Selection of Effective Thermal Insulation Materials for a Liquefied Natural Gas Tanks

O N Medvedeva¹, S D Perevalov¹

¹Yuri Gagarin State Technical University of Saratov, 77 Politekhnicheskaya street, Saratov, 410054, Russia

E-mail: medvedeva-on@mail.ru

Abstract. The object of the research is an isothermal tank container for storage and transportation of liquefied natural gases, which requires special operating conditions and is related to a technological facility of increased danger. The purpose of the study is to substantiate the type and thickness of the insulating material to reduce the losses of liquefied natural gas during storage and transportation. Based on the results of the analysis, effective insulation materials were selected for use in cryogenic tanks for isothermal storage of LNG, the optimal thickness of the insulation material was determined, which provides the required level of losses for gas evaporation.

1. Introduction

Tanks for storage and transportation of small volumes of LNG under overpressure are classified as cryogenic, and in the case of storage of large volumes under pressure close to atmospheric pressure, they are classified as isothermal [1–5].

A cryogenic tank for the transportation of liquefied natural gas (LNG) can play the role of both a gas delivery vehicle and a storage tank in the regasification systems of various categories of consumers, which reduces the time and costs of installation and dismantling. The tank container carries out the reception, storage, delivery and transportation of liquefied natural gas. Since the boiling point of the transported product, depending on the composition, is approximately minus 160 °C, due to the heat flow directed from the environment to the low-temperature part of the cryogenic tank, deeply cooled liquefied gas must be stored and transported in well-insulated containers throughout the entire transportation.

Cryogenic tank trucks used for the transportation of liquefied natural gas and storage tanks are usually designed as double-walled tanks (cisterns) with an evacuated annular space, which is partially or completely filled with highly efficient insulating material, which can be a screen-vacuum, vacuum laminated insulation or vacuum powder insulation, allowing to minimize the flow of heat from the environment, ensuring minimal losses of LNG during transportation and storage under specified operating conditions at a small overpressure. Effective insulation ensures optimal transport conditions, since uncontrolled gas evaporation is unacceptable according to safety regulations.

A sufficient number of studies by domestic and foreign authors have been devoted to the analysis of design solutions for isothermal tanks, the assessment of the dangers of isothermal storage of LNG, and the provision of safe operating conditions [1–8, etc.].
To date, there are not so many manufacturers of transport cryogenic tanks for LNG delivery in Russia that have reliability and technical characteristics at the level of world standards (table 1).

### Table 1. Tanks for LNG transportation and storage.

| Tank stamp                          | Manufacturer                        | Geometric volume (m³) | Mass of transported LNG (t) | Maximum permissible operating pressure (MPa) | Insulation type | Percentate of product evaporaton (% per day) | Control retention time (days at least) |
|-------------------------------------|-------------------------------------|-----------------------|-----------------------------|---------------------------------------------|-----------------|---------------------------------------------|---------------------------------------|
| Semi-trailer tank PPT-50/0.7        | PJSC "Cryogen mash"                 | 51.1                  | 18                          | 0.7                                         | screen-vacuum   | 0.14                                        | –                                     |
| Tank container KTM-40/0.7            | JSC Uralkryo mash                   | 40.0                  | 14.28                       | 0                                           | fiber vacuum    | –                                           | 54                                    |
| Tank wagon model 15-5106             | JSC Uralkryo mash                   | 65.4                  | 23.56                       | 0.5                                         | fiber vacuum    | 0.417                                       | 42                                    |
| Gas carrier GT7 LNG PPTT-60          | NPO "Oil and Gas Eng."             | 59/53                 | 20.7                        | –                                           | screen-vacuum   | –                                           | 12                                    |
| Cryogenic gas carrier                | CJSC "Sespel"                      | 49.5                  | 18.97                       | –                                           | vacuum          | –                                           | –                                     |
| Cryog. cont. for transp. and storage of LNG | LLC "Sosnovo borsk MBP" | up to 35               | –                           | up to 1.0                                    | perlite-vacuum  | –                                           | –                                     |

### 2. Materials and methods

At the initial stage of the development of cryogenic tanks, their isolation was carried out by filling them with powder (for example, diatomite or magnesium carbonate). In particular, the tank was insulated under vacuum, which increased the efficiency of the tank insulation by 10 times while reducing the thickness of the thermal insulation and, in some cases, reducing the cost of the tank.

The main functions of insulation in cylindrical storage tanks of vertical type are determined according to GOST P 58029–2017 [9], which will come into effect from January 01, 2022:

- maintaining vapor leakage below certain limits;
- protection of parts (materials of the tank) that are not low temperature (mainly the external tank) by maintaining these parts at the required temperature of the environment;
- limiting the cooling of the foundations (soil) under the tank to prevent damage due to the rise of the soil during freezing;
- prevention (minimization of condensation) of ice formation on the outer surfaces of the tank.

There are the following basic requirements for heat-insulating materials used in cryogenic technology [6–14]: low value of the coefficient of thermal conductivity; absence of chemical interaction with the transported LNG, with elements and materials of the tank; low hygroscopicity and density; ease of installation; operational reliability; compressive strength, etc.
For the purpose of normal operation of the tank (transport tank), all factors affecting the passage of heat through the insulation system should be taken into account, such as [9]: the temperature of the storage product; outdoor temperature and other climatic conditions (solar radiation, wind, humidity, etc.); thermal conductivity (a safety margin should be laid down during the design to take into account the impact of degradation during aging); convective heat exchange; heat inflow through radiation; heat inflow through cold bridges (supports, suspensions, pipes, etc.); the thermal resistance provided by the insulation under specified conditions; the required thermal resistance for each insulation element and the estimated duration of the random process.

For each specific case, the choice of the insulation type is determined by a number of additional factors, for example, the permissible amount of gas evaporation, the temperature of the transported LNG, the size of the insulation structure and the complexity of its configuration, the cost of the insulating material, etc. In addition, it is impractical to use effective, but expensive insulation. In addition to the above, the insulation system should be designed taking into account the design requirements: static and dynamic impacts in all directions and impermeability for the transported LNG. The specified GOST [9] recommends various insulation materials for cryogenic tanks. Thermal insulation materials used in cryogenic technology are conventionally divided into fibrous, powdery (granular) and porous (cellular).

As noted, screen-vacuum and vacuum-powder (fiber) thermal insulation, which have a low coefficient of thermal conductivity both at atmospheric pressure and in vacuum conditions, have been widely used for the thermal protection of cryogenic tanks. The use of high vacuum as insulation eliminates the transfer of heat due to convection and due to the thermal conductivity of the gas. The analysis of insulation materials allowed us to choose a screen-vacuum insulation for subsequent use and calculation.

Let us consider the design of a cryogenic tank for the transportation of liquefied natural gas [5, 13]. The tank can play the role of both a vehicle for the delivery of liquefied natural gas, and the role of a storage tank in the regasification systems of various categories of consumers, which reduces the time and costs of installation and dismantling. The total maximum volume of the tank depends on the design features of the vehicle. As an analog for the analysis, a standard tank for transporting LNG with a useful volume of 30 m³ was chosen (fig. 1). The outer shell of the tank, which is a cylindrical tank with a large moment of resistance, is calculated for atmospheric pressure. During the thermal calculation, the thickness of the insulation layer of the tank shell is determined based on the specified total maximum heat inflow and the requirements for minimizing condensation.

![Figure 1. Scheme of the existing cryogenic tank.](image)

The optimal insulation thickness should ensure minimal losses of cryogenic liquid (LNG) from evaporation. The analysis of modern methods for calculating the heat flow through the surface of the LNG tank body allows us to conclude that all the proposed methods are based on the Fourier and Newton-Richman laws of thermal conductivity. The heat flow through multilayer cylindrical surfaces on the basis of the Fourier law is determined by the equation of the following form:

\[
q_i = \frac{2\pi(t_i - t_{\text{w}})}{(\lambda_i)^\frac{1}{3} \ln \left( \frac{d_{i-1}}{d_i} \right)^\frac{1}{3}},
\]
where $\lambda_i$ is the coefficient of thermal conductivity of the i-th layer n-layer wall, W×(m×K)$^{-1}$; $t_i$ is the temperature of the i-th layer n-layer walls, K; $d_i$ is the diameter of the i-th layer n-layer wall, M.

The heat transfer between the wall surface and the liquid (gaseous) medium according to the Newton-Richman law for the outer (2) and inner (3) surfaces is determined by the equations:

$$q_{\text{out}} = \alpha_{\text{out}} (t_{\text{out}} - t_i);$$

$$q_{\text{int}} = \alpha_{\text{int}} (t_{i+1} - t_{\text{LNG}}),$$

where $\alpha_{\text{out}}$ and $\alpha_{\text{int}}$ are the heat transfer coefficients of the inner and outer surfaces of the tank shell walls, W×(m$^2$·°C)$^{-1}$; $t_{\text{LNG}}$ is the LNG temperature inside the tank, °C; $t_{\text{out}}$ is the ambient temperature, °C.

Let us assume that the length of the cylindrical shell of the container $L$ is so great that the proportion of heat penetrating through the end, non-cylindrical sections is not significant (fig. 2).

![Figure 2. Scheme of a cryogenic tank with cylindrical insulation.](image)

Let us assume that the coefficient of thermal conductivity of insulation and the total temperature difference $\Delta T = T_{\text{out}} - T_{\text{LNG}}$ are known. Due to the high thermal conductivity of the metal, the thermal resistance of the walls can be neglected. Also, the influence of thermal resistances during the transfer of heat from the environment to the outer wall of the casing and from the wall of the inner container to the boiling liquid (LNG) is insignificant. Taking into account the accepted assumptions, the amount of LNG evaporated from the heat inflow along the cylindrical part of the insulating structure per unit of time will be determined from the expression:

$$\Delta G_i = Q_t \times r^{-1},$$

where $r$ is the heat of LNG vaporization; $Q_t$ is the heat flow through the cylindrical part of the thermal insulation.

For a cylindrical cryogenic tank, the heat flow through the cylindrical part of the thermal insulation is determined by the formula:

$$q_t = \frac{\pi \cdot L \cdot \Delta T}{\left(\alpha_t \cdot d_{i+1}\right)^{-1} + \left(2L \lambda_i \right)^{-1} \ln \left[d_{i+1} \cdot \left(d_i^{-1}\right)\right] + \left(\alpha_2 \cdot d_i\right)^{-1}}.$$  

The amount of LNG $G_i$, kg, contained in the cylindrical part of the container:

$$G_i = 0.25\pi \cdot d_i^2 \cdot L \cdot \rho,$$

where $\rho$ is the density of LNG.

Jointly solving equations (1) – (6), optimal diameter of the inner cylindrical container:

$$d_{i,\text{opt}} \approx 0.6d_{i+1},$$

and the optimal insulation thickness:
The design dimensions of the cryogenic tank are determined from the optimal ratios of LNG and coolant volumes. The volume of the unfilled part of the shell is determined by the formula:

\[ V_{un} = 0.5 \cdot R^2 (\theta - \sin \theta) L \]  

(9)

where \( L \) is the length of the cylindrical shell; \( R \) is the radius of the bottom of the shell; \( \theta \) is the angle characterizing the load at any point of the tank shell.

The total volume of the unfilled part is 10% of the total volume of the vessel, then:

\[ V_\Sigma = 0.1 \cdot \pi \cdot R^2 (1.333 \cdot \delta + L) \]  

(10)

where \( \delta \) is the length of the bottom.

Taking into account the \( \theta \) angle, the height of the LNG level in the tank is determined by the formula:

\[ H = R (1 + \cos 0.5 \theta) \]  

(11)

3. Results and discussion

According to calculations, for the complete regasification of 1 m\(^3\) of LNG, 0.9 m\(^3\) of coolant is required, then the volume of LNG will be 16 m\(^3\), and the volume of coolant will be 14 m\(^3\). Based on the calculation results, we obtain the following values for the required wall thickness of the tank shells: for the inner shell – 13 mm; for the intermediate shell – 13 mm; for the outer shell – 17 mm. To ensure a good insulation effect in the inter-wall space of a vessel with high-vacuum insulation, it is necessary to maintain the residual gas pressure at a level of no more than 0.001 Pa. The share of heat transferred by the thermal conductivity of residual gases through high-vacuum insulation in the total heat flow is small [14–21]. Radiant energy is transferred from a warm wall to a cold one. The value of this heat flow at moderately low temperatures is usually small, therefore, the radiation component of the heat flow is neglected in engineering thermal calculations. At cryogenic temperatures, radiant energy can be crucial. Electromagnetic radiation of heated bodies in the wavelength range from 0.4 to 1000 microns is called thermal radiation. Studies have shown that the radiation intensity mainly depends on the temperature of the emitting and receiving surfaces, while the higher the temperature, the greater the total radiation energy. The dependence of the radiation energy on the wavelength has a maximum, which, with decreasing temperature, shifts to the region of longer waves. At the same time, Wien's law is observed.

For the gray bodies, the Stefan-Boltzmann law is expressed as follows:

\[ q_{i,2} = \left[ \frac{1}{\varepsilon} + F_i \times F_2^{-1} \left( \frac{1}{\varepsilon_2} - 1 \right) \right]^{-1} \cdot 5.77 \cdot \left[ (0.01T_i)^4 - (0.01T_2)^4 \right] \cdot H_{1,2}, \]  

(12)

where \( \varepsilon \) is the reduced degree of blackness of the system of radiating bodies under consideration; \( F_i \) and \( F_2 \) are the surfaces of bodies 1 and 2 are involved in radiant heat transfer, m\(^2\); \( H_{1,2} \) is the mutual radiation surface.

In cryogenic tanks, the insulation thickness is usually chosen less than the optimal value. The thickness of the insulation structure approaches the optimal design value only in vessels of relatively small capacity, since the total heat flow from the surrounding medium to LNG is determined not only by the thickness and quality of the insulation. The above analytical expressions allow us to consider the choice of the optimal thickness of thermal insulation. Such problem arises when designing railway tanks, cryogenic tanks mounted on motor vehicles, i.e., with specified external dimensions of the tank.

The optimal insulation thickness should ensure minimal losses of cryogenic liquid from evaporation. Usually, solutions related to the search for the optimal insulation thickness assume the
The constancy of the diameter of the insulated object. In this case, as the thickness of the insulation structure increases, the outer surface of the insulation increases, which under certain conditions can lead to an increase in the heat flow through the thermal barrier. In our case, the diameter of the outer surface is determined by design considerations, so the thickness increase is due to a decrease in the diameter of the LNG container. Under such conditions, for all types of insulation considered above for conventional gas-filled insulation, with the exception of high-vacuum insulation, an increase in the thickness of thermal insulation leads to a decrease in heat inflows to the insulated volume. The concept of the optimal insulation thickness is not related to the value of heat flows, but to the specific evaporation of liquid LNG, which is the ratio of losses from evaporation per unit of time, for example, per hour, \( \Delta G \), to the maximum weight of LNG in the \( G_{\text{LNG}} \) tank:

\[
\Delta g = \Delta G \times (G_{\text{LNG}})^{-1}.
\]  

(13)

An increase in the insulation thickness is accompanied by a decrease in the heat supply and a decrease in losses from evaporation \( \Delta G \), but at the same time, the useful volume of the internal vessel and the maximum weight of LNG in the \( G_{\text{LNG}} \) tank decreases.

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