Research of the influence of the kinetics of a hydrogen-containing medium on the stress-strain state of a cylindrical shell made of titanium alloy

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Abstract. This paper considers a mathematical model of the stress-strain state of a circular cylindrical shell made of titanium alloy VT1-0, operating in an aggressive hydrogen-containing environment. The shell is under the action of an internal evenly distributed pressure. To formulate the problem and carry out calculations, a model with triple nonlinearity is used, formulated within the approach associated with normalized stress spaces. The resulting algorithm for solving the problem of studying the effect of an aggressive medium on titanium alloy shells effectively takes into account the substantially nonlinear change in the parameters of the stress-strain state depending on the time factor. In the study, a system of nonlinear resolving equations for calculating the shell was formulated, results were obtained for the key parameters of the effect of a hydrogen medium on the stress-strain state of a cylindrical shell, taking into account embrittlement.

1 Introduction

Titanium alloys, initially not showing sensitivity to the type of stress state, in the process of saturation with hydrogen exhibit an induced dependence of deformation and strength characteristics on the type of stress state with inhomogeneity along the directions of the gradient effect of the medium. The effect of induced and time-varying resistivity must be taken into account when calculating structural elements made of titanium alloys operating in an aggressive hydrogen-containing environment.

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In works [1 – 3] Ovchinnikov I.G. is recommended to present a model of a structure interacting with an aggressive environment in the form of a combination of the following elements: a model of a structural element, a model of a material, a model of the effect of the environment and a limiting state. Using this approach, here we study the stress-strain state of a circular cylindrical shell made of VT1-0 titanium alloy, taking into account hydrogen embrittlement.

Earlier, in a number of studies it was proposed to apply the theory of structural parameters of Rabotnov Yu.N. [4, 5], taking into account the physicochemical effects on the surface and in the volume of the deformable material. With regard to the problem under consideration, this theory has a number of drawbacks, in particular, it does not take into account the triple nonlinearity and the effect of induced differential resistance. Therefore, in this work, it was proposed to use a refined nonlinear mathematical model to solve the problem of the effect of an aggressive hydrogen-containing medium on the deformation processes of a cylindrical shell loaded from the inside by a uniformly distributed pressure, as well as by a medium acting on the inner surface of the shell.

2 Theoretical part

Consider the equilibrium of a thin-walled circular cylindrical shell made of VT1-0 titanium alloy, loaded with internal pressure increasing to 5 MPa, rigidly clamped along the ends of the cylinder. The shell length is 4 m, the radius is 0.6 m, and the thickness is 0.05 m. In this problem, the Lamé parameters and the main curvatures have values:

$$\mathrm{A} = 1; \quad \mathrm{B} = \mathrm{R}; \quad \mathrm{k}_1 = 0; \quad \mathrm{k}_2 = \mathrm{R}^{-1} \tag{1}$$

where R – radius of the middle surface of the shell.

The position of an arbitrary point of the middle surface of a cylindrical shell is determined by Gaussian coordinates α_1 and α_2, taking into account: u – axial, ϑ – district, w – radial displacements (deflections) under the influence of a transverse load q, according to the figure 1.

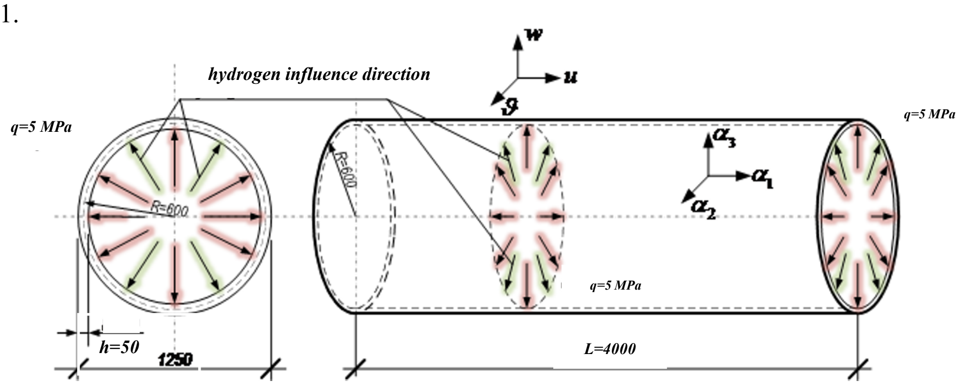

Fig. 1. Statement of the problem.

We write the kinetic potential of deformations in the form [6, 7]:

$$W_1 = (A_e(\lambda) + B_e(\lambda)\xi)\sigma^2 + (C_e(\lambda) + D_e(\lambda)\xi + E_e(\lambda)\eta Cos3\phi)\tau^2 + \\ +[(A_p(\lambda) + B_p(\lambda)\xi)\sigma^2 + (C_p(\lambda) + D_p(\lambda)\xi + E_p(\lambda)\eta Cos3\phi)\tau^2]^n, \tag{2}$$

where $A_e(\lambda)$, $B_e(\lambda)$, $A_p(\lambda)$, $B_p(\lambda)$, – are functions of the quasilinear and nonlinear parts of the kinetic potential, depending on the hydrogen concentration and describing the mechanical properties of the alloy, which are determined by interpolating the coefficients at a fixed level of hydrogen saturation λ (λ – percentage of hydrogen content in the medium); $\sigma = \sigma_{ij}\delta_{ij}/3$ – medium or normal octahedral stress; $\tau = (S_{ij}S_{ij}/3)^{1/2}$ – tangential octahedral stress; δ_{ij} – Kronecker symbol; $S_{ij} = \sigma_{ij} - \delta_{ij}\sigma$ – stress deviator ($i,\ j = 1,\ 2,\ 3$); $\xi = cos\,\psi = \sigma/S_0$ – normal octahedral normalized stress; $\eta = sin\,\psi = \tau/S_0$ – tangential octahedral normalized stress; $cos\,3\,\phi = \sqrt{2}\,det(S_{ij})/\tau^3$ – phase invariant; $S_0 = \sqrt{\sigma^2 + \tau^2}$ – the norm of the vector space associated with the octahedral area or the modulus of the total stress vector on it.

For titanium alloy VT1-0 material functions can be defined as follows [6, 7]:

$$
\begin{gathered}
V_{ek}(\lambda) = e_{0k} + e_{1k}\cdot\lambda + e_{2k}\cdot\lambda^2;\\
V_{pk}(\lambda) = p_{0k} + p_{1k}\cdot(p_{2k})^{\lambda};\\
A_e(\lambda) = V_{e1}(\lambda);\ B_e(\lambda) = V_{e3}(\lambda);\ C_e(\lambda) = V_{e2}(\lambda);\ D_e(\lambda) = V_{e4}(\lambda);\\
E_e(\lambda) = V_{e5}(\lambda); A_p(\lambda) = V_{p1}(\lambda);\ B_p(\lambda) = V_{p3}(\lambda);\\
C_p(\lambda) = V_{p2}(\lambda);\ D_p(\lambda) = V_{p4}(\lambda);\ E_p(\lambda) = V_{p5}(\lambda),
\end{gathered} \tag{3}
$$

where e_{ik}, p_{ik} – polynomial coefficients i = 0…2; k = 1...5.

The numerical values of these parameters at a fixed value of the degree of saturation of hydrogen are presented in the table 1.

Table 1. Numerical values.

Constants	**Titanium alloy VT1-0**		
	λ= 0%	**λ=0,01%**	**λ= 0,03%**
Ae, MPa-1	4,775·10-6	4,327·10-6	4,771·10-6
Ce, MPa-1	1,750·10-5	1,586·10-5	1,749·10-5
Be, MPa-1	0	2,008·10-7	1,516·10-9
De, MPa-1	0	-2,151·10-6	-1,625·10-8
Ee, MPa-1	0	-8,318·10-7	-6,281·10-9
Ap, MPa(1-2n) n	4,448·10-6	5,685·10-6	6,487·10-6
Cp, MPa(1-2n) n	1,631·10-5	2,084·10-5	2,378·10-5
Bp, MPa(1-2n) n	0	-5,556·10-7	-9,155·10-7
Dp, MPa(1-2n) n	0	5,953·10-6	9,809·10-6
Ep, MPa(1-2n) n	0	2,301·10-6	3,791·10-6

The relationship between stresses and strains can be obtained by applying to the strain potential (2), according to [8, 9], Castigliano's formulas:

$$
\gamma_{ij} = \frac{\partial W_1}{\partial \tau_{ij}};\quad \mathrm{e}_{kk} = \frac{\partial W_1}{\partial \sigma_{kk}};\quad (i, j, k = 1,2,3, i \neq j). \tag{4}
$$

In accordance with Kirchhoff's hypotheses for cylindrical shells [9] in conditions of large deflections, we obtain the following geometric relations:

a) deformation components in the median surface:

$$
\begin{gathered}
\varepsilon_1 = u_{,1} + 0{,}5\theta_1^2\\
\varepsilon_2 = \vartheta_{,2} + k_2 w + 0{,}5\theta_2^2\\
\gamma_{12} = \vartheta_{,1} + u_{,2} + \theta_1\theta_2
\end{gathered} \tag{5}
$$

where ε_1, ε_2 – axial relative deformations in the middle surface; γ_{12} – shear deformations in this surface; u – axial displacements along the generating surface; ϑ – circumferential displacements; w – radial displacements under the load q; $\theta_1,\ \theta_2$ – the angles of rotation of the normal to the middle surface, calculated as follows: $\theta_1 = -w_{,1}$; $\theta_2 = -w_{,2} + k_2\vartheta$

b) the component of the bending deformation of the middle surface depends on the displacements as follows:

$$\chi_1 = -w,_{11}\,; \quad \chi_2 = -w,_{22}\,; \quad \chi_{12} = -w,_{12} = -w,_{21}, \qquad (6)$$

where χ_1, χ_2 – curvatures, χ_{12} – torsion.
The values of deformations at an arbitrary point of the shell, spaced at a distance α_3 from the middle surface, are presented as the sum of the deformations of the middle surface and bending deformations:

$$e_{11} = \varepsilon_1 + \alpha_3\chi_1;\, e_{22} = \varepsilon_2 + \alpha_3\chi_2;\, \gamma_{12} = \gamma + 2\alpha_3\chi_{12}., \qquad (7)$$

where α_3 – is coordinate along the thickness of the shell, measured from the middle surface.

Due to the axial symmetry of the problem and taking into account the fact that the shell is under uniformly distributed internal pressure q, geometric relations are simplified and takes the form:

$$\varepsilon_1 = u,_1 + 0{,}5(w,_{11})^2;\;\; \varepsilon_2 = k_2 w;\, \chi_1 = -w,_{11}\,;\;\; e_{11} = \varepsilon_1 + \alpha_3\chi_1;\;\; e_{22} = \varepsilon_2. \quad (8)$$

Applying Castigliano's formulas (4) to the strain potential W_1 (2), the dependence of deformations on stresses is obtained in the following form:

$$\begin{Bmatrix} e_{11} \\ e_{22} \end{Bmatrix} = [A]\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \end{Bmatrix};\;\; [A] = \begin{bmatrix} A_{11}(\lambda) & A_{12}(\lambda) \\ A_{21}(\lambda) & A_{22}(\lambda) \end{bmatrix}. \qquad (9)$$

Inverting the relations (9), the correlation of stresses from deformations is obtained:

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \end{Bmatrix} = [B]\begin{Bmatrix} e_{11} \\ e_{22} \end{Bmatrix};\;\; [B] = \begin{bmatrix} B_{11}(\lambda) & B_{12}(\lambda) \\ B_{21}(\lambda) & B_{22}(\lambda) \end{bmatrix}, \qquad (10)$$

where $[B] = [A]^{-1}$. Here A11, A12, – components of the symmetric compliance matrix [A], which are functions of the degree of gas saturation λ. These components are defined as follows:

$$A_{11}(\lambda) = \{2[R_1(\lambda) + 2R_3(\lambda)]/3 + R_2(\lambda)\xi(3 - 2\xi^2)/3 + R_4(\lambda)[\xi(2 - \eta^2)/3 +$$
$$+4(\sigma_{11} - 2\sigma_{22})/9S_0] + R_5(\lambda)[\eta Cos3\phi(1 + \xi^2) + 2\sqrt{2}\xi - 2Cos3\phi - \sqrt{2}\sigma_{22}/S_0]\}/3;$$
$$A_{12}(\lambda) = \{2[R_1(\lambda) - R_3(\lambda)]/3 + [R_2(\lambda) + R_4(\lambda)/3]\xi + R_5(\lambda)[Cos3\phi(1 - \eta) -$$
$$\sqrt{2}\xi]\}/3;\, A_{12}(\lambda) = A_{21}(\lambda);\, A_{22}(\lambda) = \{2[R_1(\lambda) + 2R_3(\lambda)]/3 + R_2(\lambda)\xi(3 - 2\xi^2)/3 +$$
$$R_4(\lambda)[\xi(2 - \eta^2) + +4(\sigma_{22} - 2\sigma_{11})/9S_0] + R_5(\lambda)[\eta Cos3\phi(1 + \xi^2) + 2\sqrt{2}\xi -$$
$$2Cos3\phi - \sqrt{2}\sigma_{22}/S_0]\}/3;\, R_k(\lambda) = L_{ek}(\lambda) + n[(A_p(\lambda) + B_p(\lambda)\xi)\sigma^2 + \big(C_p(\lambda) +$$
$$D_p(\lambda)\xi + E_p(\lambda)\eta\cos 3\phi\big)\tau^2]^{n-1}L_{pk}(\lambda);\, L_{m1}(\lambda) = A_m(\lambda);\, L_{m2}(\lambda) = B_m(\lambda);\, L_{m3}(\lambda) =$$
$$C_m(\lambda);\, L_{m4}(\lambda) = D_m(\lambda);\, L_{m5}(\lambda) = E_m(\lambda);\, m = e, p;\, k = 1\ldots5.$$

By integrating stresses (10) over the thickness, it is possible to determine the forces and moments using standard formulas:

$$N_1 = \int_{-h/2}^{h/2}\sigma_{11}d\alpha_3\,;\;\; N_2 = \int_{-h/2}^{h/2}\sigma_{22}d\alpha_3\,; \qquad (11)$$

$$M_1 = \int_{-h/2}^{h/2}\sigma_{11}\alpha_3 d\alpha_3\,;\quad M_2 = \int_{-h/2}^{h/2}\sigma_{22}\alpha_3 d\alpha_3\,; \qquad (12)$$

Having described the force coefficients by deformations, the following expressions can be obtained:

$$N_1 = K_{11}(\lambda)\varepsilon_1 + K_{12}(\lambda)\varepsilon_2 + P_{11}(\lambda)\chi_1;\ N_2 = K_{12}(\lambda)\varepsilon_1 + K_{22}(\lambda)\varepsilon_2 + P_{21}(\lambda)\chi_1; \quad (13)$$

$$M_1 = P_{11}(\lambda)\varepsilon_1 + P_{12}(\lambda)\varepsilon_2 + D_{11}(\lambda)\chi_1;\ M_2 = P_{12}(\lambda)\varepsilon_1 + P_{22}(\lambda)\varepsilon_2 + D_{21}(\lambda)\chi_1, \quad (14)$$

where:

$$K_{ij} = \int_{-h/2}^{h/2} B_{ij}(\lambda)d\alpha_3;\ \ P_{ij} = \int_{-h/2}^{h/2} B_{ij}(\lambda)\alpha_3 d\alpha_3;\ \ D_{ij} = \int_{-h/2}^{h/2} B_{ij}(\lambda)\alpha_3^2 d\alpha_3. \quad (15)$$

Due to the presence of triple nonlinearity in the problem, the resolving equations can be written in linearized form using the two-step method of sequential perturbations of the parameters of V.V. Petrov [10 – 12]. Physical dependencies in linearized form will be presented in the following form:

$$\delta e_{11} = \frac{\partial e_{11}}{\partial \sigma_{11}}\delta\sigma_{11} + \frac{\partial e_{11}}{\partial \sigma_{22}}\delta\sigma_{22};\ \ \delta e_{22} = \frac{\partial e_{22}}{\partial \sigma_{11}}\delta\sigma_{11} + \frac{\partial e_{22}}{\partial \sigma_{22}}\delta\sigma_{22}; \quad (16)$$

Inverting relations (16), it is possible to obtain the relationship between stresses and deformations in increments:

$$\delta\sigma_{11} = B_{11}(\lambda)\delta e_{11} + B_{12}(\lambda)\delta e_{22};\ \ \delta\sigma_{22} = B_{21}(\lambda)\delta e_{11} + B_{22}(\lambda)\delta e_{22},$$

where $B_{11}(\lambda) = \frac{\Delta_{22}}{\Delta}$; $B_{12}(\lambda) = B_{21}(\lambda) = -\frac{\Delta_{21}}{\Delta} = -\frac{\Delta_{12}}{\Delta}$; $B_{22}(\lambda) = \frac{\Delta_{11}}{\Delta}$; $\Delta_{11} = \frac{\partial e_{11}}{\partial \sigma_{11}}$; $\Delta_{22} = \frac{\partial e_{22}}{\partial \sigma_{22}}$; $\Delta_{12} = \Delta_{21} = \frac{\partial e_{11}}{\partial \sigma_{22}} = \frac{\partial e_{22}}{\partial \sigma_{11}}$; $\Delta = \Delta_{11}\Delta_{22} - \Delta_{12}\Delta_{21}$; $\delta\varepsilon_1 = \delta u_{,1} + w_{,1}\,\delta w_{,1}$; $\delta\varepsilon_2 = k_2\delta w$; $\delta\chi_1 = -\delta w_{,11}$; $\delta e_{11} = \delta u_{,1} + w_{,1}\,\delta w_{,1} - \alpha_3\delta w_{,11}$; $\delta e_{22} = k_2\delta w$

The problem is considered, in which the process of the impact of an aggressive external hydrogen medium on the shell is completed. Consequently, the concentration distribution of a hydrogen-containing medium in a solid can be considered steady and expressions (16) will not contain increments in value λ [13]. This is necessary when hydrogen saturation is accompanied by an increase in the load and, as a consequence, an increase in tensile stresses. The equations for the connection of forces with deformations of the middle surface in increments are transformed to the form:

$$\delta N_1 = K_{11}(\lambda)\delta\varepsilon_1 + K_{12}(\lambda)\delta\varepsilon_2 + P_{11}(\lambda)\delta\chi_1;$$
$$\delta N_2 = K_{12}(\lambda)\delta\varepsilon_1 + K_{22}(\lambda)\delta\varepsilon_2 + P_{21}(\lambda)\delta\chi_1; \quad (17)$$

$$\delta M_1 = P_{11}(\lambda)\delta\varepsilon_1 + P_{12}(\lambda)\delta\varepsilon_2 + D_{11}(\lambda)\delta\chi_1;$$
$$\delta M_2 = P_{12}(\lambda)\delta\varepsilon_1 + P_{22}(\lambda)\delta\varepsilon_2 + D_{21}(\lambda)\delta\chi_1, \quad (18)$$

The axial symmetry of the problem under consideration obviously makes it possible to simplify the equilibrium equations in increments, which in this case can be written as:

$$\delta N_{1,1} = 0;\ \delta M_{1,1} - \delta Q_1 + w_{,1}\,\delta N_1 + N_1\delta w_{,1} = 0;\ \delta Q_{1,1} - k_2\delta N_2 + \delta q = 0 \quad (19)$$

Due to the axisymmetricity of the task, there is no horizontal force in the cylindrical shell if it is not applied at the boundaries, therefore, $N_1 = 0$. From here we have $\delta Q_1 = \delta M_{1,1}$ and as a result, we come to two equilibrium equations. Integrating expressions (17) for stresses over the thickness of the shell according to formulas (11), (12) and substituting the result into the equilibrium equations, we obtain a system of two differential resolving equations in linearized form:

$$K_{11}(\lambda)_{,1}(\delta u_{,1}+w_{,1}\delta w_{,1})+K_{11}(\lambda)(\delta u_{,11}+w_{,11}\delta w_{,1}+w_{,1}\delta w_{,11})+K_{12}(\lambda)_{,1}k_2\delta w+ K_{12}(\lambda)k_2\delta w_{,1}-P_{11}(\lambda)_{,1}\delta w_{,11}-P_{11}(\lambda)\delta w_{,111}=0, \quad (20)$$

$$P_{11}(\lambda)_{,11}(\delta u_{,1}+w_{,1}\delta w_{,1})+2P_{11}(\lambda)_{,1}(\delta u_{,11}+w_{,11}\delta w_{,1}+w_{,1}\delta w_{,11})+ +P_{11}(\lambda)(\delta u_{,111}+w_{,111}\delta w_{,1}+2w_{,11}\delta w_{,11}+w_{,1}\delta w_{,111})+P_{12}(\lambda)_{,11}k_2\delta w+ 2P_{12}(\lambda)_{,1}k_2\delta w_{,1}+P_{12}k_2\delta w_{,11}-D_{11}(\lambda)_{,11}\delta w_{,11}-2D_{11}(\lambda)_{,1}\delta w_{,111}-D_{11}(\lambda)\delta w_{,1111}- -k_2[K_{12}(\lambda)(\delta u_{,1}+w_{,1}\delta w_{,1})+K_{22}(\lambda)k_2\delta w-P_{12}(\lambda)\delta w_{,11}]+\delta q=0. \quad (21)$$

The resulting gradient system of equations (20-21) is supplemented with boundary conditions in increments, in particular, the conditions for pinching the cylinder along the ends (considering the axial symmetry of the problem):

- at the end of the cylinder with the coordinate L=0 м: $\delta w=0; \delta w_{,1}=0, \delta u=0;$
- at the end of the cylinder with the coordinate L=4 м: $\delta w=0; \delta w_{,1}=0, \delta u=0.$

Chemical adsorption is characterized by the decomposition of hydrogen into atoms, which then penetrate into the thickness of the material. [2]. In accordance with the experiments, the results of which are given in [14], it was concluded that for small differences in the hydrogen concentration in the medium, it is possible to apply Fick's first law, which states that the amount of substance penetrating through the cross section perpendicular to the direction of diffusion is strictly proportional to the following quantities: the concentration gradient of the substance in this section, the cross-sectional area and the time of the diffusion process:

$$J=-Dgrad(\lambda)=-D\frac{\partial\lambda}{\partial\alpha_3}, \quad (22)$$

where D – diffusion constant, α_3 – coordinate in the direction of diffusion.
In the problem under consideration, the physically active medium is in contact with the shell only along the upper or lower surface, which leads to the one-dimensionality of the diffusion process. For titanium alloys, the concentration does not affect the diffusion coefficient; therefore, the second law [15] follows from Fick's first law (22) in the form:

$$\frac{\partial\lambda(\alpha_3,t)}{\partial t}=D\frac{\partial^2\lambda(\alpha_3,t)}{\partial\alpha_3^2}, \quad (23)$$

where t – current time.

As can be seen from expression (23), the rate of the diffusion process in time depends only on the constant D. For one-sided diffusion, the solution to equation (23) is known and has the form:

$$\lambda(\alpha_3,t)=\lambda_1+(\lambda_2-\lambda_1)\alpha_3/h+(2/\pi)\sum_{i=1}^{\infty}sin(i\cdot\pi\cdot\alpha_3/h)\,exp(-F_0\pi^2i^2)\times[\lambda_2 cos(i\cdot\pi)-\lambda_1]/i, \quad (24)$$

where $F_0=Dt/h^2$ – Fourier number; i – number of members; λ_1 and λ_2 – edge values of the concentration of the medium on the opposite surfaces of the shell; h – thickness of shell.
The boundary conditions are presented as follows under the influence of the medium from the side of application of the transverse force load:

$$\lambda(-h/2,\ t) = \lambda_\infty = \lambda_1,\ \ \lambda(+h/2,\ t) = 0 = \lambda_2, \qquad (25)$$

where λ_∞ – equilibrium concentration of a hydrogen-containing medium.

The initial conditions take the form:

$$\lambda(z,\ 0) = 0 \qquad (26)$$

3 Solution of the model problem

The calculations were carried out using specially developed computational procedures built using the universal mathematical packages Maple and MATLAB similar to [16]. The figures below show the results of calculating a cylindrical shell operating in an aggressive hydrogen environment at different concentrations from 0 to 0.08%, using the model proposed by the authors.

4 Results and its discussion

As a result of solving the problem, it was reliably established that the effect of hydrogen leads to a significant change in the mechanism of behavior of the material and, consequently, to a significant change in the parameters characterizing the stress state in the shell, and therefore, in comparison with the initial state without exposure to a hydrogen-containing medium, in compressed stresses change by up to 10% in fibers, and up to 85% in stretched fibers. This approach uses a rather flexible mechanism for taking into account a variety of stress states and demonstrates a high accuracy of agreement between the results obtained and experimental data on the deformation of a wide range of materials under complex types of stress states. Initially, taking into account the influence of the type of stress state was most effectively applied in works [8, 9], on the basis of which a model was developed for accounting for induced differential resistance, since for most materials even the initial differential resistance is taken into account with high accuracy, therefore this mechanism is also applicable for induced differential resistance, which is shown in papers [8, 9].

As a practical applicability of the data obtained, we give an example of the operation of a heat exchanger.

For ground tests, the methods described in the study [9, 19] are suitable. There are three cooling methods: air jet cooling, water jet cooling and spray cooling. For jet cooling at the inlet and outlet of the jet field, the pressure boundary conditions are assumed. The input pressure fluctuates from 0.1 MPa to 1.0 MPa. Ambient atmospheric pressure is standard atmospheric pressure. The relative pressure at the outlet is 0 Pa, and the ambient temperature - 25°C. For spray cooling, the pressure boundary conditions are adopted at the inlet and outlet of the nozzle. The boundary conditions at the nozzle inlet consist of an air inlet and a water inlet. The water pressure ranges from 0.1MPa to 1.0MPa, and the air pressure is the same as the water pressure. The ambient atmospheric pressure is the standard atmospheric pressure, the outlet relative pressure is 0 Pa, and the ambient temperature is 25°C.

Therefore, for a security system in zero gravity, liquid cooling is more rational.

Heat exchangers are the main components of waste heat recovery and are used to exchange heat between fluid circuits. Heat exchangers are modeled as counterflow heat exchangers using the NTU ε method. Using the heat capacity of both fluids, the maximum theoretical rate of heat transfer between the fluids is determined [20],

$$Q_{max} = C_{min} \cdot (T_{min} - T_{max}) \qquad (27)$$

where, $C_{min} = m_{min} \cdot c_{p,min,}$ where Q_{max} - maximum possible rate of heat transfer between two fluids [Вт], C_{min} - the smallest heat capacity of two liquids [Wt/°C]. T_{min} - cold fluid inlet [°C], a T_{max} – hot liquid inlet [°C]. cp - mass flow rate of the liquid with the lowest heat capacity [kg/s], a c_p, - specific heat capacity of the liquid with the lowest heat capacity [G/(kg °C)]. For modeling, it is assumed that the specific heat capacity of each liquid is constant depending on the temperature.

The physical properties and geometry of this problem are described by Singh, Jain and Rizwan-Uddin [21], where there is also an analytical solution to this problem. The inner surface of the sphere always has zero temperature. The outer hemisphere with a positive value of y has a non-uniform heat flux.

5 Conclusions

Most of the fundamental studies confirm the fact that the effect of a hydrogen environment on structural materials is accompanied by the appearance in them of inhomogeneity and induced differential resistance, which changes over time. This necessitates the creation of new models that will determine the stress-strain state of bodies, taking into account the susceptibility of the mechanical properties of materials to hydrogenation in a wide range of changes in the quantitative characteristics of the stress state.

In general, in this study, on the basis of the constructed mathematical model of the effect of hydrogenation on the stress-strain state of a circular cylindrical shell, a numerical solution of the model problem is carried out, the changes in the values of deflections, displacements and stresses at different values of hydrogen concentration are illustrated.

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