Article

Improvement of the Liquefied Natural Gas Vapor Utilization System Using a Gas Ejector

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Abstract: The production, transportation, and storage of liquefied natural gas (LNG) is a promising area in the gas industry due to a number of the fuel's advantages, such as its high energy intensity indicators, its reduced storage volume compared to natural gas in the gas-air state, and it ecological efficiency. However, LNG storage systems feature a number of disadvantages, among which is the boil-off gas (BOG) recovery from an LNG tank by flaring it or discharging it to the atmosphere. Previous attempts to boil-off gas recovery using compressors, in turn, feature such disadvantages as large capital investments and operating costs, as well as low reliability rates. The authors of this article suggest a technical solution to this problem that consists in using a gas ejector for boil-off gas recovery. Natural gas from a high-pressure gas pipeline is proposed as a working fluid entraining the boil-off gas. The implementation of this method was carried out according to the developed algorithm. The proposed technical solution reduced capital costs (by approximately 170 times), metal consumption (by approximately 100 times), and power consumption (by approximately 55 kW), and improved the reliability of the system compared to a compressor unit. The sample calculation of a gas ejector for the boil-off gas recovery from an LNG tank with a capacity of 300 m^3 shows that the ejector makes it possible to increase the boil-off gas pressure in the system by up to 1.13 MPa, which makes it possible to not use the first-stage compressor unit for the compression of excess vapours.

Keywords: liquefied natural gas; LNG tank; LNG storage system; boil-off gas; gas ejector

1. Introduction

The growth vector of the world energy market is changing rapidly; this is primarily linked to the search for and development of new methods of production, transportation, and storage of energy resources [1,2]. Due to a major global growth in natural gas consumption, an increasing number of countries, including the Russian Federation, are developing technologies for its storage and transportation in a liquefied form, in which natural gas is cooled down to cryogenic temperatures (around −161 °C). Liquefied natural gas (LNG) is increasingly used as a natural gas motor fuel as it reduces greenhouse gas emissions by 15–20% compared to gasoline [3] and is becoming an alternative to pipeline transportation [4,5], thereby expanding the fuel supply chain and ensuring the energy stability of consuming countries [6]. Due to its high density, liquefied natural gas can be stored in tanks and makes it possible to accumulate large fuel reserves. However, the storage technologies and safety requirements applicable to LNG tanks feature a number of disadvantages [7].

Despite the thermal insulation of the tank, an increase in fuel temperature is inevitable, which causes the evaporation of the fuel and the formation of the vapor phase,

known as boil-off gas (BOG). In order to maintain constant pressure in LNG storage, boil-off gas should be recovered [6]. Methods of boil-off gas recovery are suggested in the works of many authors [6–18] and specified in the regulatory documents of a number of countries [19–22].

For instance, the LNG tankers use a method of boil-off gas combustion that leads to the emission of combustion products into the atmosphere [23] and involves energy losses. Boil-off gas can be used as fuel for ship engines for marine transportation or be re-liquefied to return to storage by means of a boil-off gas compressor, which requires additional energy and capital costs [17].

The typical process flow diagram of an LNG receiving terminal introduced by the authors [6] recommends using boil-off gas to displace LNG from the tankers during their unloading or compressing to the customer's pipeline pressure. In the absence of new LNG supplies or compressors in the system, the recovery of excess vapor should be carried out by flaring or relief to the atmosphere.

The Linde Group [12] offers the process storage system of LNG, StarLiteLNG, which includes a complex of compressors and an expander. The unit uses a boil-off gas compressor for boil-off gas re-liquefaction. The cycle consists of a boil-off gas compressor, where boil-off gas is cooled down in a boil-off gas desuperheater, condensed in a boil-off gas condenser, and returned to the LNG tank. Thus, the fuel is regenerated without emissions to the flare or gas vent [13].

Process piping with a compressor is also proposed by B.S. Rachevsky [14]. The principle behind the operation of such a circuit is that the gas evaporates as a result of the heat inflow passing through the heat exchanger and enters the compressor suction, after which it is fed to the cooler-condenser, where it is condensed at a constant pressure; the condensed liquid is additionally supercooled by the counter gas flow in the heat exchanger and then throttled in the valve to the pressure corresponding to the storage mode when entering the LNG tank.

In order to recover the boil-off gas and prevent emissions of methane vapor, the cryogenic equipment market offers LNG boil-off gas compressors of various types. Pnevmomash, OOO produces and supplies equipment for compressing natural gas, including for preventing methane vapor emissions and their re-liquefaction [24]. To implement this technology, the company offers a reciprocating compressor MIKUNI DN6-25BG2 for boil-off gas compression with a capacity from 0.1 m^3/min to 19 m^3/min; discharge pressure 0.85 MPa; power 55 kW; and cost of about $8–9000.

Regardless of the manufacturer, the reciprocating compressor is a machine for compressing and supplying gas under pressure, which is carried out by means of a reciprocating movement of the piston in the cylinder. This machine requires additional energy costs to ensure the operation of the electric motor, capital investments, and operating costs. Moreover, due to the presence of moving parts, the compressor's reliability rate is lower compared to devices not involving mechanical motion, e.g., to the ejector. Therefore, the development of new, more efficient technical solutions for the recovery of boil-off gas in LNG storage is of importance.

The purpose of this work is to justify the possibility of boil-off gas recovery in LNG storage using a gas ejector, where high-pressure natural gas from the supply pipeline serves as a working fluid.

The ejector is characterized by a simple design, as well as the provision of medium pumping without additional power consumption. Moreover, not featuring complex structural elements, the ejector features a high operational reliability rate. Furthermore, the ejector can be used in a wide range of changing gas parameters, as well as offering the possibility of adjusting the operation mode. Due to the aforementioned advantages, the ejector systems became widely used in gas-collecting systems with high- and low-pressure wells, in condensing systems of steam power plants to increase the power of steam engine or turbine, and in systems in which ejectors were used to increase the thrust of a jet engines, etc. [25].

Scientific research by such scientists as K.G. Donets [26], G.N. Abramovich [25], A.P. Erokhin [27], E.Y. Sokolov [28], A.N. Drozdov [29], Zin Aidoun [30], E.A. Lyubin [31,32], N.V. Morozova [33], Khaled Ameur [34], etc. are dedicated to developing the calculation methods of the operating characteristics of the ejector and searching for its most effective designs. That said, no information on the ejector use for the transportation of boil-off gas from the LNG tank, no for the calculation methods of its operating characteristics and physical dimensions for this case, was found in the body of relevant research.

2. Materials and Methods

2.1. Description of the Technical Solution

The authors of this article developed a technical solution that allows the recovery of the excess boil-off gas from the LNG tank by means of a gas ejector (Figure 1).
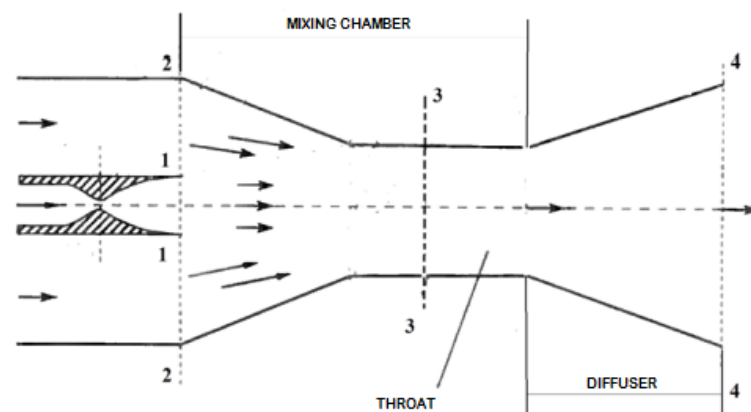

Figure 1. Ejector design [25]: 1—a high-pressure flow nozzle; 2—a low-pressure flow nozzle; 3—a mixing chamber; 4—a diffuser.

The technical solution consists of the following: the boil-off gas discharged from the LNG tank acts as the ejected (low-pressure) gas, while the gas coming from a high pressure source, which is the main natural gas pipeline, is the ejecting (high-pressure) gas.

High-pressure flow can be supplied from any other process line containing natural gas of sufficiently high pressure to operate the ejector. It is important that the composition of the ejecting flow differ slightly from the composition of the boil-off gas to allow the re-use of their mixture.

The proposed solution excludes fuel losses at the flare and vent stack, improves environmental safety, and makes it possible to avoid the use of a boil-off gas compressor, since the flow is compressed due to the already available energy of the main gas flow and the ejector.

The sequence of operations when implementing the technical solution is as follows.

Via line 1 (Figure 2), tank 2 is filled with LNG, whose pressure is monitored and, if the rated values are exceeded, a signal is sent to open gate valve 8. Consequently, the pressure of the natural gas from high-pressure pipeline 6 is reduced to the operating pressure in reducer 7, fills gas ejector chamber 10 and, via gate valve 12, flows into tank 13. Next, pressure relief valve 3, which is used to relieve the excess boil-off gas, is actuated, carried by the working medium of gas ejector 10 to the mixing chamber by means of the low-pressure zone created in it. Check valve 5 prevents the flow with higher pressure from entering into the tank. Having passed the gas ejector, the mixture of the boil-off gas and natural gas flows into tank 13, where, via discharge line 14, and when gate valve 15 is open, it is used for the process needs of the tank farm or fed to the second stage compressor for further liquefaction; thus, the ejector system replaces the first-stage compressor.
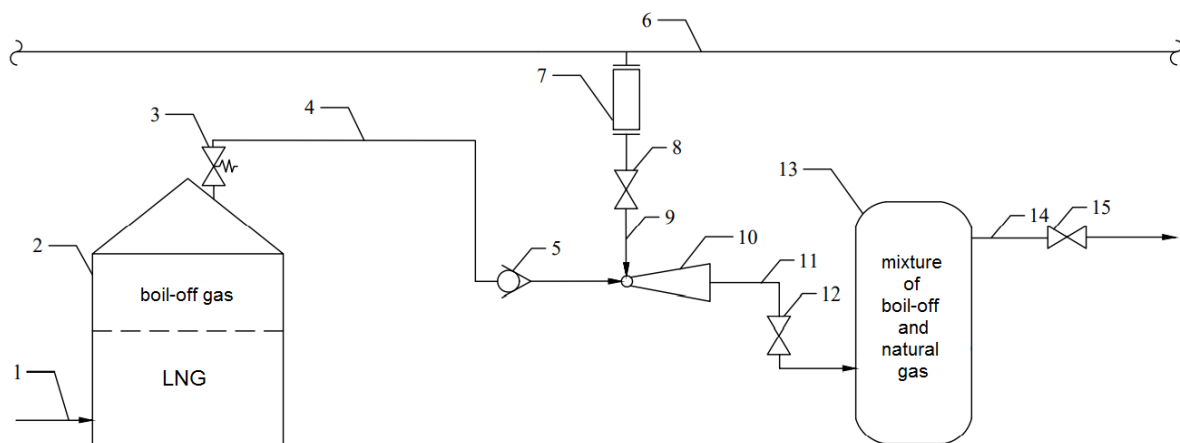
Figure 2. Flow diagram of liquefied natural gas (LNG) vapor disposal using an ejector [(by the authors, Y.V. Martynenko, V.I. Bolobov, and V.A. Voronov): 1—LNG tank fill line; 2—LNG tank; 3—pressure safety valve for relieve of excess boil-off gas; 4—boil-off gas feed line to ejector; 5—check valve; 6—high-pressure natural gas line; 7—natural gas pressure reducer; 8—gate valve at natural gas feed line to ejector; 9—natural gas feed line to ejector; 10—gas ejector; 11—rundown line for boil-off gas and natural gas mixture from ejector; 12—gate valve at the rundown line for boil-off gas and natural gas mixture to the storage tank; 13—storage tank for boil-off gas and natural gas mixture; 14—rundown line for boil-off gas and natural gas mixture for process needs and re-liquefaction; 15—gate valve on the rundown line for boil-off gas and natural gas mixture for process needs and re-liquefaction.

Based on the conditions of LNG storage in the tank and the basic gas dynamics equations [35–37], the proposed calculation method for operating characteristics and the physical dimensions of the ejector applicable for the BOG recovery are presented below. The calculation was performed under the assumptions set forth in "Appendix A". The list of symbols is in "Abbreviations/Nomenclature".

2.2. Determination of Boil-Off Gas Parameters during LNG Storage in a Tank

The calculation was carried out for a tank with a capacity of $V_t = 300$ m^3, which is widely used for low-scale storage of LNG for regional supplies to its consumer [38].

Source data:

- Filling level of the cryogenic tank with liquid—80%;
- $V_l = 0.8V_t = 240$ m^3; $V_g = 0.2V_t = 60$ m^3—volume of the liquid and vapour phase in the tank, respectively;
- $T_0 = 120$ K, $T_1 = 140$ K—temperature in the tank prior to the moment of intensive vaporization and at the time of discharge, respectively;
- $p_0^{s.v.} = 0.192$ Mpa; $p_1^{s.v.} = 0.64$ Mpa—pressure of saturated vapours corresponding to temperatures T_0, T_1 (according to the phase diagram);
- $\rho^{140} = 390.38$ kg/m^3—LNG density at T_1 and $p_1^{s.v.}$;
- $M = 16.04$ g/mol—molar mass of methane as the main constituent component (95%) of LNG [39].

Calculated parameters:

- Gas molar volume before (V_m^0) and after (V_m^1) evaporation, based on the Clapeyron-Mendeleev equation: $V_m = \frac{22.4 \cdot p_{atm} \cdot T}{T_0 \cdot p^{s.v.}}$;
- Mass of saturated vapours in the tank: $m_{s.v.} = \frac{V_{s.v.}}{V_m} \cdot M$;
- Mass of boil-off gas to be discharged: $\Delta m = m_{s.v.}^1 - m_{s.v.}^0$.

2.3. Calculation of the Flow Rate of Boil-Off Gas Passing through the Pressure Safety Valve and Determination of the Diameter of the Valve Flow Area

Source data:

- $P_1 = p_1^{s.v.}$—actuation pressure of the pressure safety valve;
- $P_2 = 0.32$ MPa—pressure maintained in the pipeline system at the valve outlet prior to the pressure release from the tank;
- $k = 1.4$—boil-off gas adiabatic exponent (determined from the phase diagram);
- Boil-off gas density at the valve inlet does not change significantly and can be assumed equal to $\rho_{inlet} = 8.8$ kg/m^3;
- $R_{spec} = 519$ J/kg $\cdot$ K—specific heat of methane vaporization;

Formulas used:

- Geometry factor of the pressure safety valve: $B_3 = 1.59 \sqrt{\frac{k}{k+1}} \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}}$;
- Valve flow rate: $G = F_{effective} \cdot 3.16 \cdot B_3 \sqrt{P_1 \rho_{inlet}}$;
- Temperature and velocity at critical gas outflow: $T_{critical} = T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$, $V_{critical} = \sqrt{k R_{spec} T_{outlet}}$;
- Gas density in the outlet section of the discharge pipeline: $\rho_{outlet} = \frac{10^6 (P_2 + 0.1)}{R_{spec} T_{outlet}}$;
- Area of the discharge pipeline: $F_{outlet} = \frac{10^3 G}{3.6 V_{critical} \rho_{outlet}}$; diameter of the discharge pipeline: $D_{outlet} = \sqrt{\frac{4 F_2}{\pi}}$.

2.4. Determination of the Operational Efficiency Indicators of the Ejector for the Transportation of Boil-Off Gas with the Specified Parameters

Source data:

- $T_1^{NG} = 293$ K—natural gas temperature;
- $P_1^{NG} = 2.2$ MPa—natural gas pressure (absolute);
- $\rho_1^{NG} = 0.316$ kg/m^3—natural gas density;
- $k_1^{NG} = 1.3$—adiabatic exponent of natural gas (determined based on the physical-chemical properties of gas);
- $T_2^{BOG} = T_{critical} = 114.5$ K—boil-off gas temperature;
- $P_2^{BOG} = 0.32$ MPa—boil-off gas pressure (absolute);
- $G_2^{BOG} = 1.9$ kg/s—boil-off gas mass flow rate;
- $k_2^{BOG} = 1.41$—boil-off gas adiabatic exponent (determined based on the physical-chemical properties of gas);
- $F_2^{BOG} = 5026.6$ mm^2—boil-off gas flow area;
- $R_{spec} = 519$ J/kg $\cdot$ K—specific heat of methane vaporization;

Formulas used:

- Critical outflow velocity from the ejector nozzle: $V_{critical1} = \sqrt{2 \frac{k_1^{NG}}{k_1^{NG}-1} R_{spec} T_1^{NG} \left(1 - \beta^{\frac{k_1^{NG}-1}{k_1^{NG}}}\right)}$;
- Pressure ratio: $\beta = \frac{P_2^{BOG}}{P_1^{NG}}$;
- Ejection coefficient: $n = \frac{G_2^{BOG}}{G_1^{NG}}$;
- Natural gas mass flow rate: $G_1^{NG} = \rho_1^{NG} V_{critical1} F_1^{NG}$;
- Natural gas flow area: $F_1 = F_2 \alpha$;
- Mixture flow area: $F_3 = \frac{F_1}{\alpha} + F_1$;
- Absolute pressure of the mixture: $P_3^{MIX} = \frac{\alpha P_1^{NG} + P_2^{BOG}}{1+\alpha}$;
- Mixture temperature: $T_3^{MIX} = \frac{\left(n \cdot \frac{T_2^{BOG}}{T_1^{NG}} + 1\right) T_1}{n+1}$;
- Mixture critical velocity: $V_{critical3} = V_{critical1} \sqrt{\frac{\left(n \frac{T_2}{T_1} + 1\right)}{n+1}}$;

- Ejector efficiency: $\eta = \dfrac{G_2^{BOG} P_2^{BOG} (P_3^{MIX} - P_2^{BOG})}{P_3^{MIX} G_1^{NG} (P_1^{NG} - P_3^{MIX})} \cdot \dfrac{T_2^{BOG} (T_3^{MIX} - T_2^{BOG})}{T_3^{MIX} (T_1^{NG} - T_3^{MIX})} \cdot 100\%.$

3. Results and Discussion

The calculation results are presented in the Table 1.

Table 1. The results of calculating the performance characteristics and geometric dimensions of the ejector for the disposal of vapours from a liquefied natural gas (LNG) tank.

Parameters of the boil-of gas during storage of LNG in the tank	- gas molar volume before and after evaporation: $V_m^0 = 5.2$ m^3/kmol, $V_m^1 = 1.82$ m^3/kmol; - mass of saturated vapours in the tank: $m_{s.v.}^0 = 185.2$ kg, $m_{s.v.}^1 = 528.8$ kg; - mass of boil-off gas to be discharged: $\Delta m = 528.8$ kg.
Parameters of the safety valve for the discharge of boil-of gas from the LNG tank	- valve flow rate : $G = 1.9$ kg/s; - temperature and velocity at critical gas outflow : $T_{critical} = 114.5$ K; $V_{critical} = 290$ m/s; - gas density in the outlet section of the discharge pipeline : $\rho_{outlet} = 4.4$ kg/m^3; - area and diameter of the discharge pipeline : $F_{outlet} = 5026.6$ mm^2; $D_{outlet} = 80$ mm.
Parameters of the efficiency of the ejector for the transportation of boil-of gas	- critical outflow velocity from the ejector nozzle : $V_{critical1} = 687$ m/s; - pressure ratio : $\beta = 0.145$; - ejection coefficient : $n = 2.35$; - natural gas mass flow rate : $G_1^{NG} = 0.82$ kg/s - natural gas flow area and diameter $F_1 = 3770$ mm^2; $D_1 = 70$ mm; - mixture flow area and diameter : $F_3 = 8797$ mm^2; $D_3 = 106$ mm; - absolute pressure of the mixture : $P_3^{MIX} = 1.13$ MPa. - mixture temperature : $T_3^{MIX} = 167.8$ K - mixture critical velocity : $V_{critical3} = 520.6$ m/s; - ejector efficiency : $\eta = 14.6\%$.

The calculation results given in Table 1 show the applicability of the proposed technical solution for improving the LNG vapours recovery system by using a gas ejector, taking the LNG tank with a capacity of 300 m^3 as an example. The proposed calculation method of process piping for a tank with an ejector for boil-off gas recovery includes the calculation of the parameters for the boil-off gas in the LNG tank, its thermodynamic characteristics at discharge through the safety valve, as well as the efficiency parameters and physical dimensions of the ejector. This allows the performance of a comprehensive calculation of the vapour recovery system in LNG storage facilities with an ejector.

Further, the substantiation of the effectiveness of the proposed technical solution is presented.

1. The calculations of the boil-off gas parameters in the tank showed that an increase in the ambient temperature by 20 °C would change the boil-off gas flow rate by 8.7%, i.e., by 0.4% at 1 °C. Using mathematical modeling, the authors [40] concluded that an increase in ambient temperature of 1 °C causes a change in the boil-off gas flow rate of about 0.2%. The authors of [41] propose the construction of a tank with thermal insulation, in which the boiling rate of the fuel is 0.25% per day. This indicator may vary depending on the tank wall heat transfer and the type of insulation; however, the calculated value is objective, which confirms the applicability of the chosen method.

2. The use of the ejector makes it possible to increase the pressure of the boil-off gas discharged from the tank from 0.32 MPa to 1.13 MPa, which makes it possible to avoid using a compressor for this purpose. The generation of high boil-off gas pressure is relevant not only for tank farms, but also for LNG ships. For instance, the authors of [3] consider it economically feasible to re-liquefy boil-off gas by compressing it

using the compressor and subsequently expanding it using the Joule Thomson cycle. However, when using the ejectors in gas carriers, other sources of high-pressure operating flow should be considered for BOG compression. The replacement of the compressor with an ejector is applicable in the previously described methods of the boil-off gas recovery [5,9–11,13,14,17,18].

3. The ejector used for the recovery of boil-off gas eliminates the release to the atmosphere or flaring, which prevents the loss of fuel and its release into the atmosphere. The authors of [42] consider the method of disposal by flaring as one of the possible; however, they also believe that it should be used only under extreme deviations from the norm or emergency conditions in order to reduce the greenhouse effect.

4. The efficiency factor of 14.6% of the device slightly exceeds the typical indicators for gas ejector systems, e.g., 10%, as per the data [26]. This excess can be explained by the fact that the calculation of the proposed ejector was carried out at the maximum allowable ejection coefficient determined by the maximum allowable flow rate of high-pressure natural gas flow, as well as the high-pressure ratio obtained due to the high pressure of the main flow.

5. The power of the gas ejector used for compression is 3451 kW, which exceeds by about 60 times the compressor operating power (55 kW) [24]. However, this energy is converted from the main stream of the natural gas, in which pressure is already generated, which makes it possible to avoid the use of external power supplies, and the pressure at the ejector outlet exceeds by 1.3 times the discharge pressure of the above-mentioned compressor MIKUNI DN6-25BG2. The power of the boil-off gas compressor proposed in [43] is 1600 kW, at a flow rate of 4.2 kg/s, while the power of the ejector described in this article is about five times greater, taking into account the same flow rate.

6. According to the estimate of the ejector dimensions with the fixed required diameters, its length shall be about 2.8 m and its weight shall be about 30 kg. The authors were not able to compare the obtained physical dimensions and weight of the ejector with findings in previous research as no information about the existence of ejectors designed for such high flow rates was found. Proceeding from the cost of stainless steel pipes of $5–6/running meter and the labour costs required for a gas ejector manufacture, the cost can be estimated at $50. These indicators are 103 times lower in terms of metal consumption and 172 times lower in cost than when using a compressor (3.1 tons, $8600).

7. The component composition of the ejector operating flow, which is natural gas from the main pipeline, is similar to the boil-off gas composition, which offers the opportunity of re-liquefaction and using the resulting mixture.

Thus, the proposed technical solution and calculation method prove their effectiveness at the stage of theoretical justification. It should be concluded that the developed method of LNG vapor recovery and the method for evaluating its effectiveness may be subject to field experiments and further implemented at newly constructed facilities with LNG storage facilities.

4. Patents

The results of this study are contained in the application, «Method of utilization of steam gas from a liquefied natural gas (LNG) tank», No. 2021118599, at the Federal Institute of Intellectual Property of the Russian Federation (incoming number W21039183, registration date 25 June 2021).

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

V_t	tank capacity, m^3;
V_l	volume of the liquid phase in the tank, m^3;
V_g	volume of the vapour phase in the tank, m^3;
T_0	temperature in the tank prior to the moment of intensive vaporization, K;
T_1	temperature in the tank prior at the time of discharge, K;
$p_0^{s.v.}, p_1^{s.v.}$	pressure of saturated vapours corresponding to temperatures T_0 and T_1, MPa (according to the phase diagram);
ρ^{140}	LNG density at T_1 and $p_1^{s.v.}$, kg/m^3;
M	molar mass, g/mol;
V_m	gas molar volume, m^3/kmol;
p_{atm}	atmospheric pressure, MPa;
$m_{s.v.}$	mass of saturated vapours in the tank, kg;
$V_{s.v.}$	volume of saturated vapours in the tank, m^3;
Δm	mass of boil-off gas to be discharged, kg;
P_1	actuation pressure of the pressure safety valve, MPa;
P_2	pressure maintained in the pipeline system at the valve outlet prior to the pressure release from the tank, MPa;
$k = k_2^{BOG}$	boil-off gas adiabatic exponent (determined from the phase diagram);
ρ_{inlet}	boil-off gas density at the valve inlet, kg/m^3;
R_{spec}	specific heat of methane vaporization, J/kg $\cdot$ K;
B_3	geometry factor of the pressure safety valve;
G	safety valve flow rate
$F_{effective}$	value of safety valve effective area, mm^2;
$T_{critical}, V_{critical}$	temperature and velocity at critical gas outflow of safety valve, K, m/s;
ρ_{outlet}	gas density in the outlet section of the discharge pipeline, kg/m^3;
T_{outlet}	temperature in the outlet section of the discharge pipeline, K;
F_{outlet}, D_{outlet}	area and diameter of the discharge pipeline, mm^2, m;
T_1^{NG}	natural gas temperature at the inlet to the ejector, K;
T_2^{BOG}	boil-off gas temperature at the inlet to the ejector, K;
P_1^{NG}	natural gas pressure (absolute) at the inlet to the ejector, MPa;
P_2^{BOG}	boil-off gas pressure (absolute) at the inlet to the ejector, MPa;
ρ_1^{NG}	natural gas density of the ejector at the inlet to the ejector, kg/m^3;
k_1^{NG}	adiabatic exponent of natural gas (determined based on the physical-chemical properties of gas);
G_1^{NG}	natural gas mass flow rate at the inlet to the ejector, kg/s;
G_2^{BOG}	boil-off gas mass flow rate at the inlet to the ejector, kg/s;
F_1	flow area of the natural gas pipe of the ejector, mm^2;
F_2	flow area of boil-off gas pipe of the ejector, mm^2;
F_3	flow area of mixture pipe of the ejector, mm^2;
D_1	flow area diameter of natural gas pipe of the ejector, mm^2;
D_2	flow area diameter of boil-off gas pipe of the ejector, mm^2;
D_3	flow area diameter of mixture pipe of the ejector, mm^2;
α	ratio of the cross-sectional areas of the low-pressure to high-pressure flows of the ejector;
$V_{critical1}$	critical outflow velocity from the ejector nozzle, m/s;
β	pressure ratio at a critical outflow at the ejector nozzle;
n	ejection coefficient;
P_3^{MIX}	mixture pressure in the ejector (absolute), MPa;
T_3^{MIX}	mixture temperature in the ejector, K;
$V_{critical1}$	critical outflow velocity from the ejector nozzle, m/s;
$V_{critical3}$	mixture critical velocity in the ejector, m/s;
η	ejector efficiency

Appendix A

Table A1. Adopted assumptions and designations.

To calculate the parameters of the boil-off gas when storing liquefied natural gas (LNG) in a tank	• The discharge of boil-off gas from the tank is carried out when the maximum allowable pressure of saturated vapors $p_1^{s.v.}$ is reached and continues until reaching $p_0^{s.v.}$ • Due to the limited capacity of the tank, during the LNG evaporation, the volume occupied by the gas phase changes insignificantly, therefore it is assumed to be constant.
To calculate the flow rate of the boil-off gas passing through the safety valve and to establish the diameter of the flow section of the valve	• Gas outflow in the seat of the pressure safety valve is close to critical. • The value $F_{effective} = 1200$ mm^2 can be adopted as the value of effective area, as an area corresponding to the minimum diameter of the valves produced. • Diameter of the discharge pipeline is adopted as the nearest to the design one as per the pipe standards of the Russian Federation.
To calculate the performance indicators of the ejector for the transportation of boil-off gas of the specified parameters	• Calculation is carried out according to the method of G.N. Abramovich [25]. • The pressure of the high-pressure flow P_1^{NG} is determined by the maximum allowable pressure in the ejector that causes no blocking effect. • Ratio of the cross-sectional areas of the low-pressure to high-pressure flows of the ejector can be assumed to be equal to $\alpha = 0.75$, accounting for the reduction of metal consumption of the device. • Process of mixing gases in the ejector is close to adiabatic. • Natural gas outflow from the ejector nozzle—critical. • Shape of the mixing chamber of the ejector—cylindrical. • Parameters of the ejecting gas in the input section of the ejector have an index 1, parameters of the ejected gas have an index 2, parameters of the mixture in the output section have an index 3.

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