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Dzhus A.,
Yurych A.

IMPROVEMENT OF TANK FOR GAS TRANSPORTATION IN COMPRESSED CONDITION AND COMPARATIVE EVALUATION CRITERIA

Об'єктом дослідження є конструктивні особливості ємностей для транспортування газу в стиснутому стані та критерії їх порівняльної оцінки. Одним з найбільш проблемних місць є відсутність єдиного підходу до неекономічної оцінки ефективності перевезення стиснутого газу в ємностях високого тиску. Особливої важливості питання набуває за умов транспортування газу морськими шляхами і, зокрема, видобутого на шельфі. Це зумовлено різноманітністю пропонованих виробниками варіантів конструкцій ємностей, що характеризуються різними робочими тисками та конструктивним виконанням. Для створення можливості оцінки масогабаритної досконалості ємностей високого тиску проведено аналіз конструкцій, придатних для формування вантажних систем морських транспортних засобів, та критеріїв їх порівняльної оцінки. Також запропоновано конструкцію багатопорожнинної ємності високого тиску підвищеної працездатності, що складається зі сталевих і склопластикових труб та спеціальних з'єднань зі вставними фіксуючими елементами. З огляду на те, що для обліку газу прийнято використовувати нормальні метри кубічні, для порівняльної оцінки їх досконалості запропоновано новий універсальний критерій. Він визначається відношенням маси ємності до приведеного до нормальних умов об'єму газу, що транспортується в ній. Критерій встановлює зв'язок між кількістю транспортованого газу та основним параметром ємностей з огляду на їх включення до складу вантажних систем транспортних засобів. За вказаним критерієм багатопорожнинні ємності є конкурентоздатними за умов їх виконання у вигляді довгомірної конструкції, обмеженої параметрами морського транспортного засобу. Завдяки універсальності запропонованого критерію забезпечується можливість його використання виробниками ємностей високого тиску при просуванні продукції в різних галузях промисловості. Для сприйняття нового критерію споживачами необхідним є проведення його порівняльного аналізу із використовуваними на сьогодні критеріями оцінки досконалості для ємностей різних типів і параметрів.

Ключові слова: *транспортування стиснутого природного газу, ємності комбінованого типу, критерії досконалості конструкцій, маса ємності, об'єм газу.*

1. Introduction

When extracting gas on the shelf, it is important to create a system for its transportation to the shore, which can be carried out by pipeline transport or special tanks in the liquefied (LNG) or compressed (CNG) condition. Given the low cost of coastal infrastructure, the possibility of changing routes and relatively low transport tariffs, it is advisable to use CNG technology. The results of the technical and economic analysis indicate the efficiency of transportation from the shelf deposits to 1 billion m^3 of gas per year in a compressed state, self-propelled or non-self-propelled by barges [1, 2]. To implement the technology, a prerequisite is the availability of gas transportation tanks. At the same time, they should be characterized by low mass-dimensional indicators and be workable under certain operating conditions.

2. The object of research and its technological audit

The object of research is the design features of tanks for gas transportation in a compressed state and the criteria for their comparative evaluation.

At present, there is no unified approach to the non-economic evaluation of the efficiency of transportation of compressed gas in high-pressure tanks. This is due to the variety of designs of tanks offered by manufacturers, and requires the development of new or improvement of existing methods.

To account for gas produced from wells and transported to the consumer, it is customary to use normal or standard cubic meters. Therefore, it is advisable to introduce a new criterion that would establish the connection between the amount of gas in the tank and one of its main parameters. At the same time, a prerequisite is its universality.

3. The aim and objectives of research

The aim of research is creation of the possibility of evaluation of the mass-dimensional perfection of tanks, characterized by different working pressures and design.

To achieve this aim it is necessary to perform the following objectives:

1. To analyze the design solutions and criteria for the comparative evaluation of high-pressure tanks, suitable for the formation of the cargo systems of marine vehicles.
2. To offer a universal comparative evaluation criterion and check the possibility of its use for existing and developed designs of high-pressure tanks.

4. Research of existing solutions of the problem

In recent years, EnerSea Transport LLC (USA) [3] and Sea NG Management Corporation (Canada) [4] have been most focused in developing marine compressed natural gas transportation systems. The vehicles designed by the companies are designed for transportation from 3 to 33 million m^3 of natural gas. For gas transportation in smaller volumes, TransCanada Pipeline Ltd. offers separate solutions (Canada) [5].

According to the results of further analysis of the technical solutions offered by leading companies in the industry, it has been established that the use of special modules with CNG-4 composite tanks is possible for the formation of cargo systems for marine vehicles, and in particular barges [6]. The main advantage of such tanks in most cases is their relatively low mass. The liner of the composite tank is form-generating, and the main load is perceived by the winding impregnated with a bonding material. The use of a plastic liner in combination with carbon fiber allows minimizing the mass of the tank, provided that the required strength is provided, is a tangible competitive advantage. Also, the advantages of composite tanks should include a high level of safety. Thus, under the action of internal pressure, the destruction of cylinders occurs without the formation of fragments. The only significant disadvantage of any composite tank is its low resistance to shock loads.

Although the production of composite tanks is expensive, their characteristics determine the main areas of application. It is advisable to use such tanks for storing compressed gases under high pressure under operating conditions that require their frequent movement. In order to reduce gas treatment requirements, the option of vertical arrangement of tanks is optimal; it creates the possibility of removing, if necessary, the liquid condensed from natural gas. However, when mounting such tanks on barges, their own adjustments introduce restrictions on their allowable height. With this in mind, the use of tanks of the combined type (CNG-2), both in modular design [1] and in the form of a long pipe [7], can be an alternative. For all-metal cylindrical high-pressure tanks, and in particular CNG-1 cylinders, a common disadvantage are their large mass, due to the considerable wall thickness, and, as a result, the inefficient use of the strength properties of the material.

In addition to multi-layered ones, such as CNG-2, CNG-3, and CNG-4 type tanks, in order to reduce the size of gas transportation (in particular, by barges), multi-cavity tanks can also be used. Today, multi-cavity tanks (tanks, cylinders, etc.) of high pressure are known, the design of which is based on the principle of unloading the shell from high pressure on the one hand using back pressure on the other [8].

All the above types of tanks are characterized by certain advantages and disadvantages. Therefore, in order to compare and select cargo tanks, special criteria for their evaluation are introduced.

With a known mass of tanks for transporting compressed natural gas and the mass of gas transported to them, commonly known criteria are used. The most common is the ratio of the mass of the cargo in the cargo tank to the mass of the empty cargo tank (G) and the ratio of the mass of the cargo in the cargo tank to the mass of the filled cargo tank (η) [9].

Also known criterion, called the «perfection coefficient» or «packaging coefficient», which is determined by the ratio of the mass of the tank to its useful internal volume, measured in liters of water. The heavier the tank, the higher its packaging coefficient. For example, the packaging coefficient is for cylinders:

– CNG-1 (carbon steel) – from 0.9 to 1.2 kg/l;
– CNG-2 (alloyed steel and ring winding) – from 0.65 to 0.85 kg/l;
– CNG-3 (aluminum liner and winding of composite material) – from 0.3 to 0.5 kg/l;
– CNG-4 (composite material) – from 0.25 to 0.55 kg/l [10].

It should be noted that these coefficients are correctly compared in conditions of equal working pressures of cylinders of various types (for example, 20 MPa).

Structurally mass or mass perfection of high-pressure tanks and cylinders are also commonly evaluated by the parameter of constructive perfection (PCP), which is a more universal energy indicator, allows to compare tanks of any shape [11]:

$$PCP = W_{WST} = \frac{P_d \cdot V_{vol}}{M_{WST}}, \quad (1)$$

where $P_d \cdot V_{vol}$ – design (constructive) parameter; P_d – destructive pressure; V_{vol} – internal volume of the shell; M_{WST} – mass of the whole structure of the tank as a whole.

The mass perfection parameter W_{WST} has the dimension of the specific strength of the material σ_B/ρ_m, kJ/kg. The total mass of the tank includes the mass of the power and sealing shells, the mass of fittings, flanges, coatings and other structural elements. In this case, the parameter W_{WST} itself does not depend on the shape and geometrical dimensions of the tank (cylinder). Therefore, the expression (1) can be used to compare not only the whole structure, but also the power shells, made of metals and composite materials. However, this parameter takes into account the values of not the working pressure, but destructive, does not allow to determine the amount of gas transported in the tank, according to known mass-dimensional parameters.

5. Methods of research

Despite the drawbacks caused by the use of multi-modular materials for the manufacture of tanks and the orthotropy of main indicators of the strength of composites, one of the ways to solve a number of problematic issues is to transform them from multi-layer shells into multi-cavity ones. This is achieved by separating the shells and, as a result, the formation of annular space between them. Under these conditions, both the inner and outer shells should be completely sealed. The presence of back pressure in the annular space reduces the load on the inner shell and, accordingly, its thickness.

A variant of a multi-cavity high-pressure tank is a structure formed by concentric placement of steel and composite pipes with a length limited by the features of their fixing or vehicle dimensions. The design scheme of multi-cavity high pressure tanks is proposed in [12] and has the form shown in Fig. 1.

Today, in accordance with ISO 2001, ISO 14692, DIN, ANSI, DNV, API, ASTM standards, fiberglass-reinforced

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epoxy (GRE) pipes are made from 50 to 1000 mm in diameter with a standard length of 6 and 12 m. These pipes are designed for pressure up to 24.5 MPa. For the formation of pipelines are used as adhesive and mechanical connections [13]. However, they are the limiting factor in relation to maximum working pressures. The research results obtained by the authors of [14] confirm the possibility of expanding the field of use of fiberglass pipes by introducing special plug-in fixing elements into the joint structure.

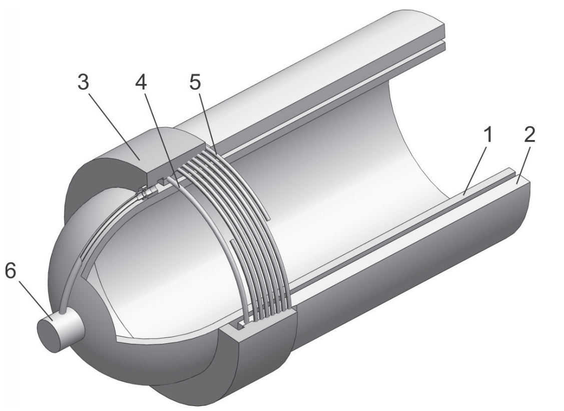

Fig. 1. Scheme of construction of a multi-cavity high-pressure tank formed using composite and steel pipes: 1 – steel pipe with a hemispherical bottom; 2 – composite pipe; 3 – steel half coupling; 4 – sealing element; 5 – plug-in locking element; 6 – multivalve

In order to compare the proposed design of the tank for transporting compressed natural gas with analogues with a known mass of gas, the above-mentioned criteria G and η can be used. The «perfection coefficient» for tanks with a working pressure other than 20 MPa, and for multi-cavity ones is unused.

Despite the fact that, as already noted, gas is measured in normal or standard cubic meters, the new, more universal criterion is the ratio of the mass of the tank to the volume of gas transported in it, reduced to normal conditions:

$$j = \frac{m_T}{V_{vol}}, \tag{2}$$

where m_T – mass of the tank, kg; V_{vol} – gas volume, n. m^3.

To determine the mass of the tank, it is necessary to establish its main design parameters.

In the basic version, the outer shell is made of fiberglass pipe with a diameter of 600 mm with a working internal pressure of 10 MPa, and the inner shell is made of a pipe with a diameter of 530 mm made of steel of strength group X80. The pressure in the inner shell is taken equal to 20 MPa.

According to ASTM D2992 [15], the formula is used to calculate annular stresses in a pipe made of composite pipes, which are considered as thick-walled structures:

$$\sigma = p\frac{D - t_r}{2t_r}, \tag{3}$$

where σ – ring stress, Pa; D – outer diameter, m; p – internal pressure, Pa; t_r – wall thickness, m.

Then the required wall thickness is:

$$t_r = \frac{pD}{2[\sigma] + p}, \tag{4}$$

where $[\sigma]$ – allowable value of ring stresses, Pa.

Allowable stresses are determined taking into account the properties of the material and the safety factor:

$$[\sigma] = \frac{\sigma_B}{K}, \tag{5}$$

where σ_B – tensile strength of the composite material in a circular direction; K – safety factor.

According to [13], the properties of the pipe material and fixing element are given in Table 1. The density of the material is 1920 kg/m^3. Under these conditions, the calculated wall thickness of the outer shell with a safety factor of 2.5 is 24 mm.

Table 1

Material properties of the pipe and fixing element

Material properties	Pipe and fittings			Fixing element
	Radial	Axial	Circular	
Strength, MPa	65	65	300	48
Young's modulus, MPa	2000	10000	25300	350
Poisson's ratio	0.35	0.4	0.49	0.4
Shear modulus, MPa	741	3471	8490	1250

As for the inner shell, it should be noted that for CNG-2 cylinders, the destructive pressure of the metal liner should be at least 26 MPa [16]. In this design, the cylindrical part and the spherical bottoms are thin-walled shells. According to the Laplace equation [17] for spherical thin-walled shells, parts of which are the bottoms of a metal cylinder liner, the circular and meridional stresses are equal to each other and are defined as:

$$\sigma_t = \sigma_m = \frac{p \cdot R}{2 \cdot h}, \tag{6}$$

where R – radius of the middle surface of the shell; h – shell wall thickness.

For cylindrical thin-walled shells, the meridional (axial) stresses are determined by a similar relationship, and circular ones are twice as large. Moreover, since the shell is thin-walled, the radius of the middle surface can be replaced by the radius of the outer surface of the shell. Thus, for CNG-2 type cylinders, the strength of which in the axial direction is determined precisely by a metal liner, the safety factor in this direction at an operating pressure of 20 MPa will be equal to 2.6.

In terms of manufacturing the inner shell of cargo tanks from pipes of X80 strength, for which the yield strength of the base metal is at least 555 MPa, the allowable stresses will be equal to:

$$[\sigma] = \frac{\sigma_y}{K} = \frac{555}{2.6} = 213.46 \text{ MPa}, \tag{7}$$

where σ_n – yield strength; K – safety factor.

The required wall thickness of the inner shell with regard to expression (5) is defined as:

$$t_r = \frac{p \cdot D}{4[\sigma]}, \tag{8}$$

and is 12.4 mm.

Having assumed for a steel shell a wall thickness of 13 mm, the circular stresses in it with a pressure in the annular space of 10 MPa, and directly in the shell – 20 MPa, be 203.8 MPa. In the absence of pressure in the annular space, circular stresses can reach 407.7 MPa. In this case, the safety factor will be equal to 1.3.

Considering the presence of a joint zone of spherical and cylindrical parts of the steel shell, which is characterized by the so-called edge effect, fixing the fiberglass pipe to the metal is carried out using a half-coupling with a special thread with an inserted fixing element, is mounted in this zone and acts as a ring of rigidity.

For security reasons, let's take finally the wall thickness of the outer shell is equal to 25 mm. At the same time, the weight of one meter of the 600×25 pipe will be 86.7 kg, and that of the 530×13 pipe – 165.7 kg. The cross-sectional area of the inner pipe is 0.1994 m^2, and the annular space is 0.0169 m^2. Accordingly, the volume of one meter of the cavity of the inner pipe is 0.1994 m^3, and the annular space is 0.0169 m^3.

It is possible to reduce the mass of tanks of the proposed design by using materials with better strength characteristics. Thus, according to [18], variants of the design of elements of combined type tanks, and CNG-2 cylinders in particular, made of steel X80 and 30ХГСА are considered. The mechanical properties of the metal of welded joints from steel 30ХГСА are much higher. The minimum value of the tensile strength is 1100 MPa, and the yield strength is 1000 MPa. Then, for the inner shell of cargo tanks of 30ХГСА pipes, the allowable stresses will be 384.62 MPa, and the required wall thickness of the inner shell with axial loads will be 6.9 mm. For a pipe with a standard wall thickness of 7 mm, the mass of one meter is 90.3 kg, and the internal volume is 0.2091 m^3.

6. Research results

Returning to the expression (2), it should be noted that the volume of gas V_{vol} in the tank, reduced to normal conditions by its known mass m, is defined as:

$$V_{vol} = \frac{m}{\rho_0}, \tag{9}$$

where ρ_0 – gas density under normal conditions.

When taking into account the compressibility of gas, namely, the ratio PV of the product for methane under the specified conditions PV in at 0 °C and 760 mm Hg. the authors of [6] denoted as $S(p, t)$, the expression to determine its mass in the cargo tank takes the form:

$$m = \frac{P \cdot V \cdot \mu}{R \cdot S(p,t) \cdot T_0}, \tag{10}$$

where V – internal volume of cargo tank; P – working pressure in the cargo tank during transportation; μ – molar mass of the transported gas; R – universal gas constant, $R = 8314.41$ J/kmol deg; T_0 – temperature under normal conditions (273.15 K).

Since, under normal conditions, natural gas can be considered as an ideal gas, its density from the Mendeleev-Clapeyron formula for an ideal gas can be defined as:

$$\rho_0 = \frac{P_0 \cdot \mu}{R \cdot T_0}, \tag{11}$$

where P_0 – pressure under normal conditions (101325 Pa).

Substituting expressions (10) and (11) into (9):

$$V_0 = \frac{\dfrac{P \cdot V \cdot \mu}{R \cdot S(p,t) \cdot T_0}}{\dfrac{P_0 \cdot \mu}{R \cdot T_0}} = \frac{P \cdot V}{S(p,t) \cdot P_0}. \tag{12}$$

For multi-cavity tanks obtained above dependence will take the form:

$$V_0 = \frac{1}{P_0} \cdot \sum_{i=1}^{n} \frac{P_i \cdot V_i}{S_i(p,t)}, \tag{13}$$

where n – the number of individual cavities in the tank; P_i – working pressure in the i-th cavity; V_i – volume of the i-th cavity; $S_i(p,t)$ – compressibility of methane for the conditions of the i-th cavity.

For the proposed tank design, the entered criterion will depend on the length of the tank. For the purpose of comparison, its value is determined for a tank with a fiberglass pipe 6 and 12 m long and designed as a long pipe. The mass of the tank with a length of 6 and 12 m includes the mass of the cylindrical parts of the inner and outer shells, the mass of the spherical bottoms of the inner shell and the mass of the two coupling halves. For long pipes, the mass of the bottoms and half couplings is not taken into account. At the same time for a tank length of 6 m $j = 6.727$ kg/n.·m^3, and 12 m – $j = 6.241$ kg/n.·m^3. For a lengthy design in the basic version $j = 5.544$ kg/n.·m^3. In the manufacture of the inner shell of a long construction of steel 30ХГСА proposed criterion is significantly improved. For tanks with a length of 6 and 12 m, the decrease in the criterion j is less noticeable due to the significant mass of the coupling halves.

Thus, it is optimal to perform multi-cavity tanks in the form of a lengthy design, limited by the parameters of the marine vehicle for which the criterion is introduced is $j = 3.63$ kg/n.·m^3. For comparison, CNG-4 cylinders manufactured by HEXAGON Lincoln USA, which are part of the TITAN 4 modules, are characterized by the parameter $j = 1.042$ kg/n.·m^3, and CNG-1 type cylinders manufactured by NK CO LTD Korea – $j = 5.634$ kg/n.·m^3.

7. SWOT analysis of research results

Strengths. The use of the proposed criterion for mass-dimensional perfection creates the prerequisites for a comparative evaluation of tanks characterized by different working pressures and design. By this criterion, multi-cavity tanks are competitive in terms of their performance in the form of a lengthy design.

Weaknesses. It should be noted that the design and use of multi-cavity tanks with a length of 6 and 12 m is impractical both in comparison with CNG-2 and CNG-1 tanks.

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Opportunities. For the perception by producers and consumers of the introduced criterion for evaluation of the perfection of high pressure tanks, it is necessary to conduct its comparative analysis with those used today in promoting products in various industries.

Threats. Despite the fact that the gas metering in normal cubic meters is carried out during the extraction, transportation and consumption of natural gas, the use of the proposed criterion may be limited to objects of the specified industries.

8. Conclusions

1. According to the research results, a multi-cavity high-pressure tank of increased working tank has been created using fiberglass and steel pipes and special connections with a plug-in fixing element. It is established that the optimum is its implementation in the form of a lengthy design, limited by the parameters of the marine vehicle.

2. To evaluation of the perfection of high-pressure tanks, and in particular when transporting compressed natural gas, a new universal criterion is proposed. It is determined by the ratio of the mass of the tank to the volume of gas transported in it to normal conditions. The criterion establishes the relationship between the amount of gas transported and the main parameter of the tanks, taking into account their inclusion in the freight systems of vehicles. Its versatility is confirmed by the use of the proposed multi-cavity tanks for evaluating the perfection of various versions and comparison with CNG-1 and CNG-4 vessels.

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Dzhus Andriy, *Doctor of Technical Sciences, Associate Professor, Department of Oil and Gas Machines and Equipment, Ivano-Frankivsk National Technical University of Oil and Gas, Ukraine, e-mail: andriy_dzhus@i.ua, ORCID: http://orcid.org/0000-0002-2660-5134*

Yurych Andriy, *PhD, Associate Professor, Department of Oil and Gas Well Drilling Engineering, Ivano-Frankivsk National Technical University of Oil and Gas, Ukraine, e-mail: a.r.yurych@gmail.com, ORCID: http://orcid.org/0000-0002-8772-6191*