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Modeling of Stress-Strain State of Piping Systems with Erosion and Corrosion Wear

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The problems of modeling the stress-deformed state of erosion or corrosion-worn rectilinear sections and the ball-shaped bends of pipeline systems are proposed to solve in a cylindrical coordinate system. For this purpose, formulas of Christophell type II, non-zero components of the strain tensor and a system of equilibrium equations in the framework of linear torsional theory are given. The system of equilibrium equations is reduced to one equation, which is the basic equation of the Lame's problem. Formulas for the calculation of ring stresses that occur in the wall of erosion or corrosion worn rectilinear sections, and the removal of pipelines from the action of internal pressure are derived. The influence of the change in the wall thickness of the pipeline bends in the place of their erosion or corrosion wear on the amount of ring stresses is determined.

Keywords: ring stresses, erosion, corrosion, bend, internal pressure, cylindrical coordinate system.

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Introduction

Modern pipeline systems are complex networks that consist of straight sections, curves of hot (bends) and cold bending, tees, reducing couplings. Bends contain pipelines of various purpose (gas pipelines, oil pipelines, oil products pipelines, nitrogen pipelines, steam pipelines of nuclear and thermal power plants, pipelines of pneumatic transport, etc.). The largest number of bends is found in the pipework of various technological objects, compressor and pumping stations, underground gas storage, gas distribution stations and etc. Bends contain Г-, Z- and П-shaped compensators of above-ground pipelines;

In the pipelines bends, the direction of flow changes by an angle of 45º, 60º, 90º, and the particles contained in the flow of the transported product are hitting the wall of the bend, causing erosion wear (Fig. 1a). Under the influence of aggressive contaminants contained in pipeline flows, corrosion of the inner wall of the pipelines occurs, and under the action of aggressive components contained in the environment, corrosion wear of the outer wall takes place (Fig. 1b). External and internal defects of rectilinear sections, pipeline bends affect their stress-strain state.

One of the requirements that apply to the pipelines to ensure their reliability is to control the changing magnitude of erosion and corrosion defects of the wall during the operation of the pipeline by, and the most accurate determination of the stress state of the defective areas.

In order to investigate the stress-strain state of erosion and corrosion-worn pipelines, it is necessary to identify and mathematically describe the factors of force action that operate during the operation of pipelines.

Numerous publications, as a rule, concern either the estimation of the change in the stress-strain state of the pipeline sections by data on the displacement of surface points under the action of force factors of unknown nature [1-6], or the determination of ring stresses in the wall of erosion-worn pipeline sections that are caused by internal pressure [5, 7-10] or equivalent stresses by computer finite element modeling [11-13]. Questions of complex assessment of changes in stress-strain state under the action of a complex of force factors of different nature require more detailed study of them, taking into account the curvature of the axis of quasi-rectilinear and hurricane sections of the pipeline (bends of hot bending), erosion and corrosion wear and tear, which causes wear and tear.

a) b)

Fig. 1. Pipeline bends' defects: a) – erosion; b) – corrosion.

The purpose of the article is to develop mathematical models of the deformation process and the stress state of rectilinear sections and pipeline bends on the data on the displacement of points on their outer surface and on the change of the cross-section configuration caused by erosion and corrosion wear.

I. Theoretical model

To describe the change in the stress-strain state of pipelines according to the data of displacement of surface points, a technique that has received theoretical justification in [1, 2] is used, according to which the coordinates of the radius vector of any point of the studied area are obtained:

$$\vec{r}\left(s,\varphi,r,t,p_i\right)=\vec{r}_l\left(s,\varphi,r,t,p_i\right)+\rho\left(s,\varphi,r,t,p_i\right)\times$$
$$\times\left(\cos\omega(s,\varphi,r,t,p_i)\vec{b}_l+\sin\omega(s,\varphi,r,t,p_i)\vec{n}_l\right)+$$
$$+\psi\left(s,\varphi,r,t,p_i\right)\cdot\vec{\tau}_l-\frac{D}{2}\vec{n}_l, \qquad (1)$$

where s, φ, r – components of the body-related quasi-cylindrical coordinate system (s – longitudinal coordinates), $0\le s\le l$; φ – polar angle in section $0\le\varphi\le 2\pi$; r – radial component, $R_{in}\le r\le R_{ex}$); l – section length; R_{in}, R_{ex} – respectively the inner and outer radii of the pipe; t – time; p_i – coefficients that take into account the type of external loads (internal pressure, torsion, longitudinal displacements, temperature gradients, etc.); $\vec{r}_l$ – radius vector of a point on the upper part of the pipeline (for the construction of $\vec{r}_l$ according to the data on the movement of the points of the upper part using interpolation smoothing splines [1, 2], taking into account the accuracy of measurement of coordinates by geodetic [6, 14] by techniques or methods of inline inspection [9, 15, 16]; $\vec{n}_l$, $\vec{b}_l$, $\vec{\tau}_l$ – vectors of surface normal, binormal and tangent to the surface of the genera [17, 18]; $\rho(s,\varphi,r,t,p_i)$, $\omega(s,\varphi,r,t,p_i)$, $\psi(s,\varphi,r,t,p_i)$ – functions characterizing respectively radial, polar and longitudinal displacements of points of the investigated section (for a rectilinear section of the pipeline, it is assumed: $\rho(s,\varphi,r,t,p_i)=r$, $\omega(s,\varphi,r,t,p_i)=\varphi$, $\psi(s,\varphi,r,t,p_i)=0$; D – outside pipeline diameter. For more complex deformations, these functions are either given by the deformation method, or they are assumed to be linear combinations of components, and the coefficients of decomposition are determined by the method of minimal residuals [1].

According to the known representation (1) the following quantities are determined:

– components of local basis vectors at initial and control time points [19]:

$$\vec{f}_i=\frac{\partial\vec{r}}{\partial x_i};\ x_1=s;\ x_2=\varphi;\ x_3=r; \qquad (2)$$

– components of the metric tensor at the initial and control points of time [6]:

$$g_{ij}=\frac{\partial\vec{r}}{\partial x_i}\frac{\partial\vec{r}}{\partial x_j}=\vec{f}_i\vec{f}_j; \qquad (3)$$

– deformation tensor components [17]:

$$\varepsilon_{ij}=\frac{1}{2}(g_{ij}-g_{ij}^0), \qquad (4)$$

where g_{ij}, g_{ij}^0 – components of the metric tensor at the initial and control points of time;

– components of the stress tensor σ_{ij} within the isotropic body model [19]:

$$\sigma^{ij}=\lambda I_l(\varepsilon)\,g^{ij}+2\mu\varepsilon^{ij}, \qquad (5)$$

where $\sigma^{ij}, g^{ij}, \varepsilon^{ij}$ – contravariant components of stress tensors, metric and strain tensors respectively.

Components g^{ij} are determined by the multiplication of the matrix inverted to $\{g^{ij}\}$, determined by (3). For other contravariant components [17], the known relation between the covariant and contravariant components of the tensors [17]:

$$\begin{cases} \sigma^{ij} = \sum_{k,l=1}^{3} g^{ik} g^{jl} \sigma_{kl}, \\ \varepsilon^{ij} = \sum_{k,l=1}^{3} g^{ik} g^{jl} \varepsilon_{kl}, \end{cases} \quad (6)$$

In the case of an anisotropic body [19], the components of the stress tensor are defined as follows:

$$\sigma_{ij} = \sum_{k,l=1}^{3} c_{ijkl} \varepsilon_{kl}, \quad (7)$$

where c_{ijkl} – components of round modules matrix.

Model (1)-(7) allows us to estimate the change in the stress-strain state at the coordinates change of the pipeline inner surface points.

In places of curved sections of pipelines, bell-shaped bends, the pipeline undergoes particularly significant erosion wear resulting in a decrease in wall thickness.

When modeling the stress state of pipeline sections with variable cross-section shape (erosion or corrosion wear of the wall), the problem of stress-strain state estimation is solved in a cylindrical coordinate system with the following assumptions;

$$\begin{cases} x = r\cos\varphi & 0 \le \varphi \le 2\pi \\ y = r\sin\varphi & R_{вн} \le r \le R_{ex} \\ z = s & 0 \le s \le L \end{cases} \quad (8)$$

for which the Christopheles symbols of type II [17] have only two non-zero components: $\Gamma^1_{22} = -r;\ \Gamma^2_{12} = \Gamma^2_{21} = \frac{1}{r}$. In this case, assumptions are made for the components of the displacement vector:

$$\begin{cases} \omega_1 = \omega(r,\theta) \\ \omega_2 = v(r,\theta) \\ \omega_3 = 0 \end{cases} . \quad (9)$$

The nonzero components of the strain tensor will be as follows:

$$\begin{cases} \varepsilon_{11} = \frac{\partial \omega}{\partial r};\ \varepsilon_{22} = \frac{\partial v}{\partial \theta} + \omega r;\ \varepsilon_{33} = 0;\ \varepsilon_{13} = 0 \\ \varepsilon_{12} = \frac{1}{2}\left(\frac{\partial v}{\partial r} + \frac{\partial \omega}{\partial \theta} - 2v\frac{1}{r}\right);\ \varepsilon_{23} = 0 \end{cases} . \quad (10)$$

In this case, the system of equilibrium equations within the linear theory of torsion to determine the components takes the following form:

$$\begin{cases} (\lambda+2\mu)\left(\frac{\partial^2\omega}{\partial r^2} + \frac{1}{r}\frac{\partial\omega}{\partial r} - \frac{\omega}{r^2}\right) - \lambda\left[\frac{\partial v}{\partial\theta}\frac{2}{r^3} - \frac{1}{r}\frac{\partial^2 v}{\partial r^2}\right] + \mu\left[\frac{\partial^2 v}{\partial r\partial\theta}\frac{1}{r^2} + 2\frac{\partial^2\omega}{\partial\theta^2}\frac{1}{r^2} - \frac{4}{r^3}\frac{\partial\omega}{\partial\theta} - 2\frac{\partial v}{\partial\theta}\frac{1}{r^4}\right] = 0 \\ -4\mu\left[\frac{1}{2}\left(\frac{\partial v}{\partial r} + \frac{\partial\omega}{\partial\theta} - 2\frac{v}{r}\right)\frac{1}{r^3}\right] + \frac{2\mu}{r^2}\left[\frac{1}{2}\left(\frac{\partial^2 v}{\partial r^2} + \frac{\partial^2\omega}{\partial\theta^2} - 2\frac{\partial v}{\partial r}\frac{1}{r} - \frac{2v}{r^2}\right)\right] + \\ +2\mu\left(\frac{1}{2}\frac{\partial^2 v}{\partial r\partial\theta} + \frac{\partial^2\omega}{\partial r\partial\theta} - \frac{2}{r}\frac{\partial v}{\partial r}\right)\frac{1}{r^2} + \frac{3\mu}{r^3}\left(\frac{\partial v}{\partial r} + \frac{\partial\omega}{\partial\theta} - \frac{2v}{r}\right) = 0 \end{cases} . \quad (11)$$

With boundary conditions:

$$\begin{cases} \sigma^{22}\big|_{r=R_{in}} = P_{in} \\ \sigma^{22}\big|_{r=R_{ex}} = P_{ex} \end{cases} , \quad (12)$$

where P_{in}, P_{ex} – internal and external pressure respectively.

In the same way, a coordinate system is introduced for the pipelines with the following relations:

$$\begin{cases} x = (R + r\cos\varphi)\cos\theta \\ y = (R + r\cos\varphi)\sin\theta \\ z = r\sin\varphi \end{cases} , \quad (13)$$

where R – bending radius of toroidal bend.

Formulas of Christopher type II are defined as follows:

$$\begin{cases} \Gamma^1_{33} = \cos\theta(R - r\cos\theta);\ \Gamma^1_{22} = -r;\ \Gamma^2_{12} = \Gamma^2_{21} = \frac{1}{r} \\ \Gamma^2_{33} = -\frac{\sin\theta(R - r\cos\theta)}{r};\ \Gamma^3_{13} = -\frac{\cos\theta}{R - r\cos\theta} \\ \Gamma^3_{23} = \frac{r\sin\theta}{R - r\cos\theta} \end{cases} . \quad (14)$$

The nonzero components of the strain tensor are as follows:

$$\begin{cases} \varepsilon_{11} = \dfrac{\partial u}{\partial r}; \varepsilon_{22} = \dfrac{\partial v}{\partial \theta} + ur \\ \varepsilon_{33} = -u\cos\theta(R - r\cos\theta) + v\dfrac{\sin\theta(R - r\cos\theta)}{r} \\ \varepsilon_{12} = \dfrac{1}{2}\dfrac{\partial v}{\partial r} + \dfrac{1}{2}\dfrac{\partial u}{\partial \theta} - \dfrac{v}{r} \end{cases} \quad (15)$$

within the assumption:

$$\begin{cases} u = u(r,\theta) \\ v = v(r,\theta) \\ \omega = 0 \end{cases}. \quad (16)$$

In this case, the system of equilibrium equations considering the components $u(r,\theta)$; $v(r,\theta)$ is written as follows:

$$\begin{cases} (\lambda + 2\mu)\left[\dfrac{\partial^2 u}{\partial r^2} + \dfrac{\partial u}{\partial r}\dfrac{1}{r} - \dfrac{u}{r^2}\right] + \dfrac{\partial^2 u}{\partial \theta^2}\mu\dfrac{1}{r^2} + \dfrac{\partial^2 v}{\partial r \partial \theta}\left(\lambda\dfrac{1}{r^2} + \mu\dfrac{1}{r^2}\right) + (\lambda + 2\mu)\dfrac{\partial u}{\partial r}\dfrac{\cos\theta}{(R - r\cos\theta)} + \\ + \mu\dfrac{\partial u}{\partial \theta}\dfrac{\sin\theta}{r(R - r\cos\theta)} + \dfrac{\partial v}{\partial r}(\lambda + 2\mu)\dfrac{\sin\theta}{r(R - r\cos\theta)} - 2\dfrac{\partial v}{\partial \theta}(\lambda + 2\mu)\cdot\dfrac{1}{r^3} + \\ + u\left(-\dfrac{1}{r^2}(\lambda + 2\mu) - (\lambda + 2\mu)\dfrac{\cos^2\theta}{(R - r\cos\theta)^2}\right) + v\left[(\lambda + 2\mu)\dfrac{\sin\theta\cos\theta}{r(R - r\cos\theta)^2} - \dfrac{\sin\theta(\lambda + 2\mu)}{r^2(R + r\cos\theta)}\right] = 0 \\ \dfrac{\partial^2 u}{\partial r \partial \theta}(\lambda + \mu)\dfrac{1}{r^2} + \dfrac{\partial^2 v}{\partial r^2}\mu\dfrac{1}{r^2} + (\lambda + 2\mu)\dfrac{\partial^2 v}{\partial \theta^2}\dfrac{1}{r^4} + \dfrac{\partial u}{\partial \theta}\left(3\mu\dfrac{1}{r^3} + \lambda\dfrac{1}{r^3} - \dfrac{(\lambda + \mu)\cos\theta}{r^2(R + r\cos\theta)}\right) + \\ + \dfrac{\partial v}{\partial r}\left(-\mu\dfrac{1}{r^3} - \mu\dfrac{1}{r^2}\dfrac{\cos\theta}{R - r\cos\theta}\right) + (\lambda + 2\mu)\dfrac{\partial v}{\partial \theta}\dfrac{\sin\theta}{r^3(R - r\cos\theta)} + u\left((\lambda + \mu)\dfrac{1}{r^2}\dfrac{R\sin\theta}{(R - r\cos\theta)^2}\right) + \\ + \dfrac{v(\lambda + 2\mu)}{r^3}\dfrac{R\cos\theta - r}{(R - r\cos\theta)^2} = 0 \end{cases} \quad (17)$$

with boundary conditions similar to (12). The numerical solution of systems (11) and (17) requires considerable computational effort, however, for the practical solution of them it is possible to accept the assumption that $R \to \infty$ $v << u$; $\dfrac{\partial v}{\partial \theta}$; $\dfrac{\partial^2 v}{\partial \theta^2}$; $\dfrac{\partial u}{\partial \theta}$; $\dfrac{\partial^2 u}{\partial \theta^2}$; $\dfrac{\partial^2 u}{\partial \theta \partial r}$; $\dfrac{\partial^2 v}{\partial \theta \partial r} << u$; $\dfrac{\partial u}{\partial r}$; $\dfrac{\partial^2 u}{\partial r^2}$, which leads to the conclusion that system (17) degenerates into one equation (first application of system (17), first equation):

$$\frac{\partial^2 u}{\partial r^2} + \frac{\partial u}{\partial r}\frac{1}{r} - \frac{u}{r^2} = 0, \quad (18)$$

which is the basic equation of the Lamé problem [19].

II. Results

Taking into account the above hypothesis that with the reduction of the thickness of the pipeline wall as a result of erosion or corrosion wear, the configuration of the cross-section is slightly different from the circular one and the calculation of the nomination ring stresses that arise in the bend wall from the action of internal pressure can be performed by the formula:

$$\sigma_{cs}^{n} = \frac{P_{in}R_{ex}}{\delta(\theta)}, \quad (19)$$

where $\delta(\theta)$ – the wall thickness of the pipe bend, depending on the polar angle (рис. 2):

$$\delta(\theta) = R_{ex} - R_{in}(\theta), \quad (20)$$

where $R_{in}(\theta)$ – internal radius of pipeline bend, subject to change as a result of erosion or corrosion worn wall (Fig. 2).

If the corrosion occurs in the outer wall of the bend then:

$$\delta(\theta) = R_{ex}(\theta) - R_{in}, \quad (21)$$

where $R_{ex}(\theta)$ – external radius of pipeline bend, subject to change as a result of erosion or corrosion worn wall.

Formula (19) is an integral focus of the more general formula [18]:

$$\sigma_{cs}^{n} = \frac{R_{in}^2(\theta)P_{in}}{R_{ex}^2 - R_{in}^2(\theta)}\left(1 + \frac{R_{ex}^2}{r^2}\right) - \frac{R_{ex}^2 P_{ex}}{R_{ex}^2 - R_{in}^2(\theta)}\left(1 + \frac{R_{in}^2(\theta)}{r^2}\right), \quad (22)$$

Whereas $P_{in} >> P_{ex}$ then it can be accepted that $P_{ex} = 0$.

The results of the calculations show that the pipeline bend with an outside diameter $D = 1420$ mm and nominal wall thickness $\delta_n = 24$ mm at pressure $P = 5$ MPa reduction of wall thickness by 6 mm as a result of erosion or corrosion wear leads to an increase in nomination ring stresses by 34%, which does not pose a threat to the durability of the pipeline (Fig. 3).

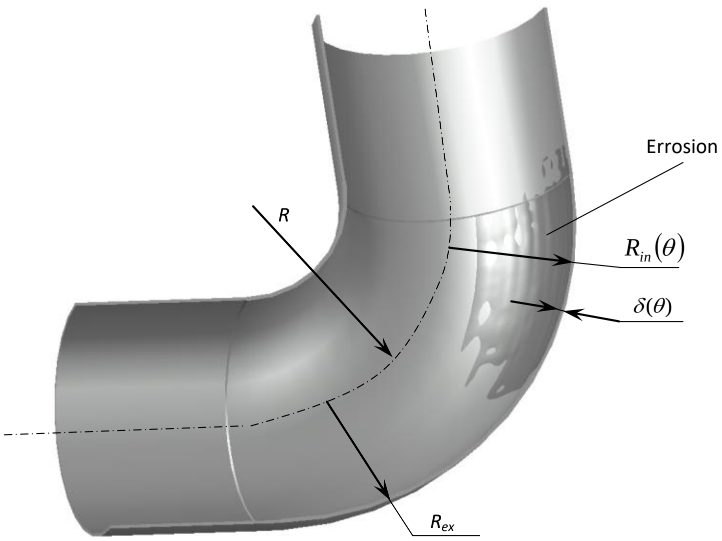

Fig. 2. Calculation scheme of erosion-worn bend.

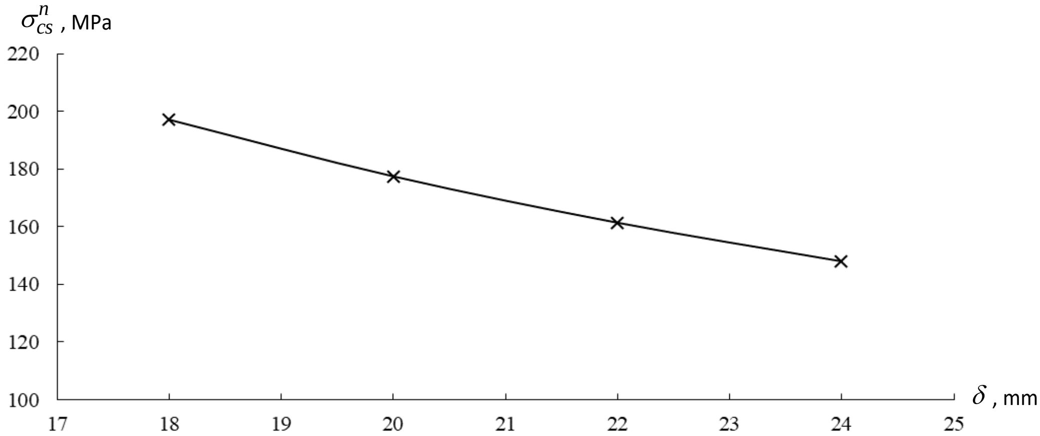

Fig. 3. The change in nomination ring stresses in the pipeline bend wall is caused by its erosion or corrosion wear.

III. Discussion and conclusion

Assuming the elastic nature of the stresses in the pipeline material, a complex estimation of the stresses can be carried out on the principle of superposition of solutions to the problems of elasticity theory [18]:

$$\tilde{\sigma}_g = \tilde{\sigma} + \tilde{\sigma}_{cs}, \qquad (23)$$

where $\tilde{\sigma}_g$ – general stress tensor; $\tilde{\sigma}$ – stress tensor calculated by the algorithm (1)-(7); $\tilde{\sigma}_{cs}$ – stress tensor calculated by (21) taking into account the change in wall thickness as a result of erosion or corrosion wear.

When constructing the tensor using (1)-(7), it is necessary to involve the interpolation apparatus with smoothing interpolation cubic splines in order to eliminate the influence of inaccuracies caused by the error of measurements of the displacements of the points of the upper generating tube by instrumental geodetic methods. [14, 6].

The advantage of formula (19) is its simplicity in comparison with other methods, which makes it possible to determine the nomination ring stresses quickly in the wall of erosion or corrosion worn rectilinear sections of pipelines, pipeline bends and to evaluate their strength. The use of (19) is limited by the assumption that erosion or corrosion wear results in a cross-sectional configuration of the pipe that is slightly different from the circular one, which was adopted to solve systems (11) and (17), and therefore this formula can be used when the magnitude of erosion or corrosion wear is not more than half the pipe wall thickness. Further studies are planned towards assessing the technical condition of pipelines bend with significant wall defects.

When evaluating the nomination ring stresses according to formulas and approaches (19)–(22), taking into account the erosion or corrosion wear of the pipeline taps, it is established that if the wall thickness decreases by 6 mm, the nomination ring stresses increase by 34 %, which will not lead to the loss of the pipeline strength.

The obtained results are tested by comparing them with the results of three-dimensional modeling of the stress state of the bends of the main gas pipelines in the software complex ANSYS Fluent R18.2 Academic, taking into account the complex three-dimensional geometric shape of the erosion defects of the wall and the results of the experimental measurement of the wall thickness of the bends and the measurements of the magnitudes of the gas pipelines. Almost 90 % of the similarities obtained with these three methods were found.

Further studies may be related to the modeling of stress-strain state of erosion-corrosion worn tees and pipeline fittings.

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Моделювання напружено-деформованого стану ерозійно- корозійно зношених трубопровідних систем

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Задачі моделювання напружено-деформованого стану ерозійно чи корозійно зношених прямолінійних ділянок та тороподібних відводів трубопровідних систем запропоновано розв’язувати в циліндричній системі координат. Для цього записано формули Кристофеля II роду, ненульові компоненти тензора деформацій та систему рівнянь рівноваги в рамках лінійної теорії крученості. Систему рівнянь рівноваги зведено до одного рівняння, яке є основним рівнянням задачі Ламе. Виведено формули для розрахунку кільцевих напружень, які виникають у стінці ерозійно чи корозійно зношених прямолінійних ділянок, відводів трубопроводів від дії внутрішнього тиску. Визначено вплив зміни товщини стінки відводів трубопроводів в місці їх ерозійного чи корозійного зношення на величину кільцевих напружень.

Ключові слова: кільцеві напруження, ерозія, корозія, відвід трубопроводу, внутрішній тиск, циліндрична система координат.