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Energy-saving management of liquid's transportation in pipelines

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Annotation. Transportation of coolants, oil and oil products are associated with the flow of liquid medium through pipelines of circular cross-section. When the fluids move through the pipes, pressure losses arise on the friction of the flow against the pipe wall. Reduction of wall friction, and accordingly energy loss for pumping liquid can be achieved by pulsating flow in the pipeline. The pulsating mode has acceleration phases, which corresponds to a more complete velocity and deceleration profile, which is characterized by less filled velocity profile, in comparison with a stationary flow. The mathematical model is based on the theory of the boundary layer, using the Prandtl hypothesis on the length of the mixing path. As a result of the numerical experiment, qualitative and quantitative information on the effect of harmonic oscillations of the fluid flow on the hydrodynamic flow characteristics was obtained. The influence of frequency factors and the amplitude of flow oscillations is shown, as well as one of the main characteristics determining the economic effect of the process that is pressure loss on friction along the length of the channel. A method for creating harmonic and nonharmonic oscillations is proposed.

Introduction

The territory of the Russian Federation has a huge length of heating mains and oil product pipelines. Pipeline transportation is characterized by the lowest costs, high speed of delivery and throughput and it is the most environmentally friendly transportation mode. Losses of the transported product in pipeline transport can be minimized [1].

Relevance

To move the fluid through the pipeline of any section and any configuration, a pressure drop is necessary. The flow of liquids is associated with a change in a large number of hydrodynamic and thermal parameters. These include the properties of the fluid being transported, the characteristics of the pipeline and the technological parameters of the equipment that creates the driving force. All these parameters mutually affect to each other and they are interconnected by complex dependencies.

The friction of the fluid on the streamlined surface has a major effect on the pressure loss in the pipelines, which in turn is determined by the velocity gradient in the near-wall region. The velocity gradient depends on the velocity profile, i.e. on the flow regime and the influencing factors, such as the longitudinal pressure gradient, the injection or suction of the boundary layer, heat and mass

transfer in the near-wall region, and the nonstationarity of the hydrodynamic and thermal flow parameters.

The choice and justification of the mathematical model

As a rule, the flow of liquid through main pipelines occurs in a turbulent mode. Two flow sections can be distinguished in the pipe. In the first one, the boundary layer originates and develops, which is formed due to the fact that the fluid particles flow "glued to" on the pipe wall. The boundary layer increases in thickness along the pipe. Gradually, the boundary layers in the pipe are closed, and the second section occurs that is a developed turbulent flow. Moreover, under the influence of the longitudinal pressure gradient and the nonstationarity of the hydrodynamic parameters, the developed flow may collapsed, recurrent flows may arise and the boundary layers may develop again.

The mathematical model is based on the theory of the boundary layer. A two-layer model, consisting of a viscous sublayer and a turbulent core, is simple, but insufficiently complete, describing complex hydrodynamics in channels of circular cross-section.

In this paper, the intensification [4] of the process of turbulent flow along the circular channel is carried out in order to reduce pressure losses due to friction along the length of the channel. Effect of flow nonstationarity is created by realization of flow's liquid fluctuations at the entrance to the channel.

The hydrodynamic parameters of the boundary layer [2], [3] are calculated on the basis of a two-dimensional flow model. The system of differential equations is written with respect to the integral parameters of the boundary layer. Such mathematical model includes a greater number of empirical relations for closing the system of differential equations. The model is relatively simple in calculation, which is important for the possibility of application in engineering practice.

A nonstationary turbulent flow of an incompressible single-phase fluid flow in a circular channel is studied. The flow in the boundary layer is assumed to be turbulent directly from the inlet section of the tube. The velocity and temperature profiles in the inlet section are uniform (Fig. 1).
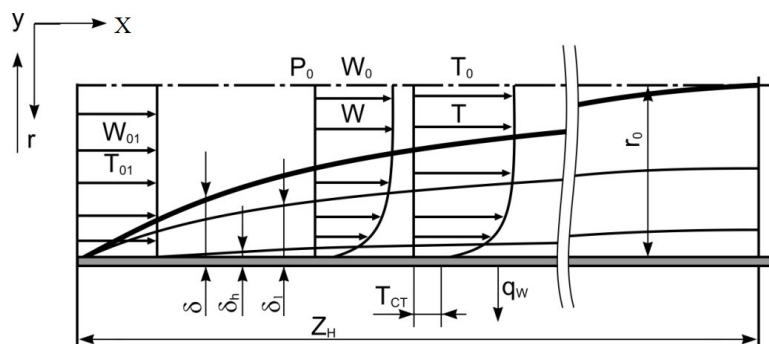

Fig.1. The nonstationary flow of a single-phase flow of a Newtonian fluid in a circular channel: $X = x/2r_0$ is dimensionless longitudinal coordinate; $W = w/w_{01}$ is the relative velocity; P is pressure, N/m2; δ is the thickness of the boundary layer.

The influence of the amplitude and frequency of flow oscillations on hydrodynamic flow parameters are determined by means of mathematical modeling.

The analys of joint influence of factors is carried out using parametric methods developed by S.S. Kutateladze and A.I. Leont'ev [5]. They allow quantitative expression of the investigated characteristics of the fluid flow and establish the interrelations between the factors.

Nonstationary differential equations [6] of motion and continuity:

$$\rho \frac{\partial w_X}{\partial t} + \rho w_r \frac{\partial w_X}{\partial r} + \rho w_X \frac{\partial w_X}{\partial x} = \frac{\partial P}{\partial x} + \frac{1}{r} \frac{\partial (r\tau_X)}{\partial r} , \qquad (1)$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho w_X}{\partial x} + \frac{\partial \rho w_r}{\partial r} + \frac{\rho w_r}{r} = 0 \qquad (2)$$

are written in an axisymmetric formulation and are transformed into integral:

$$\frac{dW_0}{dX} = \frac{Re_{01}\left(C_g + \frac{C_f}{2}\right) + P}{\frac{Re_{01}}{4H} + \frac{Re^{**}}{W_0}(2 + H)} \qquad (3)$$

$$4HRe^{**} = Re_{01}(W_0 - 1) \qquad (4)$$

where ρ is density, kg/m³; w_0 is main flow velocity; $W = w/w_{01}$ is relative velocity; Re_{01} is Reynolds number from the input parameters of the channel; Re^{**} is specific Reynolds number in terms of the thickness of the momentum loss; P is pressure, N/m²; t is the time, s; $C_f/2 = \tau_w/\rho_0 w^2$ is dimensionless coefficient of friction; τ is wall shear stress, N/m²; δ is thickness of the boundary layer; $\xi = x/\delta$ is dimensionless lateral coordinate; η is stability parameter of the viscous sublayer; indexes: $_0$ is parameters of the main (external with respect to boundary layer) flow; $_1$ is parameters at the boundary of the viscous sublayer; $_w$ means parameters on the wall; * is parameter of braking; $_{01}$ is parameters at the entrance to the channel.

These integral equations can be solved numerically with help of the momentum transfer law obtained according to the Prandtl hypothesis and the tangential stresses approximation

$$\sqrt{\frac{C_f}{2}} = (1 - w_1)\bigg/ \int_{\xi_1}^{1} \sqrt{\frac{\tau}{\tau_0}} \frac{d\xi}{\chi \xi} \qquad (5)$$

The parameters at the outer boundary of the viscous sublayer are determined from the equation of motion and the assumption of a linear velocity profile:

$$w_1 = Re^{**}\frac{\delta}{\delta^{**}}\frac{C_f}{2}\xi_1\left(1 + \frac{\bar{\tau}_w'\xi_1}{2}\right) \qquad (6)$$

$$\xi_1 = \eta_1\left[Re^{**}\frac{\delta}{\delta^{**}}\sqrt{\frac{C_f}{2}\left(1 + \frac{\bar{\tau}_w'\xi_1}{2}\right)}\right]^{-1} \qquad (7)$$

The loss of pressure on friction is calculated by formula (9).

$$\Delta P_{C_f} = 4\frac{C_f}{2}\rho_0 w_0^2 \qquad (8)$$

The system of equations (3-7) is numerically integrated by the Runge-Kutta method for the initial and boundary conditions presented in Fig. 1

Results of calculations

Figure 2 shows the results of calculating the frictional pressure loss in a non-stationary pulsating

flow in a pipeline. The calculation was carried out at different flow rates.

As can be seen from the graph, the pressure loss is minimal if the flow pulsations occur in the frequency range from 0.1 to 0.5 Hz [7]. As the frequency and amplitude of the oscillations increase, the pressure loss also increases, which agrees with the data [8].
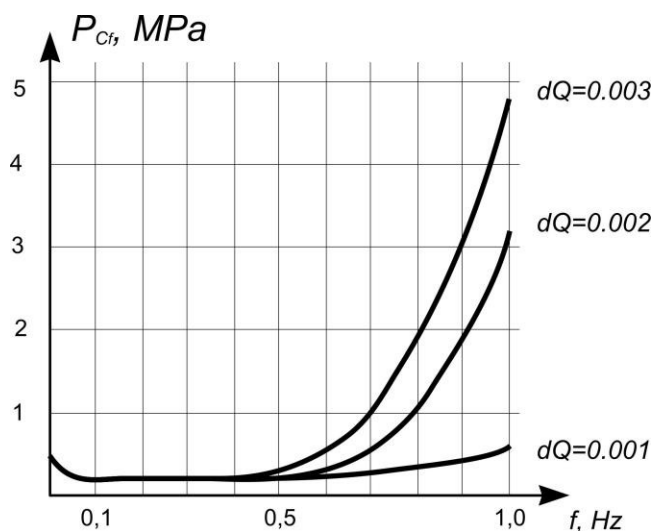

Fig.2. Loss of pressure on friction with harmonic fluctuations in fluid flow

The magnitude of the frictional pressure loss increases during the acceleration phase of the fluid flow. This effect is observed because of the increase in the values of tangential stresses due to the contraction of the boundary layer by the turbulent core [9]. Accordingly, the frictional pressure loss decreases in the phase of the flow deceleration. Creation of the necessary oscillations is carried out by an electric drive with frequency control.
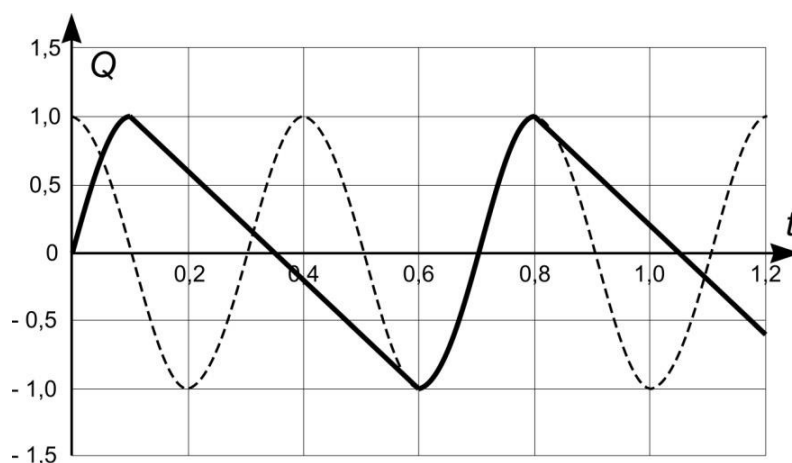

Fig. 3. Change in fluid velocity, where Q, m^3/s is flow rate of the liquid in the pipeline; t, s is time

Using of non-harmonic flow oscillations to influence the flow of liquid can be carried out as shown in Fig. 3. Acceleration of the flow occurs according to a linear law, and the deceleration - according to the sinusoidal. By increasing the deceleration phase in time and decreasing the acceleration phase of the flow, it is possible to achieve a reduction in pressure loss due to friction.

Conclusions

The numerical experiment on the effect on wall friction and pressure loss on pumping liquid in a pipeline of finite length of the frequency of flow oscillations 0,1 -1,0 Hz and amplitude of 16%, 33% and 50% of the nominal flow is carried out. It is shown that pressure losses in a pipeline of 23,000 diameters in length using a pulsating harmonic regime can be reduced by 64%. A method for creating harmonic and nonharmonic oscillations is proposed.

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