SIMULAÇÃO DO ESTADO DE TENSÃO-DEFORMAÇÃO PARA TUBOS FLEXÍVEIS LONGOS

SIMULATION OF THE STRESS-STRAIN STATE FOR LONG-LENGTH FLEXIBLE PIPES

МОДЕЛИРОВАНИЕ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ ДЛИННОМЕРНЫХ ГИБКИХ ТРУБ

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RESUMO

Um algoritmo para calcular o estado de tensão-deformação para um sistema de tubos flexíveis de comprimento longo em um tambor é proposto. O material do qual o tubo é feito opera na área de deformação plástica devido ao diâmetro relativo pequeno do tambor. Para levar em conta as propriedades não-lineares do material de construção, o conceito de um módulo variável (secante) é usado. O algoritmo para calcular o estado de tensão-deformação de um tubo de comprimento longo flexível reforçado foi compilado com base no método de iteração em termos da magnitude da mudança no módulo secante. Um diagrama de blocos é fornecido. Resultados numéricos da análise de tensões de um tubo flexível de polietileno reforçado são apresentados na forma de gráficos e tabelas.

Palavras-chave: *Diagrama de blocos, algoritmo de cálculo, estado de tensão-deformação, deformação plástica, tubo flexível, tambor.*

ABSTRACT

An algorithm for calculating the stress-strain state for a system of long-length flexible pipes on a drum is proposed. The material which the pipe is made of operates in the area of plastic deformation due to the relative small drum diameter. To take into account the nonlinear properties of the construction material, the concept of a variable (secant) module is used. The algorithm for calculating the stress-strain state of a flexible reinforced long-length pipe was compiled on the basis of the iteration method in terms of the magnitude of the change in the secant modulus. A block diagram is given. Numerical results of the stress analysis of a flexible pipe made of reinforced polyethylene are presented in the form of graphs and tables.

Keywords: *block diagram, calculation algorithm, stress-strain state, plastic deformation, flexible tube, drum*

АННОТАЦИЯ

В работе предложен алгоритм расчета напряженно-деформированного состояния для системы длинномерных гибких труб на барабане. Материал, из которого изготовлена труба, работает в области пластической деформации из-за относительно малого диаметра барабана. Для учета нелинейных свойств строительного материала использовано понятие переменного (секущего) модуля. Алгоритм расчета напряженно-деформированного состояния гибкой армированной длинномерной трубы был составлен на основе метода итерации по величине изменения секущего модуля. Дана блок-схема. Численные результаты анализа напряжений гибкой трубы из армированного полиэтилена представлены в виде графиков и таблиц.

Ключевые слова: блок-схема, алгоритм расчета, напряженно-деформированное состояние, пластическая деформация, гибкая трубка, барабан

INTRODUCTION

The technology of producing of long-length so-called flexible pipes of corrosion-resistant materials, as well as creating new methods for testing and calculating them for strength is one of the ways to solve the problem of equipping the oil and gas industry with new high-strength pipes resistant to aggressive environments with the least number of threaded joints. At present, the use of long-length flexible pipes or flexible tubing strings of various materials, including polymer-containing ones, has become very popular during downhole operations, as well as for oil and gas transportation. Especially active units with flexible pipes are used for laying pipelines, as well as for conducting drilling operations in marine conditions (Yakubovskaya, 1998; Yakubovskaya *et al.*, 2000; Krasovskaya, 2001).

The installation of a string with flexible tubing (coiled tubing) is a construction based on a drum with a wound continuous pipe string and a system for feeding it into the well. Installation with flexible pipes is usually carried out in transportable form on the basis of a powerful car and trailer. The large drum diameter allows the pipes to maintain their shape and state at stresses below the strength yield of the pipe material. The main work parameters of a flexible tubing string are as follows: the minimum diameter of the drum or guides, which the bending of flexible tubing takes place on; process fluid pressure in the pipe; diameter and thickness of the pipe wall; maximum depth of descent of the flexible tubing string.

Research works to solve the problems associated with the use of a new generation of pipes from alternative materials, including

composite ones are intensively conducted. Tubing of reinforced polymers is produced. Reinforcement increases in the thermoplastic strength in the direction of the fibers by 20-100 times. Armored pipes are resistant against the effects of various corrosive media with an increase in the temperature to 20-1000°C. Only stainless steel is as resistant against corrosion as plastic reinforced pipes are.

MATERIALS AND METHODS

Multilayered reinforced materials and their structures, as well as systems of composite materials, have a number of features: constructive orthotropy, stratified structure, the need to take into account the influence of technological factors on the physical and mechanical properties of the structure, and the presence of nonlinear effects associated with the work of structures in the field of plastic deformations (Potemkin, 1999; Alekseev *et al.*, 1991). Experimental studies of the influence of these features on the stress state of the tubes in combination with theoretical calculation methods make it possible to evaluate the behavior of structures of the materials in question and to determine the scope of their application.

In operation, flexible pipes undergo a complex stress state, which must be considered by the stages of the technological process (Yakubovskaya, 2000). At the first stage of operation, the pipe wound on the drum, undergoes bending and internal pressure when the process fluid is fed into the borehole. In this case, the material which it is made of operates in the area of plastic deformations due to the relatively small drum diameter.

To take into account the nonlinear

properties of the construction material, the concept of the variable module (E_c) is used, which is determined by the following relationship (Equation 1):

$$E = \frac{E_0}{1 + b\sigma_{in}^2} \quad (\text{Eq. 1})$$

where E_0 is the instantaneous elasticity modulus of the material (MPa); b coefficient of dependence of material stiffness on deformation (MPa⁻²); σ_{in} stresses intensity, MPa (Equation 2).

$$\sigma_{in} = \sqrt{(\sigma_s^2 + \sigma_\theta^2) / 2}, \quad (\text{Eq. 2})$$

where σ_s is the bending stress along the axis of the curved rod, i.e. pipe axis, MPa (Equation 3); σ_θ stresses from the action of internal pressure, MPa (Equation 4).

$$\sigma_s = \frac{E_c z}{R_{rasch}}; \quad (\text{Eq. 3})$$

$$\sigma_\theta = \frac{p_a(d_n + d_{vn})}{4h}, \quad (\text{Eq. 4})$$

where z ($-d_n/2 < z < d_n/2$); is the height coordinate of the pipe cross-section ($-d_n/2 < z < d_n/2$); $R_{rasch} = (R + d_n/2)$ is design radius of curvature; R is the radius of the drum core; d_n and d_{vn} are the outer and inner pipe diameters, respectively; p_a is the internal pressure of the supplied process fluid; h is the thickness of the pipe wall.

As the ratio between the thickness of the pipe wall and its diameter increases, the magnitude of the stresses from the internal pressure is determined by the formulas of the theory of elasticity (Equation 5 – Equation 7):

$$\sigma_r = -\frac{p_a r_{vn}^2}{r_n^2 - r_{vn}^2} \left(\frac{r_n^2}{r^2} - 1 \right); \quad (\text{Eq. 5})$$

$$\sigma_\theta = \frac{p_a r_{vn}^2}{r_n^2 - r_{vn}^2} \left(\frac{r_n^2}{r^2} + 1 \right). \quad (\text{Eq. 6})$$

$$\sigma_{in} = \sqrt{(\sigma_s^2 + \sigma_\theta^2 + \sigma_r^2) / 2}. \quad (\text{Eq. 7})$$

Calculation of stresses for the design in question is determined by changing in the value of the secant module when winding the pipe onto the drum taking into account the effect of the

internal pressure of the process fluid (Kartashov *et al.*, 2001; Vainshtok *et al.*, 1998).

To determine the stresses under the considered state of the pipe, taking into account the physical nonlinearity of the material, a calculation algorithm and a program for a PC were developed (Potemkin, 1999; Alekseev, 1991). The algorithm for determining the stress-strain state of a flexible pipe, taking into account its work in the field of plastic deformations, is presented in the form of a block diagram (Figure 1).

The block diagram includes 16 steps (see Figure 1):

1. Getting started the program.

2. Input of initial data:

– E_0 is the elasticity modulus of the pipe material in MPa (determined from the experiment);

– R is the radius of the drum core in mm;

– r_n is the pipe outer radius in mm; r_{vn} is the pipe internal radius in mm;

– h is the pipe wall thickness in mm;

– b is the coefficient of the dependence in the section of the diagram $\sigma - \varepsilon$ MPa⁻² (determined as a result of approximation of the experimental curve using the methods of mathematical statistics);

– p_a is internal pressure of process fluid in MPa;

– ε_{ps} is the permissible error value in %.

3. Opening the cycle to determine the design stresses at the each drum pipe turn (M is the number of turns).

4. Determination of the design drum radius on each turn.

5. Determination of bending stresses of a pipe on a drum σ_s and internal pressure σ_θ in a physically nonlinear setting.

6. Determination of the stresses intensity.

7. Determination of the secant module at the first iteration in a linear formulation.

8. Opening the iteration cycle by the amount of the change in the secant module. $i = 2$; N is the number of iterations.

9. Determining the value of the averaged secant modulus between i and $(i + 1)$ iterations.

10. Determining the magnitude of the secant module and its corresponding stresses.

11. Also determining the magnitude of the secant module and its corresponding stresses.

12. Computation of the error between two iterative cycles and comparing it with the specified allowable value.

13. Also, the calculation of the error between two iterative cycles and comparison with a specified allowable value.

14. Determining of the stress values on the section height.

15. Printing of the results of the calculation of stresses and the corresponding geometric parameters of the structure.

16. Program termination.

The algorithm for calculating the stress-strain state of a flexible reinforced long-length pipe was compiled on the basis of the iteration method in terms of the magnitude of the change in the secant modulus (Kartashov, 1980; Agapchev *et al.*, 1988; Pasternak and Sedykh, 1981).

The iteration cycle begins with the solution of the problem in a linear formulation, and then, as the secant module changes, the stress values are recalculated. The cycle continues until the value of the secant module of the subsequent and previous iterations will differ by 0.01%.

RESULTS AND DISCUSSION:

The parameters of the stress-strain state of a long-length flexible pipe of reinforced polyethylene depend on the following design parameters: the radius of the drum core R , the pipe diameter d and the pipe wall thickness h .

A series of calculations for stress determination was performed (Zozulya *et al.*, 2000). Some numerical results of calculating the stress state of a long-length flexible pipe of reinforced polyethylene wound on a drum, without taking into account the internal pressure, are shown in Figure 2.

It can be seen from the graph that the value of the stress magnitude during operation of the long-length pipe material of reinforced polyethylene in the field of plastic deformations depends on the drum diameter and the pipe diameter itself (Vainshtok *et al.*, 1998).

Thus, with a drum radius of 1000 mm and a pipe diameter of 75 mm, the maximum bending stresses on a drum are 16.3 MPa, which does not exceed the yield strength (21.4 MPa).

The calculations are performed for various parameters of the structure under consideration. The recommended parameters (drum radius, outer pipe diameter) are those for which the design stresses do not exceed the allowable values of the yield stress of the pipe material.

According to the proposed algorithm for calculating the stress state of multilayer long-length flexible pipes, the effect of the pressure of process fluid supplied to the borehole on the stress values was analyzed. Figure 3 shows the dependence of the stress values on the internal pressure.

The general tendency of the dependence in the magnitude of the stresses on the internal pressure of the process fluid against the pipe walls is that the stresses increase with a decreasing in the wall thickness and decrease with a decreasing in the pipe diameter. Thus, with a pipe diameter of 60 mm and a wall thickness of 16.5 mm at a pressure of 10 MPa, the stresses are 13.2 MPa, and with a pipe wall thickness of 20 mm and the same pressure and diameter the stresses are 10 MPa. With a pipe diameter of 50 mm and a wall thickness of 15 mm at a pressure of 10 MPa, the stresses are 11.6 MPa (Agapchev, 1988; Pasternak, 1981; Ulyashev, 1993; Nikiforov *et al.*, 2001).

The calculation results of the stressed state of a flexible pipe wound on a drum, with simultaneous action of internal pressure when supplying the process fluid to the well are presented in Table 1 and Table 2.

Analyzing a series of calculation results (Mathur, 1998; Bukhin, 2002; Ronkin, 2003) [14 – 27] of the stress state of multilayer long-length flexible pipes on a drum with allowance for internal pressure, it can be concluded that for borehole operations using a flexible polyethylene pipe with double-layer reinforcement, the following dimensions of the structure are recommended:

- the drum radius – 750 mm; the outer pipe diameter – 50mm; the pipe wall thickness – 15 mm; the operating pressure – up to 15 MPa;
- the drum radius – 750 mm; the outer pipe diameter – 60mm; the pipe wall thickness – 16.5 mm; the operating pressure – up to 15 MPa;
- the drum radius – 1000 mm; the outer pipe diameter – 75mm; the pipe wall thickness – 20 mm; the operating pressure – up to 15 MPa.

CONCLUSIONS:

The presented algorithm for calculating the stress-strain state of long-length flexible pipes allows to predict the behavior of the structure during operation and to recommend the geometric parameters of the installation for a

specific pressure value of the process fluid supplied to the well.

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Figure 1. Block diagram of calculation

Figure 2. Dependences of stresses on pipe diameter without taking into account the internal pressure. Notation: R – radius of the drum; d – outer pipe diameter; h – wall thickness

Figure 3. Dependence of stresses on the value of internal pressure of process fluid. Notation: d – outer pipe diameter; h – wall thickness; p – internal working pressure

Table 1. Stress state of a flexible pipe with a diameter $d_H=50$ mm and a wall thickness $h=15$ mm

Drum radius R, mm	σ_s , MPa (without taking into account the internal pressure)	σ_{in} , MPa (taking into account the internal pressure)				
		P, MPa				
		0.6	5.0	10.0	15.0	20.0
500	19.7	19.8	20.0	20.8	22.3	24.8
750	16.4	16.5	16.8	17.7	19.7	22.7
1000	14.3	14.3	14.7	15.6	18.1	21.6
1500	11.5	11.6	12.1	13.5	16.3	20.5
2000	9.8	9.8	10.3	12.2	15.4	20.1

Table 2. Stress state of a flexible pipe with a drum radius $R=1000$ mm and wall thickness $h=20$ mm

Pipe diameter, d_H , [mm]	σ_s , MPa (without taking into account the internal pressure)	σ_{in} , MPa (taking into account the internal pressure)				
		P, MPa				
		0.6	5.0	10.0	15.0	20.0
100	19.6	19.7	20.5	23.3	28.8	36.9
90	18.8	18.8	19.4	21.6	25.9	32.4
75	17.3	17.3	17.8	19.2	21.8	25.9
60	15.6	15.6	15.9	16.7	18.1	20.3
50	14.2	14.2	14.5	14.9	15.8	17.0