Study of two-phase transportation mode of liquefied natural gas through a pipeline by the gravitational method

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Abstract. The given paper considers the choice of method and technology of liquefied natural gas transportation from an isothermal LNG storage facility via a pipeline to a transport cryogenic tank. Theoretical studies have been performed, including mathematical modeling of thermal and hydro-dynamic processes during the transportation of liquefied natural gas with partial evaporation through a pipeline. A new method for calculating the transportation of liquefied natural gas with partial evaporation through a pipeline using the gravitational method has been proposed in the paper.

1. Introduction

At present, a significant share of hydrocarbon energy resources market is occupied by liquefied natural gas (LNG). Countries with natural gas deposits have developed technologies that allow natural gas to be liquefied, stored in special isothermal tanks, and transported in cryogenic tanks on water methane carriers, as well as by air, rail, and road transport.

The largest LNG producers and exporters are Algeria, Libya, Brunei, Abu Dhabi, Indonesia, Malaysia, Australia, Qatar and the United States. The largest LNG importer is Japan, which accounts for about 60% of global LNG consumption. Other major importers are South Korea, France, Spain, and Belgium. One of the most promising LNG markets in the world is the United States’ LNG market which is both an importer and an exporter [1].

Russia possesses the largest natural gas deposits, which are found in remote areas (the Barents Sea, the Kara Sea shelf, Sakhalin Island, etc.) and which are unfavorable for the construction of main gas pipelines [2]. Therefore, two large natural gas liquefaction plants have already been built on Sakhalin Island and the Yamal Peninsula and they continue to increase their capacity [1].

Countries that import LNG must also have receiving terminals and storage tanks for LNG, as well as equipment and communications for transporting it to consumer tanks. This paper considers the choice of method and technology for transporting liquefied natural gas from a stationary isothermal LNG storage via a pipeline to a transport cryogenic tank.

LNG transportation from one container to another container via a pipeline is possible by several methods: using submersible self-priming pumps, displacement by an inert gas with a lower boiling point, displacement by its own LNG vapor obtained in the evaporator [3, 4].

According to some sources [5 - 9], LNG transportation is most appropriate via a pipeline using the gravitational method, i.e. due to the action of gravity, provided that there is a large difference in the height of the tank being emptied and filled. In addition to that, there are no energy costs, expensive
cryogenic pumps are not used, and there is no need to raise high pressure in the emptied storage, which can lead to the rupture of its walls. The gravitational method is widely used in the discharge and filling of petroleum products from railway tanks [3, 4].

The main feature of LNG transportation through a pipeline is that LNG in this process can boil to form a vapor-liquid flow. LNG is a cryogenic liquid with a boiling point of minus 161.5°C at atmospheric pressure, which at a positive ambient temperature causes intense heat flows to LNG and, subsequently, the evaporation of part of LNG. The appearance of LNG vapor-liquid flow in the pipeline leads to a significant decrease in its through capacity and an increase in its hydraulic resistance, to large losses of gas into the atmosphere, and a longer duration of the pumping process [10 - 12, 19, 20].

At the initial stage of LNG transportation, the “warm” pipeline is cooled and filled. LNG enters the pipeline which has ambient temperature, where all the liquid quickly evaporates and the pipeline is filled with steam. The steam pressure in the pipeline increases quickly enough and so much that it can be equalized with and even exceed the pressure at the inlet to the pipeline, thereby leading to the release of liquid back into the tank being emptied. This phenomenon is known as the “geyser” effect [5, 10 - 13].

As the initial section of the pipeline cools, the liquid front moves towards the outlet and gradually the entire pipeline acquires an operating temperature close to the temperature of the transported liquid. After cooling the pipeline up to cryogenic temperatures, LNG is transported in a single-phase state or with partial evaporation [5, 6, 10, 11].

To prepare a cryogenic pipeline for LNG transportation in steady-state, the “warm” pipeline can be pre-purged with another inert cryogenic liquid, such as liquid nitrogen, which has a boiling point even lower than that of LNG – minus 196°C [10 - 13].

2. Materials and methods

When operating cryogenic pipelines, LNG transportation parameters are selected in such a way as to prevent the formation of a vapor phase in the pipeline. There are a number of ways to achieve that: 1) increasing pressure in the system above the saturated vapor pressure; 2) preliminary supercooling of the liquid relative to the saturation temperature; 3) reducing heat flows through the pipeline walls [10, 11].

- During LNG transportation, a certain pressure must be created above the liquid surface in the tank being emptied. It must exceed the pressure of saturated vapors. Raising pressure in the tank increases the subcooling of LNG up to the saturation temperature, providing a single-phase flow in the pipeline [10, 11].
- LNG must be sufficiently supercooled relative to the saturation temperature at the pipeline pressure. To perform this, LNG is sent by a pressure pump to a heat exchanger being cooled by the pumped LNG at atmospheric pressure [10, 11].

Figure 1. Schematic designs of inner tube supports in the casing: a) finger-type; b) wire; C) ball; d), d) disk; e) trunnion.
The use of vacuum types of thermal insulation – vacuum-powder, layered-vacuum or pure vacuum for cryogenic pipelines (figure 1) allows reducing heat flows up to the minimum values [10 - 13].

Pipelines with bulk-type thermal insulation are also widely used: loose, porous and fibrous thermal insulation (figures 2, 3). Domestic and foreign experts recommend foamed materials as thermal insulation: polyurethane foam, expanded polystyrene, cork, foamed epoxy resin, foam glass [13, 14].

Figure 2. Sliding construction of heat-insulated pipeline coating: 1 – heat-insulation material; 2 – sliding elements; 3 – pipeline; 4 – casing.

Figure 3. Heat-insulation construction for pipe bend angle: 1 – pipe; 2 – inner heat-insulation layer; 3 – steam tight layer; 4 – rigid segments; 5 – soft segments; 6 – antifriction layer; 7 – outer casing.

However, these methods of keeping LNG in a single-phase state directly depend on the chosen method of LNG transportation (by pump, by pressurization of inert liquid vapors, by own LNG vapors, or by the gravitational method).

In [15, 16], a mathematical model of LNG transportation by the gravitational method in a single-phase state is proposed, and the calculation technique proposed on its basis allows finding the length of a single-phase LNG flow section and the parameters of its transportation: pressure p, temperature T, mass flow G (figure 4).

The parameters of LNG transportation through a low-pressure pipeline are found near the saturation line, so even minor changes in pressure and temperature can lead to the evaporation of part of LNG and the appearance of a two-phase vapor-liquid flow, which significantly reduces the efficiency of LNG transportation by the gravitational method. Therefore, when calculating the parameters of LNG transportation through a pipeline, changes in the thermal properties of LNG should be taken into account [5-7, 17].

LNG is transported through the pipeline under the influence of available pressure difference in the storage and in the receiver tank and is characterized by the following parameters: pressure Pvx, temperature Tx, mass flow Gvx = G1.

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![Design model of LNG transportation from one tank to another tank by the gravitational method.](image)

**Figure 4.** Design model of LNG transportation from one tank to another tank by the gravitational method.

LNG is transported through the pipeline under the influence of available pressure difference in the storage and in the receiver tank and is characterized by the following parameters: pressure $P_{vx}$, temperature $T_{vx}$, mass flow $G_{vx} = G_1$.

The pipeline consists of horizontal and vertical sections and has a thermal insulation thickness $\delta$ with a thermal conductivity coefficient $\lambda$. For example, these may be patented technical solutions [8, 9]. The ambient temperature is assumed to be a constant value $T_n = \text{const.}$

3. Results

The calculation of heat input to LNG is performed according to the well-known laws of the theory of thermal conductivity and convective heat transfer: Fourier’s law and Newton–Richman equation [18].

The well-known equations of hydraulics: Bernoulli and Darcy–Weisbach [18] are used to calculate pressure loss in the section of a single-phase LNG flow.

As a result of heat flows $q_f$ from the external environment and pressure drop in the pipeline $\Delta p_v$ due to the hydraulic resistance of the LNG pipeline at a certain distance from the inlet $z = l$, the state of saturation is reached with parameters $T(l) = T_1$, $p(l) = p_1$, $G_1$ [15, 16].

Based on the above said, the length of a single-phase LNG flow section through the pipeline is found by the expression [15, 16]:

$$l' = \frac{103 + 0.000083 \cdot p_v - T_{vh}}{0.000083 \cdot k_g + a_1 - a_2 T_{vh}}$$

where $a_1, a_2$ – complex values that take into account the influence of heat flows from the environment and the parameters of LNG transportation on its temperature:

$$a_1 = \frac{\pi D \Delta T_p}{G_1 c_P \delta} + \frac{\lambda n G_1^2}{2D^2 \rho^2 c_P} - \frac{g \cos \alpha}{c_P}$$

$$a_2 = \frac{\pi D \lambda}{G_1 c_P \delta}$$

$\kappa_g$ — specific pressure loss in the horizontal section of the pipeline, Pa/m;
Below this section, a two-phase LNG flow occurs with parameters $T_g, p_{cm}, G_{cm}, x$. The calculation of pressure loss in the section of a two-phase LNG flow using the formulas for a single-phase flow leads to significantly understated results [10, 11].

In engineering practice, simplified methods are usually used for calculating two-phase flows that are not related to the consideration of specific flow modes: a model with phase slip (Martinelli - Lockhart - Nelson correlation) and a homogeneous model [10,11,18].

When calculating a two-phase flow according to the model with slip phase, the pressure loss in the turbulent flow mode is found by the equation [11]:

\[
\frac{\Delta p}{\Delta l}_{cm} = \left( \frac{\Delta p}{\Delta l} \right)_{j0} \cdot (1 - x)^{1.75} \cdot \Phi_j^2,
\]

where \((\Delta p/\Delta l)_{j0}\) – pressure drop per length unit of the pipeline when the liquid phase moves with full flow $G = G_g + G_j$. It is found by the well-known Darcy – Weisbach equation, Pa/m; $x$ – mass vapor content of the flow; $\Phi_j$ – function expressing the ratio of pressure loss of a two-phase mixture to pressure loss of a single-phase liquid.

The influence of heat flows on the flow hydrodynamics is taken into account by changing mass vapor content along the length of the pipeline.

$\Phi_j$ function in expression (5) is found graphically (figure 5) depending on parameter $\chi$ [11, 18]:

\[
\chi = \left( \frac{\rho_g}{\rho_j} \right)^{0.5} \cdot \left( \frac{\mu_j}{\mu_g} \right)^{0.125} \cdot \left( \frac{1}{x} - 1 \right)^{0.875}
\]

where $\rho_g, \rho_j$ – density of vapor and liquid phases, respectively, kg/m$^3$; $\mu_g, \mu_j$ – dynamic viscosity of vapor and liquid phases, respectively, Pas.

**Figure 5** – Ratio between $\Phi_g(\chi)$ and $\Phi_j(\chi)$ in turbulent phase flow.

With low vapor content of the flow and high mass velocities, the homogeneous model has the greatest agreement with experimental data. The essence of the model is that a two-phase flow is considered as a single phase. Its specific volume in each section of the flow is related to mass vapor content and specific volume of each phase [10]:

\[
u_{cm} = u_j (1 - x) + u_g \cdot x
\]

The equation for calculating friction loss is written in a form similar to Darcy – Weisbach equation [10]:

\[
\kappa_g = \frac{\lambda_{np} \rho W^2}{2D_g}
\]
\[
(\frac{\Delta p}{\Delta l})_{cm} = \frac{\lambda_{cm}(\rho W)^2 v_{cm}}{2D}
\]

where \(\lambda_{cm}\) – resistance coefficient of a two-phase flow which can be represented by the resistance coefficient of a single-phase flow \(\lambda_{tr}\) and some empirical function \(\psi\) of two-phase flow parameters, i.e.

\[
\lambda_{cm} = \psi \lambda_{tr}
\]

Due to the complex nature of dependence \(\psi\) on the operating parameters of a two-phase flow, engineering calculations take \(\psi = 1\).

The basic assumptions of the homogeneous model consist in the assumption of linear velocities equality of steam and liquid, thermodynamic equilibrium of phases, applicability of dependencies for calculating the friction coefficient of a single-phase flow to two-phase flow [10].

After analyzing the known mathematical models of two-phase fluid flows, the authors suggest the following technique for calculating a two-phase LNG flow.

The initial data for calculating the parameters of a two-phase LNG flow are the values of parameters \(T, \rho, l\), obtained from the calculation of a single-phase flow [15, 16].

The section of a pipeline \(l_{cm} = l - l'\), where liquid vaporization occurs is divided into equal segments \(\Delta l\). Within each segment, mass vapor content \(x\) and the parameters of each phase are assumed to be constant. At the end of each segment, vapor content and pressure loss are calculated.

Mass vapor content in section \(l_{i+1}\) is determined by the vapor content of flow in the previous section \(l_{i}\) and the increase in vapor content in segment \(\Delta l = l_{i+1} - l\) due to heat inflow and pressure drop over the saturated liquid:

\[
x_{i+1} = x_i + \frac{4q\Delta l}{D \rho W r} + \frac{i_s(p_i) - i_s(p_{i-1})}{r}
\]

where \(i_s(p_i)\) – enthalpy on LNG saturation line at a pressure of \(p_i\), J/kg; \(r\) – the specific heat of vapor formation, J/kg; \(q\) – the amount of heat input to LNG, which can be found by the formula:

\[
q_i = \frac{2\pi \lambda_{from}(T_{a} - T_{LNG})}{\ln(D_{from}/D)}
\]

The pressure at the end of each segment in section \(l_{i+1}\) is connected with the pressure in section \(l_i\) by the following ratio:

\[
p_{i+1} = p_i - \Delta p_{cmtr} - \frac{\Delta l \cdot \cos \alpha}{v_{cm}},
\]

where \(\alpha\) – the angle of inclination of segment \(\Delta l\) to the vertical, \(v_{cm}\) – the specific volume of vapor-liquid mixture, \(m^3/kg\).

The necessary data on the physical and thermodynamic properties of LNG (specific volume, enthalpy on the saturation line, heat of vaporization, heat capacity and others) are found according to table dependencies in [17].

When moving to the next segment, changes in vapor content and density of vapor phase due to heat inflow and pressure drop in the previous segment are taken into account.

To calculate pressure loss due to friction \(\Delta p_{cmtr}\) in a two-phase flow at segments \(\Delta l\), the ratios of both the slip flow model and the homogeneous model can be assumed.

The calculation is correct if the following condition is met:

\[
\frac{p_{pykh} - p_{vykh}}{p_{vykh}} < \varepsilon,
\]

where \(p_{vykh}\) – the estimated pressure at the end of the pipeline, Pa; \(p_{pykh}\) – pre-determined pressure magnitude, Pa; \(\varepsilon\) – the specified relative error of calculation.
If the estimated pressure happens to be higher than the pre-determined value, in that case it is necessary to increase flow rate and repeat the calculation; if the estimated pressure is lower, then one should reduce flow rate and repeat the calculation. The values \( \rho W \) and \( x_{vykh} \) corresponding to ratio (13) will be the ones being sought for.

4. Conclusions
The main conclusions of the paper are as follows:

- when LNG is delivered from a storage facility by the gravitational method, LNG subcooling at the pipeline inlet is provided by the hydrostatic pressure of liquid column and the excess pressure of LNG vapors in the storage;
- in the process of transportation, the temperature of LNG along the length of the pipeline changes slightly due to heat inflows, taking into account the use of effective thermal insulation, and the state of LNG saturation is achieved mainly due to pressure loss caused by the hydraulic resistance of the pipeline;
- if a pipeline is long, LNG boils at a certain section of it and then is piped by a two-phase flow, creating vapor lock in the vertical pipeline section with the possibility of circulation reversal, the so-called "geyser" effect;
- a method for calculating pressure loss in a two-phase LNG flow section has been proposed. According to the method, a two-phase LNG flow section is divided into segments, within which vapor content \( x \) and the parameters of each phase are assumed to be constant. To calculate pressure loss due to friction \( \Delta p_{cm.tr} \) at the segments \( \Delta l \), the ratios of both the slip flow model (5-6) and the homogeneous model (7 - 12) can be adopted.

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