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METHODS OF MINIMIZING THE RISKS OF CAVITATION IN UNDERWATER PIPELINES

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A B S T R A C T

In the article, the classification of various loads that affect underwater pipelines during construction and operation is given. Offshore pipelines are subject to bending moment, hydrostatic pressure, tension, waves, and currents. In addition, the issues of determining the load that the pipeline can withstand or, conversely, the thickness of the pipe wall corresponding to the given load were also considered. At great depths, where the external pressure (hydrostatic pressure) is greater than what can be released, the pipeline is crushed, and the accident propagates along the length at a high speed. Therefore, it is recommended to protect pipelines in deepwater basins from possible crushing. Also, an overview of cavitation is given, and the conditions and consequences of its occurrence, currently known as a hydraulic phenomenon, are listed. It is noted that despite the negative effect of the cavitation factor, it is possible to use it for useful purposes. It is also shown that such effects can be applied in perspectival technologies by preserving them in new nanoobjects at meso and microscales.

1. INTRODUCTION

In connection with the necessity of conducting work at great depths due to the commissioning of new fields in the Caspian Sea and the intensification of oil and gas production, the requirements for the technologies of laying underwater pipelines have significantly increased and become more urgent. The purpose of calculating the stability of underwater pipelines at the bottom of the sea is to select the appropriate laying option to ensure the accident-free operation of the pipelines under the influence of various loads. Therefore, the strength of submarine pipelines should be given very serious consideration, and very strict requirements should be imposed on pipes (quality of material, surface of pipes, accuracy of dimensions, quality of welding works). External influences on pipelines include loads from hydrostatic pressure, temperature changes, loads from wind and water waves, the mass of pipes and their covers, etc. An example can be given. The internal effects are mainly related to the pressure created in the pipeline during the transportation of liquids and gases.

In a word, pipelines are in a state of complex tension under the influence of internal forces both during the test and during the entire operation period and are subjected to corresponding stresses. Radial, annular, and longitudinal stresses are formed in the belt due to the pressure inside the pipe (Goroshko, 2003; Evdokimov & Losev, 2007).

Since radial stresses are small, they are usually not taken into account in calculations. The annular stress is mainly caused by the internal pressure and is determined by the expression $\sigma h = P \cdot D / (2\delta)$. Here: P - internal pressure, MPa; D - tube inner diameter, m; δ is the thickness of the pipe wall, m.

Thus, the longitudinal stress of different origins is defined as follows:

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$$\sigma_u = \mu \frac{PD}{2\delta} - E\alpha\Delta t \mp \frac{ED}{2\rho} \tag{1}$$

The purpose of calculating the strength of the pipeline is to determine the load that the pipeline can withstand or, conversely, the thickness of the pipe wall corresponding to the given load. Strength calculation of main pipelines is carried out by the limit state method (Sorokin & Khavkin, 2007; Huseynova et al., 2024). A limit state means a situation in which the normal operation of the already calculated construction is not possible. For the main pipeline, the stress reaching the yield point does not mean the loss of its working capacity (Mineev & Boligatova, 2004). The pipeline can then be operated successfully until the stress reaches the strength limit. When calculating the strength of the pipeline, it is assumed that its cross-section is ideally circular, and only the internal pressure, which is considered the main effect, is taken into account (Persiyantsev, 2000). Thus, the strength condition is $n \cdot P \cdot D \leq R1 \cdot 2\delta$, where n is the factor of reliability due to the load and R1 is the calculated resistance. If we take into account that $D = Dx - 2\delta$ in the strength condition, then we get the following expression for calculating the thickness of the pipe:

$$\delta = \frac{n \cdot P \cdot D_x}{2(R_1 + nP)} \tag{2}$$

The thickness of the pipe wall in case of longitudinal compressive stresses along the axis:

$$\delta = \frac{n \cdot P \cdot D_x}{2(\psi_1 R_1 + nP)}\ , \tag{3}$$

$$R_1 = R_1^n m / k_1 \cdot k_e \tag{4}$$

Here Rn1 - normative resistance is equal to temporary tension; m - pipeline operating conditions factor; kt - reliability coefficient for the material; ke - belt determination reliability factor; ψ1 is a coefficient that takes into account the biaxial stress state of the pipe and is found from the following expression:

$$\psi_1 = \sqrt{1 - 0.75(|\sigma_{u.x}|/R_1)^2} - 0.5|\sigma_{u.x}|/R_1\ , \tag{5}$$

$$\sigma_{u.x} = -\alpha \cdot E \cdot \Delta t + \mu \cdot n \cdot P \cdot D/(2\delta_n) \tag{6}$$

where: Δt - calculated temperature difference; δn is the nominal thickness of the pipe wall (Tronov, 1970; Kayumov et al., 2006).

2. LITERATURE REVIEW

When calculating the strength, the value of the thickness of the pipe wall is rounded up to the nearest upper values stipulated by the state standards or technical conditions (Sorokin & Tabakaeva, 2009). If we take into account that the internal pressure decreases along the length of the pipeline, then the variable thickness of the pipeline under construction (including taking into account the relief of the track) allows to achieve considerable efficiency in terms of reducing metal consumption (Nebogina et al., 2008).

Conducted studies show that the effect of water depth (hydrostatic pressure) and cavitation on the strength and reliability of underwater pipelines can be significantly greater (Baimukhametov, 2005). Currently, in connection with the depletion of natural oil reserves and the rise in prices for liquid motor fuels, interest in high-efficiency oil processing technologies and alternative non-petroleum raw materials is constantly growing (Goroshko, 2003).

Cavitation is often considered as one of the methods of intensification of physical and chemical processes in the production of fuels from oil, bio-oil, and vegetable oils. Under the influence of high-intensity cavitation, C-C bonds in paraffin molecules are broken for a long time, as a result of which there are changes in the physical and chemical composition, a decrease in molecular weight, crystallization temperature, and properties of oil and oil products, viscosity, density, and flashpoint. In the process of pulsed cavitation processing of oil and petroleum products, the energy released during the collapse of cavitation bubbles is used to break chemical bonds between atoms of large molecular hydrocarbon compounds (Sharifullin et al., 2006a). To break bonds in the molecules of hydrocarbon compounds, it is necessary to provide a complex multicomponent system, which is oil and petroleum products, with a multifactorial energy impact in pulse form. It should be emphasized that acoustic cavitation is an effective means of concentrating the energy of a sound wave of low density into a high energy density associated with pulsations and clogging of cavitation bubbles (Sergienko, 1959). This circumstance has long provoked researchers to relatively high-energy macrovolume studies. Microvolume cavitation processes remained poorly studied.

The essence of promising nanocavitron technologies and circuit engineering is variable local concentration of complementary processes of cavitation and other processes on different physical effects for high-speed control of multiple states interconnected micro and nanoobjects in a certain type of closed, open, or periodically opened meso or microspace (Ibragimov et al., 1986). Systemic nanoobjects, the state of which is determined by the course of the complementary set of named processes in their interconnection, are nanocavitrons. An example of the simplest nanocavitron is a nanosystem made of a single nanoparticle connected to a single cavern of a conglomerate of cavitation cavities placed in one or another registering, activating, or controlling its state field (Petrova et al., 2005).

Targeted operation with single or group caverns is still associated with certain known difficulties. In concrete real conditions, a certain complex of measures is necessary to ensure the existence of a single bubble (Ibragimov, 2003; Kusi-Sarpong et al., 2018). At a pressure that does not exceed the threshold of cavitation, many cavitation bubbles immediately appear, occupying a certain part of the space, called the cavitation region. In it, during pulsed tensile stresses, nuclei grow in the liquid, gradually forming a cavitation cluster (Sharifullin et al., 2006b; Sharifullin et al., 2006c).

Now the requirements are added to the size of controlled nanoobjects used in the system with caverns. Currently, there are no satisfactory models of both a separate cavitation bubble and nanocavitrons. However, in practice, the tasks of the development of research, both nanoobjects and nanocavitonics as a whole (Ismayilov et al., 2015). Creation of the theory and models of monobubble cavitation, its generation, localization, control of cavern life, and its interaction with newly developed nano-objects, for example, nanoparticles, nano-fibers, nanoplanes, and nanotubes, their verification in practice and application to new technologies is an important task of upcoming studies (Usubaliev et al., 2015; Zevakin & Mukhametshin, 2008).

Cavitation treatment allows to increase the yield of fractions at the same distillation temperature. Hence, it can be concluded that hydrodynamics and the ultrasonic vibrations created by it accelerate the diffusion of oil in the paraffin cavity and intensify the process of its destruction (Nurullayev et al., 2016; Nurullayev & Usubaliyev, 2021). Acceleration of paraffin dissolution is due to the intensification of oil mixing at the oil-paraffin interface and the action of pressure pulses that, as it were, spray paraffin particles.

In the process of cracking, the energy released during the collapse of cavitation bubbles is used to break chemical bonds between the atoms of large molecular hydrocarbon compounds. The bond breaking energy varies widely in hydrocarbons, approximately from 40 to 400 kJ/mol. The strength of the C2-H bond is less than C-H, the hydrogen atom is easier to detach in the middle of the normal paraffin molecule than at the end. The breaking energy of C-C bonds in molecules of normal paraffins also decreases somewhat towards the middle of the carbon chain, i.e. long hydrocarbon molecules are automatically broken in the middle part (Usubaliev et al., 2015; Nurullayev, 2014).

In addition to static stresses, the pipeline is also subjected to dynamic influences during the laying of underwater pipelines in the "J" method. Such effects are caused by the movement of pipeline vessels, waves, and currents. Thus, they significantly increase the tension in the belt during drawing, and in some cases cause the tubes to collapse. Therefore, along with static effects, it is necessary to study dynamic effects during each specific shooting.

3. METHODOLOGY

As the considered "J"-method drawing technologies are usually carried out in deeper water basins, the issue of investigating the effect of hydrostatic pressure on the strength of the pipeline is discussed below. The load distribution diagram for the calculation of the resistance of the pipeline wall is given in figure 1. During J-laying, underwater pipelines are subjected to hydrostatic pressure at the pipe suspension point, as well as bending moment, which leads to the loss of strength of the cylindrical shape of the pipeline wall.

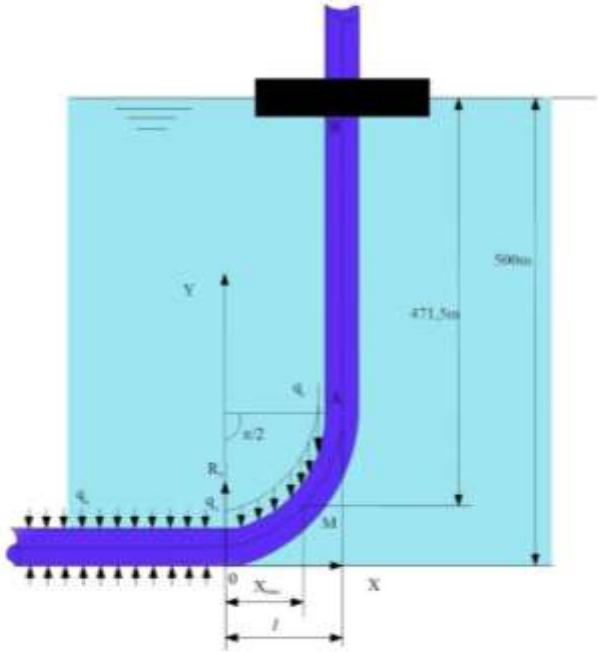


Figure 1. For the calculation of the resistance of the pipeline wall cargo distribution system.

It is known that the longitudinal compressive stress due to hydrostatic pressure is defined as:

$$\sigma_{hid.} = -2v\frac{D_X^2}{D_X^2 \quad -D_d^2} q_{hid.} \qquad (7)$$

where: v – Poisson'sc oefficient of pipe material; Dx. – outer diameter of pipe wall, m; Dd. – inner diameter of pipe wall, m; q_{hid}.- hydro static pressure from the water column, MPa.

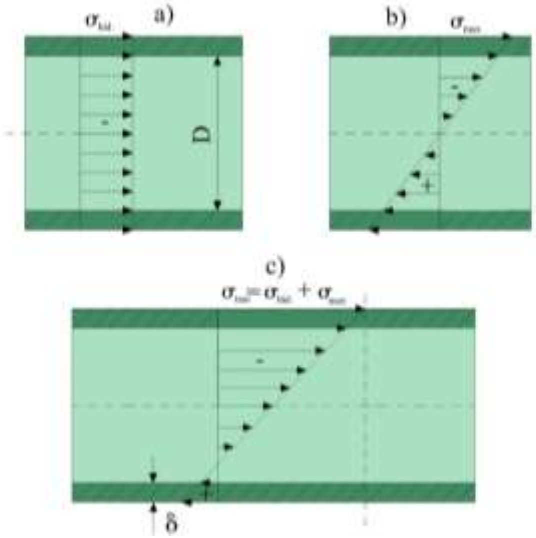
As can be seen from the last statement, the bending moment that creates additional stress on the pipe wall at great depths is not taken into account. It is known from the resistance of materials that the maximum compressive stress caused by bending in the compressed part of the pipe wall is expressed as follows:

$$\sigma_{max} = \pm\frac{M_{max}}{W} \qquad (8)$$

where: Mmax – maximum bending moment; W is the moment of resistance. The mentioned σ_{hid}. and the distribution of σ_{max} stresses across the cross-section of the under water pipe line wall is shown in figure 2. Then the total tension generated in the cross section of the belt will be.

$$\sigma_{tam} = \sigma_{hid.} \pm \sigma_{max} \qquad (9)$$

These stresses are added when they are on the upper wall, and subtracted (depending on the direction of the bending moment) on thelower wall (Figure 2).



a) longitudinal compressive stress due tohydrostaticpressure, b) maximum compressive stress due tobending, c) full stress

Figure 2. Longitudinal stress componentsofpipeline wall widthcross-sectionaldistribution

It should be in accordance with the condition of checking the strength of the pipeline e$\sigma_{tam} \leq [\sigma_{th.}^{det}]$ wall ($[\sigma_{th.}^{det}]$ - the allowable strength limit of the pipeline determined through experience).

4. RESEARCH RESULTS AND DISCUSSION

Let's look at the calculation of the resistance of the pipeline wall. For this purpose, let'sassume $[\sigma_{th.}^{det}] = 4000$kgs/cm^2 and water depth H=500 m.

According to the calculation of the stress-deformation state of pipelines during the construction of underwater pipelines by the "J" method, the maximum value of the bending moment can be estimated from the following conditions:

$$\left.\begin{array}{c} q_0 x_{max} + \frac{q_1}{l}\frac{x_{max}^2}{2} + c_1 = 0 \\ q_0 \frac{x_{max}^2}{2} + \frac{q_1}{l}\frac{x_{max}^2}{6} + c_1 x_{max} + c_2 \leq [\sigma_{th}]W \end{array}\right\} \quad (10)$$

In the last statement, q_0=1.002 kgs/cm; q_1=11,573 kgs/cm; c_1=-7271 kgs; Taking into account that c_2=82460 kgs, for the value of x_{max}=1701.41 cm, the maximum compressive stress will be 3738 kgs/cm^2. Then y(x_{max})=28.5 m and the depth corresponding to the maximum value of bending moment will be h=H-y(x_{max})=500-28.5=471.5 m.

Let's calculate the hydrostatic pressure at point M $q_{hid.}=h\cdot\gamma_{wat}$ (where $\gamma_{wat}=10.06\cdot10^{-3}$ N/cm^3 – specific gravity of sea water).

$q_{hid.}$=471,5·10^2·10,06·10^{-3}=474,329N/sm^2 ≈4,74MPa=48,34 kgs/sm^2

According to expression (7) when v=0.3

$$\sigma_{hid.} = -2\cdot 0.3\frac{529^2}{529^2-(529-20)^2}\cdot 48.34 \approx -391\ kgs/sm^2$$

Then the full value of the compressive stress is:

$$\sigma_{tam} = -391 - 3738 = -4129\ kgs/sm^2$$

As itturns out$\sigma_{tam} > [\sigma_{th.}^{det}]$, bending will occur in the pipe wall, and it is important to take various measures to prevent it. The resulting bends lead to the formation of a cavitation field, which is one of the main risk factors for accidents. Since cavitation bubbles can be generated with the help of intense acoustic radiation in any liquid, it can be assumed that the breaking of chemical bonds can therefore be carried out in any chemical compound at sound intensity corresponding to the strength of the bond energy. Any radical must be connected to the site of the chemical bond break. When there is a lack of free radicals in the reaction medium, molecules with an unsaturated bond can curl into a ring, forming cyclic or aromatic compounds. The analysis of samples showed that after cavitation treatment, the degree of conversion of any class of organic compounds was insignificant and did not exceed 1.1%. The products of the cavitation effect are normal alkanes and their isomers and products of autoxidized oxygen-containing derivatives of treated organic substrates, which are formed as a result of the oxidation of the organic phase by oxygen dissolved in it. Based on the obtained experimental data, the energy efficiency of cavitation during the cracking of alkanes was estimated, which was 0.002%. Thus, the use of cavitation directly for the initiation of chemical transformations in the cracking process of various organic compounds. The effect of cavitation is manifested primarily in the effects of heating the processed liquids and intensification of heat and mass exchange processes in them. When cavitation bubbles collapse, the temperature reaches several thousand degrees Celsius in a very short time (less than 1 μs) and a pressure of more than 1000 atm develops. Thus, directly in the stream, the conditions for oil processing, specified above, are created. As a result of greater stability of operating frequencies, high homogeneity of the finished product is achieved, and the output of light petroleum products increases to 3-5%. It should be noted that this technology allows not to dehydrate crude oil, which contains up to 20% water, but, by exposing it to ultrasonic cavitation, to involve it in a series of chemical reactions that lead to the formation of alcohols, simple and complex ethers, while increasing the calorific properties of the fuel at the reduction of its cost. The experimental studies carried out by us show that, when passing through the cavitation zone, the rheological properties of Azerbaijani oil improve.

The share of paraffinic hydrocarbons decreases, and the share of resinous and asphaltene hydrocarbons increases (Nurullayev et al., 2012). Thus, if the mass fraction of paraffin hydrocarbons in the stream decreases, then, as is known, the amount of asphaltic paraffin deposits decreases regardless of the fraction of resinous and asphaltene hydrocarbons. Despite the change in oil parameters, its elemental composition does not change. This is due to the fact that a phase transition occurs during hydrodynamic cavitation in oil. When the phase transition occurs, each phase is separated from the competing surface by a partition, at the intersection of which the chemical and physical characteristics of the oil fractions change almost instantly (Table 1). This is due to the fact that a phase transition occurs during hydrodynamic cavitation in oil.

Table 1 - Rheophysical-chemical properties of oil passing through the "J"-shaped drawing and cavitation field.

Indicators	Itisdrawn bythe "J" method	After thecavitati onzone
Distilations, - b.p.^{0}C	64	58
- in350^{0}C (%)	58	52
Oil density 20^{0}C, kg/m^3	856,8	853,4
Paraffin car/hid. Mas.%	4,25	3,74
Asphaltenecar/hid. Mas.%	0,79	0,67
Rezincar/hid. Mas. %	12,63	11,25
Iodine number g iodine per 100g fraction.	0,8	0,7
Pour point, ^{0}C	-24	-27

When the phase transition occurs, each phase is separated from the competing surface by a partition, at the intersection of which the chemical and physical characteristics of the oil fractions change almost instantly. Changing such factors by applying cavitation in pipeline transport is one of the methods of combating asphalt-tar-paraffin deposits. But, despite the improvement of the rheological properties of oil, if the process takes place for a long time, it can lead to emergency situations in oil pipeline systems. The main disadvantage of this device is the intensive cavitation wear of its working surfaces, which generate cavitation bubbles, most of which collapse on these surfaces (Figure 3).

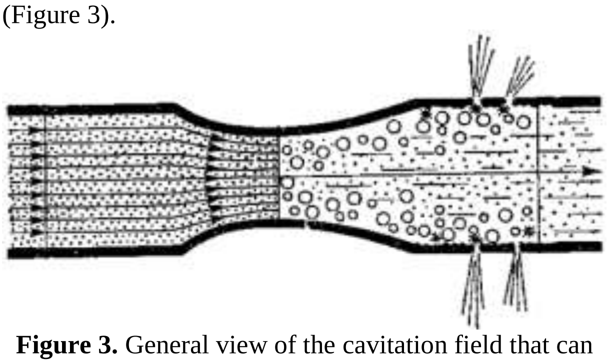


Figure 3. General view of the cavitation field that can occur in an oil pipeline**.**

During "J" laying, offshore pipelines are subjected to bending moment, hydrostatic pressure, tension, waves and currents. At great depths, where the external pressure (hydrostatic pressure) is greater than what can be released, it is possible to observe the collapse of the pipeline and its propagation along the length at great speed. Therefore, pipelines in deepwater basins should be protected from possible crushing.

5. CONCLUSIONS

In order to minimize the risk of cavitation in offshore pipelines during drawing with the "J" method, it is usually considered appropriate to take the following measures in practice:

- increasing the thickness of the pipe wall;
- additional welding to welding locations;
- patching the outside of the pipe.

Increasing the thickness of the pipe wall is not effective for many reasons (high cost, manufacturing and welding of thick-walled pipes, as well as the impossibility of eliminating the difficulties that occur during the installation of the belt).

The most economically viable measure to protect marine pipelines against crushing is the use of reinforced couplings. Although such limiters do not completely prevent belt crushing, they can localize them between two neighboring limiters. The selection of the geometric parameters and frequency of placement of such limiters is determined based on special technical and economic calculations.

After the cavitation zone, a hydraulic shock occurs in the pipe. Based on the observations made and the study of the nature of the effect of cavitation on oil, it can be concluded that cavitation leads to the destruction of paraffins and supramolecular structures of oil, associates, micelles and their size reduction, which contributes to a decrease in viscosity. But over time, the broken particles restore intermolecular bonds, which leads to the restoration of the dynamic viscosity of oil.

Experiments have shown that after cavitation processes, the dynamic viscosity of Azerbaijani oil decreases by 9%. For oil, it is characteristic to restore the original value of viscosity within 72 hours after the processes.

It follows from this that on the basis of cavitation processes, it is possible to establish general regularities of regulating the physical and chemical properties of oil for use in the technology of pipeline transport of highly paraffinic oils.

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