Строительные материалы и изделия
Construction Materials and Products

journal homepage: https://bstu-journals.ru

ISSN 2618-7183

DOI: 10.58224/2618-7183-2025-8-4-5

Analysis of the influence of temperature loads on the stress-strain state of a pre-stressed cylindrical shell

Zhangabay N.Zh. [1], **Moldagaliyev A.B.** [1], **Buganova S.N.** [2], **Bektursunova A.K.** [1], **Tursunkululy T.** [*] [1], **Ibraimova U.B.** [1]

[1] M. Auezov South Kazakhstan University, Republic of Kazakhstan,
[2] Management International Education Corporation (KazGASA), Republic of Kazakhstan

Abstract. The progressiveness of the idea of prestressing consists, on the one hand, in the possibility to regulate the stress state in accordance with the peculiarity of the structure operation, and on the other hand, in the expansion of the economically advantageous range of application of high- and high-strength steels. Such strengthening is also relevant for cylindrical shells, the throughput or storage volumes of which are directly proportional to the operating pressure. The most effective type of prestressing in this case is considered to be winding on the shell body at an angle to the longitudinal axis or in the annular direction without tilting the high-strength profile. In this regard, in this work, a theoretical study of the influence of temperature loads on the stress state of the combined shell was carried out. As a result of the study, an analytical evaluation method was developed that takes into account the mechanical, geometric values of the wall and wrapping material, as well as the parameters of the prestress, taking into account temperature effects. The developed method also found that the established ring stresses in the shell wall increase with an increase in the temperature gradient, and the stresses in the wrapping decrease. At a temperature gradient of 70°C, the ring stresses increased by 1.8 times, and the stresses in the wrapping decreased by 1.3 times. At the same time, the change in operating temperature has a noticeable effect on the distribution of stresses in the wall of the shell and wrapping. Thus, calculations of a main pipeline pre-stressed with steel wire showed that at a temperature gradient of ΔT=30°C, the achieved level of prestressing can decrease by 10-12% compared to the initial one, and at ΔT=50°C, the pre-stressed wrapping does not affect the stress state of the shell wall. The obtained results of the study indicate that, taking into account the temperature loads on the structure, it is possible to adopt the necessary design parameters for further design of steel shells even more accurately.

Keywords: steel shells, prestress, winding angle, winding thickness, temperature loads

Please cite this article as: Zhangabay N.Zh., Moldagaliyev A.B., Buganova S.N., Bektursunova A.K., Tursunkululy T., Ibraimova U.B. Analysis of the influence of temperature loads on the stress-strain state of a pre-stressed cylindrical shell. Construction Materials and Products. 2025. 8 (4). 5. DOI: 10.58224/2618-7183-2025-8-4-5

*Corresponding author E-mail: timurtursunkululy@gmail.com

Received April 27, 2025; Received in revised form June 23, 2025; Accepted August 25, 2025

1. INTRODUCTION

Since the 1960s, the concept of prestressing metal structures has gained growing global acceptance due to its technological advantages and innovative potential [1-3]. The merit of prestressing lies, firstly, in the ability to control the internal stress distribution in accordance with the structural performance requirements, and secondly, in the broader economic feasibility of utilizing high-strength and ultra-high-strength steels. This method of structural enhancement is especially relevant for cylindrical shells, whose storage capacity or throughput is directly proportional to the operating pressure. Among various prestressing techniques, the most efficient approach is considered to be the application of high-strength profiles wound around the shell either at an angle to its longitudinal axis or circumferentially without inclination [4]. The principal concept of such a composite shell system is to induce pre-stresses that are opposite in direction to those arising from service loads. During structural operation under such loads [5], the pre-induced stresses are initially neutralized, and subsequently, the operational stresses build up until the design strength of the shell material is reached. Prestressing not only enhances the structural load capacity but also improves stiffness and reduces residual deformations. The effectiveness of prestressed shells is further increased when this process enables a balance between longitudinal and circumferential stresses within the shell wall [6-8].

By virtue of the relevance of this area, the global scientific and technical community has been solving various problems for a long time to achieve safety and durability of steel shells. Thus, the work [9] presents the generalized experience of the European research group specializing in the study of strength characteristics of main gas pipelines. The study covers a wide range of existing engineering and scientific approaches to assessing the resistance of pipeline structures to plastic failure. Particular attention is paid to the analysis of the behavior of the pipe metal under extreme mechanical loads, accompanied by the formation and development of cracks. The authors propose an improved plastic model of failure based on numerical modeling of the material's stressed-deformed state near the initiated crack. This model takes into account complex mechanisms of plastic deformation, including stress localization, the crack tip effect and the dynamics of the redistribution of internal forces, which allows for a more accurate prediction of the critical conditions under which failure occurs. The paper [10] presents a detailed review of existing analytical methods for calculating gas pipeline failure processes caused by the impact of internal gas pressure circulating in the pipeline system. Particular attention is paid to the analysis of the stressed-deformed state of the pipe wall under conditions of exceeding critical pressure values, which can lead to the initiation and subsequent propagation of longitudinal cracks. Theoretical approaches and engineering solutions aimed at preventing avalanche-like failure of pipelines are also considered, including methods based on stress management, defect localization and structural reinforcement of potentially weakened areas. The paper [11] presents the results of numerical modeling of the process of crack development in a pipeline using the finite element method, which are compared with the data of experimental studies performed on shell models. During the comparative analysis, special attention is paid to the behavior of structures during rapid crack propagation and the nature of their destruction. The paper [12] examines in detail the features of viscous failure of pipeline steels of API 5L and X52 grades, widely used in the oil and gas industry. The finite element method in the ABAQUS software environment was used for the analysis, which allows for high-precision modeling of the material's stressed-deformed state in the potential failure zone. Particular attention is paid to the influence of the mechanical characteristics of steels and geometric parameters on the resistance of pipelines to crack propagation. The paper [13] presents a comprehensive review of the most common failure modes of pipeline components subject to corrosive wear. Cases of failure under internal pressure and axial compressive stresses typical of real operating conditions are considered. The causes of premature pipe failure are analyzed, including defects that occur during the manufacturing process, mechanical aging, and aggressive environmental influences. The authors identify critical stress zones and provide recommendations for improving the reliability of such pipeline systems. In [14], the authors conducted a comprehensive study of damage and defects occurring in prestressed pipes, with an emphasis on their impact on the dynamic characteristics of the structure. The authors found that defects such as breaks and cracks in the wire used to create prestressing significantly reduce the rigidity of the pipe, which in turn leads to a decrease in its natural frequencies. This can adversely affect the stability and vibration reliability of the pipeline system, especially under dynamic and seismic loads. The work emphasizes the need to monitor the condition of prestressed elements and develop methods for early detection of such damage to ensure operational safety. The study [15] examines the behavior of prestressed circular cylindrical shells under free vibration conditions. The authors performed a nonlinear analysis that takes into account geometric and material nonlinearities to more accurately model real operating conditions. The results showed that prestressing has a significant effect on the frequency characteristics of the shells, with amplitude-dependent nonlinearity causing shifts in natural frequencies and changes in vibration modes. These data are important in the design of pipelines, tanks, and other cylindrical structures subject to dynamic impact. At the same time, temperature changes affect the physical and mechanical properties of the material – strength, elasticity, and plasticity [18], which directly affects the ability of the shell to withstand external loads and deformations [19-21].

A review of the literature highlights the wide range of properties, structural behavior, and service conditions characteristic of shell structures. In most cases, analyses focus primarily on material properties and prestress parameters, while the influence of operational factors – such as temperature – is not fully accounted for. Moreover, existing methods for modeling and analysis are often complex and time-consuming, making it challenging to efficiently evaluate the key parameters required for accurate structural assessment. At the same time, the review showed that the achieved initial prestressing profile wrapping, which goes into the work reserve of structures, is very important from the point of view of the efficiency of the work of prestressed structures. Consequently, from the point of view of controlling the initial stress state of the prestressed shell, it is very important to select the design parameters: pitch, angle and tension force of the wrapping thread, prestressed structures taking into account the actual operating conditions.

In accordance with the problem statement and the objectives of the study, the influence of thermal effects on the initial stressed-deformed state of a pre-stressed cylindrical shell is investigated.

At this stage, a theoretical analysis was undertaken to examine the impact of temperature loads on the overall stressed-deformed state of the shell, with the aim of developing a simplified analytical method for its evaluation. In line with this objective, the following tasks were formulated for the theoretical part of the study:

- to derive analytical expressions for evaluating the stressed-deformed state of the pre-stressed shell at the stage of winding the wrapping wire;
- to assess the stressed-deformed state of the pre-stressed shell under temperature effects and various design parameters of winding the wrapping.

2. METHODS AND MATERIALS

2.1 Evaluation of the stressed-deformed state of the shell wall depending on temperature loads

The stressed-deformed state of a thin-walled cylindrical shell of medium length with radius R closed at the ends and under internal pressure p is considered in line with Fig. 1 [4].

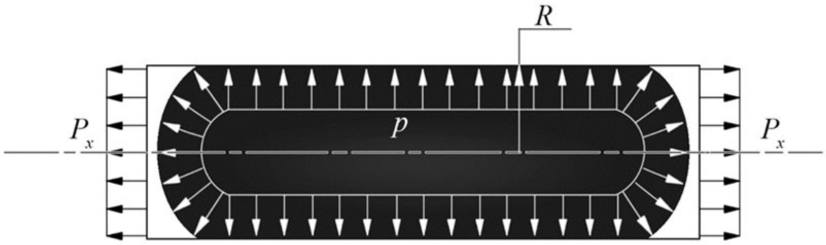

Fig. 1. Computational model of the cylindrical shell.

Additionally, the vessel is subject to an external longitudinal tensile force P_x. Considering that the temperature at the calculated points of the shell wall, and wrapping, owing to the thin-walled nature of the structure is equal to: $T_1 = T_2 = T$.

For convenience and to avoid misinterpretations in the calculation formulas, let's introduce the following notations: δ_1, δ_2, E_1,ε_{1x}, $\varepsilon_{1\theta}$,ε_{1r}, σ_{1x}, $\sigma_{1\theta}$, $\alpha_1 T$, $\alpha_2 T$ – temperature elongation in the wrapping.

For the general case, let's assume that high-strength wire is wound on the shell at an angle α to its longitudinal axis. The wrapping turns at the outer ends of the shell are fixed [4-6].

The wire wrapping threads work only in tension, and there are no tangential stresses. Let's express the relative elongation of the wrapping through

$$\varepsilon_2 = \sigma_2 / E_2. \quad 1$$

The shell element with the resulting forces at the ends is presented in accordance with Fig. 2 [4].

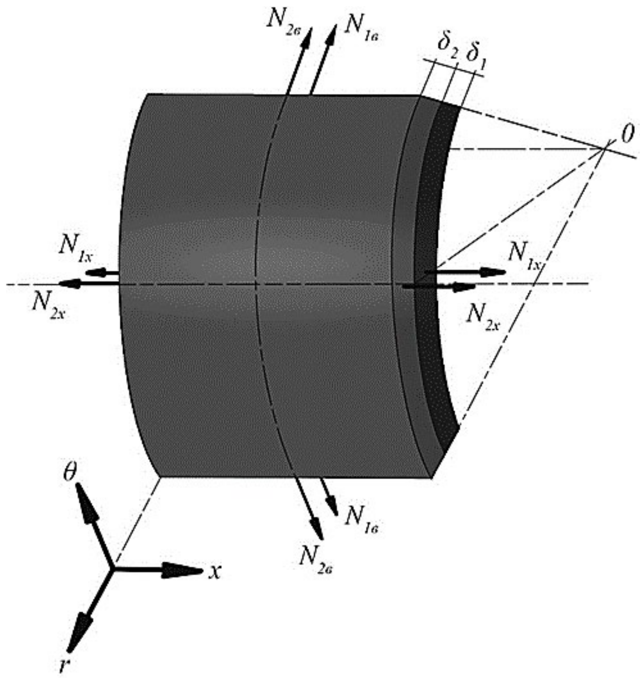

Fig. 2. Shell element with the wrapping thread wound at an angle α.

Correlation between the acting forces N_x and N_θ in the shell and the stress lengthwise the thread axis σ_2 taking into account the stress formula along the oblique area, is presented in the form:

$$N_{2x} = \sigma_2 \delta_2 \cos^2 \alpha, \quad 2$$

$$N_{2\theta} = \sigma_2 \delta_2 \sin^2 \alpha. \quad 3$$

Taking into account (1), expressions (2) and (3) are written as

$$N_{2x} = E_2 \varepsilon_2 \delta_2 \cos^2 \alpha, \quad 4$$

$$N_{2\theta} = E_2 \varepsilon_2 \delta_2 \sin^2 \alpha, \quad 5$$

from which

$$\frac{N_{2\theta}}{N_{2x}} = tg^2 \alpha. \quad 6$$

Considering the dependence of the deformation of the wrapping element lengthwise the axes x and θ on the deformation lengthwise the axis of the wrapping thread ε_2, as well as the potential variation in temperature, the following expression can be derived:

$$\varepsilon_2 = \varepsilon_x cos^2 \alpha + \varepsilon_\theta \, sin^2 \alpha - \alpha_2 \Delta T. \quad 7$$

Substituting (7) into (4) and (5) yields equations describing the relationship between the forces lengthwise the boundaries of the wrapping element and the elongations lengthwise the corresponding axes:

$$N_{2x} = E_2 \delta_2 cos^2 \alpha \, (\varepsilon_x cos^2 \alpha + \varepsilon_\theta \, sin^2 \alpha - \alpha_2 \Delta T), \quad 8$$
$$N_{2\theta} = E_2 \delta_2 sin^2 \alpha \, (\varepsilon_x cos^2 \alpha + \varepsilon_\theta \, sin^2 \alpha - \alpha_2 \Delta T). \quad 9$$

Given the symmetry of the wrapping, the tangential forces lengthwise the boundaries of the wrapping element are assumed to be zero. Let's accept the condition $\varepsilon_x = \varepsilon_{1x} = \varepsilon_{2x}$ $\varepsilon_\theta = \varepsilon_{1\theta} = \varepsilon_{2\theta}$, i.e. the deformations along the corresponding axes in the shell wall and wrapping are equal.

The following equations define the correlation between forces, stresses, and deformations in the shell structure:

$$\varepsilon_{1x} = \frac{1}{E_1}(\sigma_{1x} - \mu\sigma_{1\theta}) + \alpha_1 \Delta T, \quad 10$$
$$\varepsilon_{1\theta} = \frac{1}{E_1}(\sigma_{1\theta} - \mu\sigma_{1x}) + \alpha_1 \Delta T, \quad 11$$
$$N_{1x} = \sigma_{1x}\delta_1 = \frac{E_1\delta_1}{1-\mu^2}(\varepsilon_x + \mu\varepsilon_\theta) - \frac{E_1\delta_1\alpha_1\Delta T}{1-\mu}, \quad 12$$
$$N_{1\theta} = \sigma_{1\theta}\delta_1 = \frac{E_1\delta_1}{1-\mu^2}(\varepsilon_\theta + \mu\varepsilon_x) - \frac{E_1\delta_1\alpha_1\Delta T}{1-\mu}. \quad 13$$

By means of calculation, the stressed-deformed state of the pre-stressed shell must be determined taking into account temperature effects, the ratio of thicknesses, elastic moduli of the shell and wrapping materials, as well as the level of the wire's pretension, and the wrapping thread α winding angle must be determined so that under the action of operating pressure p, longitudinal force P_x, and temperature gradient ΔT , the strength of the shell is ensured with a simultaneous reduction in the weight of the structures.

As a result of the calculation, the stressed-deformed state of the shell wall will also be assessed depending on the temperature elongations and design parameters of the shell.

2.2 Evaluation of initial (assembly) stresses from the wrapping pretension

Let's assume that when the wire wrapping thread is tensioned, preset stresses σ_{11} arise in it, which, as a result of elastic deformation of the shell after winding, decrease to σ_n^2. In this case, the forces in the wrapping and in the shell wall are in mutual equilibrium and satisfy the following equalities [4]:

$$N_{1xн} + N_{2xn} = 0, \quad 14$$
$$N_{1\theta н} + N_{2\theta n} = 0.$$

Then the following condition will be true

$$W_2 = W_1. \quad 15$$

In expression (15) the work of the wrapping deformations can be represented as:

$$W_2 = \frac{1}{2}\left[\left(N_{2xпр}\varepsilon_{2xпр} - N_{2xн}\varepsilon_{2xн}\right) + \left(N_{2\theta пр} \cdot \varepsilon_{2\theta pr} - N_{2\theta n} \cdot \varepsilon_{2\theta n}\right)\right], \quad 16$$

Substituting the values N_{2x} and $N_{2\theta}$ from (8) and (9) into (16) taking into account (1) and assuming $\alpha_2 T = 0$, yields:

$$W_2 = \left(\frac{\delta_2}{2E_2}\right)\left(\sigma_{11}^2 - \sigma_n^2\right). \quad 17$$

The work perceived by the shell wall will be equal to:

$$W_1 = \frac{1}{2}\left(N_{1xn}\varepsilon_{1xn} + N_{1\theta n}\varepsilon_{1\theta n}\right). \quad 18$$

Substituting expressions (12) and (13) into (18) yields:

$$W_1 = \left(\frac{\delta_1}{2E_1}\right)\left({\sigma_{1xn}}^2 - 2\mu \cdot \sigma_{1xn} \cdot \sigma_{1\theta n} + {\sigma_{1xn}}^2\right). \quad 19$$

According to condition (15), the right-hand sides of expressions (17) and (19) are equated, resulting in an equation that relates the stresses in the wrapping thread before and after winding to the stresses in the shell wall after winding:

$$\frac{\delta_2}{E_2}\left(\sigma_{11}^2 - \sigma_n^2\right) = \frac{\delta_1}{E_1}\left({\sigma_{1xn}}^2 - 2\mu \cdot \sigma_{1xn} \cdot \sigma_{1\theta n} + {\sigma_{1\theta n}}^2\right). \quad 20$$

Substituting into (14) the values $N_{xн}$ and $N_{\theta н}$ for the shell and wrapping yields the following equations:

$$\sigma_{1xn}\delta_1 + \sigma_n\delta_2 cos^2\alpha = 0, \quad 21$$
$$\sigma_{1\theta n}\delta_1 + \sigma_n\delta_2 sin^2\alpha = 0. \quad 22$$

Equations (20), (21), and (22) form a system of equations for determining the initial stresses. From equations (21) and (22), the following can be obtained:

$$\sigma_{1xn} = -\frac{\delta_2}{\delta_1} cos^2\alpha \cdot \sigma_{нn}, \quad 23$$
$$\sigma_{1\theta n} = -\frac{\delta_2}{\delta_1} sin^2\alpha \cdot \sigma_n. \quad 24$$

Substituting (23) and (24) into (20), and assuming that σ_{11} is known in advance, the formula for determining the stresses in the wrapping can be written in the following general form:

$$\sigma_n = k \cdot \sigma_{11}, \quad 25$$

where *k* is the stress relaxation coefficient in the wrapping thread,

$$k = \frac{1}{\sqrt{1 + \frac{E_2\delta_2}{E_1\delta_1}\left(cos^4\alpha - 2\mu \cdot sin^2\alpha \cdot cos^2\alpha + sin^4\alpha\right)}}. \quad 26$$

The pressure arising in the shell wall under the tensioned wrapping thread is calculated by the formula:

$$P_{PN} = \frac{N_{2\theta н}}{R} = \frac{N_{1\theta н}}{R} = \frac{\sigma_{2\theta н} \cdot \delta_2}{R} = \frac{\sigma_{1\theta н}\delta_1}{R}, \quad 27$$

and the compressive axial force at the ends of the shell is given by:

$$N_n = \sigma_{1xn}\delta_1 2\pi R = 2\pi R\delta_2\sigma_н = 2\pi kR\delta_2\sigma_{11}. \quad 28$$

After determining the initial stresses, it is necessary to check the stability of the shell wall from compression by the wrapping wire with axial force N_n according to (28).

Then the critical stresses for loss of stability will consist of:

$$\sigma_{cr} = \sigma_{cr}^{Ppn} + \sigma_{pr}^{Nxn}. \quad 29$$

The first term of the right-hand side of equation (29) is determined by the formula of W. Euler or by the formula of E. Ramazanov [4].

Critical stresses $\sigma_{cr}^{P_{xн}}$ can be determined from the following dependence [4-8]:

$$\sigma_{cr}^{N_{xn}} = 0{,}15\frac{E_1\delta_1}{R}. \quad 30$$

If σ_{11} is known, then σ_n is determined from (25), and the initial stresses in the shell wall from the prestressing are determined from (23) and (24).

With known values of stresses σ_{1xn} and $\sigma_{1\theta n}$ from (10) and (11) it is possible to determine the deformations in the shell wall and wrapping.

2.3 Stress-deformed state of the cylindrical shell with the wrapping thread at an angle α to its longitudinal axis

When considering the stressed-deformed state of pre-stressed shells, two states are usually distinguished. The first state is characterized by initial stresses arising in the wrapping and in the shell wall due to winding the wrapping with some prestressing σ_{11}. The second state, which arises after the action of the operating pressure p and longitudinal force P_x on the pre-stressed shell with initial stresses from the tension of the wrapping thread.

Let's consider the stress state in the pre-stressed cylindrical shell under the action of internal pressure p and longitudinal axial tensile force P_x [4-6].

At the initial stage, it is assumed that the wrapping process was performed at equal initial temperatures of both the shell and the wrapping wire, after which their temperatures changed by ΔT .

The equilibrium conditions for the shell with the wire wrapping can be formulated as follows:

$$N_x = N_{1x} + N_{2x} = \frac{pR}{2} + \frac{P_x}{2\pi R}, \quad 31$$

$$N_\theta = N_{1\theta} + N_{2\theta} = pR . \quad 32$$

Substituting into equations (31) and (32) the expressions for force factors (8), (9), (12) and (13), the following system of equations will be obtained for determining the relative deformations ε_x and ε_θ

$$\left.\begin{aligned}&\varepsilon_x\left(E_2\delta_2\cos^4\alpha+\frac{E_2\delta_2}{1-\mu^2}\right)+\varepsilon_\theta\left(E_2\delta_2\cos^2\alpha\sin^2\alpha+\mu\frac{E_1\delta_1}{1-\mu^2}\right)=\\&=\frac{pR}{2}+\frac{P_x}{2\pi R}+\frac{E_1\delta_1\alpha_1\Delta T}{1-\mu}+E_2\delta_2\alpha_2\Delta T\cos^2\alpha;\\&\varepsilon_x\left(E_2\delta_2\sin^2\alpha\cos^2\alpha+\mu\frac{E_1\delta_1}{1-\mu^2}\right)+\varepsilon_\theta\left(\frac{E_1\delta_1}{1-\mu^2}+E_2\delta_2\sin^4\alpha\right)=\\&=pR+\frac{E_1\delta_1\alpha_1\Delta T}{1-\mu}+E_2\delta_2\alpha_2\Delta T\sin^2\alpha.\end{aligned}\right\} \quad 33$$

Solving the system of equations (33) with respect to ε_x and ε_θ the following expressions will be obtained:

$$\varepsilon_x=\frac{C_1\left(E_2\delta_2\sin^4\alpha+\frac{E_1\delta_1}{1-\mu^2}\right)-C_2\left(E_2\delta_2\sin^2\alpha\cos^2\alpha+\mu\frac{E_1\delta_1}{1-\mu^2}\right)}{\frac{E_1\delta_1}{1-\mu^2}[E_2\delta_2(\cos^4\alpha+\sin^4\alpha-2\mu\sin^2\alpha\cos^2\alpha)+E_1\delta_1]}; \quad 34$$

$$\varepsilon_\theta=\frac{C_2\left(E_2\delta_2\cos^4\alpha+\frac{E_1\delta_1}{1-\mu^2}\right)-C_1\left(E_2\delta_2\sin^2\alpha\cos^2\alpha+\mu\frac{E_2\delta_2}{1-\mu^2}\right)}{\frac{E_1\delta_1}{1-\mu^2}[E_2\delta_2(\cos^4\alpha+\sin^4\alpha-2\mu\sin^2\alpha\cos^2\alpha)+E_1\delta_1]}; \quad 35$$

Where

$$C_1=\frac{pR}{2}+\frac{P_x}{2\pi R}+\frac{E_1\delta_1\alpha_1\Delta T}{1-\mu}+E_2\delta_2\alpha_2\Delta T\cos^2\alpha, \quad 36$$

$$C_2=pR+\frac{E_1\delta_1\alpha_1\Delta T}{1-\mu}+E_2\delta_2\alpha_2\Delta T\sin^2\alpha. \quad 37$$

Let's determine the stresses from the expressions

$$\sigma_{1x}=\frac{E_1}{1-\mu^2}(\varepsilon_x+\mu\varepsilon_\theta)-\frac{E_1\alpha_1\Delta T}{1-\mu}; \quad 38$$

$$\sigma_{1\theta}=\frac{E_1}{1-\mu^2}(\varepsilon_\theta+\mu\varepsilon_x)-\frac{E_1\alpha_1\Delta T}{1-\mu}; \quad 39$$

$$\sigma_2=E_2(\varepsilon_x\cos^2\alpha+\varepsilon_\theta\sin^2\alpha-\alpha_2\Delta T). \quad 40$$

Substituting the values (34) and (35) into (38), (39) and (40), expanded formulas will be obtained for determining the stresses in the shell wall and wrapping:

longitudinal stresses:

$$\sigma_{1x}=\frac{\frac{P_x}{2\pi R}\left[\sin^4\alpha-\mu\sin^2\alpha\cos^2\alpha+\frac{E_1\delta_1}{E_2\delta_2}\right]+\frac{pR}{2}\left[\sin^4\alpha+2\mu\cos^4\alpha-\sin^2\alpha\cos^2\alpha(2+\mu)+\frac{E_1\delta_1}{E_2\delta_2}\right]+E_1\delta_1\alpha_1\Delta T\cos^2\alpha}{\delta_1\left(\sin^4\alpha+\cos^4\alpha-2\mu\sin^2\alpha\cos^2\alpha+\frac{E_1\delta_1}{E_2\delta_2}\right)}; \quad 41$$

ring stresses:

$$\sigma_{1\theta}=\frac{\frac{P_x}{2\pi R}\sin^2\alpha\left[\mu\sin^2\alpha-\cos^2\alpha\right]+\frac{pR}{2}\left[2\cos^4\alpha+\mu\sin^4\alpha-\sin^2\alpha\cos^2\alpha(2\mu+1)+2\frac{E_1\delta_1}{E_2\delta_2}\right]+E_1\delta_1\alpha_1\Delta T\sin^2\alpha}{\delta_1\left(\sin^4\alpha+\cos^4\alpha-2\mu\sin^2\alpha\cos^2\alpha+\frac{E_1\delta_1}{E_2\delta_2}\right)}; \quad 42$$

stresses in the wrapping:

$$\sigma_2 = \frac{\frac{P_x}{2\pi R}\left(\cos^2\alpha - \mu\sin^2\alpha\right) + \frac{pR}{2}\left[(1-2\mu)\cos^2\alpha + (2-\mu)\sin^2\alpha\right] - E_2\delta_2\alpha_2\Delta T}{\delta_2\left[\sin^4\alpha + \cos^4\alpha - 2\mu\sin^2\alpha\cos^2\alpha + \frac{E_1\delta_1}{E_2\delta_2}\right]}. \qquad 43$$

The final formulas for determining the relative deformations in the shell wall will look like this:

$$\varepsilon_x = \frac{\frac{P_x}{2\pi R}\left(E_2\delta_2\sin^4\alpha + \frac{E_1\delta_1}{1-\mu^2}\right) + \frac{pR}{2}\left[E_2\delta_2\sin^2\alpha\left(\sin^2\alpha - 2\cos^2\alpha + \frac{E_1\delta_1}{1-\mu^2}(1-2\mu)\right]+\right.}{\frac{E_1\delta_1E_2\delta_2}{1-\mu^2}\times}$$

$$\frac{+\frac{E_1\delta_1E_2\delta_2}{1-\mu^2}\left\{\alpha_1\Delta T\left[(1+\mu)\left(\sin^2\alpha - \cos^2\alpha\right)\sin^2\alpha + \frac{E_1\delta_1}{E_2\delta_2}\right] + \alpha_2\Delta T\left(\cos^2\alpha - \mu\sin^2\alpha\right)\right\}}{\times\left(\sin^4\alpha + \cos^4\alpha - 2\mu\sin^2\alpha\cos^2\alpha + \frac{E_1\delta_1}{E_2\delta_2}\right)}; \qquad 44$$

$$\varepsilon_\theta = \frac{-\frac{P_x}{2\pi R}\left(E_2\delta_2\sin^2\alpha\cos^2\alpha + \mu\frac{E_1\delta_1}{1-\mu^2}\right) + \frac{pR}{2}\times\left[E_2\delta_2\cos^2\alpha\left(2\cos^2\alpha - \sin^2\alpha\right) + \frac{E_1\delta_1}{1-\mu^2}\times\right.}{\frac{E_1\delta_1E_2\delta_2}{1-\mu^2}\times}$$

$$\frac{\left.\times(2-\mu)\right] + \frac{E_1\delta_1E_2\delta_2}{1-\mu^2}\left\{\alpha_1\Delta T\left[(1+\mu)\left(\cos^2\alpha - \sin^2\alpha\right)\cos^2\alpha + \frac{E_1\delta_1}{E_2\delta_2}\right] + \alpha_2\Delta T\left(\sin^2\alpha - \mu\cos^2\alpha\right)\right\}}{\times\left(\sin^4\alpha + \cos^4\alpha - 2\mu\sin^2\alpha\cos^2\alpha + \frac{E_1\delta_1}{E_2\delta_2}\right)} \qquad 45$$

In this case, the shell wall's total stresses be equal to the prestresses' sum from the wrapping, determined from formulas (21) and (22), stresses from internal pressure p, longitudinal force P_x and temperature effects, determined from formulas (41) and (42).

2.4 Cylindrical shell with the wrapping thread perpendicular to its longitudinal axis ($\alpha = 90^0$)

It is known that in cases where there is a need to reduce ring stresses, it is precisely perpendicular winding to the longitudinal axis of the shell that is used, Fig. 3 [4].

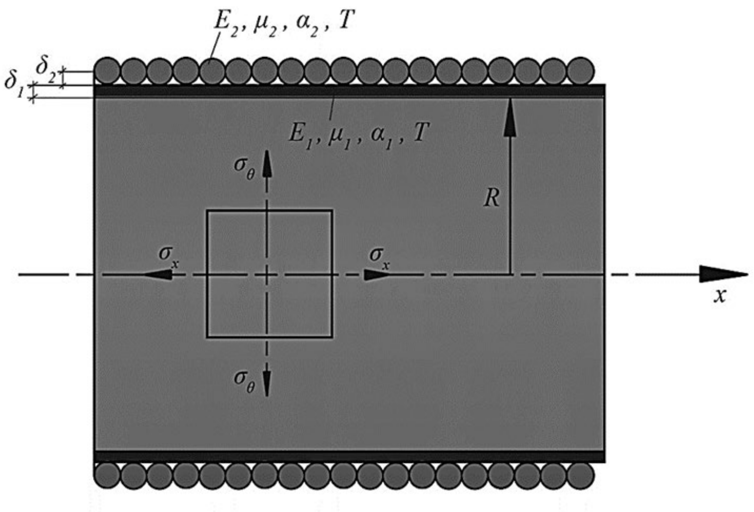

Fig. 3. Diagram of the cylindrical shell with the wrapping thread applied at an angle $\alpha = 90^0$.

Reasoning from the analysis of the calculation formulas obtained in the previous paragraph, let's try to obtain formulas for calculating the stress state of the shell wall and wrapping when winding the wrapping thread perpendicular to the shell's longitudinal axis, i.e. equating in the calculation formulas $\alpha = 90^0$.

Thus, based on (23) and (24), the initial stresses due to the pretension of the wrapping thread are given by:

$$\sigma_{1xn} = 0, \quad \sigma_{1\theta н} = -\sigma_n\frac{\delta_2}{\delta_1}, \qquad 46$$

$$\sigma_n = k\sigma_{11},\ k = \frac{1}{\sqrt{1+E_2\delta_2/E_1\delta_1}}, \quad 47$$

where k is the stress relaxation coefficient in the wrapping thread.

The shell wall's stresses occurring from the action of the internal excess pressure p and longitudinal force P_x, taking into account the temperature effects in accordance with (41) and (42), will be determined from the following expressions:

$$\sigma_{1x} = \frac{1}{2\delta_1}\left(pR + \frac{P_x}{\pi R}\right), \quad 48$$

$$\sigma_{1\theta} = \frac{pR\left(\frac{\mu}{2}+\frac{E_1\delta_1}{E_2\delta_2}\right)+\frac{\mu P_x}{2\pi R}+E_1\delta_1(\alpha_1\Delta T)}{\delta_1\left(1+\frac{E_1\delta_1}{E_2\delta_2}\right)}. \quad 49$$

From (48) it can be concluded that longitudinal loads are perceived only by the shell wall, the wrapping in the longitudinal direction does not work.

The stresses induced in the wrapping σ_2 in accordance with (43) will be determined from the expression:

$$\sigma_2 = \frac{pR\left(1-\frac{\mu}{2}\right)+\frac{\mu P_x}{2\pi R}-E_1\delta_1(\alpha_1\Delta T)}{\delta_2\left(1+\frac{E_1\delta_1}{E_2\delta_2}\right)} \quad 50$$

When winding at an angle $\alpha = 90^0$, by changing the wrapping layer thickness and prestressing level, it is possible to relieve the shell from ring stresses $\sigma_{1\theta}$, in order to equalize them with longitudinal stresses σ_{1x} and achieve equal strength of the structures. To ensure equal strength and the lowest weight of the shell, the thickness, initial tension and elastic modulus of the wrapping layer material should be selected so that the tensile ring stresses in the shell $\sigma_{1\theta}$ are approximately equal σ_{1x}, and the safety margin in the wrapping is sufficient. To satisfy this condition, the wrapping layer thickness δ_2 should be selected slightly less than the shell thickness, otherwise the shell will be underloaded in terms of ring stresses $\sigma_{1\theta}$.

2.5 Analysis of the pre-stressed cylindrical shells with consideration of temperature effects on the wrapping thread tension

Based on the calculation method for the pre-stressed cylindrical shells in the elastic stage of operation, described in detail in [4-6], let's study the stressed-deformed state of the wall of the cylindrical shell with the stressed wrapping, taking into account the influence of temperature effects on the tension of the wrapping thread.

Let's consider an infinitely long cylindrical shell with a wrapping wire with tightly adjacent turns. The wrapping is wound with a certain tension.

The formulas derived in [4-8] for calculating the ring σ_1 and longitudinal σ_2 stresses in the cylindrical shell from prestressing – applicable within the elastic deformation range and accounting for thermal stresses – are expressed as follows:

$$\sigma_1 = \frac{P_{PN}\cdot R}{\delta_1} + \frac{T_0}{\delta_1} + \frac{6\mu\cdot M_0}{\delta_1^2} + \alpha_1\Delta T E_1, \quad 51$$

$$\sigma_2 = \frac{P_{PN}\cdot R}{2\delta_1} + \frac{6M_0}{\delta_1^2} - \alpha_1\Delta T E_1. \quad 52$$

The values of the moment M_0, force T_0 and wrapping pressure P_{PN} on the wall of the cylindrical shell will be determined from the expression:

$$P_{PN} = \frac{\left[2\delta_1 E_1 \Delta + (2-\mu)pR^2\right]\pi d^2 E_2 C}{R^2(k_1 E_2 \pi d^2 A + 8\delta_1 E_1 C)}; \quad 53$$

$$T_0 = -\frac{1}{2} k_1 R P_{PN} \frac{A}{C}; \quad 54$$

$$M_0 = \frac{1}{4k_1} P_{PN} \frac{B}{C}. \quad 55$$

In formulas (53)…(55) the coefficients *A, B, C* are calculated using formulas [4]:

$$A = shk_1 a + \sin k_1 a; \quad 56$$

$$B = shk_1 a - \sin k_1 a; \quad 57$$

$$C = chk_1 a - \cos k_1 a, \quad 58$$

where

$$k_1 = \frac{\sqrt[4]{3(1-\mu^2)}}{\sqrt{\delta_1 R}}. \quad 59$$

In the context of temperature influence, the magnitude of the tension Δ generated during the wire winding process is of particular significance.

The force necessary to stretch the wrapping wire to attain the desired tension is given by the following relation:

$$S_1 = \frac{\Delta}{R} E_2 \cdot F_2 = \frac{\Delta}{4R} E_2 \pi d^2. \quad 60$$

It should be noted that as the temperature increases, the elongation of the wrapping wire leads to a change in the tension Δ initially generated during the winding process.

The tension value, accounting for the thermal effect, can be expressed in general form as:

$$\Delta = \Delta_{PN} \pm \Delta_t \,. \quad 61$$

Here, Δ_{PN} can be determined from equation 60, while Δ_t is given by the following expression:

$$\Delta_t = \alpha \Delta T R. \quad 62$$

Thus, the total tension in the wrapping thread is significantly reduced as a result of temperature increase. This effect is associated with the adverse influence of temperature on the prestress level in the cylindrical shell and must be taken into account in engineering design and analysis.

Taking into account (53), (54), (55), (61), (62), equations (51) and (52) can be written as:

$$\sigma_1 = \sigma_1 = \frac{pR}{\delta_1} + \frac{(3\mu B - k_1^2 \delta_1 R A)[2\delta_1 E_1(\Delta_{ПН} - \alpha_1 \Delta T R) + (2-\mu)pR^2]\pi d^2 E_2}{k_1 \delta_1^2 R^2 (k_1 E_2 \pi d^2 A + 8\delta_1 E_1 C)} + \alpha_1 \Delta T E_1, \quad 63$$

$$\sigma_2 = \frac{pR}{2\delta_1} + \frac{3[2\delta_1 E_1(\Delta_{ПН} - \alpha \Delta T R) + (2-\mu)pR^2]\pi d^2 E_2 B}{k_1 \delta_1^2 R^2 (k_1 E_2 \pi d^2 A + 8\delta_1 E_1 C)} - \alpha_1 \Delta T E_1. \quad 64$$

In this case, the stress in the wrapping can be determined using the formula:

$$\sigma_{PN} = \frac{4P_{ПН}R}{\pi d^2} = \frac{4[2\delta_1 E_1(\Delta_{ПН} - \alpha_1 \Delta T R) + (2-\mu)pR^2]E_2 C}{R(k_1 E_2 \pi d^2 A + 8\delta_1 E_1 C)}. \quad 65$$

Let's assume that there is no pressure in the cylindrical shell, i.e. *p=0.* Then in expressions (63)…(65) only the stresses caused by the pretension and temperature effect will remain:

$$\sigma_1 = \frac{(3\mu B - k_1^2\delta_1 RA)[2\delta_1 E_1(\Delta_{PN} - \alpha_1 \Delta TR)]\pi d^2 E_2}{k_1\delta_1^2 R^2(k_1 E_2 \pi d^2 A + 8\delta_1 E_1 C)} + \alpha_1 \Delta T E_1, \quad 66$$

$$\sigma_2 = \frac{3[2\delta_1 E_1(\Delta_{PN} - \alpha_1 \Delta TR)]\pi d^2 E_2 B}{k_1\delta_1^2 R^2(k_1 E_2 \pi d^2 A + 8\delta_1 E_1 C)} - \alpha_1 \Delta T E_1, \quad 67$$

$$\sigma_{PN} = \frac{4[2\delta_1 E_1(\Delta_{PN} - \alpha_1 \Delta TR)]E_2 C}{R(k_1 E_2 \pi d^2 A + 8\delta_1 E_1 C)}. \quad 68$$

Let's consider the case when the tension Δ is caused not by prestress, but by heating the wrapping to a certain temperature T_1.

Then it is sufficient to put Δ= $\alpha \Delta TR$ in formulas (63) and (65). The length of the wire in the heated state should be equal to $2\pi(R + d/2)$, and in the cold state $2\pi(R + d/2 - \Delta)$.

$$2\pi\left(R + \frac{d}{2} - \Delta\right)(1 + \alpha_2 \Delta T_1) = 2\pi\left(R + \frac{d}{2}\right). \quad 69$$

From (69) it is easy to determine the heating temperature T_1 to obtain the set tension Δ:

$$T_1 = \frac{1}{\alpha} \cdot \frac{\Delta}{R\frac{d}{2} - \Delta} \approx \frac{1}{\alpha_2} \cdot \frac{\Delta}{R + \frac{d}{2}} \quad 70$$

3. RESULTS AND DISCUSSION

Analysis of calculation formulas (41)…(45) indicates that the stress distribution and overall strength of the pre-stressed cylindrical shell are significantly influenced by several factors. These include the winding angle of the wrapping thread α, the ratio of wall thicknesses of the shell and the wrapping layer δ_1/δ_2, the ratio of the elastic moduli of the shell and wrapping materials E_1/E_2, on the pretension value of the wrapping thread σ_{11}, and the operating temperature ΔT.

The dependences of the stresses in the shell wall on the ratio of the wall thicknesses of the shell and wrapping δ_1/δ_2 and the ratio of the elastic moduli of the shell and wrapping materials E_1/E_2 are presented in line with Fig. 4 and 5.

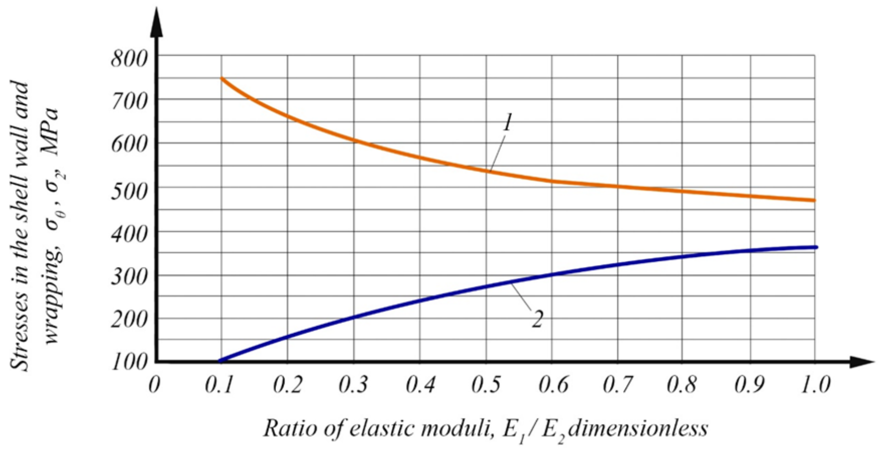

Fig. 4. Dependences of stresses in the shell wall and wrapping on the ratios of elastic moduli of their materials:1. Stresses in the wrapping; 2. Stresses in the shell wall.

In establishing the above dependences, the influence of temperature was not considered, and the winding angle of the wrapping thread was taken as $\alpha = 90^0$. Calculations were carried out using the following initial data: shell radius $R = 0.3$ m, Poisson's ratio $\mu = 0.3$, pressure in the shell $p = 3$ MPa, shell wall thickness $\delta_1 = 0.15 \cdot 10^{-2}$ m, reduced wrapping thickness $\delta_2 = 0.785 \cdot 10^{-2}$ m, elastic moduli of the shell material $E_1 = 1.88 \cdot 10^5$ MPa, wrapping $E_2 = 2.05 \cdot 10^5$ MPa. When determining the dependence of stresses in the shell wall and wrapping on the ratio of their thicknesses, the ratio of the elastic moduli of the shell and wrapping materials was assumed to be unity.

Analysis of the shell wall ring stresses' dependence on the ratio of the elastic moduli of the shell and wraping materials shows that the efficiency of the pre-stressed shell is increased when the elasticity modulus of the wrapping is much higher than the elasticity modulus of the shell material.

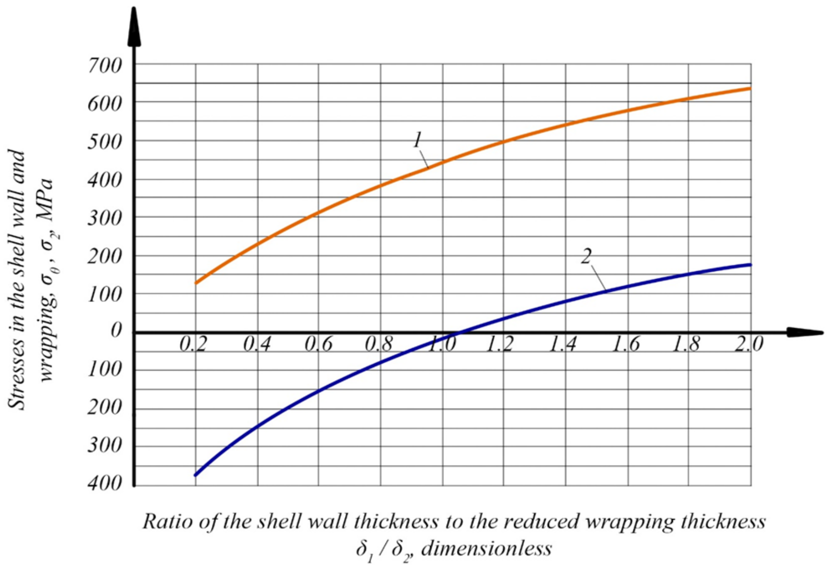

Fig. 5. Dependences of stresses in the shell wall and wrapping on the ratio of their thicknesses: 1. Stresses in the wrapping; 2. Stresses in the shell wall.

As the ratio of the shell wall and wrapping thicknesses increases, in accordance with Figure 5, the efficiency of prestressing decreases.

Efficient stress distribution in the shell wall can be obtained when the wall thickness is taken to be minimal from the condition of loss of its stability during compression of the wrapping wire, and the wrapping thickness is taken from the condition of ensuring the strength of the prestressed shell.

As noted above, the main design parameter of the wrapping, the selection of which can control the stress state of the shell wall, can be the winding angle of the wrapping thread.

According to Fig. 6, when the winding angle changes from perpendicular to the shell axis to technically possible angles of inclination of the wrapping thread, the ring stresses in the shell wall decrease, and the longitudinal stresses increase. Changing the winding angle of the wrapping thread leads to a redistribution of stresses in the shell wall and has a favorable effect on the stress state of the shell operating under internal pressure, bringing the structure closer to equal strength. From Figure 6, it is possible to establish the limits of the winding angle of the wrapping thread, at which the optimal distribution of stresses in the shell wall is achieved, which is equal to 40-45°.

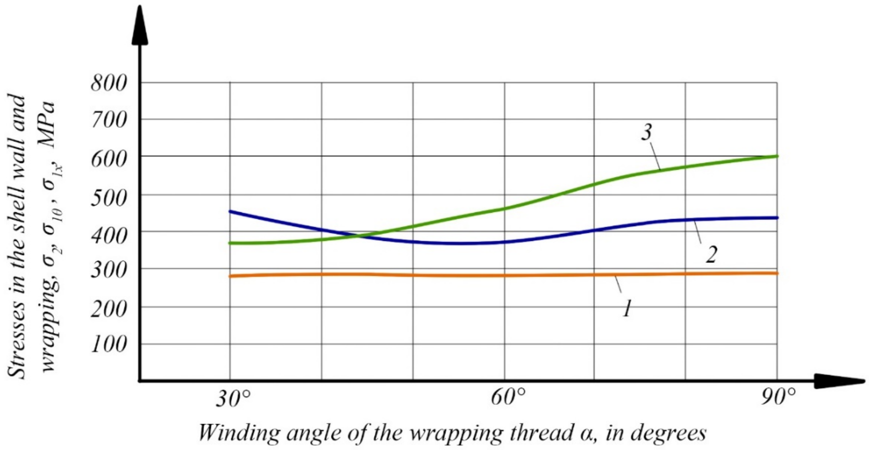

Fig. 6. Dependences of stresses in the shell wall and wrapping on the winding angle of the wrapping thread: 1. Stresses in the wrapping; 2. Longitudinal stresses in the shell wall; 3. Ring stresses in the shell wall.

In connection with the above, effective design of prestressed shells is carried out by selecting design parameters of prestressing and performing verification calculations.

In accordance with the purpose and objectives of the work, an assessment of the effect of temperature on the stress state of the prestressed shell was made.

The calculations were made for the cylindrical aluminum shell with a radius R =0.3 m, a wall thickness $\delta_1 = 0.15 \cdot 10^{-2}$ m, wrapped with a steel wire of 3 mm in diameter $\delta_2 = 0.785 \cdot 10^{-2}$ m, operating under an internal pressure $p = 3$MPa, with the following initial data: $E_1 = 1.18 \cdot 10^5$ MPa, $E_2 = 2.06 \cdot 10^5$ MPa, $\mu = 0.3$, $\alpha = 90^0$, $\alpha_1 = 0.24 \cdot 10^{-4}$ C^{-1}, $\alpha_2 = 0.12 \cdot 10^{-4}$ C^{-1}.

The calculation results in the form of dependences of stresses in the shell wall and wrapping on the temperature gradient are presented in accordance with Fig. 7.

The nature of the obtained dependences, in accordance with Fig. 7, shows a significant influence of the operating temperature on the stress state of the shell with the pre-stressed wire wrapping.

Thus, at a temperature gradient ΔT=30°C, the ring stresses increase by approximately 1.34 times, at 50°C – 1.57 times, at 70°C – 1.8 times compared to the initial ones. A linear relationship is observed between the ring stresses in the shell wall and temperature gradient.

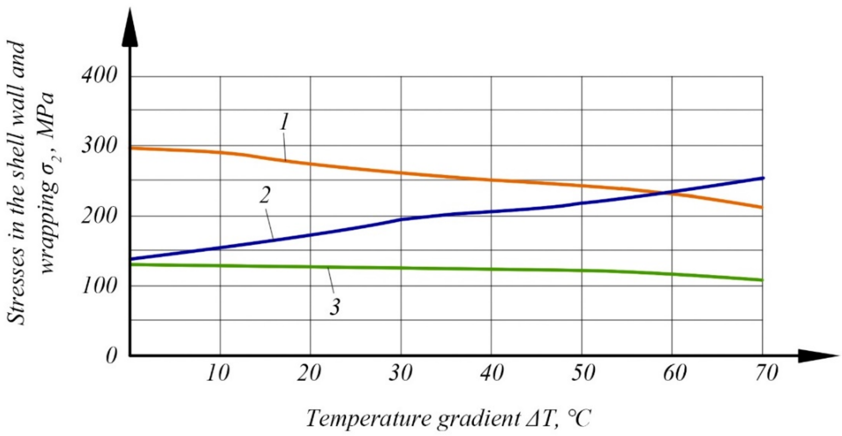

Fig. 7. Dependences of stresses in the shell wall and wrapping on the temperature gradient *ΔT:* 1. Stresses in the wrapping; 2. Longitudinal stresses in the shell wall; 3. Ring stresses in the shell wall.

Note that longitudinal loads are perceived only by the shell wall, the wrapping does not work in the longitudinal direction.

According to Fig. 7, the stress in the wrapping decreases with an increase in the temperature gradient: at ΔT = 30°C by 1.1 times, ΔT = 50°C – 1.18 times, ΔT = 70°C – 1.3 times.

To assess the effect of temperature on the achieved level of prestress using the formulas obtained above, calculations were performed for a main gas pipeline with a diameter of 1220 mm, made of 17G1C steel with $\sigma_v = 520$ MPa, prestressed with the wire winding of steel wire with a diameter of 5 mm, loaded with an internal excess pressure of p = 7.5 MPa. To simplify the calculation procedure, it was assumed that $E_1 = E_2 = 2 \cdot 10^5\ MPa$.

The calculation results are given in Table 1.

Table 1. Values of prestressing in the shell wall depending on temperature.

Calculation parameters	Values ΔT, (°C)						
	0.0	10.0	20.0	30.0	40.0	50.0	60.0
The value of the total tension Δ, (10^{-2} cm)	3.83	3.07	2.35	1.62	0.89	0.16	-0.058
Ring stresses in the shell wall, $\sigma_{1\theta}$, (MPa)	-84	-68	-51	-35	-21	-4.0	0.0
Stresses in the wrapping, σ_2, (MPa)	81	66	50	34	18	4.0	0.0

Analysis of the calculation results shows that with an increase in the temperature gradient, the achieved level of prestress decreases. Consequently, the operating temperature of the pipeline significantly affects the stress state of the shell wall and wrapping. The calculation results confirm the need to take into account temperature effects in engineering calculations and design of prestressed shells.

4. CONCLUSIONS

As a result of the conducted theoretical studies of the influence of temperature loads on the stressed-deformed state of steel shells, it was established:

– Based on the results of the analysis of the operation of the thin-walled cylindrical shell of medium length, compressed by the stressed wire wrapping and loaded with internal pressure, on the basis of conditions (8) and (9) of the equilibrium of the shell wall element, dependences were obtained between the forces along the boundaries of the shell element and the elongations along the corresponding axes.

– The initial stress σ_{11} from the pretension of the wrapping thread was estimated and formulas were obtained for determining the stresses in the wrapping (25), (26) and the pressure arising in the shell wall under the wrapping thread (27).

– Expressions (41), (42) and (43) were obtained for determining the ring $\sigma_{1\theta}$ and longitudinal σ_{1x} stresses in the shell wall and stresses in the wrapping σ_2, taking into account the design parameters of the prestressing and temperature effects, as well as formulas (44) and (45) for determining the relative deformations $\varepsilon_x, \varepsilon_\theta$ in the shell wall.

– Analysis of the obtained calculation formulas showed that the stress distribution and the strength of the prestressed shell largely depend on the winding angle of the wrapping thread α, on the ratio of the wall thicknesses of the shell and wrapping δ_1/δ_2, the ratio of the elastic moduli of the shell and wrapping materials E_1/E_2, on the value of the pretension of the wrapping thread σ_{11} and the ratio of the coefficients of thermal expansion of the shell α_1 and wraping α_2 materials.

– A calculation experiment was carried out to assess the effect of temperature on the stress state of the prestressed shell. It was found that the ring stresses in the shell wall increase with increasing temperature gradient, while the stresses in the wrapping decrease. At a temperature gradient of 70°C, the ring stresses increased by 1.8 times, while the stresses in the wrapping decreased by 1.3 times.

– The calculation of prestressed shells was carried out taking into account the effect of temperature on the tension of the wrapping thread. It was shown that with an increase in the temperature gradient, the level of the achieved prestressing significantly decreases. At the same time, a change in the operating temperature has a noticeable effect on the distribution of stresses in the shell wall and wrapping. Thus, calculations of the main pipeline prestressed with the steel wire showed that at a temperature gradient of $\Delta T = 30^0$C, the achieved level of prestressing can decrease by 10-12% compared to the initial one, and at $\Delta T = 50^0$C, the prestressed wrapping does not affect the stress state of the shell wall.

5. ACKNOWLEDGEMENTS

This research is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP19680589).

APPENDIX

a	winding pitch of the wrapping thread, m
d	wrapping wire diameter, m
R	shell radius, m
E_1	shell material elasticity modulus, MPa
E_2	wrapping material elasticity modulus, MPa
k	stress relaxation coefficient in the wrapping thread
P_{11}	pressure on the shell body under the wrapping thread, MPa
P_x	line longitudinal force in the shell, N/m
p	internal pressure in the shell, MPa
p_{max}	maximum internal pressure in the shell, MPa
R_1, R_2	calculated strength limits of the shell and wrapping material, MPa
S_{cr}	critical tension force of the wrapping thread, N
S_1	tension force of the wrapping thread, N
T_1, T_2	calculated heating temperatures of the shell layers, °C
ΔT	range of fluctuations (gradient) of the calculated temperature, °C
α	winding angle of the wrapping thread, in degrees
α_1, α_2	temperature coefficients of linear expansion of the shell wall and wrapping materials, °C^{-1}
Δ	tension, m
δ_1, δ_2	thickness of the shell wall and wrapping, m
$\varepsilon_{1x}, \varepsilon_{1\theta}$	ring and longitudinal relative deformations in the shell wall
μ	Poisson's ratio
$\sigma_{01}, \sigma_{11}^1$	stresses in the shell sections arising as a result of winding the wrapping, MPa
σ_{02}, σ_{11}	stresses in the wrapping arising as a result of winding the wrapping, MPa;
$\sigma_{1\theta}$	ring stress in the shell, MPa
σ_{1x}	longitudinal stress in the shell, MPa
σ_2	stress in the wrapping, MPa
σ_{cr}	critical stress of loss of stability of the shell wall, MPa;
Δ_{PN}	tension from mechanical tension of the wrapping thread, MPa
Δ_t	change in the wrapping thread tension due to temperature effects, permissible prestresses, MPa
T_1	heating temperature, °C
α_2	coefficient of linear expansion of wire

REFERENCES

1. Leis B.N., Zhu X.K., Forte T.P., Clark E.B. Modeling Running Fracture in Pipelines – Past, Present, and Plausible Future Directions. 2015. P. 1 – 7. https://www.researchgate.net/publication/237235879_Modeling_running_fracture_in_pipelines_-_Past_present_and_plausible_future_directions (accessed on 22 May 2024)
2. Sugie E., Matsuoka M., Akiyama T., Mimura H., Kawaguchi Y. A Study of Shear Crack Propagation in Gas-Pressurized Pipelines. Journal Pressure Vessel Technol. 1982. 104 (4). P. 338 – 343. DOI: https://doi.org/10.1115/1.3264226
3. Sugie E., Kaji H., Taira T., Ohashi M., Sumitomo Y. Shear Fracture Arrestability of Controlled Rolled Steel X70 Line Pipe by Full-Scale Burst Test. Journal Energy Resour. Technol. 1984. 106 (1). P. 55 – 62. DOI: https://doi.org/10.1115/1.3231024
4. Ibraimova U., Zhangabay N., Tursunkululy T., Rakhimov M., Dossybekov S., Kolesnikov A., Karshyga G., Tengebayev N., Zhirenbayeva N., Liseitsev Y.Development of method for calculation of pre-strained steel cylindrical sheaths in view of the winding angle, pitch and thickness. Case Studies in Construction Materials. 2023. 19. P. e02233. DOI: https://doi.org/10.1016/j.cscm.2023.e02233
5. Zhangabay N., Ibraimova U., Suleimenov U., Moldagaliyev A., Buganova S., Jumabayev A., Kolesnikov A., Tursunkululy T., Zhiyenkulkyzy D., Khalelova A., Liseitsev Y.Factors affecting extended avalanche destructions on long-distance gas pipe lines: Review. Case Studies in Construction Materials. 2023. 19. P. e02376. DOI: https://doi.org/10.1016/j.cscm.2023.e02376
6. Zhangabay N., Ibraimova U., Ainabekov A., Buganova S., Moldagaliev A. Finite-Element Modeling of the Temperature Effect on Extended Avalanche Damage of Gas Main Pipelines. Materials. 2024. 17 (9). P. 1963. DOI: https://doi.org/10.3390/ma17091963
7. Zhangabay N., Tursunkululy T., Bonopera M., Azatkulov O. Laboratory Investigation of the Dynamic Response of a Prestressed Composite Steel Cylindrical Tank Subjected to Horizontal Loading. Journal of Composites Science. 2023. 7 (9). P. 373. DOI: https://doi.org/10.3390/jcs7090373
8. Zhangabay N., Bonopera M., Utelbayeva A., Tursunkululy T., Rakhimov M. Experimental and Theoretical Reproducibility Research on the Earthquake Resistance of Cylindrical Steel Tanks. Vibration. 2023. 6 (4). P. 960 – 974. DOI: https://doi.org/10.3390/vibration6040057
9. Di Biagio M., Demofonti G., Mannucci G., Iob F., Spinelli C.M., Schmidt T. Development of a reliable model for evaluating the ductile fracture propagation resistance for high grade steel pipelines. Proceedings of the 2012 9th International Pipeline Conference. 2012. P. 24 – 28. Calgary. Alberta. Canada. DOI: https://10.1115/IPC2012-90614
10. Zhu X.K. Review of fracture control technology for gas transmission pipelines. Proceedings of the 10th International Pipeline Conference. 2014. IPC2014-33121 P. V003T07A004. DOI: https://10.1115/IPC2014-33121
11. Fengping Y., Chunyong H., Jinheng L., He, L., Yang L.I. Crack Propagation and Arrest Simulation of X90 Gas Pipe. International Journal of Pressure Vessels and Piping. 2017. 149. P. 120 – 131. DOI: https://10.1016/j.ijpvp.2016.12.005
12. Elyasi N., Shahzamanian M., Lin. M., Westover L., Li Y., Kainat M., Yoosef-Ghodsi N., Adeeb S. Prediction of Tensile Strain Capacity for X52 Steel Pipeline Materials Using the Extended Finite Element Method. Applied Mechanics. 2021. 2. P. 209 – 225. DOI: https://doi.org/10.3390/applmech2020013
13. Arumugam T., Vijaya Kumar S.D., Karuppanan S., Ovinis M. The Influence of Axial Compressive Stress and Internal Pressure on a Pipeline Network: A Review. Applied Sciences. 2023. 13. P. 3799. DOI: https://doi.org/10.3390/app13063799
14. Alavinasab A., Padewski E., Holley M., Jha R., Ahmadi G. Damage identification based on vibration response of prestressed concrete pipes. In Pipelines 2010: Climbing New Peaks to Infrastructure Reliability: Renew, Rehab, and Reinvest; ASCE Library: Reston. VA USA 2010. P. 909 – 919. DOI: https://doi.org/10.1061/41138(386)87

15. Bakhtiari-Nejad F., Bideleh S.M. Nonlinear free vibration analysis of prestressed circular cylindrical shells on the Winkler/Pasternak foundation. Thin Walled Structures. 2012. 53. P. 26 – 39. DOI: https://doi.org/10.1016/j.tws.2011.12.015
16. Chen J., Wang H., Salemi M., Balaguru P.N. Finite Element Analysis of Composite Repair for Damaged Steel Pipeline. Coatings. 2021. 11. P. 301. DOI: https://doi.org/10.3390/coatings11030301
17. Marvin C.W. Determining the Strength of Corroded Pipe. Materials Protection and Performance. 1972. № 11. P. 34 – 40. https://yandex.kz/search/?text=Marvin+C.+W.+Determining+the+Strength+of+Corroded+Pipe.+Materials+Protection+and+Performance.+1972.+№+11.+P.+34+–+40.&lr=162&clid=9582 (accessed on 24 May 2025)
18. Yang Y., Zhang H., Wu K., Chen P., Sui Y., Yang D., Liu X. Strain capacity analysis of the mismatched welding joint with misalignments of D 1,422 mm X80 steel pipelines: an experimental and numerical investigation. Journal of Pipeline Science and Engineering. 2021. 1 (2). P. 212 – 224. DOI: https://doi.org/10.1016/j.jpse.2021.05.002
19. Yuan J., Tian L., Zhu W., Tan Sh., Xin T., Li D., Feng W., Zhang H., Li X., Huang J., Fu A., Feng Y. Internal localized corrosion of X65-grade crude oil pipeline caused by the synergy of deposits and microorganisms. Engineering Failure Analysis. 2023. 149. P. 107276. DOI: https://doi.org/10.1016/j.engfailanal.2023.107276
20. Rosado D.B., De Waele W., Vanderschueren D., Hertelé. S. Latest developments in mechanical properties and metallurgical features of high strength line pipe steels. International Journal of Sustainable Construction and Design. 2013. 4 (1). P.122. DOI: https://doi.org/10.21825/scad.v4i1.742
21. Wu K., Liu X., Zhang H., Sui Y., Zhang Zh., Yang D., Liu Y. Fracture response of 1422-mm diameter pipe with double-V groove weld joints and circumferential crack in fusion line. Engineering Failure Analysis. 2020. 115. P. 104641. DOI: https://doi.org/10.1016/j.engfailanal.2020.104641

INFORMATION ABOUT THE AUTHORS

Zhangabay N.Zh., e-mail: Nurlan.Zhanabay777@mail.ru, ORCID ID: https://orcid.org/0000-0002-8153-1449, SCOPUS: https://www.scopus.com/authid/detail.uri?authorId=57211557292, M. Auezov South Kazakhstan University, Department of Architecture and Urban Planning, Candidate of Technical Sciences (PhD), Associate Professor

Moldagaliyev A.B., e-mail: arm_mold81@mail.ru, ORCID ID:https://orcid.org/0000-0002-4286-8401, SCOPUS: https://www.scopus.com/authid/detail.uri?authorId=59215762100, M. Auezov South Kazakhstan University, Department of Mechanics and Mechanical Engineering, Candidate of Technical Sciences (PhD), Associate Professor

Buganova S.N., e-mail: svetlanabuganova7@gmail.com, ORCID ID: https://orcid.org/0000-0003-2005-3305, SCOPUS: https://www.scopus.com/authid/detail.uri?authorId=5719428174, Management International Education Corporation (KazGASA), Department of Building Technologies and Infrastructure, Candidate of Technical Sciences (PhD), Associate Professor

Bektursunova A.K., e-mail: Bektursunova7979@mail.ru, ORCID ID: https://orcid.org/0000-0001-5514-5870, SCOPUS: https://www.scopus.com/authid/detail.uri?authorId=57193453995, M. Auezov South Kazakhstan University, Department of Technology and Design of Textile Materials, Doctor of Philosophy (PhD), Senior Lecturer

Tursunkululy T., e-mail: timurtursunkululy@gmail.com, ORCID ID: https://orcid.org/0000-0001-6215-7677, SCOPUS: https://www.scopus.com/authid/detail.uri?authorId=57687675500, M. Auezov South Kazakhstan University, Department of Architecture and Urban Planning, PhD, Associate Professor

Ibraimova U.B., e-mail: ibraimova_uljan@mail.ru, ORCID ID: https://orcid.org/0009-0004-9786-1348, SCOPUS: https://www.scopus.com/authid/detail.uri?authorId=58368006200, M. Auezov South Kazakhstan University, Department of Architecture and Urban Planning, PhD