODEL FOR IMPROVING THE EFFICIENCY OF CRYOGENIC PUMPS FOR LIQUEFIED NATURAL GAS

# FORMIRANJE MODELA ZA POBOLJŠANJE EFIKASNOSTI KRIOGENIH PUMPI ZA UTEČNJENI PRIRODNI GAS

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**Keywords**

- cryocondensation pump
- process modelling
- liquefied natural gas
- pump speed
- equipment efficiency
- cryopanel geometry

*Abstract*

*The increasing need for energy and the need to ensure sustainable development and ecology of the environment places forward new requirements for improving the technology and increasing the production of liquefied natural gas (LNG). It is possible to solve such problems only by simultaneous involvement of mathematical, physical and technical, and technological methods. At the same time, the development of such optimisation solutions can be carried out for specific equipment, which will allow to increase the productivity and quality of LNG production technology as a whole. One of the key elements of LNG production process chain is cryocondensation. The equipment used in this process is subjected to a wide range of physical and chemical influences, and its design and operating principle have significant impact on LNG production. An important element of system operation which requires improvement is the rapidity of operation of the cryocondensation pump. The operation speed is conditioned by a large complex of interrelated and complicated processes: mass and heat transfer, phase transformations, continuous growth of the cryo-sediment, formation and constant change of the structure and thermophysical properties of the cryo-sediment. Besides, it is necessary to pump out not a single-component gas, but a multicomponent gas medium having different thermophysical properties. Understanding the nature of forces holding gas particles on the cooled surface, as well as the mechanism of cryocondensation capture of gas molecules is one of the most difficult problems of modern physics and the subject of numerous experimental and theoretical works. Fast performance of the cryocondensation pump determines the amount of useful product output and affects its quality. In this study we set a task to carry out mathematical modelling of the cryocondensation pump performance and analyse the factors affecting the process. Taking into account the obtained model, technical solutions that improve the quality of cryocondensation pump operation are formed.*

**Ključne reči**

- krio-kondenzaciona pumpa
- modeliranje procesa
- utečnjeni prirodni gas
- brzina pumpe
- efikasnost opreme
- geometrija krio-panela

*Izvod*

*Sve veća potreba za energijom i za obezbeđenjem održivog razvoja i ekologije sredine stavljaju u prci plan nove zahteve za poboljšanje tehnologije i porasta proizvodnje utečnjenog prirodnog gasa (LNG). Ovakve probleme je moguće rešavati samo istovremenom primenom matematičkih, fizičkih i tehničko-tehnoloških metoda. Osim toga, razvoj optimizacije ovakvih rešenja se može izvesti za specifičnu opremu, gde se dopušta povećanje produktivnosti i kvalitet u tehnologiji proizvodnje LNG u celini. Jedan od ključnih elemenata u lancu proizvodnog procesa LNG je kriogena kondenzacija. Oprema u ovom procesu trpi široki raspon fizičkih i hemijskih uticaja, a njen dizajn i princip funkcionisanja imaju značajan uticaj u proizvodnji LNG. Bitan element u sistemu rada koji zahteva poboljšanje je ubrzani rad kriogene kondenzacione pumpe. Brzina rada je uslovljena velikim kompleksom međusobno povezanih komplikovanih procesa: prenos mase i toplote, fazne transformacije, kontinualno nagomilavanje krio-sedimenta, formiranje i stalna promena strukture i termo-fizičkih osobina krio-sedimenta. Pored toga, potrebno je ispumpavanje ne samo jedne komponente gasa, već višekomponentne gasne sredine različitih termofizičkih osobina. Razumevanje prirode sila koje zadržavanju čestice gasa na rashlađenoj površini, kao i mehanizam izdvajanja molekula gasa kriogenom kondenzacijom, je jedan od najtežih problema savremene fizike i tema mnogih eksperimentalnih i teorijskih radova. Brze performanse krio kondenzacione pumpe utiču na količinu proizvoda i njegov kvalitet. Cilj rada je matematičko modeliranje performansi kriogene kondenzacione pumpe i analiza uticajnih faktora. Razmatranjem dobijenog modela, formiraju se tehnička rešenja za poboljšanje kvaliteta rada kriogene kondenzacione pumpe.*

## INTRODUCTION

The assigned task of modelling of cryocondensation pump performance and development of recommendations for its improvement at the initial stage requires the analysis of the technological process itself. Operation of pumps assumes three main modes of operation: cooling, regeneration and pumping. The first stage involves pre-cooling of the pumped fluid and condensation of components of mixture (water vapour or hydrocarbons), the second stage involves direct condensation of cryogenic liquid, and the third stage involves pumping. Temperature regimes of the first stage are 60-100 K, and in the second 10-20 K, /1/.

When designing cryogenic pumps, first of all, it is necessary to solve vacuum and engineering issues, i.e., to estimate the required pumping speed and working pressure, which gases will be released in the system more than others, what is the value of non-condensable components. It is necessary to determine the required pumping forevacuum system and so on.

Special attention should be paid to solving a number of cryotechnical problems, including the reduction of thermal load on the ‘cold’ part of the pump when the required pumping rate is reached. When designing cryopumps, it is also important to take into account the deformation of the materials used at low temperatures, which allows to ensure tightness of connections. It is also important to choose the method of cooling the cryopump, which determines its performance characteristics, /2/.

Thus, based on the analysis of cryovacuum requirements, it is necessary to select the design scheme of the pump and perform vacuum and thermal calculations. In the present study we consider the following indicators for cryogenic pumps: pumping capacity, operating temperature and value range, and pumping speed of the cryogenic pump. Pump capacity affects the scale of production in which a given cryogenic pump can be applied: low-tonnage (as a rule, piston cryogenic pumps are more common), medium-tonnage (piston or centrifugal pumps), large-tonnage (centrifugal pumps, more often submersible ones). The operating conditions of cryogenic pumps are greatly complicated by extremely low temperatures. The pumped agents in most cases maintain a liquefied state not only due to low temperatures, but also due to high pressures. Thus, liquefied natural gas is pumped at a pressure of 4-5 MPa and a temperature of minus 100-120 °C, /2/.

Due to the high vacuum, the operating pressure characteristic is often insufficient for cryogenic pumps, so three values are defined for this type of equipment: pump limit pressure, starting pressure of vacuum pump, and maximum backing pressure. The pump limit pressure is $p_{mp}$. This is the minimum pressure that the pump can provide, operating without the pumped object. The rapidity of pump action tends to zero when approaching maximum pressure. The maximum pressure of most vacuum pumps is determined by the gas emission of materials from which the pump is made, gas flow through gaps and other phenomena occurring in the pumping process. Starting pressure of a vacuum pump $p_S$ is the maximum pressure in the inlet cross-section of the pump at which it can start operation. The maximum backing pressure $p_{back}$ is maximum pressure in the pump outlet cross-section at which the pump can operate.

Speaking of pumping speed it should be noted that the advantage of this indicator is that it is determined by several parameters simultaneously. These parameters can be divided into two groups: characteristics of the vacuum system (sticking coefficient, amount of accumulated gas) and characteristics of the thermal system (pump insulation - surface temperatures). Consequently, pumping speed is a comprehensive indicator of cryogenic pump assignment.

Due to the fact that cryocondensation pump operation depends on a large number of factors and is difficult to formalise in a general way, it is required to introduce a number of assumptions for the simulation and to provide initial data for specific equipment. In the future, the obtained results can be interpreted for other cryocondensation pumps.

## BASIC ASSUMPTIONS AND INPUT DATA FOR MODELLING CRYOCONDENSATION PUMP OPERATION

When carrying out calculations of high-vacuum cryopumps it is necessary to introduce a number of assumptions. Let us define the gas flow mode as a molecular one. It is created under conditions of high vacuum and at this mode molecules practically do not interact with each other but collide only with pipeline walls. We will assume that the motion of gas molecules obeys Maxwell's law (the law of distribution of molecules by velocities). Also, in fact, we will not take into account the temperature resistance of the cryo-sediment (we will assume it to be negligibly small). To simplify the modelling, we will also assume that the properties of surfaces at the same temperature levels are identical. Due to the small influence in the simplified calculation, we will not take into account the heat flux due to condensation and the heat flux due to heat conduction, /3/.

Rapidity of the cryogenic pump is calculated by Eq.(1):

$$S_H = S_0 \nu \, , \tag{1}$$

where: $S_0$ is empirical value of the rapidity of vacuum pumps (depending on pump type); $\nu$ is correction factor for different types of vacuum pumps: $\nu = 4$ for sorption pumps, $\nu = 1.3$-$1.4$ for positive displacement pumps.

This method is used for an ideal vacuum pump. As a rule, a vacuum pump with a nominal rapidity greater than or equal to the design value is selected. That is $S_n \geq S_{ndes}$. As for the calculation for a cryocondensation pump (the type used in LNG pumping), the mathematical model for calculating the rapidity of this type of pump is presented below. It also takes into account the assumptions made earlier.

If we assume that the cryosurface is located in a medium in which the velocities of molecules are distributed according to Maxwell's law, then from the relations of the kinetic theory of gases, the theoretical value of the cryopump speed of action $S_T$ is determined by, (2):

$$S_T = \frac{1}{4} F \nu_a = 36.4 F \sqrt{\frac{T}{M}} \, , \tag{2}$$

where: $F$ is surface area of the cryopanel; $\nu_a$ is arithmetic mean velocity of molecules; $T$ is temperature of pumped gas; $M$ is molecular mass of pumped gas, /3/.

It should be emphasised that Eq.(2) does not take into account the dependence of the rapidity of cryogenic pump operation on the pressure of pumped medium, that is, according to the above formula, the pressure of the cryoagent can take infinitely low values. In practice, the limit of high vacuum created in the working chamber of the pump is always limited by the elasticity of the pumped medium. The more close to reality process of pumping by cryopump can be described by the following expression with already taken into account dependence of ultimate vacuum on vapor elasticity:

$$S'_H = S_T\sqrt{\left(1-\frac{p^*}{p}\right)} = 36.4\eta F\sqrt{\frac{T}{M}\left(1-\frac{p^*}{p}\right)}, \qquad (3)$$

where: $p^*$ is vapour pressure; $p$ is gas pressure; $\eta$ is capture ratio.

This equation shows that if the gas pressure is much higher than the elasticity of its vapor, i.e., when $p >> p^*$, the rapidity of the cryopump action is practically independent of the value of $p$, /3/. The rapidity of operation starts to decrease only when the pressure in the pumped object approaches the pressure of saturated vapour and becomes equal to zero when $p = p^*$. Dependence of vapour elasticity of some gases on temperature is shown in Fig. 1.

Using the nomogram, it is possible to trace the relationship between temperature and vapour elasticity: as the temperature increases, the vapour elasticity increases /4/. Consequently, in the cryogenic temperature range, vapour elasticity values ($p^*$) tend to minimum, which is confirmed by nomogram data. To determine the value of $p^*$ at a given temperature, it is necessary to find the point of intersection of the line of the corresponding temperature with the curve representing the dependence of vapour elasticity on temperature.

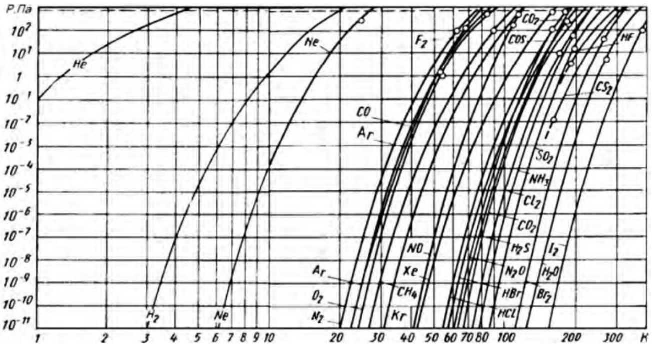

Figure 1. Dependence of vapour elasticity on the temperature of the pumped agent, /3/.

The calculation of the rapidity of cryogenic pump operation according to Eq.(3) must be started by setting the temperature value of the pumped medium, /5/. In this calculation it is assumed that all molecules that have interacted with the cryopanel are condensed. Consequently, the temperature of the pumped agent can be assumed to be equal to the temperature of the condensing surfaces.

An additional assumption in the calculations is that the crypanel does not significantly change the Maxwell distribution of gas molecules. Fulfilment of this condition is possible when the pressure value tends to a minimum and when the size of the condensing surface is much smaller than the size of the pump working chamber, /3/.

As initial data for the calculation, we will take into account the molecular weight of LNG in the amount of 16.07-17.07 kg/mol, as well as the temperature of the pumped agent of 200 K. Next, let us proceed directly to the modelling procedure.

## SIMULATION OF CRYOCONDENSATION PUMP OPERATION

During calculations, the pumping speed of the cryogenic pump is calculated for the sticking coefficient $\alpha$, the value which in practice varies from 0.1 to 0.8 (provided that the theoretical value of the coefficient can vary from 0 to 1, but cryopanels whose sticking coefficient is less than 0.1 are taken out of service, and cryopanels whose sticking coefficient values during operation are greater than 0.8 are not observed) /6, 7/. It should be kept in mind that the pumping coefficient directly depends on the temperature of the cryopanel (the lower the temperature, the higher the cryopumping coefficient). The average values of the pumping coefficient depending on the cryopanel temperature are given in Table 1.

Table 1. Averaged values of pumping coefficient depending on the cryosurface temperature, /9/.

| Pumping device | Cryocondensation pump | | | | |
|---|---|---|---|---|---|
| Surface temperatures (K) | 10 | 14 | 17 | 21 | 23 |
| $H_2$ | - | 0.5 | 0.48 | 0.4 | 0.37 |
| $CH_4$ | 0.8 | 0.6 | 0.4 | 0.2 | 0.1 |

In this case, the cryopanel is represented by a flat absorbing surface. The value of cryogenic plane capture coefficient is determined by the graph presented in Fig. 2, which demonstrates the variation of the capture coefficient of structures in the form of a flat absorbing surface. In this graph, the variables are the cryosurface pumping coefficient $\alpha$ and the size ratio $L/R$, /8/. To determine the inlet cross-sectional area of the pump, a centrifugal cryogenic pump from APD-IGC Cryogenics Inc. (Japan) is taken as an example, since this type of pump is the most frequently used in the world oil and gas practice (in LNG pumping) /9/. The cross-sectional area is 0.02895 m$^2$. Calculations are performed according to Eq.(3). Calculation results are presented in Table 2.

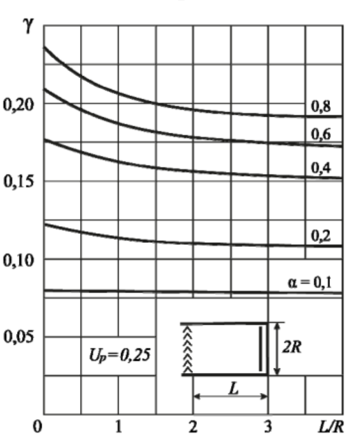

Figure 2. Cryosurface capture coefficient as a function of $L/R$ and pumping coefficient $\alpha$. $L/R$ is the ratio of geometric dimensions of the cryopanel.

According to calculation results, the following graphs are drawn: dependence of the rapidity of action on the surface temperature (Fig. 3), dependence of temperature on the geometric parameters of the cryopanel (Fig. 4), dependence of temperature on the capture coefficient (Fig. 5). These three groups of factors have the greatest influence on the operating characteristics of the cryopump. Thus, according to the calculations based on the developed model, it can be concluded that the cryocondensation rapidity parameter depends on the characteristics of both vacuum and thermal systems of the pump.

Table 2. Calculation results of the cryopump rapidity.

| Size ratio *L*/*R* | Pumping ratio | Capture ratio | Rapidity of operation ($m^3/s$) |
|---|---|---|---|
| 1 | 0.1 | 0.06 | 0.17051 |
| | 0.2 | 0.11 | 0.312602 |
| | 0.4 | 0.165 | 0.468902 |
| | 0.6 | 0.18 | 0.51153 |
| | 0.8 | 0.21 | 0.596785 |
| 2 | 0.1 | 0.06 | 0.17051 |
| | 0.2 | 0.105 | 0.298392 |
| | 0.4 | 0.155 | 0.440484 |
| | 0.6 | 0.177 | 0.503004 |
| | 0.8 | 0.195 | 0.554157 |
| 3 | 0.1 | 0.06 | 0.17051 |
| | 0.2 | 0.1 | 0.284183 |
| | 0.4 | 0.15 | 0.426275 |
| | 0.6 | 0.175 | 0.497321 |
| | 0.8 | 0.18 | 0.51153 |
| 4 | 0.1 | 0.06 | 0.17051 |
| | 0.2 | 0.08 | 0.227347 |
| | 0.4 | 0.145 | 0.412066 |
| | 0.6 | 0.17 | 0.483112 |
| | 0.8 | 0.175 | 0.497321 |

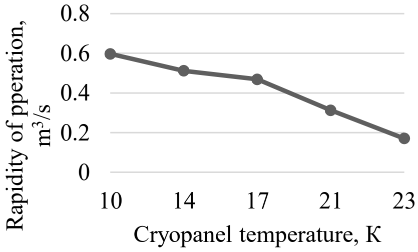

Figure 3. Dependence of pump speed on surface temperature.

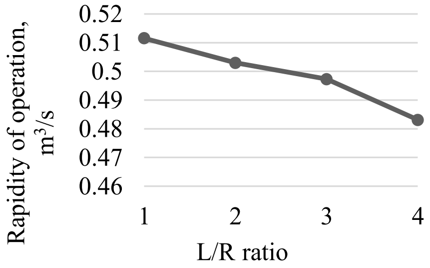

Figure 4. Dependence of pump speed on geometric parameters of the cryopanel.

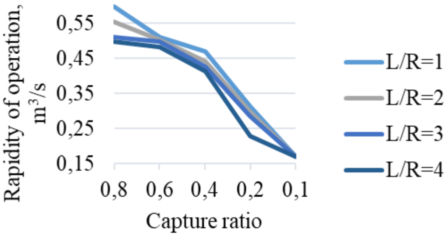

Figure 5. Dependence of pump speed on the capture ratio.

As the temperature of condensing surface increases, the rapidity of the pump decreases. It should be noted that the temperature range of the condensation stage varies from 10 to 20 K /10/, and, judging by the graph in Fig. 7, after passing the mark of 20 K, the speed of the pump action rapidly decreases.

Also based on the calculations we can conclude that the highest value of the calculated index is reached at the ratio of panel sizes equal to 1 and at the maximal capture coefficient. The received results require a comprehensive analysis, let's carry out an estimation of influence of the given factors on efficiency of work of the cryocondensation pump as a whole.

## ANALYSIS OF MODELLING RESULTS AND DEVELOPMENT OF RECOMMENDATIONS TO IMPROVE EQUIPMENT EFFICIENCY

According to the results of modelling, the dependence of the cryogenic pump rapidity on the parameters of both thermal and vacuum system is established. Among other things, it is noted that as temperature increases, the pumping speed of the cryogenic pump decreases significantly. This factor determines the importance of heat inflows to the condensing surface and determination of the most effective scheme of cryopanel location in the design of the considered type of equipment, Fig. 6.

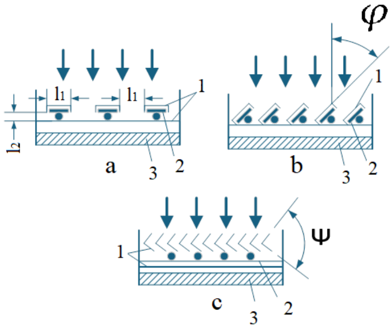

Figure 6. Location of cryopanels in the designs of cryogenic pumps: a) flat-slotted; b) inclined-slotted; c) chevron; 1- shield, 2- cryopanel, 3- pump casing, /13/.

Specific theoretical speed of operation (or specific theoretical speed of condensation) $S_T$ is determined by the gas flow /11, 12/. In the molecular flow regime this parameter is calculated by the following formula, Eq.(4):

$$S_T = 3.64\sqrt{\frac{T_r}{M}} \,, \tag{4}$$

where: $T_r$ is temperature of pumped agent; M is molecular weight.

The surface area of the cryopanel is determined by the following formula, Eq.(5):

$$F_n = \frac{S}{S_T P_n} \,, \tag{5}$$

where: $S$ is required pumping speed ($m^3/s$); $P_n$ is probability of molecules passage through the screen (determined by the location of screens in cryogenic pumps), /13/.

When designing cryogenic pumps, special attention is paid to optimising the design in terms of ensuring the minimal value of thermal inflows while maintaining the required values of pumping speed, /14/. This issue is solved by the choice of schemes of arrangement of condensing surfaces in the cryogenic pump, taking into account the provision of good access of the working agent to the cryopanel while maintaining effective protection from thermal radiation, /15/. There are three most common design schemes of cryogenic pump panels, their characteristics are presented in Table 3.

Considering that the ratio of working chamber dimensions $2r_K = h$, the diameter and height of the cryopanel are calculated by Eq.(6):

$$2r_K = h = \sqrt{\frac{F_n}{1.5\pi}}\,. \qquad (6)$$

The required pumping speed directly depends on the type of LNG production: small tonnage, medium tonnage, large tonnage. Based on the required capacity of different types of production, the following values of the required cryopump speed are selected:

- for low-tonnage production $S_T = 0.00576$ m$^3$/s;
- for medium-tonnage production $S_T = 0.1035$ m$^3$/s;
- for large-capacity production $S_T = 0.144135$ m$^3$/s.

Results of calculating the surface area of the cryopanels are presented in Table 4. The radius and height of cryopanels for different variants of their location depending on the type of LNG production are calculated by Eq.(6). The results of calculations are presented in Table 5.

Table 3. Characteristics of cryopanel layouts, /13/.

| Layout scheme | Geometric characteristic | | Probability passage of molecules |
|---|---|---|---|
| | Designation | Value | |
| Flat-slotted | l1/l2 | 0.080 | 0.090 |
| | | 0.125 | 0.122 |
| | | 0.250 | 0.134 |
| Inclined-slotted | φ (°) | 45 | 0.360 |
| Chevron | ψ (°) | 60 | 0.290 |
| | | 90 | 0.324 |
| | | 120 | 0.360 |

Table 4. Results of calculating the area of the cryopanel.

| Layout scheme | Probability passage of molecules | Cryopanel area (m$^2$) | | |
|---|---|---|---|---|
| | | light-tonnage | medium-tonnage | large-tonnage |
| Flat-slotted | 0.090 | 0.00704 | 0.12654 | 0.17622 |
| | 0.122 | 0.00520 | 0.09335 | 0.13000 |
| | 0.134 | 0.00473 | 0.08499 | 0.11836 |
| Inclined-slotted | 0.360 | 0.001761 | 0.031636 | 0.04406 |
| Chevron | 0.290 | 0.002186 | 0.03927 | 0.05469 |
| | 0.324 | 0.001956 | 0.03515 | 0.04895 |
| | 0.360 | 0.001761 | 0.03164 | 0.04406 |

Table 5. Results of calculation of radius and height of cryopanels.

| Layout scheme | Probability of passage of molecules | light-tonnage | | medium-tonnage | | large-tonnage | |
|---|---|---|---|---|---|---|---|
| | | $r_k$ (m) | $h$ (m) | $r_k$ (m) | $h$ (m) | $r_k$ (m) | $h$ (m) |
| Flat-slotted | 0.09 | 0.01933 | 0.03867 | 0.08196 | 0.16391 | 0.09671 | 0.19343 |
| | 0.122 | 0.01661 | 0.03321 | 0.07039 | 0.14078 | 0.08307 | 0.16614 |
| | 0.134 | 0.01584 | 0.03169 | 0.06717 | 0.13433 | 0.07926 | 0.15852 |
| Inclined-slotted | 0.36 | 0.00967 | 0.01933 | 0.04098 | 0.08196 | 0.04836 | 0.09671 |
| Chevron | 0.29 | 0.01077 | 0.02154 | 0.04566 | 0.09131 | 0.05388 | 0.10776 |
| | 0.324 | 0.01019 | 0.02038 | 0.04319 | 0.08639 | 0.05097 | 0.10195 |
| | 0.36 | 0.00967 | 0.01933 | 0.04098 | 0.08196 | 0.04836 | 0.09671 |

Obviously, the larger the area of cryopanels, the more efficient is the process of ‘capture’ and condensation of the pumped agent. However, the size of cryopanels, on the one hand, is limited by the overall dimensions of the pump itself and, on the other hand, by the thermal characteristics of the system /16, 17/, in particular, by the heat flux due to condensation on the cryopanels:

$$F_K = \gamma F_n \rho \frac{1}{\sqrt{2\pi R T_r}}, \qquad (7)$$

where: $F_K$ is heat inflow due to condensation on the cryopanel; $\gamma$ is condensation coefficient; $R$ is universal gas constant; $\rho$ is pumped medium density /13/. When selecting the size of cryopanels and their layout, it is necessary to choose the optimal variant - to provide the largest area of the cryopanel with the minimum possible heat flux, /18/.

We assume that the condensation coefficient of the cryopanel of the pump already in operation, taking into account the formed condensate layer, is $\gamma = 0.5$. LNG density is assumed to be $\rho = 440$ kg/m$^3$. In order to select the best arrangement of cryopanels, the heat flux due to condensation is calculated for each variant of their location depending on the type of LNG production, the calculations are presented in Table 6.

According to the results of correlation of the cryopanel area and heat flow to it, the boundary values are obtained, when passing beyond which the cryogenic pump operation efficiency significantly decreases, in particular, due to the increase in heat flow to the condensing surfaces, /19/.

According to the results of calculations, it was found that each of the schemes is effective only at certain values of heat inflow: the flat-panel scheme is effective at values of heat inflow up to 0.056 W/m$^2$, the inclined-panel scheme at values up to 0.168 W/m$^2$, the chevron scheme is effective at maximum values of heat inflow - up to 0.251 W/m$^2$. Depending on the volume of LNG production and cryopanel layout, a summary table of optimal, permissible and undesirable values of heat flux was formed (Table 7).

Table 6. Results of heat flow calculation (W/m$^2$).

| Layout scheme | Probability passage of molecules | light-tonnage | medium-tonnage | large-tonnage |
|---|---|---|---|---|
| Flat-slotted | 0.09 | 0.02145 | 0.38537 | 0.53667 |
| | 0.122 | 0.01582 | 0.28429 | 0.39590 |
| | 0.134 | 0.01440 | 0.25883 | 0.36045 |
| Inclined-slotted | 0.36 | 0.00536 | 0.09634 | 0.13417 |
| Chevron | 0.29 | 0.00666 | 0.11960 | 0.16655 |
| | 0.324 | 0.00596 | 0.10705 | 0.14908 |
| | 0.36 | 0.00536 | 0.09634 | 0.13417 |

Table 7. Recommendations for selecting the layout of cryopanels.

| Layout scheme | Geometric characteristic | | Heat inflow value (W/m$^2$) | | |
|---|---|---|---|---|---|
| | Designation | Value | light-tonnage | medium-tonnage | large-tonnage |
| Flat-slotted | l1/l2 | 0.080 | 0.02145 | 0.38537 | 0.53667 |
| | | 0.125 | 0.01582 | 0.28429 | 0.39590 |
| | | 0.250 | 0.01440 | 0.17883 | 0.36045 |
| Inclined-slotted | φ (°) | 45 | 0.00666 | 0.11960 | 0.26655 |
| Chevron | ψ (°) | 60 | 0.00596 | 0.10705 | 0.14908 |
| | | 90 | 0.00536 | 0.09634 | 0.13417 |
| | | 120 | 0.00536 | 0.09634 | 0.13417 |

Design of cryogenic pumps should be carried out taking into account the results of calculations aimed at optimisation of operating efficiency and reasonable choice of cryopanel configuration (condensing surfaces). Cryogenic losses should be minimised, for example, by reducing the reverse heat flow and increasing the efficiency of vapour condensation, /20, 21/.

Thus, the variants of cryopanel arrangement in the pump stage, the application of which is the most desirable, are highlighted in green colour. According to the table it is necessary to pay attention to the following:

- any of the existing schemes can be used in pumps for light tonnage LNG production, /21/;
- for medium-tonnage LNG pumps, the most optimal are the inclined-slotted and chevron design of panels, /22/;
- in large-tonnage LNG pumps, the largest area at minimal heat input is achieved only in the chevron layout, /23/;
- schemes recommended for use with rough surface of cryopanels are highlighted in yellow colour in the table, as rough surface increases the area of contact between the cryopanel and pumped medium, which increases pumping efficiency.

## CONCLUSIONS

Cryogenic pumps are specialised systems designed for moving liquids at extremely low temperatures. They operate under strict technical requirements due to the unique characteristics of working with liquids in a cryogenic state.

In this study, we analysed the operating conditions of cryogenic pumps and identified key indicators of their operational efficiency. We focused on the dynamic characteristics, particularly the speed of the pumps. Based on mathematical calculations, we derived functional dependences between the performance indicator and the parameters of thermal and vacuum systems in cryocondensation pumping units.

One of the main factors determining the efficiency of cryogenic pumps is the amount of heat transferred to the condensation stage. This has negative consequences for the performance of cryopanels. When the temperature of the cryopanels increases, the pumping efficiency of the pumped fluid decreases, emphasising the importance of carefully designing the condensing surfaces.

A generalised rule that is confirmed during the study is that increasing the area of the cryopanel improves the efficiency of the condensation process. However, this also leads to an increase in heat transfer to the cooled components. As a result of the research, methodological recommendations have been developed for optimising the placement of cryopanels in pumps used to pump cryogenic fluids. These recommendations are based on the concept of maximising pumping speed while minimising heat transfer and cover various pump types, including small, medium, and large tonnage units for LNG.

The proposed recommendations on cryopanel configuration and obtained boundary values can be implemented as part of developing a draft national standard for designing pumps used in LNG production. These findings will also be significant for establishing regulatory standards for cryogenic pump efficiency and serve as a basis for developing a testing methodology for LNG pumps. Overall, these results are an essential component of process quality management /24, 25/.

The use of the proposed recommendations for the design, manufacture and operation of cryogenic pumps would significantly improve their efficiency and reliability while reducing production costs. This is a crucial aspect of ensuring the efficient operation of gas liquefaction systems and a key element in the development of advanced cryogenic technology.

Furthermore, by taking into account the findings of this research, it is feasible to enhance the competitiveness of our products on the market by enhancing the performance of our cryogenic pumps. This would lead to increased customer satisfaction and trust in our products.

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