Peculiarities of cryogenic pipelines insulation selection at small scale liquefied natural gas production and consumption facilities

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Abstract. The article analyzes the typical design and materials of thermal insulation of cryogenic pipelines, compares them on the basis of thermal conductivity, and considers the key differences in the regulatory and technical documents of the Russian Federation, the People's Republic of China and the European Union, which should be taken into account in the design of thermal insulation of pipelines at low-tonnage LNG facilities. A number of regulatory requirements in the Russian Federation restrict the use of commonly used materials such as polyisocyanurate and pouleorethane foam without the development of a safety case or the use of additional compensating measures. Thermal insulation structures based on aerogels or foam glass are acceptable, but have a number of shortcomings.

1 Introduction

The development of liquefied natural gas (hereinafter - LNG) production and transportation technologies, as well as the expansion of the range of possible applications leads to an increase in demand for LNG, both among large power generating companies and among regional and local enterprises in the commercial transportation sector [1]. The demand for LNG for autonomous gasification and as a motor fuel has led to the development of the segment of low-tonnage LNG production and consumption, which includes plants with a capacity of up to 20 t/h, as well as consumption facilities with a storage volume of up to 1500 tons.

On the territory of the Russian Federation, the low-tonnage LNG segment first received numerical indicators and development directions in 2021 [2]. Thus, this direction is new and dynamically developing, which requires continuous improvement of the regulatory framework for design and fire safety requirements.

LNG is natural gas artificially cooled to the temperature of 111-135 K and converted into liquid form for storage and transportation when pipeline transportation is inexpedient [3]. LNG is a cryogenic liquid characterized by a low value of latent heat of vaporization, which means that a small amount of heat can lead to vaporization of LNG, pressure increase in the storage system and significant process losses. During vaporization, the

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change of aggregate state of the substance occurs and a two-phase flow is formed in the pipelines, which additionally leads to a decrease in the throughput capacity of pipelines, as well as disturbances in the operation of dynamic equipment [4]. For example, according to [5], when designing systems with cryogenic centrifugal pumps, the formation of two-phase flow, which can lead to cavitation of the pump, should be avoided. Similar requirements exist for metrological equipment in cryogenic media. According to [6] two-phase flow affects the accuracy of measurements in cryogenic media. Thus, the task of reducing the heat flux to the pumped product and increasing the drainage-free storage time, as well as maintaining the homogeneity of the pumped medium is the key to maintaining a stable process flow, as well as ensuring economic and environmental efficiency of LNG production and consumption facilities. This reduction is achieved through the use of highly efficient thermal insulation materials and designs of LNG storage and transportation systems, as well as optimal design and selection of equipment.

This paper considers a typical design of a cryogenic pipeline, reviews the applied thermal insulation materials, considers their efficiency, comparing the requirements of norms and rules for the design of cryogenic pipelines in the Russian Federation, the People's Republic of China and the European Union. The paper identifies the optimal technical solutions for application in small tonnage LNG facilities in the Russian Federation.

2 Cryogenic pipeline design

Cryogenic pipeline is one of the elements of the LNG transportation system consisting of a pipeline made of steel resistant to cryogenic temperatures, as well as thermal insulation in the construction of which consists of thermal insulation, vapor barrier and cover layers.

A typical design of a cryogenic pipeline is shown in Figure 1 [7].

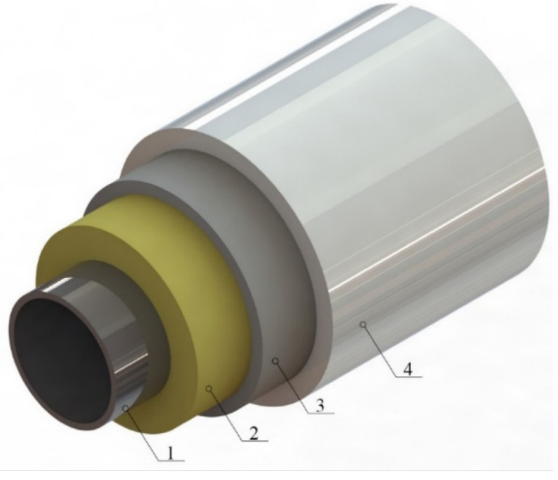

Fig. 1. Typical design of cryogenic pipe: 1 - pipeline, 2 - thermal insulation layer, 3 - vapor barrier layer, 4 - covering (protective) layer.

The main functions of thermal insulation are: preservation of the transported product by reducing heat exchange with the environment and protection of personnel from low temperatures as a result of touching the surface of the pipeline. Depending on the characteristics of the materials used and the peculiarities of fixing, the thermal insulation of a cryogenic pipeline may include layers that give additional functions to the entire structure (e.g., a safety layer or a leveling layer).

3 Comparison of regulatory requirements for thermal insulation

3.1 Types of materials

Currently, aerogels, foamed synthetic rubbers, polyurethane foams and screen-vacuum insulation are widely used as thermal insulation for cryogenic pipelines. Let's consider the main characteristics of each type of insulation presented in Table 1.

Table 1. Characteristics of thermal insulation materials.

Heat insulation	Effective thermal conductivity, W/m*K	Degree of combustibility	Structure
Vacuum-multilayer insulation	1.0·10–4	Non-combustible	Closed
Aerogel	0.012	Non-combustible	Open
Polyurethane	0.027	Flammable	Closed
Polyisocyanurate	0.025	Flammable	Closed
Foam glass	0.036	Non-combustible	Closed

When selecting a thermal insulation material, it is necessary to take into account a whole range of factors, including: material characteristics, cost, labor intensity of installation, pipeline operating conditions, required service life and requirements of the state supervisory authorities for the projected facility. To date, there is a regulatory framework in the Russian Federation and abroad regulating the procedure for calculating thermal insulation and requirements for thermal insulation materials used in LNG production and consumption facilities.

Let's consider the main standards that contain regulatory requirements for LNG production and consumption facilities, presented in Table 2.

Table 2. Main regulatory requirements for thermal insulation.

No.		Russian Federation	People's Republic of China	European Union
1	Main regulatory documents	SP 326.1311500.2017	GB-50264-2013	EN 1473:2007
2	Main properties of thermal insulation	The construction of the thermal insulation must be non-combustible	The use of combustible materials is allowed. The oxygen index must not be less than 30%.	The exposed areas of the insulation must be non-combustible

The key difference between the regulatory requirements of the Russian Federation and the People's Republic of China and the European Union is obviously the need to ensure the non-combustibility of the entire thermal insulation. This requirement significantly limits the choice of materials and makes it virtually impossible to use widely used solutions.

3.2 Efficiency of thermal insulation materials

Another important aspect of insulation selection is its efficiency. In order to compare this parameter for the thermal insulation materials considered in this article, Aspen Hysys has been used to calculate the required thickness of thermal insulation to provide the normalized heat flux to the pumped medium W/m.

Characteristics of thermal insulation coatings for cryogenic pipelines are taken from open information for the following brands: Cryogel-Z (Aerogel based glass fleece), K-Flex (synthetic rubber foam), PIR Cryo (Polyisocyanurate).

The input data is presented in the Table 3.

Table 3. Initial data accepted for calculating the thickness of thermal insulation.

Name	Unit.	Value
Steel grade of pipelines	-	12Cr18NI10Ti
Length of pipelines	м	10
Heat conductivity coefficient of pipelines	W/m·K	15
Wall thickness of pipelines	mm	3
Roughness of pipelines	grid (micron)	600 (30)
Ambient temperature (air)	K	298.15
Air velocity	m/s	5
Speed of pumped medium (LNG)	m/s	3
LNG density	kg/m^3	411.1
LNG equilibrium pressure	bar abs.	4.0
Cryogel-Z heat transfer coefficient	W/m·K	0.0145
K-Flex heat transfer coefficient	W/m·K	0.0310
PIR-Cryo heat transfer coefficient	W/m·K	0.0250
Foam glass	W/m·K	0.0390

Calculation was performed for pipelines with nominal diameter DN50 and DN150.

Liquefied natural gas with model component composition of grade A according to GOST 34894-2022 was accepted as the pumped medium.

The standardized heat flux density was accepted according to SP 61.13330.2012. For pipelines DN50 and DN150 at LNG temperature 128.55 K is 16 W/m and 23 W/m respectively.

Thermal conductivity coefficients for thermal insulation coatings are taken as averaged in the range of operating temperatures (from 298.15 K to 128.55 K).

Figures 2 and 3 show the Aspen Hysys calculation models in which the calculation was performed.

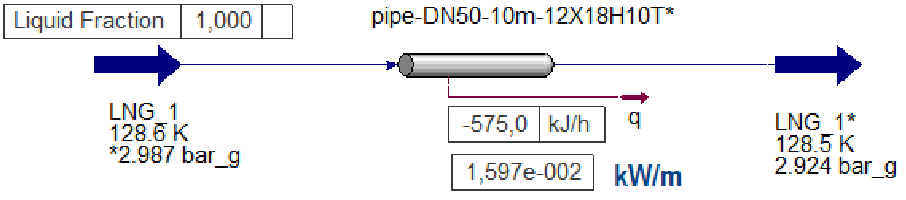

Fig. 2. Calculation of thermal insulation thickness for cryogenic LNG pipeline with nominal diameter DN50 in specialized software.

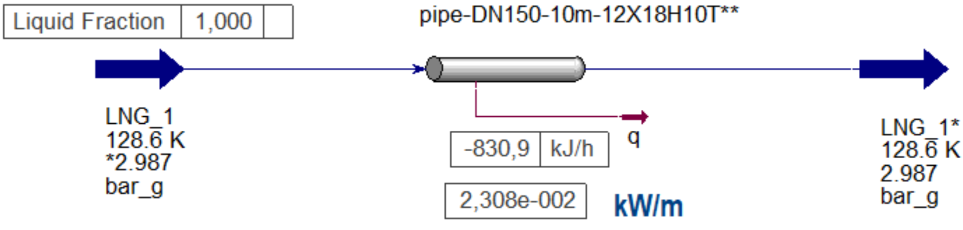

Fig. 3. Calculation of insulation thickness for cryogenic LNG pipeline with nominal diameter DN150 in specialized software.

The calculated thicknesses of thermal insulation coatings for cryogenic LNG pipelines according to the standardized heat flux density for each material are shown in Figures 4 and 5.

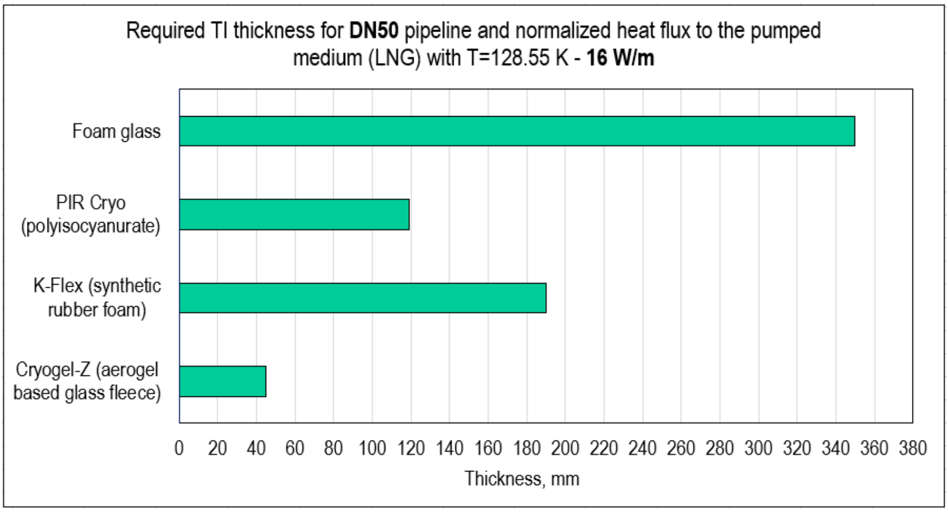

Fig. 4. Results of calculation of the required insulation thickness for cryogenic LNG pipeline DN50 based on the standardized heat flux density of 16 W/m.

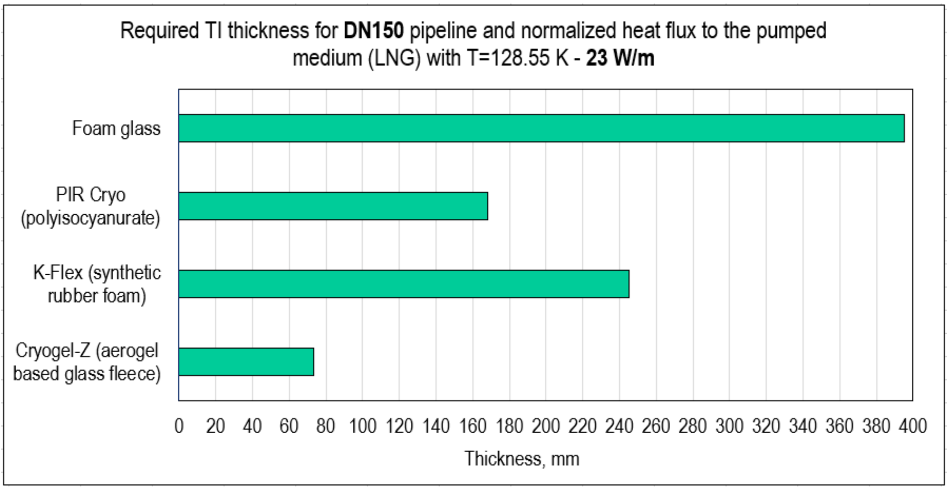

Fig. 5. Results of calculation of the required thickness of thermal insulation for cryogenic LNG pipeline DN150 according to the standardized heat flux density of 23 W/m.

According to the results obtained, it can be concluded that the most effective thermal insulation coating is Cryogel-Z aerogel. Higher efficiency of insulation allows to carry out installation in cramped conditions providing achievement of required values of standardized heat flux where it is impossible when using other materials. The use of this material in technological equipment allows to achieve a reduction of dimensions, and therefore the cost of its logistics and the cost of construction and installation work.

It should be noted that the use of vacuum-insulated pipelines allows to achieve a significant reduction in the heat flux density compared to traditional solutions [8]. As a rule, for pipelines DN50 and DN150 it is possible to achieve the standardized heat flux density of 1 and 3 W, respectively. At the same time, the thickness of the outer casing depends on the manufacturer's decision, but as a rule it is less than the thickness of pipelines in EFI.

4 Conclusion

From the review of Tables 1 and 2, the applicability of each type of insulation for cryogenic pipelines in low-tonnage LNG can be concluded:

- Shield-vacuum insulation is the most effective of the existing insulation types due to its low heat transfer coefficient, non-hygroscopic nature and closed structure provided by the presence of a casing that prevents the ingress of moisture from the outside. Moreover, the screen-vacuum insulation reduces heat transfer from radiation. At the same time, the pipelines with screen-vacuum insulation have a high cost and have a number of limitations on the geometry of the pipeline due to the technological features of manufacturing. Separately it is worth noting the labor-intensive installation of pipelines on site, i.e. high accuracy of equipment installation is required. Also pipelines with screen-vacuum insulation have end sections, which will require the application of another type of insulation in the places of installation of valves (in case of application of non-vacuum valves), as well as at the end sections.
- Aerogels are a high performance non-combustible insulation. It should be noted that the insulation has an open structure, but low sorption humidity (0.05-0.1% at relative humidity from 40 to 97%). This indicator can be further improved by applying a vapor barrier layer and provide a long service life.
- Polyisocyanurate insulation according to [9] has low thermal conductivity, retains geometric dimensions and high resistance to fire. However, the main disadvantage of this type of insulation is the combustibility coefficient G1, which directly contradicts the requirements of the standards of the Russian Federation. At the same time, these materials are actively used in the People's Republic of China and European Union countries.
- Polyurethanes are high-performance insulation that are easy to install, have low thermal conductivity and can serve as a preferred type of thermal insulation of pipelines for a number of cryogenic liquids. However, in accordance with [10], despite the high resistance to fire, the material is not incombustible and emits gas and changes shape when exposed to fire (in accordance with GOST have a fire resistance group G1), which also prevents its use at low-tonnage LNG facilities in the Russian Federation without the development of safety justification.
- Foam glass is a non-combustible material that can withstand combustion in LNG [11] and also has a closed structure, which allows for a long service life. LNG according to However, this material has a high cost, low impact strength, and high density, which leads to increased labor intensity and complexity of installation work.

When installing thermal insulation of cryogenic pipelines to ensure the durability of the structure, as a rule, glue is used, as well as a vapor barrier layer, which is a special mastic or aluminum foil with an adhesive layer, which are combustible materials.

Based on the analysis we can conclude that in the design of cryogenic pipelines for low-tonnage LNG production and consumption facilities in the territory of the Russian Federation today it is allowed to use only pipelines with screen-vacuum insulation or with insulation made of foam glass or aerogels, and it is required to search for and select materials of other layers with confirmed non-combustibility properties. At the same time, standard solutions of foreign manufacturers accepted in the industry are not applicable in the Russian Federation, which leads to increased labor intensity of equipment design and manufacturing, as well as increased cost of construction and installation works.

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