З метою безпечного транспортування стиснутого природного газу за результатами проведених досліджень запропоновано алгоритм методу оцінки працездатності ємностей комбінованого типу. Метод передбачає визначення параметрів стану газу в процесі заповнення ємності з врахуванням процесів теплообміну та оцінку напружено-деформованого стану ємності з врахуванням умов експлуатації і результатів технічного огляду. Для реалізації методу використано засоби для виявлення та визначення форми і розмірів ймовірних корозійних пошкоджень поверхні металевого лейнера під композитною оболонкою. Оцінку напружено-деформованого стану ємностей з врахуванням умов експлуатації запропоновано здійснювати шляхом розроблення та аналізу відповідних моделей. Можливість отримання достовірних результатів за наявності доступних механізмів підтверджено власними дослідженнями особливостей протікання технологічних процесів завантаження та розвантаження. Для перевірки правильності побудови імітаційної моделі на етапі дослідження напружено-деформованого стану ємності з врахуванням фактичних умов експлуатації, розроблено математичну модель, яка враховує умови взаємодії елементів конструкції, дію внутрішнього тиску газу та температури. Використання моделі скорочує затрати на експериментальні дослідження та сприяє забезпеченню достовірності результатів імітаційного моделювання. Перевагою методу є визначення розрахункового тиску руйнування ємностей комбінованого типу за наявного стану небезпечних зон та впливу умов експлуатації. Практичне значення одержаних результатів визначається можливістю використання з метою забезпечення працездатності на етапі проектування та в процесі експлуатації ємностей

Ключові слова: ємності комбінованого типу, умови експлуатації, корозійне пошкодження, імітаційне моделювання, працездатність

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DEVELOPMENT OF THE METHOD FOR ESTIMATING SERVICEABILITY OF EQUIPMENT FOR THE TRANSPORTATION OF COMPRESSED NATURAL GAS

A. Dzhus
Doctor of Technical Sciences, Professor*
E-mail: andriy_dzhus@i.ua
A. Andrusyak
PhD, Associate Professor
Department of Building Mechanics**
E-mail: pirelliandgoodri@ukr.net
Ja. Grydzhuk
PhD, Associate Professor
Department of Theoretical Mechanics**
E-mail: jaroslav.gridzhuk@gmail.com
T. Romanyshyn
PhD, Associate Professor*
E-mail: tarasromanushun@gmail.com
*Department of oil and gas equipment**
**Ivano-Frankivsk National Technical University of Oil and Gas
Karpatska str., 15,
Ivano-Frankivsk, Ukraine, 76019

1. Introduction

When extracting natural gas offshore, the relevant problem is creation of the system of its transportation to the shore, which can be carried out by the transport or by special ships in the liquefied (LNG) or compressed (CNG) stage. Taking into consideration the small cost of the onshore infrastructure, the possibility of changing routes and relatively low transport tariffs, it is expedient to use the CNG technology. The results of the technical-economic analysis indicate the efficiency of the transportation from the offshore deposits of up to 1 billion cubic meters of gas per year in a compressed state by self-propelled or non-self-propelled barges [1, 2]. To implement the technology, the necessary condition is the existence of containers for the transportation of gas. In this case, they must be characterized by low weight and dimensional indicators and be serviceable within fixed operation term. Given a relatively wide range of loads, the research aimed at the maximum consideration of operating conditions and the technical state with the view to ensuring a high reliability of assessment of serviceability of the equipment is relevant.

2. Literature review and problem statement

According to the results of the analysis offered by the leading companies of the industry of technical solutions, it was found that to form freight systems marine transportation vessels, and in particular barges, it is possible to use special modules with composite tanks of the CNG-4 type [3]. The main advantage of such tanks in most cases is a relatively low weight. Liner of the composite tank is a form creating structure, and the main load is taken by the winding, impregnated with a binding material. The use of plastic a liner in conjunction with the carbon fiber makes it possible to reduce the weight of a tank, which is a sufficient competitive advantage under the conditions of ensuring a necessary strength. The advantages of composite tanks include a high safety level. Thus, the cylinder destruction takes place without the formation of debris at the influence of internal pressure. The only essential drawback of any composite tank is its low resistance to shock loads. Despite the high cost of production, existing technical specifications determine the main areas of application of composite tanks. Specifically, they are the ones that imply frequent moving of containers with compressed gas.

An alternative to the composite ones can be the use of the capacities of the combined type (CNG-2) both in modular design [1], and in the form of a long-dimensional pipe [4]. Regarding the solid-metal cylindrical high-pressure vessels, and specifically the cylinders of the CNG-1 type, a general drawback is the large weight, caused by a considerable thickness of the wall, and, consequently, inefficient use of strength properties of the material.

For reasons of decreased requirements for gas preparation, the best option is the one of the vertical location of the tanks, which creates the possibility of removal, if necessary, of the liquid, condensed from natural gas. However, restrictions of the permissible height make their corrections in the process of mounting these tanks on barges.

Regarding the requirements to tanks, namely, containers of different types, they are regulated by normative documents, including ISO 11439-2003 [5]. Establishment of compliance of the structure with the basic calculations and the support by the testing results are basic in the process of designing and manufacturing.

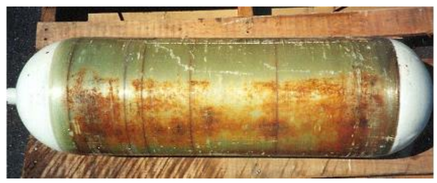
Structures of all types of cylinders at the eventual destruction of a cylinder as a result of the pressure action during normal operation must ensure the type of damage, such as "destruction leak". A leak in a metal cylinder of the CNG-1 type and metal liner cylinders of the CNG-2 and CNG-3 types must occur only in the case of the crack fatigue development. It is also necessary to determine the maximum permissible dimensions of a defect in any place of a metal cylinder that meets the requirements of a cyclic test by pressure and the "destruction leak".

According to the mentioned standard ISO 11439-2003, as well as ECE R-110, requirements for testing composite cylinders are considerably higher than for steel cylinders. The standards require holding thirteen additional tests for cylinders of the CNG-4 type in comparison with steel ones. They include circular pressure testing at extreme temperatures, namely, at minus 40 °C and plus 65 °C. It should be noted that some tests are conducted at air humidity of 95 %. Testing cylinders of the CNG-4 type, corresponding to a 30-year life cycle, testify to the possibility of operation for 20 years without re-testing.

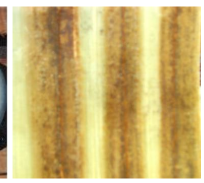
In order to determine the possible resource of operation of cylinders of the CNG-2 type, a variety of research were carried out. For cylinders with a steel shell of a welded construction, there are known tests of the mode of cyclic load by internal hydraulic pressure that varied in the range from 2.0 to 22.0 MPa at the frequency of no more than 10 cycles per minute [6]. Similar tests were conducted by the authors [7] for cylinders with a whole-walled steel shell. After the fatigue tests through creating of 20,000 cycles by the pressure from 0 to 20.7 MPa, the examined samples were brought to destruction by a constant increase in pressure from 0 to 61.5 MPa.

Analyzing the features of cylinders testing, it is necessary to note that they do not take into consideration the important operating factors, specifically: the gas temperature changes, and respectively, the walls of the cylinders with a simultaneous increase or a decrease in pressure, changes of properties of materials and the influence of corrosive processes.

The latter are possible due to existence of ring cracks in the composite reinforcement. They are formed as a result of temperature fluctuations even under conditions of the absence of internal pressure loads. These cracks do not affect the strength of the composite but make it possible for moisture to penetrate to the steel shell. As a result, unprotected shell surface is subjected to a corrosive damage. The evidence of this is the presence of corrosion products on both the outer and the inner surface of the composite reinforcement (Fig. 1).



a



b

Fig. 1. Existence of corrosion products of metal liner: *a* — at the outer surface of the composite reinforcement; *b* — at the inner surface of the composite reinforcement

Thus, metal-composite cylinders of large capacity (CNG-2 and CNG-3) are the objects of increased danger, the destruction of which during operation can lead to serious consequences and the great material damage. That is why according to [5], the service life for them should be determined by taking into consideration the peculiarities of the development of fatigue cracks in cyclic tests. Ultrasonic or equivalent to it non-destructive control of each balloon and a liner should provide the absence of defects that exceed the maximum permissible dimensions.

Selection of control methods is one of the major challenges in assessing the technical condition of the metal-composite cylinders with the view to preventing accidental destruction. In this case, it is necessary to have the means to assess the state of the surface of the metal liners of combined high-pressure vessels, the access to which is restricted due to existence of an external reinforcement layer of a composite material.

At present, we know the peculiarities of the development based on a high-frequency inductive sensor of the means that implement the possibility to identify defects by dimensions and a shape with a high measurement precision and its reproduction in a three-dimensional form [8]. The results of research using the automated monitoring control system with subsequent reproduction of metal loss areas based on spatial data about the thickness of the pipe wall are presented in [9]. The information, required for it, was derived from the dynamic transition system, created based of a high-frequency inductive sensor as the sensor of a metal loss in each control point. The authors of paper [10] based on the results of theoretical and experimental research, proposed to use the specified system for a non-destructive control of metal liners of the combined type structure.

When it comes to taking into consideration the operating factors, there are the results of research into the impact of technological processes of loading [11] and unloading [12] of marine transportation vehicles on the level of thermal loads and stressed-strained state of the elements of loading systems. However, there were no substantiated mechanisms of the equipment serviceability assessment under the existing operating conditions and the technical condition of the combined type tanks, and, in particular, those operated as part of marine transportation vessels.

3. The aim and objectives of the study

The aim of this research is to develop a method for the estimation of serviceability of the equipment for transportation of compressed natural gas, taking into consideration the technical condition and the conditions of its operation.

To accomplish the set goal, the following tasks have been set:

– to substantiate the basic principles of implementation of the method for estimation of serviceability of the equipment;

– to propose the ways of checking the validity of the results of research into stressed-strained state of the tank.

4. Substantiation of the basic principles for implementing the method for estimating the serviceability of equipment

With a probability of the corrosion damage to the metal liner of a combined type tank, control over its surface is one of the main tasks in order to ensure serviceability. It is possible to assess the actual condition of the tank and establish the terms of its further diagnostic control by the results of the electrometric tests. In accordance with the regulation documents, the permissible dimensions of a defect are established by the results of testing cylinders containing artificial defects of certain dimensions. However, during the operation of the combined type tanks, a metal liner is subject not to mechanical, but to corrosive damage. This creates the need to identify complex corrosion defects and to reduce them to simpler ones. In this case, as already noted, the priority task is the availability of tools to assess the condition of the surface of a metal liner of combined high-pressure vessels, the access to which is restricted due to existence of an external fortifying layer of a composite material.

At the same time, in accordance with applicable regulations, the estimated pressure of destruction of a liner of cylinders of the CNG-2 type should be not less than 1.3 P (P is the operating pressure). In this case, destruction pressure, determined by the results of the hydraulic tests, must not be less than the estimated destruction pressure.

Tanks for gas transportation by the CNG technology are subject to periodic filling and emptying. In this case, these technological processes can be quite rapid, cause drastic changes in gas temperature, and, therefore, capacities and binding elements [11, 12]. That is why during evaluation of the serviceability of the equipment it is also necessary to take into consideration possible temperature loads, and specifically, applying imitation simulation for it.

Today there is a common tendency to study the dynamics of mechanical systems by computer simulation [13]. However, unlike the calculation of strength by the finite element method, which long ago entered the practice of researchers [14, 15], dynamic calculations of the equipment for gas transportation with the use of specialized software are not widely used.

When simulating controlled dynamic systems, the special package Simulink, which is part of the automated system Maple, has been widely used recently [16]. The software product MapleSim makes it possible to significantly reduce the terms of designing and enhance the quality of development of models of mechanical systems and simulation of the processes occurring in these systems.

Taking into consideration the possibilities of modern software products and the results of research into peculiarities of formation of stressed-strained state of the combined type tanks and specifically, with the use of the finite element method [17], the method of evaluation of serviceability of cylinders of the CNG-2 type was proposed (Fig. 2). The method implies the maximum consideration of the operating conditions and the actual state of a metal liner.

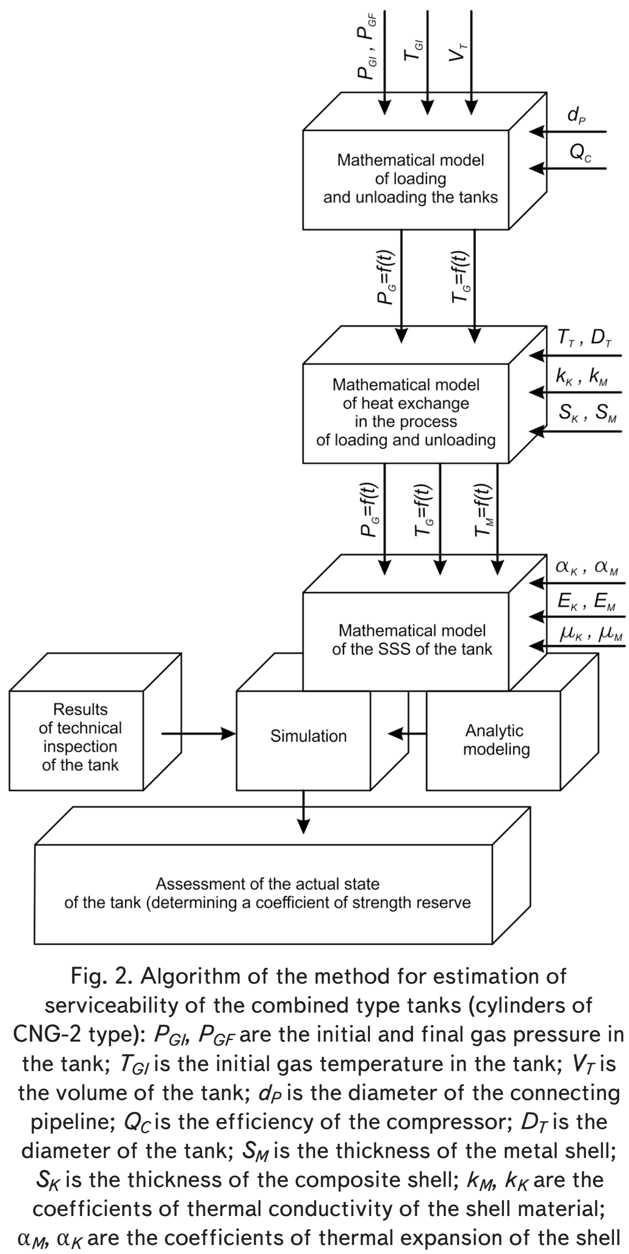


Fig. 2. Algorithm of the method for estimation of serviceability of the combined type tanks (cylinders of CNG-2 type): P_{GI}, P_{GF} are the initial and final gas pressure in the tank; T_{GI} is the initial gas temperature in the tank; V_T is the volume of the tank; d_P is the diameter of the connecting pipeline; Q_C is the efficiency of the compressor; D_T is the diameter of the tank; S_M is the thickness of the metal shell; S_K is the thickness of the composite shell; k_M, k_K are the coefficients of thermal conductivity of the shell material; α_M, α_K are the coefficients of thermal expansion of the shell material; E_M, E_K are the modules of elasticity of the material; μ_M, μ_K are the Poisson coefficients of the material

The method is implemented in accordance with the presented scheme and includes the following stages:

– determining the parameters of the state of gas in the process of filling the tank;

– defining the parameters of the state of gas taking into consideration the processes of heat exchange;

– evaluation of stressed-strained state of the tank taking into consideration the actual operating conditions;

– technical inspection of the tank in order to detect possible corrosion damage;

– evaluation of stressed-strained state of the tank, taking into consideration the results of the technical inspection;

– assessment of the actual state of the tank.

A series of studies, the results of which were already mentioned in the work and indicate the mechanisms of implementation of separate stages of the proposed method, have been conducted recently. However, agreement with the results of a single experiment or analytical research is necessary to prove validity of the results of research into stressed-strained state of the tank under actual operating conditions through simulation. Such verification may be conducted even at the intermediate stage. Despite this, additional analytical studies are more accessible. To this end, a mathematical model that takes into consideration the nature of the interaction between the elements of the structure, the action of internal pressure and gas temperature was developed.

5. Development of a mathematical model of the stressed-strained state of a tank

The mathematical model is based on the differential equation of radial deflection of the wall of the cylinder under internal pressure and temperature that takes the form:

$$D\left[\frac{d^4 w(x)}{dx^4}+\frac{d^2}{dx^2}\left(\alpha\frac{\Delta T}{h}\right)\cdot(1+\mu)\right]= = q-\frac{Eh}{r^2}+\frac{Eh}{r}\alpha T_0, \tag{1}$$

where $D=Eh^3/\left(12\left(1-\mu^2\right)\right)$ is the cylinder rigidity; E is the elasticity module of the material of the cylinder; h is the thickness of the wall of the cylinder; μ is the Poisson coefficient; $w(x)$ is the radial displacement of the points of median surface points with radius r; x is the longitudinal coordinate; q is the distributed load on the internal surface of the cylinder; α is the coefficient of thermal expansion of shell material; T_0 is the temperature of the median surface of the shell; ΔT is the difference of temperatures between the external and internal surfaces of the shell

For a structure, which is composed of a metal cylinder, onto which a composite material is wound with some tension, we will write down the system of two differential equations based on (1):

$$\begin{cases} \dfrac{E_1 h_1^3}{12\left(1-\mu_1^2\right)}\left[\dfrac{d^4 w_1(x)}{dx^4}+\dfrac{d^2}{dx^2}\left(\alpha_1\dfrac{\Delta T_1}{h_1}\right)\cdot(1+\mu_1)\right]= \\ =q_1-\dfrac{E_1 h_1}{r_1^2}+\dfrac{E_1 h_1}{r_1}\alpha_1 T_{01}, \\ \dfrac{E_2 h_2^3}{12\left(1-\mu_2^2\right)}\left[\dfrac{d^4 w_2(x)}{dx^4}+\dfrac{d^2}{dx^2}\left(\alpha_2\dfrac{\Delta T_2}{h_2}\right)\cdot(1+\mu_2)\right]= \\ =q_2-\dfrac{E_2 h_2}{r_2^2}+\dfrac{E_2 h_2}{r_2}\alpha_2 T_{02}, \end{cases} \tag{2}$$

where E_1, E_2 are the modules of elasticity of material of the metal and composite shells, respectively; μ_1, μ_2 are the Poisson coefficients of the metal and composite shells; α_1, α_2 are the coefficients of thermal expansion of the materials of the metal and composite shells; T_{01}, T_{02} are the temperatures of connecting surfaces of the metal and composite shells; ΔT_1, ΔT_2 are the difference of temperatures between the external and internal surfaces of the metal and composite shells; p_1, p_2 are the gas pressure on the internal surface of the metal shell and distributed load of mechanical tension on the internal surface of the composite shell; h_1, h_2 are the thickness of the metal and composite shells, respectively; r_1, r_2 are the radii of the median surfaces of the metal and composite shells, respectively; q_2 is the distributed load of the previous tension between the metal and composite shells, $q_2=p_2$; p_2 is the contact pressure in the connection of the metal and composite shells; q_1 is the distributed load on the metal shell surface, $q_1=p_1-p_2$; p_1 is the gas pressure inside the metal shell; $w_1(x)$, $w_2(x)$ are the functions of radial displacement of the metal and composite shells.

Considering that the bottom of the metal shell is welded to the cylindrical part, it can be simulated on both rigidity ends by the connection (Fig. 3, *a*). Believing that the composite shell, wound on the metal shell, has the possibility of elemental displacement in the axial direction, its connection with the metal shell will be simulated by the hinge connection (Fig. 3, *b*). That is why for the specified design features of connections of the metal and composite parts of the tank (Fig. 4), the functions of the radial displacements will be written as follows:

– for the metal shell:

$$w_1(x)=\frac{q_1 r_1^2}{E_1 h_1}\left[1-e^{-k_1 x}\left(\sin(k_1 x)+\cos(k_1 x)\right)\right]; \tag{3}$$

– for the composite shell:

$$w_2(x)=\frac{q_2 r_2^2}{E_2 h_2}\left[1-e^{-k_2 x}\cos(k_1 x)\right]; \tag{4}$$

where

$$k_1=\sqrt[4]{3\left(1-\mu_1^2\right)/r_1^2 h_1^2},\quad k_2=\sqrt[4]{3\left(1-\mu_2^2\right)/r_2^2 h_2^2}. \tag{5}$$

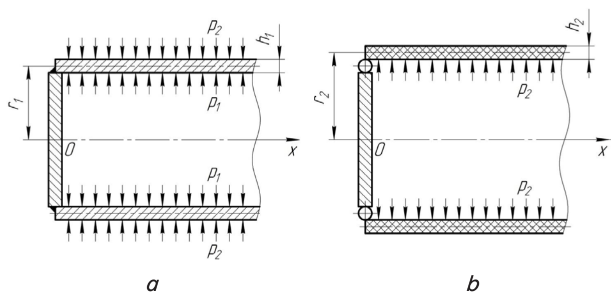


Fig. 3. Schematic of connection of the cylindrical part of the combined type tank with its bottom: *a* — metal liner; *b* — composite reinforcement

Considering the distribution of temperatures for the thickness of the wall of the cylindrical shell linear, we will write down expressions for the transverse (cutting) force and bending moment acting in the cross section of the structure:

$$Q = D\left[\frac{d^3w(x)}{dx^3}+\frac{d^2}{dx^2}\left(\alpha\frac{\Delta T}{h}\right)\cdot(1+\mu)\right]; \quad (5)$$

$$M_x = D\left[\frac{d^2w(x)}{dx^2}+\left(\alpha\frac{\Delta T}{h}\right)\cdot(1+\mu)\right]. \quad (6)$$

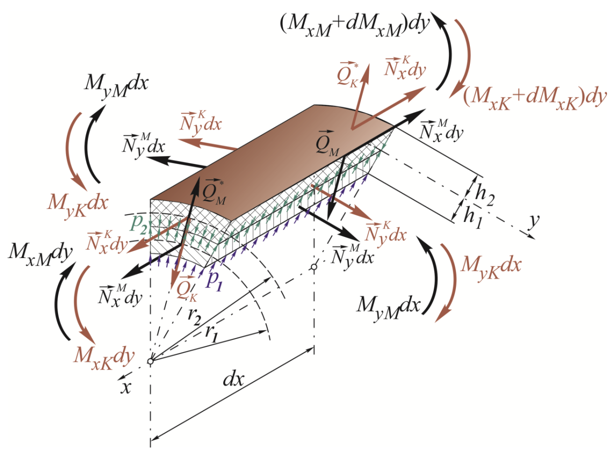


Fig. 4. Calculation scheme of the cylindrical part of the tank of the combined type (designation indices: "*K*" – composite; "*M*" – metal)

Tension force and bending moment in the longitudinal cross-section:

$$N_x = Eh\left(\frac{w(x)}{r}-\alpha T_0\right); \quad (7)$$

$$M_y = D\left[\mu\frac{d^2w(x)}{dx^2}+\left(\alpha\frac{\Delta T}{h}\right)\cdot(1+\mu)\right]. \quad (8)$$

Bending stresses and tangential stress in the cross section:

$$\sigma_x = -\frac{12M_x z}{h^3}; \quad (9)$$

$$\tau = \frac{Q}{h}\left(\frac{3}{2}-\frac{6z^2}{h^2}\right), \quad (10)$$

where $z=\pm\frac{h}{2}$ is the distance from the point to the median surface of the shell; "+" – for the external; "–" – for the internal layer of the shell.

The bending stress and the normal stretching stresses in the longitudinal section:

$$\sigma_y = -\frac{12M_y z}{h^3}; \quad (11)$$

$$\sigma_p = \frac{N_x}{h}. \quad (12)$$

With respect to dependences (3) to (8), expressions for bending, tangential and normal stresses (9) to (12) take the following form:

– for the metal shell:

$$\sigma_{x1} = -\frac{12z_1}{h_1^3}D_1\left[\begin{array}{l}\frac{2k_1^2q_1r_1^2}{E_1h_1}e^{-k_1x}\left[\cos(k_1x)-\sin(k_1x)\right]+\\+\left(\alpha_1\frac{\Delta T_1}{h_1}\right)\cdot(1+\mu_1)\end{array}\right]; \quad (13)$$

$$\tau_1 = \frac{1}{h_1}\left(\frac{3}{2}-\frac{6z_1^2}{h_1^2}\right)D_1\left[\begin{array}{l}\frac{4k_1^3q_1r_1^2}{E_1h_1}e^{-k_1x}\left[2\sin\left(\frac{k_1x}{2}\right)^2-1\right]+\\+\frac{d^2}{dx^2}\left(\alpha_1\frac{\Delta T_1}{h_1}\right)\cdot(1+\mu_1)\end{array}\right]; \quad (14)$$

$$\sigma_{y1} = -\frac{12z_1}{h_1^3}D_1\left[\begin{array}{l}\mu_1\frac{2k_1^2q_1r_1^2}{E_1h_1}e^{-k_1x}\left[\cos(k_1x)-\sin(k_1x)\right]+\\+\left(\alpha_1\frac{\Delta T_1}{h_1}\right)\cdot(1+\mu_1)\end{array}\right]; \quad (15)$$

$$\sigma_{p1} = \frac{1}{h_1}E_1h_1\times$$

$$\times\left(\frac{q_1r_1}{E_1h_1}\left[1-e^{-k_1x}\left(\sin(k_1x)+\cos(k_1x)\right)\right]-\alpha_1T_{01}\right); \quad (16)$$

– for the composite shell:

$$\sigma_{x2} = -\frac{12z_2}{h_2^3}D_2\times$$

$$\times\left[-\frac{2k_2^2q_2r_2^2}{E_2h_2}e^{-k_2x}\sin(k_2x)+\left(\alpha_2\frac{\Delta T_2}{h_2}\right)\cdot(1+\mu_2)\right]; \quad (17)$$

$$\tau = \frac{1}{h_2}\left(\frac{3}{2}-\frac{6z_2^2}{h_2^2}\right)D_2\left[\begin{array}{l}\frac{2k_2^3q_2r_2^2}{E_2h_2}e^{-k_2x}\left[\cos(k_2x)-\sin(k_2x)\right]+\\+\frac{d^2}{dx^2}\left(\alpha_2\frac{\Delta T_2}{h_2}\right)\cdot(1+\mu_2)\end{array}\right]; \quad (18)$$

$$\sigma_{y2} = -\frac{12z_2}{h_2^3}D_2\left[\begin{array}{l}-\mu_2\frac{2k_2^2q_2r_2^2}{E_2h_2}e^{-k_2x}\sin(k_2x)+\\+\left(\alpha_2\frac{\Delta T_2}{h_2}\right)\cdot(1+\mu_2)\end{array}\right]; \quad (19)$$

$$\sigma_{p2} = \frac{1}{h_2}E_2h_2\left(\frac{q_2r_2}{E_2h_2}\left[1-e^{-k_2x}\cos(k_1x)\right]-\alpha_2T_{02}\right). \quad (20)$$

The totality of the derived analytical dependences (13) to (20) is a mathematical model for studying the stressed-strained state of the tank of the combined type, specifically a metal shell that does not have corrosive damage.

6. Discussion of results of studying the implementation of the method for the estimation of serviceability of combined type tanks

Thus, according to the research results, the algorithm of the method for estimation of serviceability of combined type tanks for transportation of compressed natural gas, as well as a part of marine vessels was proposed. In addition, the list of mechanisms of realization of the separate stages of the method is supplemented by the mathematical model, which takes into consideration the conditions of interaction of the elements of the structure, the influence of internal gas pressure and temperature. The use of the model reduces costs for intermediate experimental research and promotes reliability of the simulation results. This is proved by the results obtained using the developed model and shown in Fig. 5, 6. They are displayed by the diagrams of a change in circular stresses in the elements of the combined type cylinder with the internal diameter of 0.205 m at the thickness of the wall of the metal shell of 3.15 mm, and the thickness of the composite wall of 2.8 mm [17]. Fig. 5 shows the diagram of a change in circular stresses in the metal and the composite shell in the absence of internal pressure. In this case, circular tensions in the metal liner are caused by the preload that is created during formation of a composite shell.

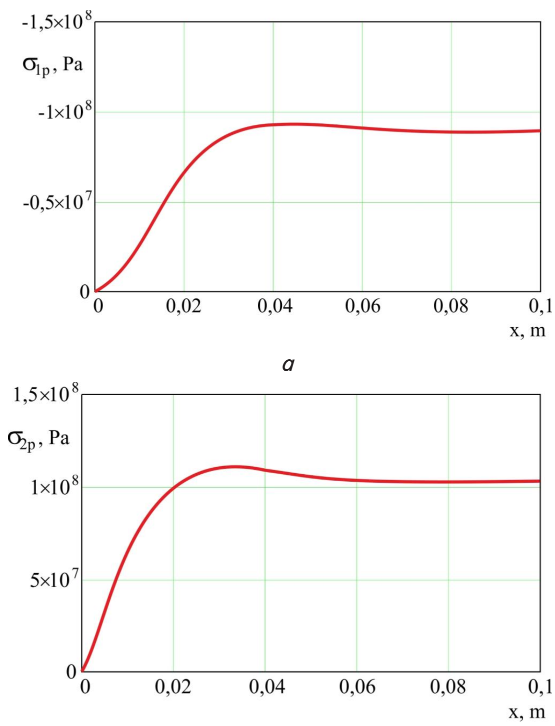


Fig. 5. Diagrams of change in circular stresses in the absence of internal pressure: *a* – in a metal shell (σ_{1p}); *b* – in a composite shell (σ_{2p})

Fig. 6 shows the diagram of change of circular stresses in a metal shell at the gas pressure in the cylinder of 20 MPa. The obtained results correlate with those presented in [17] and prove the feasibility of using the proposed mathematical model.

The possibility to obtain reliable results at the initial stages of the implementation of the method in the presence of available mechanisms was proved by our own research into the features of the flow of technological processes of loading and unloading of tanks for transporting compressed natural gas.

It should be noted that taking into consideration the results of technical inspection the tested simulation model, and in particular, possible corrosive damage, provides an opportunity to assess the actual technical condition of the combined type tanks.

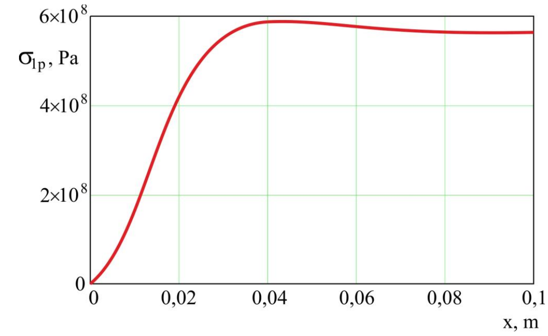


Fig. 6. Diagram of change in circular stresses in a metal shell at a pressure of gas in the cylinder of 20 MPa

The practical significance of the obtained results is determined by the possibility of using them both at the design stage and during the tanks operation.

As for the constraints of the tools for the evaluation of state of the surface of metal liners of combined high-pressure vessels, proposed for application, it is necessary to point out that they make it possible to obtain information about a state of the surface of the metal liner. The actual values of the wall thickness are determined by the difference of the initial value and the one detected by the results of research into the loss of metal.

Regarding the shortcomings of the developed mathematical model, it is necessary to emphasize the following:

1) disregarding in the functions of radial displacements $w_1(x)$, $w_2(x)$ of another variable – the radii of median surfaces of the metal and composite shells, which vary during operation;

2) distributed load from the previous tension q_2 and respectively, contact pressure p_2 in connection of metal and composite shells is considered constant, although at an increase in pressure in a metal tank and, respectively, the radius of its median surface, this pressure also increases.

Introduction of radii of median surfaces as another variable in functions w_1, w_2 will require application of partial derivatives in the system of equations (2), which will subsequently lead to the inevitable complication of formulas for practical calculation of stresses (13) to (20). A change in pressure p_2 and, correspondently, tension q_2 in the radial and axial directions is a multifactor process that depends on the features of winding composite on the metal liner, the study of which currently requires a significant amount of experimentation.

The shortcomings of the proposed method in general include the necessity of creation for its implementation of integral program complex with numerous linkages between individual subprograms.

Further research should focus on the experimental verification of the results of the implementation of the method in general. The proof of its high reliability will serve as the basis for the implementation of the method by organizations exercising control over technical condition of tanks for transportation of compressed natural gas.

7. Conclusions

1. In order to ensure safe transportation of compressed natural gas, according to the results of the research, the

algorithm of the method for estimation of serviceability of the combined type tanks was proposed. The method involves the use of tools for detection and determining the shape and dimensions of probable corrosive damage to the surface of the metal liner under the composite shell. Research into stressed-strained state of the tanks taking into consideration the operating conditions, caused by the features of the flow of technological processes, is carried out by developing and analyzing the models in modern software products. Given this, the merit of the method is determining the estimated pressure of destruction of combined type tanks at the existing state of dangerous area and the influence of operating conditions.

2. To verify correctness of the construction of the simulation model at the stage of the study of the stressed-strained state of the tank considering the actual operating conditions, the mathematical model was constructed, which takes into consideration conditions for the interaction between elements of the structure, action of the internal gas pressure, and temperature. Its application would contribute to ensuring the reliability of simulation results, eliminating the need for conducting experimental research.

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