Calculation of the Energy Complex Based on a Steam Gas Installation Assessment of the Parameters of the Contour of the Auxiliary Steam Power Plant Installation

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Abstract. In this paper, we calculate the parameters of the energy complex on liquefied natural gas (LNG), which serves for the gasification of LNG with its further utilization in the circuit of a steam turbine plant, during operation of which additional electrical energy is generated. We evaluate the effectiveness of regasification of cryoproducts and evaluate the potential of using Cold Energy.

Various schemes of power plants using Cold Energy are considered. The parameters and characteristics of the combined-cycle plant consisting of the gas-turbine circuit and the steam-turbine circuit are calculated. The coefficient of cryoproduct energy return (liquefied natural gas) of the considered schemes is calculated and and based on the data obtained, the most optimal one is selected.

1. Introduction

In many systems of aerospace technology, transport, as well as in energy complexes for various purposes, cryogenic liquids are currently widely used.

When storing a cryoproduct, losses of the cryoproduct occur due to the lack of thermal insulation and heat leakage from the environment. During storage of the cryoproduct due to the ablation of the mass, its heat content changes. You can calculate the loss of low-temperature heat cryogenic product per day, lost during storage, according to the following formulas:

\[ \Delta m = m_k \cdot \frac{\Theta}{100} \]  \hspace{1cm} (1)

\[ Q_{eva} = \Delta m \cdot r + c_p \cdot \Delta m \cdot (T_k - T_o) \]  \hspace{1cm} (2)

where \( \Delta m \) - mass of evaporated cryoproduct per day, \( m_k \) - mass of stored cryoproduct; \( \Theta \) - loss of product from evaporation per day, \( \% \); \( Q_{eva} \) - low potential heat of evaporated cryoproduct; \( r \) - cryoproduct evaporation heat; \( T_k \) - cryoproduct temperature; \( T_o \) - environment temperature.

He evaporating cryoproduct has a rather high certain potential of low-temperature energy [1-2], which can be used as a “refrigerator” in a heat engine operating in the Carnot cycle (Figure 1). The loss of available energy \( L_{ava} \) per day, provided that the low-grade heat of the cryoproduct is used according to the Carnot cycle, is calculated as follows:
The solution to the problem of the loss of a cryoproduct (for example, for LNG) during its storage and, accordingly, the loss of its disposable low-grade heat can be a low-temperature power plant based on liquefied natural gas, during operation of which additional electrical energy is produced [3-4].

The proposed power plant can provide consumers with electrical and thermal energy. The combined-cycle plant includes the contour of the gas turbine and steam turbine plants. The use of this power plant allows for higher energy efficiency during storage of LNG [5].

The gas turbine unit contour includes a compressor (C), a combustion chamber (CC), a gas turbine (GT), and an electric generator (EG). The steam-turbine plant includes a waste heat boiler (HB), a steam superheater, a steam turbine (ST), a heat exchanger-condenser (EC), a condensate pump (CP), and an electric generator (EG).

The power plant is shown in Figure 2.

2. Calculation of parameters of the cycle circuit gas turbine installation
During evaporation, part of the LNG through the reducer enters the combustion chamber of a small-sized gas turbine unit. The compressor increases the air pressure and feeds it further into the combustion chamber. During the combustion of the air-fuel mixture in the combustion chamber, the

\[
L_{\text{adv}} = \frac{Q_{\text{adv}} \cdot \eta}{1 - \eta}
\]  
(3)

\[
\eta = 1 - \frac{T_2}{T_1}
\]  
(4)
The gas temperature increases. Next, the gas enters the turbine, where its expansion occurs, with the result that we obtain effective (mechanical) work on the turbine shaft. One part of the efficient work is spent on driving the compressor. Another part of the effective work, with the help of the generator is converted into electrical energy.

The initial data for the calculation is as follows:

The flow rate of the working fluid \( G_{CH4}=0.06 \text{ kg/s} \). Point 1: air pressure at the inlet \( p_{in}=0.1 \text{ MPa} \), temperature \( T_{in}=288 \text{ K} \).

The cycle of the gas turbine is shown in Figure 3:

![Figure 3. The gas turbine installation cycle in pv - coordinates.](image)

The specific volume is found from the equation of state of an ideal gas:

\[
p_1 \cdot v_1 = R \cdot T_1 \tag{5}
\]

where it comes from:

\[
v_1 = \frac{RT_1}{p_1},
\]

where \( R \) – gas constant:

\[
R = \frac{\mu R}{\mu}, \tag{6}
\]

\[
v_1 = \frac{RT_1}{p_1}, \tag{7}
\]

Point 4: (4-1) - isobar process of heat removal
Specific volume will be found from the equation of state of an ideal gas at point 4:

\[
v_4 = \frac{RT_4}{p_4}, \tag{8}
\]

Point 3: (3-4) – adiabatic expansion of the working fluid in a gas turbine GTP;

\( T_3 = 1500 \text{ K} \);

The ratio of the parameters of the adiabatic process:

\[
\frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{k-1}{k}}, \tag{9}
\]

where \( k \) - adiabatic index:

\[
k = \frac{c_p}{c_v}, \tag{10}
\]

\( c_p \) – is the mass heat capacity at constant pressure, \( c_v \) – is the mass heat capacity at constant volume.

According to the molecular kinetic theory:

\[
c_p = \frac{i+2}{2} R, \tag{11}
\]

\[
c_v = \frac{i}{2} R, \tag{12}
\]

where \( i \) – is the number of degrees of freedom of the molecule (\( i = 5 \) for a diatomic gas);

\( R \) – air gas constant.
Point 2: (2-3) – Isobaric process of heat supply in the combustion chamber of the GTP.

\[ p_3 = p_2 = 1.57 \text{MPa}; \]

(1-2) – Adiabatic air compression in a gas turbine compressor. The ratio of parameters in the adiabatic process:

\[ \frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} \rightarrow T_2 = T_1 \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}}, \]

Specific volume will be found from the equation of state of gas at point 2:

\[ v_2 = \frac{RT_2}{p_2}, \]

The values of average isobaric heat capacities are selected from tabular data.

Specific amount of heat applied per 1 kg of working fluid in a gas turbine unit:

\[ q_1 = c_p \cdot T_3 - c_p \cdot T_2, \]

Specific amount of heat abstracted from 1 kg of working fluid in a gas turbine unit:

\[ q_2 = c_p \cdot T_4 - c_p \cdot T_1, \]

Theoretical work of 1 kg of working fluid in a gas turbine unit:

\[ l_{0 \text{GTP}} = q_1 - q_2, \]

Fuel flow \( G_{\text{fuel}} = 0.06 \text{ kg/s} \), air flow \( G_{\text{air}} = 15 \cdot G_{\Sigma} = 0.9 \text{ kg/s} \).

Then the total flow rate \( G_{\Sigma} = 0.06 + 0.9 = 0.96 \text{ kg/s} \).

GTU power:

\[ W_{\text{GTU}} = l_{0 \text{GTP}} \cdot G_{\Sigma}. \]

3. Calculation of parameters of the cycle loop of a steam turbine installation

Exhaust gases leaving the gas turbine plant are fed to the waste-heat boiler, where part of the heat of the gases escapes with the flue gases and the other part enters the steam turbine. In the steam turbine, the expansion of gases occurs, resulting in effective mechanical work on the turbine shaft. This work with the help of an electric generator is transformed into electrical energy. The exhaust gases leaving the steam turbine enter the heat exchanger-condenser, where they are condensed — they change from a gaseous state to a liquid state. Next, from the heat exchanger, with the help of a pump-condenser, the liquid flows back into the waste heat boiler.

The cycle of the steam turbine installation is presented in Figure 4.
Then the turbine is equal to:

\[ L_T = i_1 - i_2 \]  (19)

Inlet and outlet heat:

\[ q_1 = i_1 - i_4 \]  (20)

\[ q_2 = i_2 - i_3 \]  (21)

Heat balance of the heat recovery boiler:

\[ G_T \cdot (c_T \cdot T_4 - c_T \cdot T_{fg}) = G_T \cdot (c_{pw} \cdot (T_{bw} - T_{in}) + r), \]  (22)

where \( T_{fg} \) - is the flue gas temperature, \( T_{bw} \) - temperature of the boiling water, \( r \) - is the specific heat of vaporization, \( T_{in} \) - is the feed water temperature, \( c_{pw} \) - is the specific heat capacity of water,

Then steam flow:

\[ G_{ST} = \frac{G_T \cdot (c_T \cdot T_4 - c_T \cdot T_{fg})}{c_{pw} \cdot (T_{bw} - T_{in}) + r}, \]  (23)

Steam turbine power:

\[ W_{ST} = L_T \cdot G_{ST} \]  (24)

Combined-cycle power:

\[ W_{CC} = W_{GTP} + W_{ST}, \]  (25)

Thermal efficiency steam cycle:

\[ \eta_{TCC} = \frac{W_{GTP} + W_{ST}}{G \cdot q_{GTP}} \]  (26)

The installation diagram is shown in Figure 5:

![Figure 5. Schematic diagram of the installation based on thermal power plant and combined-cycle plant.
1 - Tank with liquefied natural gas (LNG); 2 - Gas receiver; 3 - Compressor; 4 - Heat exchanger-evaporator; 5 - Throttle valve; 6 - Auxiliary steam power plant; 7 - Electric generator; 8 - Heat exchanger; 9 - Reducer; 10 - Steam-gas unit (SGU); 11 - Expansion turbine.](image)

4. Alternative problem-solving schemes

Another scheme to reduce the loss of cryoproduct is the installation with a contour based on a Stirling engine (Figure 6).
The principle of operation of the circuit based on the Stirling engine is as follows. The compressor cavity of the Stirling engine is cooled with liquefied natural gas to a temperature of 158 K, and the expander cavity is heated from the exhaust gases of a gas piston installation to a temperature of 400 K. The actual engine power is 4.8 kW. Liquefied gas, passing through the heat exchanger of the compressor cavity of the Stirling engine, enters the heat exchanger-heat exchanger, where it is heated by exhaust gases from the combined-cycle plant. After complete gasification of the gas it is used to the combustion chamber of the combined-cycle plant.

![Figure 6](image)

**Figure 6.** Schematic diagram of a low-temperature power plant based on a Stirling engine.

1 - Heat exchanger-evaporator; 2 - Gas receiver; 3 - Centrifugal compressor; 4 - Throttle valve; 5 - Tank with liquefied natural gas (LNG); 6 - electric generator; 7 - Reducer by 0.1 MPa; 8 - Stirling engine; 9 - Heat exchanger-utilizer; 10 - Gas piston installation (GPI); 11 - Electric generator.

It is possible to use a thermo-acoustic motor in the installation circuit as the main energy converter (Figure 7).

![Figure 7](image)

**Figure 7.** Schematic diagram of a low-temperature power plant based on a thermo-acoustic engine.

1 - Tank with liquefied natural gas (LNG); 2 - gas receiver; 3 - centrifugal compressor; 4 - evaporator heat exchanger ;; 5 - throttle valve; 6 - Thermo-acoustic engine based on traveling wave; 7 - electric generator; 8 - heat exchanger; 9 - gearbox; 10 - gas piston installation (GPI); 11 - electric generator; 12 - receiver.
This circuit works as follows: the cold heat exchanger of the thermo-acoustic engine 6 is cooled with liquefied natural gas from the tank 1, and the hot heat exchanger is heated by the exhaust gases of the hcp. Thus, the engine 6 generates energy, which is converted into electrical energy by an electric generator 7, which drives the compressor 3. LNG, passing through the cavity of the thermoacoustic engine 6, enters the heat exchanger 8, where it is heated by exhaust gases from the gas piston unit 10, then enters in the gearbox 9, which maintains the pressure at the inlet to the gas piston installation 10 constant and equal to $p_4$. After complete gasification of the gas, it is fed to the gas piston unit 10, which produces electrical energy using an electric generator 11. The actual engine power is 1.2 kW.

The use of such an installation allows you to compensate for losses during the evaporation of LNG from the tank, as well as to obtain additional electrical energy that can be used for various purposes, including solving problems arising from the operation of a gas piston installation.

5. Calculation of energy recovery coefficient
For the energy assessment of the use of the low-temperature potential of the cryogenic product, an indicator is used that characterizes the fraction of the return energy from that which was previously spent on the liquefaction of the cryoproduct: (calculation results for the different schemes are shown in Table 1):

$$k = \frac{N}{W_{liq}} = \frac{N}{k_W}$$  

Table 1. The calculation results of the main parameters of the the power plants.

| Installation with a combined-cycle circuit | Installation with a Stirling engine | Installation with a thermo-acoustic engine |
|-------------------------------------------|-----------------------------------|------------------------------------------|
| $N$, $kWt$                                | 40                                | 4,8                                      |
| $W_{liq}$, $kWt$                          | 129,6                             | 129,6                                    |
| $k$                                       | 0,308                             | 0,037                                    |

6. Conclusion
As a result of this work, the amount of energy losses in storage systems of cryogenic products along cylindrical horizontal and vertical tanks was analyzed, energy potential losses were determined, as a result of which it was found that LNG has the greatest potential of cryogenic energy lost during storage. The proposed layouts for the organization of the LNG storage park, consisting of two, four and eight tanks, and determined that the scheme with two tanks provides the least mass loss of the cryoproduct. The weight loss of the cryoproduct for 28 days of work amounted to 1061.42 kg. The schemes of low-potential power plants that compensate for the loss of the cryoproduct during storage are considered. The calculation of the axial compressor of the gas turbine installation was carried out; as a result, the following were determined: parameters and geometrical dimensions of the compressor; the absolute speed at the exit from the impeller of the first stage is 185.73 m/s; the flow rate at the outlet of the first stage guide vane is 134.4 m/s; the absolute speed at the exit from the impeller of the last stage is 168.77 m/s; the flow rate at the exit from the guide vane of the last stage is 67.5 m/s; velocity triangles for the first and last stages are constructed; compressor power is 363.6 kW. The parameters of the gas turbine of the gas turbine unit were calculated, with the result that the specific operation of the turbine is 710.07 kJ/kg, the power of the turbine is 632.37 kW. The parameters of the heat exchanger – condenser was calculated and determined: the heat exchange surface area — 0.33 m$^2$, heat transfer coefficient — 95.13 $\frac{W}{(m^2 \cdot K)}$; the total pressure drop in the annular space is 13.366 kPa. As a result of the economic evaluation, it was determined that the payback period of a low-grade installation is 6 years.

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