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SCIENTIFIC RATIONALE FOR THE MOVABLE PIPELINE TECHNOLOGY FOR TRANSPORTING CNG BY SEA

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Abstract:
A new efficient CNG module design for the transportation of natural gas by sea is proposed and substantiated. A mathematical model for determining the technical and economic parameters of a movable pipeline module, which is designed for transporting natural gas in a compressed state and consists of a frame structure, the dimensions of which correspond to the 40-foot marine container size and a pipe coil is described. To facilitate construction, it is proposed that a large portion of the coil be made in the form of a two-layer composite construction. The inner layer consists of standard steel tubes or adapters, and the outer layer is fiberglass wound on them. On the basis of the mathematical model an algorithm and a program were compiled, which allowed to determine the technical and economic parameters of the movable pipeline module. The results obtained for the Caspian region are analyzed.

Key words: *compressed natural gas, movable pipeline, parent vessel, marine freight*

INTRODUCTION

The issue of transporting natural gas and using it as the main energy source is extremely important. Choosing the most profitable technology in economic and technological terms remains a major challenge in the industry. Therefore, the construction of new or modification of existing tanks that can carry large volumes of gas the manufacturing technology of not be cost-intensive is a top priority.

Reliable technologies for the storage and transportation of high-pressure natural gas have currently emerged. They are widely used in various industries. These include, in particular, subsea gas pipelines designed for internal pressures of up to 25 MPa and high pressure compressors, as well as offshore terminals for loading gas onto ships directly from offshore fields and receiving gas from ships at sea over a considerable distance from the coast.

The world market has also changed significantly. With the depletion of field resources in traditional areas of natural gas production and the ever-increasing demand for energy in major importing markets, the world has entered a phase of steadily high energy prices. Under these conditions, the use of new gas transportation technologies, in particular CNG technology, which allows for the commercialization of medium and small natural gas fields on the continental shelf, has become economically viable.

However, some experts argue that comparing the transport capacity of CNG tankers with that of LNG tankers may be incorrect, as both technologies are designed to work effectively across gas transportation projects of different magnitude. Thus, high capital cost LNG plants and fleets are only profitable in very large-scale projects with correspondingly large gas reserves and high-capacity markets.

In its turn, gas transportation in the form of CNG can be an effective solution to the problem of transporting small quantities of gas from deep or Arctic fields from small fields, as well as associated gas from oil fields that were previously considered unprofitable. The CNG tanker fleet can be more mobile, bigger and consist of smaller vessels, allowing gas to be delivered daily directly to the distribution pipeline. CNG projects also have a shorter construction period and a much higher net discounted income than LNG projects.

However, when comparing gas transportation by LNG and CNG tankers, the distance from which CNG gas can be transported more efficiently may vary depending on the type of project, the size of the field, the capacity of the market and other economic conditions. However, in general, the cost of CNG transportation is lower at less than 2500 km compared to LNG.

CNG transportation has several advantages over subsea pipelines: its transportation costs do not change depending on the depth of the route. CNG can also be used in high risk areas.

The aim of the paper is to substantiate and scientifically prove the efficiency of the movable pipeline technology for transporting CNG by sea.

LITERATURE REVIEW

The practice of offshore natural gas transportation is widely known for the use of subsea pipelines, transportation of liquefied natural gas (LNG) and compressed natural gas (CNG) by vessels. Given that natural gas can be transported by different types of vessels [13, 25, 26, 27], for each of them there is a large amount of specialized literature that describes the theoretical and methodological aspects of designing such vessels [1, 2, 3, 9, 10, 11, 12, 13, 14, 15, 20, 21, 22, 24]. Pipelines are impractical to transmit gas over long distances, especially across the ocean. Thus, today LNG tankers (gas carriers) are used for this purpose.

The full LNG production cycle consists of a natural gas liquefaction plant, ships (LNG fleet) for the transportation of LNG and re-gasification stations, including gas storage facilities at the arrival point. LNG technology requires high energy-consuming, high-cost liquefaction and regasification infrastructure. LNG plants are large-scale long-term investment projects that also require the construction or rental of a tanker fleet. All these factors hinder the organization of LNG gas transportation from small isolated (especially offshore) fields because of the scale and continuity of LNG production that is required to maintain thermodynamic efficiency and minimize production costs.

An alternative to offshore gas transportation is its shipping as CNG. Compressed gas is natural gas that is transported and stored in high pressure vessels (about 20-25 MPa).

The CNG production cycle includes a gas compression plant, CNG tankers, and a decompression station with gas storage facilities. CNG has a lower cost of production and storage than LNG, since CNG production does not require an expensive cooling process and cryogenic tanks.

Today long-range CNG marine tankers are under development. This is due to the fact that until recently there have been no proven technologies for the storage and transportation of high pressure natural gas.

In addition, large natural land and offshore gas fields were available for development. Deliveries from these gas fields via pipelines and by LNG vessels completely satisfied the demand for natural gas in the major importing markets of the world, which provided a low level of energy prices, whereby the use of new technologies and commercialization of medium and small fields was economically unviable.

Several well-known companies have been designing CNG carriers in the last few years. TransCanada Pipeline has offered a variant of a gas carrier with horizontal cylinders made of a gas tube reinforced with fiberglass composite material. EnerSea Transport and TransOcean propose to place vertical cylinders in airtight refrigerated modules to increase the volume of transportation at the same mass of cylinders. Sea NG proposes to replace the cylinder with a two-dimensional pipe enclosed in the bay and consider it as a length of the pipeline. It reduces the safety factor for cylinders from 2.5 to 1.7. Similar projects are currently being developed in the Russian Federation, especially for Arctic transportations.

The urgency of the study of the compressed natural gas transportation process by movable pipelines, is confirmed by the practice requests and the analysis of the state of the problem nowadays.

Considering that the Coselle system, which is based on the transportation of compressed natural gas in long length pipes in special containers, is the closest to being embodied among other systems, we can conclude that this direction is promising.

Mathematical models for calculating the strength and parameters of movable pipelines, proposed by Kryzhanivskyi Ye.I. [4, 5, 7, 25, 26, 27], Zaytsev V.V. [19, 24], Zaytsev Val.V. [20, 21, 22, 23].

MATERIAL AND METHODS

The studies were carried out by means of the complex method, which consists in the joint use of physical, mathematical and computer simulation of the object of research and experimental methods to confirm the adequacy of the obtained results on the operating equipment and at the laboratory facilities. The basic provisions, formulated conclusions and recommendations are scientifically substantiated with the use of finite element method, fracture mechanics, statistical methods of processing and analysis of experimental results.

The cargo containment system is an essential component of the CNG carrier. The main element of the system are the GCTs (gas containment tanks). Currently, there is a widespread search for the optimal form of tanks, placement of their elements on the carrier and materials for manufacture [8].

Most developers plan to use cylindrical tubes from standard pipes for subsea pipelines. The cylinders are placed on carriers both vertically and horizontally. Experiments are being conducted with steel cylinders, cylinders with outer fiberglass winding, carbon fiber cylinders with fiberglass winding. The original concepts of manufacturing cylinders out of small-diameter thin steel tubes wound on large spools mounted vertically on the carrier are also considered. The purpose of the search is to obtain the optimum ratio of the capacity, mass and cost of the cargo containment system.

The characteristics of the cargo containment system will be largely determined by the specifics of the offshore gas project for which the CNG carrier is intended. The composition and characteristics of the cargo system components depend primarily on where natural gas will be loaded into the CNG carrier and where it will be unloaded. It can be illustrated by the following example.

Complex gas preparation is not required for the CNG carrier intended for receiving gas from the main gas pipeline, as the gas loading into the carrier will be characterized by the standards necessary for transportation in the cylinders. An autonomous gas compression system on such a carrier may also be excessive if both the loading and the receiving terminal are equipped with compression stations of the required capacity.

RESULTS AND DISCUSSION

The technology of CNG transportation on CNG carrier ships, which are equipped with standard 40 foot sea containers, containing cylinders for storing compressed gas in the form of a "movable pipeline" is proposed [6, 14]. There is no need to build or purchase CNG carriers.

CNG carriers can be rented for the quick implementation of the proposed method. After the project closeout and the removal of the pipeline the carriers can be used for their original purpose. It should be noted that only domestic materials, structures, equipment and technologies can be used for the project implementation.

The main investment in this technology is the CNG module based on the sea container.

The proposed CNG module with a two-dimensional high-pressure pipe for the CNG transportation (Figure 1) consists of a standard 40-foot open-type sea container (1), in which the high-pressure cylinder in the form of a dimensional pipe coil consisting of consecutive straight (4) and curved lengths of alternating pipes is placed on the foundations (2). The pipe coil is fixed firmly to the foundations of the CNG-module by means of retainers.

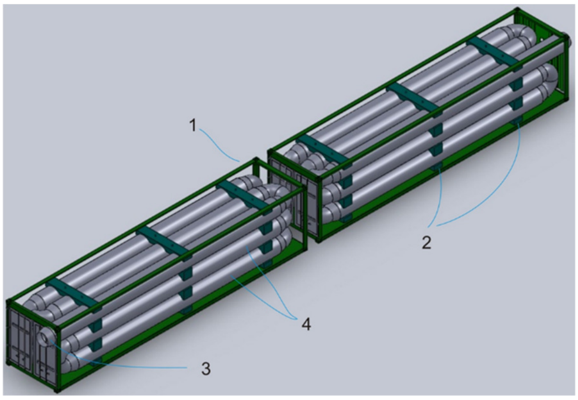

Fig. 1 CNG modules for gas transportation on CNG carriers

The CNG module with the two-dimensional high-pressure pipe is equipped with straight fittings (3) to connect modules of adjacent rows into blocks.

This design of the CNG module is new and therefore requires detailed development: selection of materials, determination of design data, manufacturing technology, assembling, loading and unloading, ensuring transportation reliability, etc.

The first and very important step is to determine all the design data of the module, which is the purpose of this project.

In order to solve the problem of designing a CNG module with optimal design data the following requirements were followed.

Firstly, the construction with the least possible metal capacity must withstand the operational loads.

Secondly, it should be compact, limited by the internal dimensions of the standard container, but at the same time have the maximum net volume and sufficient assembly producibility.

Thirdly, all module elements and the technology required to manufacture it should, where possible, be standardized.

Analyzing the possible ways to fulfill these requirements, we have found that the most rational is to design a CNG module in such a sequence.

First, we make a choice of possible options for the joint implementation of the second and third requirements based on the existing sizes of standard pipes for main pipelines and welded steel parts (adapters and bends). At this stage, we focused on structures, the main element of which is a pipe with diameter of 720 mm. In this case, the maximum internal volume of the container (9 pipes with a distance between adjacent 60 mm) is used.

In order to join the pipe into a single system (pipe coil), three possible variants were analyzed, which differ in the design of the bend: with a circular bend, at right angle and welded 4-section one with 45-degree angles between them. For all variants of construction standard adapters which are from 720 mm to 630 mm in diameter are provided. The adapters perform two important functions. First, reducing the diameter in curved sections increases their strength. It is known that under the action of internal pressure, the curved sections of the pipeline are the most loaded. Secondly, reducing of the diameter of the curved section gives the technological opportunity to carry out welding work by connecting individual pipes into a pipe coil. Thus, under these conditions, the operating space in the narrowest spot increases from 60 mm (automatic welding is not possible) to 150 mm, which makes it possible to use reliable automatic welding technology.

The design choice was made from a comparative analysis of the stress-strain state of the pipeline at different bend circuits and other identical conditions. It is almost impossible to perform such an analysis for a pipe coil loaded with internal pressure. Therefore, we used the finite element method. When creating a geometric model we used the symmetry of the design of the coil. The results obtained are shown in Fig. 2.

As you can see, the design of the right angle bend (see Fig. 2b) is much more loaded than the circular and sectional ones, which are approximately equivalent.

Thus, the design of the spatial pipeline is selected. The next stage of the work is the choice of material and wall thickness of the pipeline elements that would ensure its reliability.

The strength of the main pipe, which is reinforced with composite material, should be evaluated separately.

In cylindrical structures operating under conditions of internal pressure, the operating stresses in the annular direction are twice bigger than the longitudinal ones, and making them all-metal leads to irrational overload of the metal. It is possible to reduce the metallic capacity of long high-pressure pipes by reinforcing them with a composite material which, working together with the metal base, will bear the excess of circular loads [7, 13].

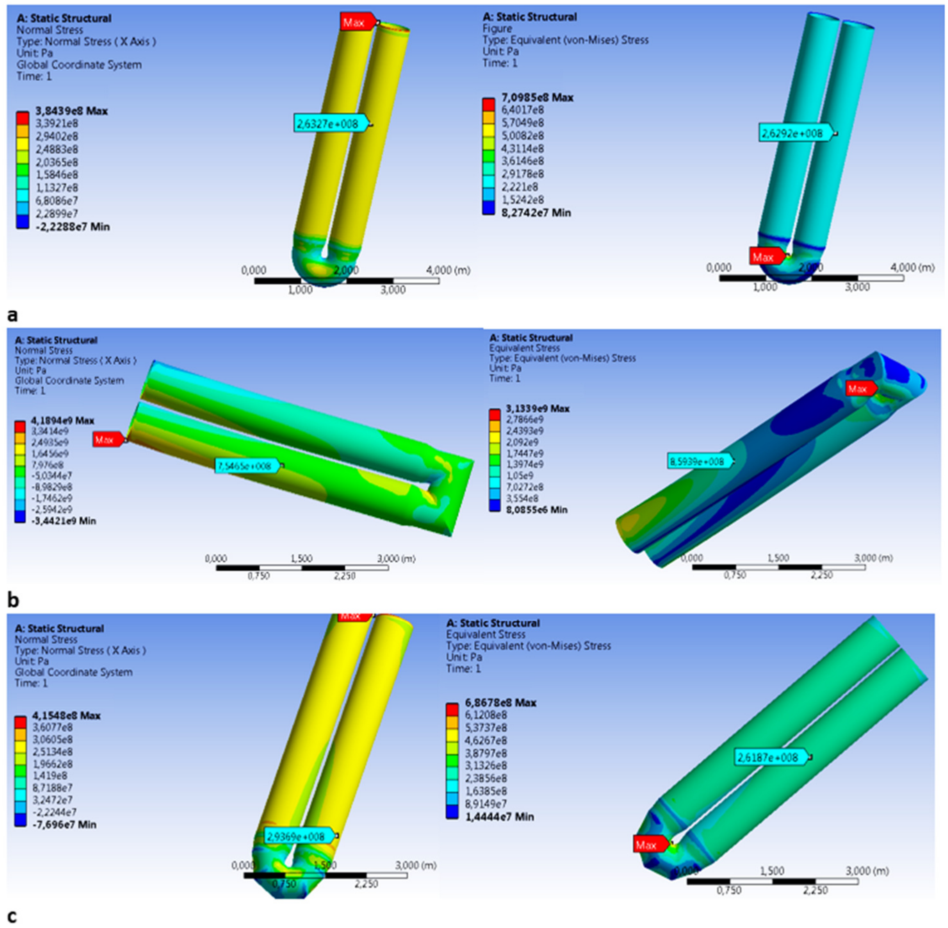

Fig. 2 Stress-strain state of the pipeline at different variants of bend design: a - circular; b - with direct bend; c - with sectional bend

Existing schemes for the formation and polymerization of the reinforcing composite cover provide structures with a length not exceeding the standard pipe length (9-12.5 m). This is due to the limited dimensions of the winding equipment, the polymerization furnaces and the dimensions of the production facilities. Therefore, when the length of the pipes exceeds several tens of meters and reaches hundreds of meters with the corresponding length of mass of construction, there are a number of problems associated with the manufacture and transportation of them to the installation and operation site.

In this case, the most rational technological scheme for manufacturing the product is modular configuration, which provides:

- factory production of separate sections of serial tubes up to 12.5 meters in length, on which the composite reinforcing shell is formed and polymerized, with the bearing faces of the pipes being stripped for the length required for welding;
- transportation of ready 12-meter sections to the installation site;
- welding sections together;
- the formation (winding) and polymerization of the reinforcing composite shell-bandage in the welding zone.

The polymerization of the composite shell in the welding zone is carried out using a clutch type split tube furnace.

The effect of the composite reinforcing shell on the durability of vessels under cyclic loading with internal pressure was investigated on a model of a welded cylindrical can with a wall thickness of 3.5 mm, the cylindrical part of which was amplified by the composite material.

The results of cyclic test of a steel welded housing of a pipe model under the pressure of 19.6 MPa and a frequency of 10 cycles per minute testified that the maximum number of cycles that the housing can with stand till depressurization (formation of a fatigue crack) does not exceed 2500-4000.

Reinforcement of the steel pipe with a composite shell, which is presented in the Fig. 4, enhances their cyclic durability, which is increased by the thickness of there inforcing composite shell. When the thickness of the composite shell (3.6 mm) equals the thickness of the steel pipe, the capacity of the cylinders under cyclic loading conditions increases up to 6-7 times compared to the capacity of the unreinforced steel pipe. At the same time, the strength of the pipe under static load almost doubles (Fig. 3).

The obtained results show that the reinforcement of steel pipes allows to increase their efficiency under cyclic loads 6-7 times, or to increase the working pressure almost twice without increasing the thickness of the metal and at the same working pressure.

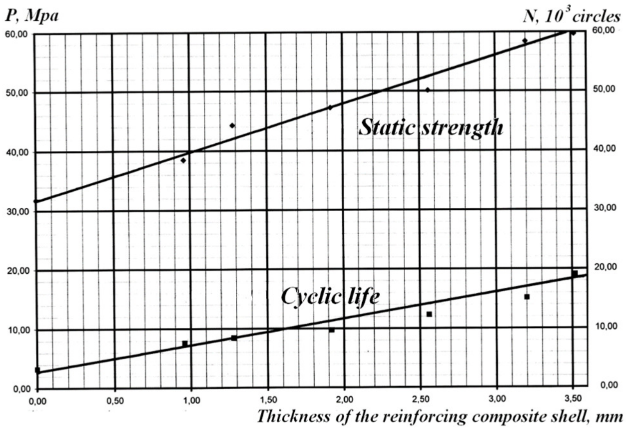

Fig. 3 The dependence of static strength and cyclic life of the structure on the thickness of the reinforcing composite shell

According to the analysis of possible steels grades, used for the production of main pipelines, 30XMA steel with the following mechanical characteristics was selected: σ_s = 800 MPa, $\sigma_{0.2}$ = 650 MPa. The calculation is carried out in accordance with the requirements for high pressure pipelines by the coefficient of reserve K_r [13]. Then, with K_r = 1.75 we obtain $[\sigma]$ = 457 MPa. The finite element model (Fig. 4) was investigated, which made it possible to determine the dependence of the minimum allowable wall thickness of the module elements on the working pressure (Fig. 5).

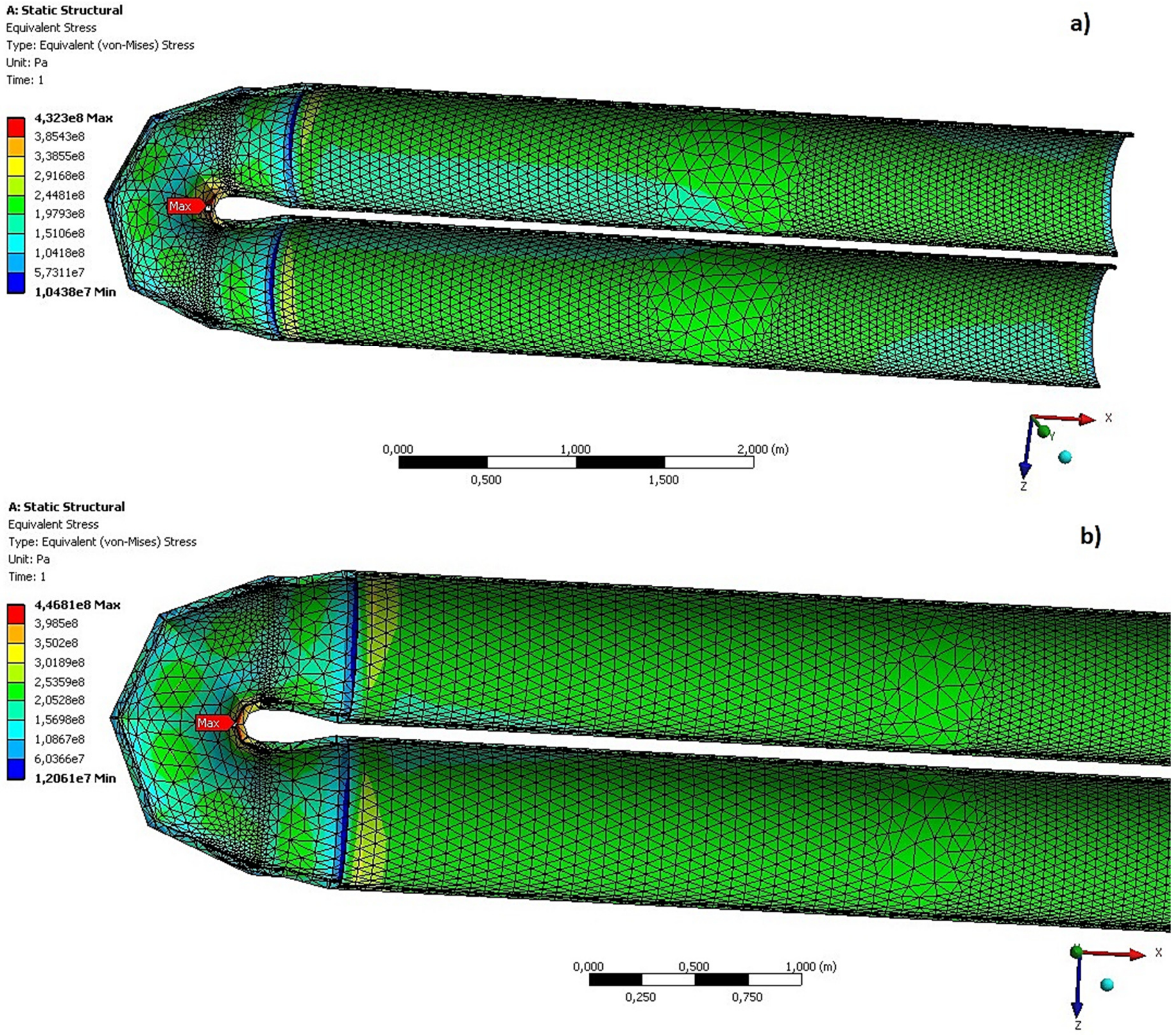

Fig. 4 stress-strain state of the pipeline construction with 15 mm wall thickness of main pipe: a - working pressure of 20 MPa, wall thickness of the bend and adapter is 33 mm; b - working pressure of 25 MPa, wall thickness of the bend and adapter is 38 mm

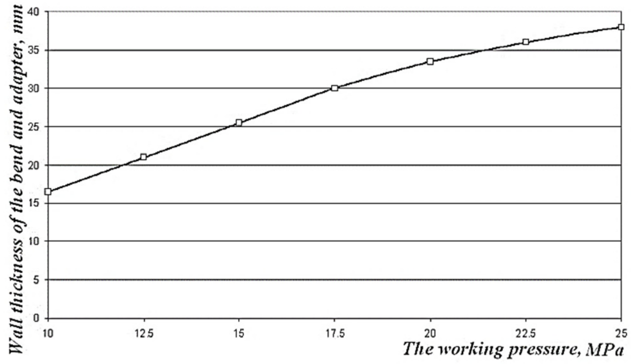

Fig. 5 Dependence of the allowable wall thickness of the bend and adapter on the working pressure

The efficiency of natural gas transportation in CNG modules is confirmed by the following calculations.

The module consists of a frame structure with dimensions that correspond to the dimensions of a 40-foot shipping container and a pipe coil (Fig. 1). To facilitate construction, most of the coil is made in the form of a two-layer composite construction. The inner layer is standard steel tubes or adapters, the outer layer is fiberglass wound on them (Figs. 6, 7).

The coil includes the following elements:

- cylindrical composite pipe sections (9 pcs.) with an outer diameter of 720 mm steel layer;
- conical adapters with a partially wound length fiberglass layer (18 pcs.) connecting cylindrical segments and the toroidal elbows;
- toroidal steel elbows (8 pcs.), which combine all pipe sections into a single spatial coil.
- steel cylindrical adapters (2 pcs.), which are required for joining modules into blocks.

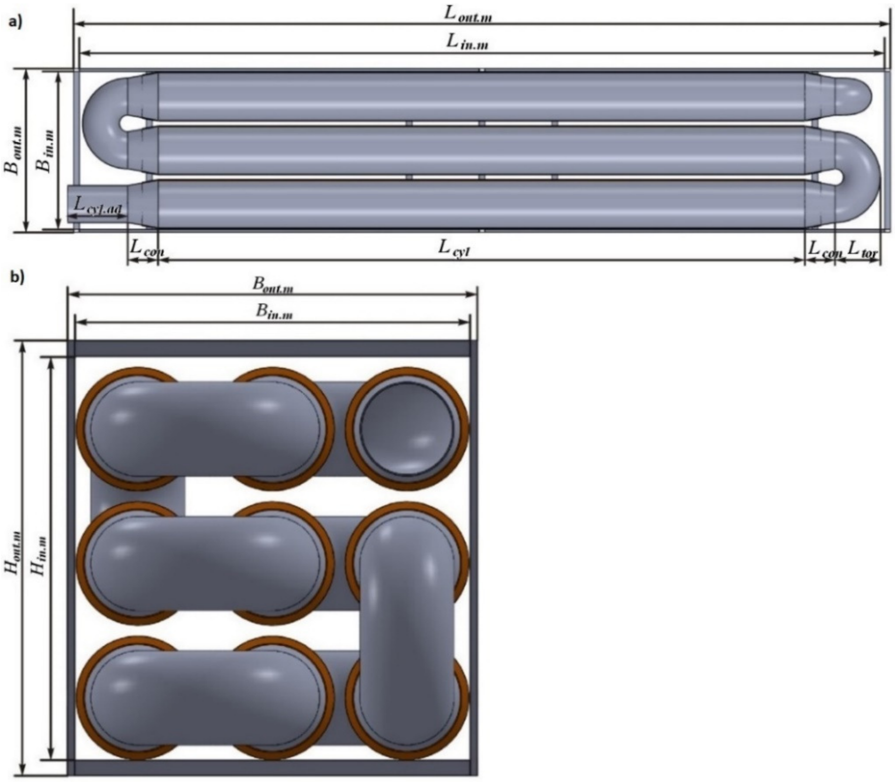

Fig. 6 Module sketch: a) - top view of the intersection of the first layer of the coil, b) - right-side view

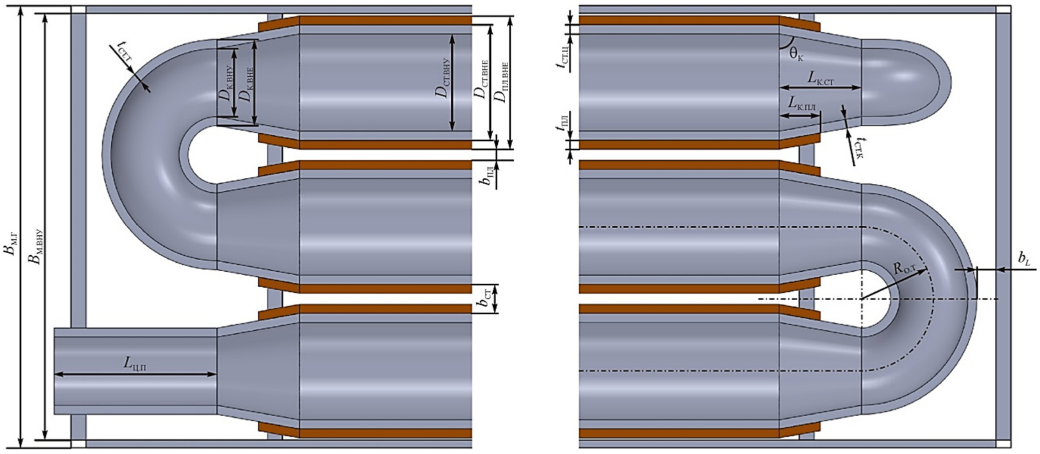

Fig. 7 Detailed sketch of the top view of the toroidal elbows

The main technical and economic parameters of the module to be determined:

- volume of gas in the coil under normal conditions, $V_{\text{gas.nc}}$, m^3;
- volume of cargo space in the coil, V_{sp}, m^3;
- mass of the module with gas, m_m, kg;
- mass efficiency of the coil, k_{eff}, kg/l;
- cost of the module, C_m, USD;
- unit cost of the module, c_{m}, USD/l.

Based on the design of the coil, the volume of its cargo space, V_{sp}, m^3 is determined by the dependence:

$$V_{sp} = 9V_{in.cyl} + 18V_{in.con} + 8V_{in.el} + 2V_{in.ad}$$

where:

$V_{in.cyl}$ – volume of space in the section of a cylindrical tube, m^3:

$$V_{in.cyl} = \pi \frac{D_{in.st}^2}{4} L_{cyl}$$

$D_{in.st}$ – the inner diameter of the steel pipe, m:

$$D_{in.st} = D_{out.st} - 2t_{cyl.st}$$

$D_{out.st}$ – outer diameter of the cylindrical steel part of the pipe, m;

$t_{cyl.st}$ – the accepted wall thickness of the cylindrical steel part of the pipe, m;

L_{cyl} – the length of the segment of the cylindrical part of the pipe, m:

$$L_{cyl} = L_l - 2(L_{con} + L_{tor})$$

L_l – length of the loading area of the module, m:

$$L_l = L_{in.m} - 2b_L$$

$L_{in.m}$ – the length of the module internal space (40-ft), m;

b_L – the gap between the module head stock and the pipe, m;

L_{con} –the length of the conical steel pipe, m:

$$L_{con} = 0.5(D_{out.st} - D_{out.con}) \cdot tg\theta_{con}$$

$D_{out.con}$ – the outer smaller diameter of the conical part of the pipe, m;

θ_{con} – the angle of inclination of the cone generatrix, rad;

L_{tor} – the outer radius of the toroidal pipe elbow, m:

$$L_{tor} = R_{c.tor} + 0.5D_{out.con}$$

$R_{c.tor}$ – the radius of the center line of the toroidal pipe elbow, m:

$$R_{c.tor} = \frac{D_{out.fg} + b_{fg}}{2}$$

$D_{out.fg}$ – the outer diameter of the cylindrical fiber-glass part of the pipe, m;

$$D_{out.fg} = D_{out.st} + 2t_{fg}$$

t_{fg} – accepted thickness of fiber-glass pipe shell, m;

b_{fg} – the maximum gap between the fiber-glass shells of the pipes, m:

$$b_{fg} = \frac{B_{in.m} - 3D_{out.fg}}{2}$$

$B_{in.m}$ – the width of the module internal space (40-ft), m;

$V_{in.con}$ – the volume of the space in the cone, m^3:

$$V_{in.con} = \pi \frac{D_{in.con}^2 + D_{in.st}^2}{8} L_{con}$$

$D_{in.con}$ – the inner smaller diameter of the conical part of the pipe, m:

$$D_{in.con} = D_{out.con} - 2t_{con.st}$$

$t_{con.st}$ – the wall thickness of the conical steel pipe, m;

$V_{in.el}$ – the space volume in the elbow fitting, m^3:

$$V_{in.el} = \pi^2 R_{c.tor} \frac{D_{in.con}^2}{4}$$

$V_{in.ad}$ – the space volume in the segment of the cylindrical adapter, m^3:

$$V_{in.ad} = \pi \frac{D_{in.con}^2}{4} L_{cyl.ad}$$

$L_{cyl.ad}$ – the length of one cylindrical adapter between modules, m:

$$L_{cyl.ad} = L_{in.m} - b_L - L_{tor} - 2L_{con} - L_{cyl} + 0.5(L_{out.m} - L_{in.m}) + 0.1$$

$L_{out.m}$ – the overall length of the module (40-ft), m.

All thicknesses of coil shells are determined on the basis of strength calculations.

The volume of gas in the coil under n. c., $V_{gas.nc}$, m^3:

$$V_{gas.nc} = V_{sp} k_{exp}$$

where:

k_{exp} – the gas expansion coefficient:

$$k_{exp} \ \frac{\rho_{gas}(P_{work}, t_{work})}{\rho_{gas}\ (P_{nc}, t_{nc})}$$

P_{nc} = 101325 Pa;

t_{nc} = 15°C;

P_{work} – the working pressure in the pipe, Pa;

t_{work} – the temperature of natural gas in the coil;

$\rho_{gas}(P, t)$ – the function describing the dependence of natural gas density on pressure and temperature, kg/m^3.

A function describing the dependence of natural gas density on pressure and temperature is based on the physical properties of methane. It is necessary to use the results of experimental studies of the properties of methane, which, for example, are described in detail by N. B. Varhaftik in [16], because the dependence of methane density on pressure and temperature does not correspond to the properties of an ideal gas.

Based on the data provided in [16], an algorithm and a program were developed that allow for determining the methane density for a given methane temperature and pressure. The program interpolates tabular data using cubic splines.

The dependence of methane density on temperature and pressure is graphically shown in Figs. 8 and 9.

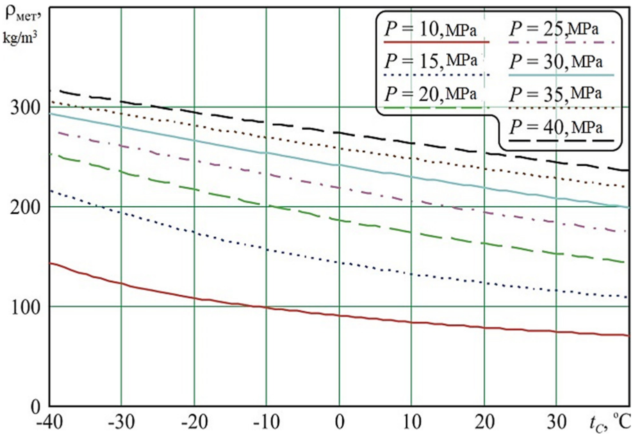

Fig. 8 Dependence of methane density on its temperature at pressure from 10 to 40 MPa

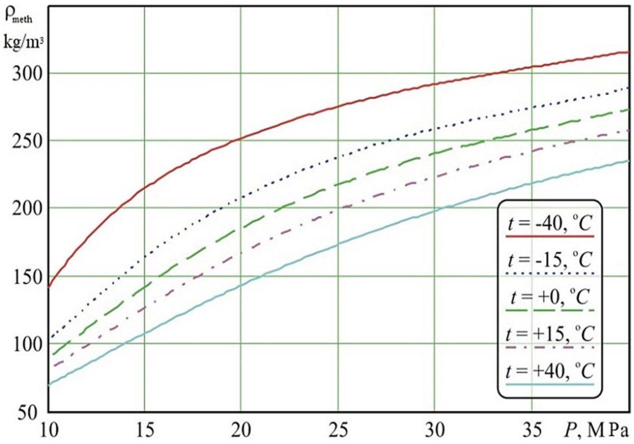

Fig. 9 Dependence of methane density on its pressure at temperatures from -40°C to +40°C

The mass of the module with gas, m_m, kg:

$$m_m = m_{sh} + m_{p.g}$$

m_{sh} – the mass of the framed shell of the module, kg;

$m_{p.g}$ – the mass of the pipe coil with gas, kg:

$$m_{p.g} = m_{gas} + m_{st} + m_{fg}$$

m_{gas} – the mass of the gas in the pipe coil, kg:

$$m_{gas} = V_{sp}\rho_{gas}$$

m_{st} – the mass of the steel in the pipe coil, kg;

m_{fg} – the mass of the fiber-glass in the pipe coil, kg.

The mass of the steel in the pipe coil, kg:

$$m_{st} = \rho_{st}V_{st}$$

where:

ρ_{st} – the density of the steel part of the pipe, kg/m^3;

V_{st} – the volume of the steel in the pipe coil, m^3:

$$V_{st} = 9V_{st.cyl} + 18V_{st.con} + 8V_{st.el} + 2V_{st.ad}$$

$V_{st.cyl}$ – the volume of the steel in the length of a cylindrical pipe, m^3:

$$V_{st.cyl} = \pi\frac{D_{out.st}^2}{4}L_{cyl} - V_{in.cyl}$$

$V_{st.con}$ – the volume of the steel in the cone, m^3:

$$V_{st.con} = \pi\frac{D_{out.con}^2 + D_{out.st}^2}{8}L_{con} - V_{in.con}$$

$V_{st.el}$ – the volume of the steel in the elbow fitting, m^3:

$$V_{st.el} = \pi^2 R_{c.tor}\frac{D_{out.con}^2}{4} - V_{in.el};$$

$V_{st.ad}$ – the volume of the steel in the length of cylindrical adapter, m^3:

$$V_{st.ad} = \pi\frac{D_{out.con}^2}{4}L_{cyl.ad} - V_{in.ad}$$

The mass of the fiber-glass in the pipe coil, kg:

$$m_{fg} = \rho_{fg}V_{fg}$$

ρ_{fg} – the density of the fiber-glass tube shell, kg/m^3;

V_{fg} – the volume of the fiber-glass in the pipe coil, m^3:

$$V_{fg} = 9V_{fg.cyl} + 18V_{fg.con}$$

$V_{fg.cyl}$ – the volume of the fiber-glass in the length of a cylindrical pipe, m^3:

$$V_{fg.cyl} = \pi\frac{D_{fg.out}^2 - D_{out.st}^2}{4}L_{cyl}$$

$V_{fg.con}$ – the volume of the fiber-glass in the blast pipe, m^3:

$$V_{fg.con} = \pi L_{fg.con}\frac{D_{out.fg}^2 + 4D_{out.fg.con}t_{fg} - D_{out.st}^2 - 4t_{fg}^2}{8}$$

$L_{fg.con}$ – the length of the conical fiber-glass part of the pipe, m;

$D_{out.fg.con}$ – outer smaller diameter of the conical fiber-glass part of the pipe, m:

$$D_{out.fg.con} = D_{out.fg} - (D_{out.fg} - D_{out.con} - 2t_{fg})\frac{L_{fg.con}}{L_{con}}$$

The mass efficiency of the pipe coil, k_{eff}, kg/l:

$$k_{eff} = \frac{m_{st} + m_{fg}}{1000V_{sp}}$$

Production costs of the module, C_m, USD:

$$C_m = (C_{sh} + C_{st} + C_{fg})k_{work}$$

k_{work} = 1.35 – coefficient taking into account the cost of welding and installation works;

C_{sh} – the price of the framed shell of the module, USD:

$$C_{sh} = m_{sh}c_{sh}$$

c_{sh} – the price for the 1 kg module frame shell products, USD/kg;

C_{st} – the price of the steel in the pipe coil, USD:

$$C_{st} = m_{st}c_{st}$$

c_{st} – the incremental cost of the metal in the pipe, USD/kg;

C_{fg} – the price of the fiber-glass in the pipe coil, USD:

$$C_{fg} = m_{fg}c_{fg}$$

c_{fg} – the incremental cost of the fiber-glass in the pipe, USD/kg.

The incremental cost of the module, c_m, USD/l:

$$c_m = \frac{C_m}{1000V_{sp}}$$

Based on the mathematical model presented above, an algorithm and a program were developed to determine the technical and economic parameters of the movable pipeline module.

As an example, let's analyze the possibilities of using the movable pipeline technology in the Caspian Sea. Operation of movable pipelines in the Caspian Sea is limited to the use of carrier vessels with a displacement of up to 70,000 tons for these purposes. For such vessels, the capacity N_m is approximately 1250 modules, the speed of travel is 20 knots. The distance between loading and unloading ports shall be no more than 200 km (108 miles).

Amount of gas transported under normal conditions on such vessel in one sea run:

$$V_{1r} = C_m N_m = 9705 \cdot 1250 = 12.1 \cdot 10^6\text{m}^3$$

The loading and unloading operations can take up to 15 hours and, accordingly, the round-trip time:

$$t_{r_t} = \frac{\frac{108\cdot 2}{20} + 15 + 15}{24} = 1.7\text{ days}$$

Therefore, the annual carrying capacity of such a carrier vessel is:

$$V_c = V_{1r}\frac{T}{t_{rt}} = 12.1 \cdot 10^6 \cdot \frac{360}{1.7} = 2.56 \cdot 10^9\text{m}^3$$

where:

T = 360 is the duration of the vessel's annual operating period, days.

CONCLUSION

The technology of CNG transportation on CNG carrier ships, which are equipped with standard 40 foot sea containers, containing cylinders for storing compressed gas in the form of a "movable pipeline" is proposed. There is no need to build or purchase CNG carriers. CNG carriers can be rented for the quick implementation of the proposed method. After the project closeout and the removal of the pipeline the carriers can be used for their original purpose. It should be noted that only domestic materials, structures, equipment and technologies can be used for the project implementation. A new efficient CNG module design for natural gas transportation by sea is offered and substantiated. Analytical dependencies were obtained, which, therefore, allow to create a mathematical model for determining the technical and economic options of the movable pipeline module with a facilitated pipe coil. The technical and economic options of the movable pipeline module in relation to the Caspian region were calculated based on the created mathematical model.

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