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CHANGES IN ENERGY CHARACTERISTICS OF PIPELINE SYSTEMS CONSIDERING HYDRODYNAMIC LOADS

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ABSTRACT

Pipeline transport is one of the most capital and metal-intensive types of transport. Being environmentally friendly during normal operation, it can cause irreparable damage to nature in case of accidents. Therefore, the issues of reliability and efficiency of operation of field and main oil and gas pipelines and control of energy characteristics during their operation are of no small importance. The amount of additional pressure in the system from hydrodynamic shocks is determined by the density and elasticity of the pumped liquid, as well as the elasticity of the walls of the pipeline itself. The article considers the problem of estimating the critical speed and dynamic loads during the movement of multiphase flows through pipelines, taking into account the interaction of the phases. Dynamic loads are calculated based on the change in critical speed for various structural forms formed as a result of the interaction of phases. These loads, compared to shell structures with separated phases, turned out to be less than when moving in a mold with dispersed bubble structures. The characteristics of the critical speed distribution are determined. It has been determined that the dynamic loads arising in multiphase flows with a predominance of the gas phase are many times higher than in systems where the liquid phase is the leading medium, and the dependence of the pressure distribution on the densities of the phases has been shown. The work analyzes various modes of hydraulic shock. The volume of oil caused by its compression during hydraulic shock was calculated. The results of calculating the increase in the volume of an oil pipeline due to a dynamic impact are presented.

Keywords: Critical speed; structural form; speed gradient; density; hydraulic shock; dynamic load; energy feature; elasticity; multiphase flow; flow structure.

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Introduction

The efficiency of pipelines depends on the technical condition of facilities and equipment and the rationality of their use. The practice of operating pipelines shows that the actual operating conditions often differ from the design ones. During operation, emergency and abnormal cases occur in them. Significant irregular pressure and flow pulsations are observed in pipelines. Waves of high and low shock pressure often occur and propagate along the pipeline. Changes in dynamic loads that arise during the operation of multiphase pipelines also occur in its straight sections because of the nature of the non-stationary hydraulics of the multiphase flow.

It is known that in the «well-collection-transport» network the most common are multiphase forms of flow of heterogeneous well products. The main feature of such flows is that, along with an external limited surface (pipe wall), they also have a phase separation surface (hydrodynamic, thermal, phase, etc.). The study of such flows and their mathematical description are quite complex, and therefore they belong to the class of unsteady moving flows [1, 2].

Experience shows that due to the high gas content, as well as interfacial slip and complex terrain of underwater and land pipelines, liquid plugs are often formed in them [3-5]. When such plugs meet an obstacle in the pipe (for example, places of bending and turning, valves, etc.), various dynamic loads arise, which are observed by pressure jumps due to the impact. It is possible that the resulting impact force can take different values depending on the speed of movement of the liquid plug, its density and the diameter of the pipeline.

It should be taken into account that the flow structure can also change when the flow rate in the pipeline changes. Thus, at high flow rates, the speed of movement of the mixture increases, and at a critical speed value, the stratified structural form existing in the pipeline gradually transforms into the form of dispersed bubble movement. In this case, the homogeneous structural form of the mixture is characterized as homogeneous with a constant density throughout the flow. At a small flow rate of the mixture, since the speed is less than the critical one, the voltage of the gradient velocity field in a multiphase flow turns out to be insufficient for the formation of a homogeneous, i.e., dispersed-bubble mixture. In this case, the multiphase mixture remains a flow consisting of alternating gas and liquid plugs. Since the components that make up the mixture in the flow are separated from each

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other by a phase boundary, the flow is considered structured, divided into these layers (phases). It is during a flow with such a shell structural form that non-stationary dynamic loads arise due to the difference in phase densities in pipeline turns and other obstacles [6-8].

Analysis of the structural forms of multiphase flows shows that there are mainly two more important and characteristic structural forms of flow [3]. One of them is the emulsified or dispersed form of movement, i.e., one phase presents disperse medium, the other - disperse phase in this disperse medium. This flow formed in maximum values of pressure gradient $(dP/dr)_{\max} > g(\rho - \rho_g)$ is considered such a flow.

The other flow form is a structural form, reflecting the situation, where movement is divided into layersphase, that is, both phases exist separately.

Such structural form occurs when $(dP/dr)_{\max} < g(\rho - \rho_g)$ and mainly in horizontal and slightly inclined flows.

As it is known, any change of parameters of pumping of oils (oil products) along the pipeline can be called hydraulic shock. Such change can take place slowly or quickly, the reason of the shock can be slow or quick closing or opening of shut off, stop or start of pump, destruction of the pressure pipeline with the release of the pumped product onto the terrain as well as various dynamic loads arizing during the operation of multiphase pipelines [9-11].

The magnitude of pressure during hydraulic shock according to Zhukovsky can be calculated using the following formula:

$$P = c \cdot \Delta v \cdot \rho \tag{1}$$

where, c is the speed of sound propagation in a fluid at rest; Δv – decrease in flow velocity in the pipeline; ρ – density of pumped oil.

The practice of operating field pipelines shows that significant irregular pulsations of pressure and flow are observed in pipelines transporting multiphase mixtures. The working environments of the oil field are characterized by the presence of liquid and gas phases, which coexist in almost all oil field pipelines [12-17].

Analysis of the parameters of hydraulic shock pressure distribution along the length of the pipeline allows to choose tactics and methods for protecting the system from shock. It was found that transient conditions during the transportation of gas-saturated oils through oil pipelines are a consequence of the same reasons as during the transportation of degassed oils. Waves of increased and decreased shock pressure also arise, propagating along the pipeline [11, 14-17]. In this case, the wave of increased pressure has the greatest magnitude and, propagating towards the previous operating station, is superimposed on the existing pressure in the oil pipeline, summing up with it. A wave of low pressure, which moves at the speed of shock wave propagation in the liquid towards the subsequent pumping station, can cause the release of gas from gas-saturated oil and lead to the formation of gas accumulations in the oil pipeline and cavitation of pumps. As for transient regimes when pumping gas-saturated oils, they do not introduce significant changes and can be assessed using existing methods for calculating transient regimes in degassed oils. In this case, the relative change in the pressure increase in the disturbed gas-saturated flows will be determined by the relative change in the bulk elasticity modulus of gas-saturated oil.

Statement of the problem and methods of solution. In the work, taking into account changes in the structural forms of flow of multiphase systems based on an assessment of the critical flow velocity, the issues of distribution of dynamic loads and their impact on the capacity of the pipeline, in the density of gas and liquid phases, were considered.

It is known that the nature of the distribution of dynamic loads that arise during the operation of pipeline systems requires the determination of their maximum values and the value of the critical speed at which a change in flow structures occurs.

Let us consider the assessment of the critical speed based on the dependence of the static pressure gradient on the flow velocity in a multiphase pipeline with gas as the leading medium.

If to take into account that the velocity distribution over the flow cross-section occurs according to the parabolic change $u = 2v(1-\alpha^2)$, then the description of the pressure gradient over the cross-section can be written [3]:

$$\frac{dP}{dr} = \frac{16 \cdot v^2 \cdot \rho_g \cdot \alpha \cdot \left(1-\alpha^2\right)}{D} \tag{2}$$

where, v – average flow rate, m/s; ρ_g – gas density, kg/m^3; α – relative coordinates ($\alpha = r/R$); D – pipeline diameter, m.

Considering that for the formation of a dispersed-bubble structure in a multiphase flow, the maximum static pressure gradient should not be less than the difference in the specific gravity of the liquid and gas phases, then taking into account expression (2) to estimate the critical speed, we obtain the following expression:

$$v_{cr} = \frac{0.25 \cdot \sqrt{\left(\dfrac{\rho_l}{\rho_g} - 1\right) \cdot g \cdot D}}{\sqrt{\alpha \cdot \left(1-\alpha^2\right)}} \tag{3}$$

As a result of the calculations, it was determined that the classification of structural modes in multiphase flows only by the parameter $(dP/dr)_{\max}$ is insufficient to increase the accuracy of further calculations. For greater accuracy, it is advisable to take $\alpha = 0.8$. In this case, if the equation $(dP/dr)_{\max} = g(\rho - \rho_g)$ is satisfied, then we can assume that the main flow is homogeneous, emulsified and dispersed.

Taking into account the above, the corresponding critical speed (v_{cr}^{hom}) for the transition to a homogeneous mode of structural motion can be calculated using the following equation:

$$\frac{4.61 \cdot \rho_m \cdot (v_{cr}^{hom.})^2}{D} = \text{g} \cdot \left(\rho_l - \rho_g\right) \tag{4}$$

Here, ρ_l, ρ_g and ρ_m are the densities of liquid, gas and gas-liquid mixture, respectively; (v_{cr}^{hom}) critical speed for the transition to a homogeneous structure.

Based on the volumetric gas content (β), the density of the mixture can be calculated using the expression

$$\rho_m = \beta \cdot \rho_g (1-\beta) \rho_l$$

Thus, for a homogeneous (dispersed) structure, the critical speed will have the form:

$$v_{cr}^{\text{hom}} = 0.466 \cdot \sqrt{\frac{\rho_l - \rho_g}{\rho_m} \cdot g \cdot D} \tag{5}$$

Similarly, to determine the critical speed for separate flow for the dominant gas or liquid phases, one can write:

$$v_{cr}^{g}=0.466\cdot\sqrt{\left(\frac{\rho_l}{\rho_g}-1\right)\cdot g\cdot D} \quad (6)$$

$$v_{cr}^{l}=0.466\cdot\sqrt{\left(1-\frac{\rho_g}{\rho_l}\right)\cdot g\cdot D} \quad (7)$$

Assessing the dynamic pressure caused by a change in the density of a multiphase mixture as the difference between the dynamic loads of the liquid and gas phases, that is, the expression $P_{dyn}=(\rho_l-\rho_g)\cdot v_{cr}^2$ and taking into account (5), (6) and (7), to evaluate the corresponding dynamic pressures we get:

$$P_{dyn}^{\text{hom}}=0.217\cdot\frac{\left(\rho_l-\rho_g\right)^2}{\rho_m}\cdot g\cdot D \quad (8)$$

$$P_{dyn}^{g}=0.217\cdot\frac{\left(\rho_l-\rho_g\right)^2}{\rho_g}\cdot g\cdot D \quad (9)$$

$$P_{dyn}^{l}=0.217\cdot\frac{\left(\rho_l-\rho_g\right)^2}{\rho_l}\cdot g\cdot D \quad (10)$$

If to compare the last expressions, depending on which of the phases is leading or dominant, then to determine dynamic loads depending on the ratio of phase densities we obtain the following dependencies:

$$P_{dyn}^{g}=\frac{\rho_m}{\rho_g}\cdot P_{dyn}^{hom} \quad (11)$$

$$P_{dyn}^{l}=\frac{\rho_m}{\rho_l}\cdot P_{dyn}^{hom} \quad (12)$$

$$P_{dyn}^{g}=\frac{\rho_l}{\rho_g}\cdot P_{dyn}^{l} \quad (13)$$

As can be seen from expressions (11), (12) and (13), the dynamic pressure arising when the gas phase dominates will be many times higher than in cases where the main role belongs to the liquid phase. In this case, the ratio of dynamic pressures will change depending on the ratio of the liquid and gas phases. Compared to a dispersed (homogeneous) mixture, the dynamic pressure that arises when the gas phase dominates is greater than when the liquid phase dominates. The dynamic load under conditions of dominance of the liquid phase can be significantly less than the dynamic pressure created by a multiphase but homogeneous flow, depending on the ratio of the densities of the mixture and the liquid phase (ρ_m/ρ_l).

As a rule, additional pressure during the operation of pipelines due to hydraulic shocks arises from the density of the transported liquid, its elasticity and the elasticity of the pipeline itself. The practice of operating field and main pipelines shows that, due to shock pressures, the energy characteristics of pipeline systems can change significantly depending on the intensity of hydraulic pressure. Hydraulic shocks pressure is determined by two factors: the elastic compression of the transported oil or petroleum product and the elastic expansion of the pipeline itself when the pressure in it changes. The change in the density of transported oil with changes in pressure can be assessed using the following relationship:

$$\rho(P)=\rho_{20}[1+\beta_o(P-P_{atm})] \quad (14)$$

Where ρ_{20} is the density of oil at 20 °C, kg/m^3; P – pressure, Pa; P_{atm} – atmospheric pressure, Pa; β_o – oil compressibility coefficient ($\beta=0.00078$ MPa^{-1})

The change in the volume of oil in the pipeline (ΔV_o) depends on its elastic modulus $E_o=1/\beta_o$ and the level of hydraulic pressure (P):

$$\Delta V_o=P\cdot V_o/E_o \quad (15)$$

where V_o is the volume of oil in the pipeline, m^3;

$$V_o=V_D=\frac{\pi D^2}{4}\cdot l \quad (16)$$

D and l – diameter and length of the oil pipeline, respectively, m

The change in pipeline volume during hydraulick shock can be calculated using the following formula [6, 7, 14]:

$$\Delta V_D=\frac{\pi D^3\cdot P\cdot l}{2E_p\cdot\delta} \quad (17)$$

Here δ is the thickness of the pipeline wall; E_p – elastic modulus of the pipe material ($E_p=2.1\cdot10^{11}$ Pa).

It should be noted that the duration of the change in liquid volume is equal to the duration of the impact phase, which is equal to the travel time of the pressure wave from the disturbance to the barrier and back

$$t=2l/c$$

The speed of sound propagation in oil is determined by the known dependence [13, 14]:

$$c=\frac{\sqrt{E_o/\rho_o}}{\sqrt{(1+E_o\cdot D/\left(E_p\cdot\delta\right)}} \quad (18)$$

Let's consider an example of calculating changes in the volume of oil and a pipeline during a hydraulic shock.

We take as initial data:

Pipeline length $l=5000$ m;

Pipe diameter $D=500$ mm;

Wall thickness $\delta=10$ mm;

Oil pipeline volume $V_p=\frac{\pi D^2}{4}=\frac{3.14\cdot\left(0.5\right)^2}{4}=981.25\,m^3$;

Oil consumption $Q_o=1500$ m^3/hour$=0.4166$ m^3/s;

Oil density $\rho_o=860$ kq/m^2;

We can calculate the hydraulic shock pressure for the full shock that occurs when the valves are instantly closed. The oil velocity in the pipeline was:

$$v=\frac{4Q_o}{\pi D^2}=\frac{4\cdot0,4166}{3.14\cdot\left(0.5\right)^2}=2.12\,m/s$$

We calculate the speed of sound propagation in oil using formula (4): $C=1074.2$ m/s

Then from formula (1) the pressure from the hydraulic shock will be:

$$P=1074.2\cdot2.12\cdot860=1958481\,\text{Pa}=1.96\,\text{Mpa}$$

As it can be seen from the calculation of hydraulic pressure, such pressure can arise with a long pipeline length exceeding $l>2\cdot c\cdot t$; t – valve closing time.

Let's consider calculations of the volume of oil caused by its compression during a hydraulic shock. It is known that the elastic property of oil when it encounters a valve will continue until the compression wave reflected from the beginning of the oil pipeline meets a direct compression wave.

The duration of the increase in pressure in the oil pipeline will be:

$$t = \frac{2l}{c} = \frac{2 \cdot 5000}{1074.2} = 9.31 s$$

Then the compression of oil in the pipeline by additional pressure at the elastic modulus of oil $E_O = \frac{1}{\beta_o} = 1.3 \cdot 10^9$ Pa will be (according to formula (15)):

$$\Delta V_\rho = 1958481 \cdot \frac{981.25}{1.3} \cdot 10^9 = 1.4782 m^3$$

At the end, we will determine the increase in the volume of the oil pipeline itself due to impact according to formula (17):

$$\Delta V_\rho = \frac{3.14 \cdot (0.5)^3 \cdot 1958481 \cdot 5000}{2 \cdot 2.1 \cdot 10^{11} \cdot 0.01} = 0.9151 m^3$$

It is also possible to calculate changes in oil density when pressure changes as a result of impact, using formula (14) we obtain:

$$\rho = \rho_{20}[1 + \beta_o(P - 1)] =$$

$$= 860[1 + 0.00078 \cdot 10^{-6}(1958481 - 10^5) = 861.29 \text{ kq/m}^3$$

Then the hydraulic shock pressure will have the following value:

$$P = 1074.2 \cdot 2.12 \cdot 861.29 = 1961419 \text{ Pa}$$

In this case, the effect of changes in density will be 1961419 - 1958481 = 2938 Pa.

Conclusions

1. It is shown that, compared to dispersed flows, the dynamic pressure is many times higher than in divided-plug forms of motion.
2. It has been determined that the dynamic loads that arise when the gas phase plays the main role (dominance) increase depending on the ratio of the densities of the liquid and gas phases, more than in the case with the dominance of the liquid phase.
3. A numerical example showed changes in the volume of transported oil (petroleum product) and pipeline during a hydraulic shock, taking into account the influence of changes in the density of the pumped medium. The importance of taking into account dynamic loads with a dispersed flow structure is shown.
4. In addition to single-phase movement, dynamic loads must also be taken into account with gas inclusions and multiphase flow with various structural forms of movement in field pipelines.

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