Non-stationary processes in oil-product pipeline using anti-turbulence additives

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Received: 18.06.2015 Accepted: 10.07.2015

Abstract

The problem of a non-stationary flow of petroleum products by the pipeline in the process of its displacement by anti-turbulence additives is studied in the article. There is made a mathematical model of motion of a contact for two liquid media with different hydraulic characteristics in the pipeline. The model implementation allows predicting the type of motion of the moving boundary, pressure distribution and flow of petroleum products during the process of non-stationary displacement. It is determined that oscillation of parameters in time is negligible, and it allows recommending the quasistationary motion models for predictive calculations.

Key words: *anti-turbulence additive, moving boundar, non-stationary process.*

Anti-turbulence additives (ATA) are high-molecular polymeric substances for reduction of hydraulic resistance coefficient of pipelines during petroleum and petroleum products pumping in the turbulent flow regime. Polymers are chemicals with repeated atomic groups, called monomer units. A polymer molecule, composed of *n* units, is called a macromolecule or a polymer chain. Polymers consisting of identical links are called homopolymers, and those of different links are copolymers. The polymer, which has no side branches of the main chain, is called a linear one.

High molecular substances that have the ability to reduce the flow resistance of liquids are conventionally divided into three classes:

synthetic or natural carbon-chain polymers;

coordination polymers;

high molecular petroleum residues.

The existing experience of high molecular substances application for reduction of hydraulic resistance shows that the additives used in industry are produced on the basis of polyolefins, related to carbon-chain polymers and formed during homo- or copolymerization of olefins.

The first report on the applicability of high molecular polymers for reduction of hydraulic resistance of fluid flow in pipelines was made by B.A.Toms [1].

To put the Toms effect in practice there have been made many attempts to find polymers, which can reduce the hydraulic resistance of liquids, and to study the interaction of polymeric macromolecules with a turbulent flow. Many works of such foreign scientists as Toms BA, Hoyt JW, Fabula AG, Parker CF, Norbury JF and Chekalova IA, Ioselevich VA, Stupina AB, Manzhei VM, Nesyna GV, Bilousov VD have been dedicated to the study of the influence of polymer additives on fluids.

It is shown in [2] that the best effect is achieved using polymers with the linear structure of molecules and high molecular weight. Polymer additives do not affect the critical Reynolds number for flow transition from laminar to turbulent regime.

The effect of hydraulic resistance reduction appears when the stress tangents on the wall reach a certain threshold, therefore the effect is not observed during the laminar flow and at the initial range of the turbulent flow [2, 3].

The hydrodynamics of the flow of diesel fuel and aviation fuel TS-1, treated with polymer additives - polibutadien and polyisoprene with different molecular weight [4] has been studied in laboratory conditions. The data on results of laboratory studies and the methodology for evaluating the efficiency of the Viol polymeric additive for reduction of the hydrodynamic resistance during pipeline transportation of oil are presented in [5]. Based on the results we have received a consignment of additives and tested them under industrial conditions [6]. The authors made assumptions about the mechanism of polymer action during turbulent flow laminarization, which consists in smoothing the pressure fluctuations of the flow through the accumulation of energy by macromolecules as a reverse elastic deformation. There has been confirmed the need to develop polymeric additives with a range of effective concentrations from 0.001 to 0.01%.

Using nuclear magnetic resonance method it has been determined in [7] that polyacrylamide polymer additive in the water flow only affects the near-wall

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turbulence of the flow and does not change the Karman constant k in the sphere of logarithmic law of velocity distribution for which:

$$\frac{U}{U_0} = \frac{1}{k} \ln \frac{y}{l_0},$$

where $U_0 = \sqrt{\frac{\tau_w}{\rho}}$ is a dynamic velocity; τ_w is a shear stress on the wall of the pipeline; ρ is the density of petroleum products; y is the distance from the wall of the pipeline; l_0 is a dynamic length.

The attempt to build a semi-empirical theory of turbulent near-wall flows of liquid that contains a polymer molecule has been made in [8]. The characteristics of turbulent transfer in solutions are associated with the ability of macromolecules to deploy and orient in the direction of stretching, abruptly increasing the local anisotropy and energy dissipation in turbulent emissions and reducing their intensity and frequency. As it is shown in [9] the resistance reduction in turbulent flow regime does not depend on the thickness of the adsorption layer as it is assumed in [10]. In case of low concentrations of polymer it can be assumed that the reduction of turbulent friction occurs "at the level" of individual polymer molecules.

Recently there has been proposed the model with the fluctuation layer. The main point of this model is that visco-elastic "drops" of a polymer with the dimensions of 3–4 orders of magnitude larger than the solvent molecules shift to the wall of a pipeline in the flow of liquid with an additive. Here is formed a specific layer of hydrodynamically active polymer. The fluctuation layer is a part of the moving fluid volume unlike the adsorption one.

The polymer concentration decreases in the bulk of the current liquid during formation of the fluctuation layer. At the same time it increases in the near-wall zone. The increase of the polymer content in the flow leads to the emergence of typical visco-elastic properties in fluid, associated with extinguishing of the turbulence.

The polymer molecules have the form of rolled coils in a calm solution. They are subjected to random combinations of vorticity and strain rate in the near-wall zone of the turbulent flow.

The calm course is interrupted by intense emissions of fluid, which is retarded near the wall, in the outer zone of the near-boundary layer. Turbulent emissions are flooded streams. Pulling with tension occurs along the axes of these streams. When the certain velocities of stretching are reached in jet emissions, molecular coils are deployed. Additive molecules absorb some energy of emissions during their deployment and then they prevent further development of jet disturbances by reducing their length and the possibility of new disturbances.

If we suppose that the rate of macromolecules conversion from the volume in the underfluctuation layer (at constant pressure and temperature) is proportional to the concentration of polymer c in solution and the area of the underfluctuation layer, which is not occupied with polymer, then the formula for calculation of the effect of hydraulic resistance reduction is offered in [11]:

$$\varphi = \frac{\lambda_0 - \lambda_f}{\lambda_0}$$

or

$$\varphi = \varphi_{\max} \frac{ac}{1 + ac}.$$

As a result we get

$$\lambda_f = \lambda_0 \left[\frac{1 + ac(1 - \varphi_{\max})}{1 + ac} \right],$$

where a is a constant for this type of additives; $\varphi_{\max}$ is the maximum effect of reduction of the coefficient of hydraulic resistance for this type of anti-turbulence additives.

Thus the development of the formula for the coefficient of hydraulic resistance for all pipelines, using ATA, is important.

Consequently, the use of anti-turbulence additives for transportation of low viscosity petroleum products by main pipelines reduces the value of hydraulic losses in energy, i.e. it facilitates saving of transport energy consumption. However, the introduction of anti-turbulence additives into the flow will result in a linear pipeline section division into two parts: one part is characterized by the motion of pure petroleum product, and another one – by the motion of petroleum product with ATA. Hydraulic losses in each part are different. The change of the length of each part results in the fact that the nature of transportation of the system is transient as long as the mixture of petroleum products and ATA fills the entire pipeline. From a technological point of view it is important to predict the time of motion of a moving boundary and the performance rate of the oil pumping station.

The problem of a non-stationary process in the oil pipeline has been solved in [12] for the conditions of successive pumping of different oils by the pipeline when less viscous oil has been displaced by more viscous one. It has been solved by the method of characteristics disregarding the movement of boundary of various oils distribution.

During implementation of the task for the non-stationary nature of the process caused by the supply of ATA into the oil product pipeline, it is supposed that the area of mixing the product with additives is significantly less than the length of the pipeline, thus it can be neglected, considering the area of contact as one section that moves in a pipeline.

It should be noted that the non-stationary movement of gas in the pipeline causes the complex mathematical models for the description of this movement. Therefore, in order to simplify the models there is made a decision to consider hydrodynamic processes in a plain pipeline because the impact of the route profile on the dynamics of the system motion is not assessed. Isothermal character of petroleum product motion and its mixture with ATA is described by a mathematical model that includes equations of motion and continuity:

$$-\frac{\partial p_j}{\partial x}=\frac{\lambda_j \rho W^2}{2d},$$
$$-\frac{\partial p_j}{\partial t}=c^2\frac{\partial(\rho W)}{\partial x}, \qquad (1)$$

where $p_j(x,t)$ is the pressure as a function of the linear coordinate x and time *t;* λ_j is the coefficient of hydraulic resistance of oil pipeline; ρ is the density of gas; *W* is the cross-sectional average velocity of oil; *c* is the speed of sound in the flow; *j* is the index, which characterizes the position of the moving boundary (the value of *j* = 1 refers to the area that moves before the moving boundary, *j* = 2 refers to the area that moves after the moving boundary).

If we exclude the medium velocity as a linear function of the time coordinate, the equation is the following:

$$-\frac{\partial p_j}{\partial t}=\aleph\frac{\partial^2 p_j}{\partial x^2}, \qquad (2)$$

where $\aleph = c^2/2a$, $2a=\lambda W/2d$ is a linearization coefficient.

The problem is solved under the following conditions:

1. The medium motion is a stationary one and the initial pressure in a pipeline is p_{in}, the final one is p_{fin} before the introduction of ATA in the flow of petroleum products.

2. After the ATA are introduced in the flow of petroleum products and till the end of the replacement process, the pressure is constant and equals p_1 at the beginning of the pipeline, and the consumption *Q* is constant at the end of the pipeline over a certain time period.

3. The equality of linear velocities before and after the contact is reached at the moving boundary.

4. It is necessary to determine the motion of the contact *l(t)* over the time period, and define the motion of petroleum products before and after ATA are introduced.

To achieve the result we can write the initial conditions for the equations (2) in the form:

$$p_1(x,0)=p_{in}-(p_{in}-p_{fin})\frac{x}{L},$$
$$p_2(x,0)=p_{in}. \qquad (3)$$

The boundary conditions are determined by the constant pressure at the beginning of the pipeline and the consumption at the end of it:

$$p_2(0,t)=p_1, \quad -\frac{\partial p_1(L,t)}{\partial x}=\frac{\lambda_1\rho_1 Q^2}{\pi^2 d^5},$$

where *L* is the total length of the pipeline.

At the contact area we assume that linear velocities at both sides of the moving boundary are equal and have the following form:

$$W_1(l,t)=W_2(l,t)=\frac{dl}{dt}. \qquad (4)$$

Based on the first equation of the system (1) the conditions at the end of the area and at the moving boundary are the following:

$$-\frac{1}{\rho_1}\frac{\partial p_1}{\partial x}=\frac{8\lambda_1 Q^2}{\pi^2 d^5},$$
$$\frac{1}{\rho_1}\frac{\partial p_1}{\partial x}=\frac{1}{\rho_2}\frac{\partial p_2}{\partial x}. \qquad (5)$$

To achieve homogeneity of boundary conditions, we introduce a new function $w_J(x,t)$ that satisfies the equation (2) and is connected with the unknown function $p_j(x,t)$ by the ratio

$$p_j(x,t)=w_j(x,t)+\gamma_j+\gamma_{1j}x^2. \qquad (6)$$

The constants γ_j and γ_{1j} should be defined in the way that their boundary conditions were homogeneous:

$$p_2=w_2(0,t)+\gamma_1,$$
$$\frac{\partial p_1}{\partial x}=\frac{\partial}{\partial x}w_1(L,t)+\gamma_1+2\gamma_{11}L.$$

Therefore

$$\gamma_1=p_1,$$
$$\gamma_{11}=\left(p_1+\frac{8\lambda_1\rho_1 Q^2 x}{\pi^2 d^5}\right)\Big/2L.$$

The initial conditions for the functions $w_J(x,t)$ are the following:

$$w_1(x,0)=p_{in}-\left(p_{in}-p_{fin}\right)\frac{x}{L}-\left(p_1+\frac{8\lambda_1\rho_1 Q^2 x}{\pi^2 d^5}\right)\frac{x}{2L}, \qquad (7)$$
$$w_2(x,0)=p_{in}-p_1.$$

According to the correlations (4) and (6) the equation at the moving boundary is the following:

$$\frac{\partial w_1}{\partial x}=\frac{\partial w_2}{\partial x}. \qquad (8)$$

Based on the Fourier method the equation (2) has the following form:

$$w_j(x,t)=X_j(x)T_j(t).$$

For the derivatives the equation is the following:

$$\frac{\partial^2 w_j}{\partial x^2}=X_j'' T_j, \quad \frac{\partial w_j}{\partial t}=X_j T_j'.$$

The equation is as follows:

$$\frac{X_j''}{X_j}=\frac{T_j'}{T_j}=-\omega^2, \qquad (9)$$

where ω is a constant number that is to be defined.

The solutions (9) are the following:

$$X_j=A_j\cos\omega x+Bj\sin\omega x,$$
$$T_j=C\exp\left(-\omega^2\aleph t\right), \qquad (10)$$

where A_j, Bj, C are the constants of integration.

Based on the condition of homogeneity of the function $w_j(x,t)$, the values are $A_2=0$, $B_1=0$ at the boundaries. In this case the condition of equality of linear velocities on the moving boundary is the following:

$$\sin\omega l=\cos\omega\left(L-l(t)\right). \qquad (11)$$

From (11) we get the following equation for ω :

$$\sin\left(\frac{\pi}{4}+\omega\left(\frac{L}{2}-l(t)\right)\right)=0 .$$

Therefore

$$\omega_n=\frac{(4n-1)\pi}{2\left(L-2l(t)\right)} . \quad (12)$$

It is obvious that the value ω depends on the position of the moving boundary in the pipeline and changes over time period. Therefore, it should be specified at each time step.

Now the solutions for $w_j(x,t)$ are the following:

$$w_1(x,t)=b_n\exp\left(-\frac{(4n-1)^2\pi^2\aleph t}{4\left(L-2l(t)\right)^2}\right)\sin\frac{(4n-1)\pi(L-x)}{2\left(L-2l(t)\right)},$$

$$w_2(x,t)=a_n\exp\left(-\frac{(4n-1)^2\pi^2\aleph t}{4\left(L-2l(t)\right)^2}\right)\cos\frac{(4n-1)\pi x}{2\left(L-2l(t)\right)}. \quad (13)$$

Constants of integration a_n and b_n can be calculated as an expansion of the Fourier coefficients of functions $w_j(x,t)$:

$$a_n=\frac{2}{l}\int_0^l(p_{in}-p_1)\cos\frac{(4n-1)\pi x}{2\left(L-2l\right)}\,dx,$$

$$b_n=\frac{2}{L-l}\int_0^{L-l}(p_{in}-p_1)\left(1-\left(1-\frac{(p_{fin}-p_2)}{(p_{in}-p_1)}\right)\frac{x}{L}\right)\times \quad (14)$$

$$\times\sin\frac{(4n-1)\pi(L-x)}{2\left(L-2l\right)}\,dx,$$

where $l=l(t),\quad p_2=\dfrac{8\lambda_1\rho_1Q^2L}{\pi^2d^5}.$

Now the dependencies for the unknown functions of pressure distribution along the length of the pipeline and in time are the following:

$$p_1(x,t)=p_1-\frac{p_1-p_2}{L}x+\frac{2}{L-l}\sum_{n=1}^{\infty}\left\{\sin\frac{(4n-1)\pi(L-x)}{2\left(L-2l\right)}\times\right.$$

$$\times\exp\left(-\frac{(4n-1)\pi^2\aleph t}{4(L-2l)^2}\right)\int_0^{L-l}\left((p_{in}-p_1)-\right.$$

$$\left.\left.-\left((p_{in}-p_1)-(p_{fin}-p_2)\right)\frac{x}{L}\right)\sin\frac{(4n-1)\pi(L-x)}{2\left(L-2l\right)}dx\right\},$$

$$p_2(x,t)=p_1+\frac{2}{l}\sum_{n=1}^{\infty}\left\{\cos\frac{(4n-1)\pi x}{2\left(L-2l\right)}\times\right. \quad (15)$$

$$\left.\times\exp\left(-\frac{(4n-1)\pi^2\aleph t}{4(L-2l)^2}\right)\int_0^{l}(p_{in}-p_1)\cos\frac{(4n-1)\pi x}{2\left(L-2l\right)}dx\right\}.$$

Implementation of (15) to determine the characteristics of hydrodynamic process requires representation of the law of motion of the contact *l(t)* in an analytical or numerical form. However, this law is unknown and needs to be determined. Therefore, the problem can be solved by the iterative method. That is why the period of motion of the contact by pipeline is broken into time intervals Δt and the velocity of the motion is constant during these intervals. The intervals can be sufficiently small to ensure this condition.

At the initial moment of time the linear velocity at the beginning of the pipeline during stationary operating regimes of a pipeline and its capacity Q_m is the following one:

$$W_0=\frac{Q_m}{F} , \quad (16)$$

where F is a sectional area of the pipeline.

It is assumed that the rate of motion of the initial contact point is equal to the linear rate of motion of the petroleum product W_0. In this case the distance, covered by the moving boundary at the time interval Δt, is the following:

$$l_0=W_0\ \Delta t . \quad (17)$$

Based on the first equation of the system (2) the linear velocity of the petroleum product is:

$$W=\left(-\frac{2d}{\lambda\rho}\frac{\partial p_j}{\partial x}\right)^{1/2} . \quad (18)$$

Then we calculate the derivative $\partial p_2/\partial x$, specify the linear velocity of a petroleum product, and the distance covered by the piston during the time interval Δt from (18) on the basis of the second equation of the system (15). Refinement is made with the required accuracy until the covered distance l coincidences. Then we calculate pressures at each point of the pipeline at time interval Δt based on (15). The initial approximation of gas linear velocity for the next time interval is its value from the previous time interval.

Thus, having successively determined the distances, covered by the contact at regular time intervals Δt, we can build the graph of its motion in the pipeline. The algorithm stops calculating if the condition $l = L$ is reached, that is, till the moment when the contact has passed the whole linear distance.

To implement the mentioned algorithm there is made a program for calculations of the conditions of the plain petroleum product pipeline. The calculation results are shown as graphs in Figures 1 and 2.

The analysis of graphs shows that the velocity of a contact grows at the constant pressure at the beginning of the pipeline for the entire period of its motion. This is due to a decrease in hydraulic resistance of a pipeline over time with increasing length of the area, which is occupied by the mixture of petroleum products with anti-turbulence additive. Correlation of the final and initial velocities of the contact in length and time is 2.61, causing an increase in the loss of petroleum products. However, in case of sustainable withdrawal, a non-stationary process at the end of a pipeline is characterized by final pressure increase due to the reduction of hydraulic losses. Calculations show that the increase in the loss of petroleum products at the beginning of the pipeline is 1.3 – 1.4 times in comparison with the initial rate of motion, and the growth of pressure at the end of the area is 2.0 – 2.1 times. This shows the high efficiency of anti-turbulence additives in pipeline transportation of petroleum products.

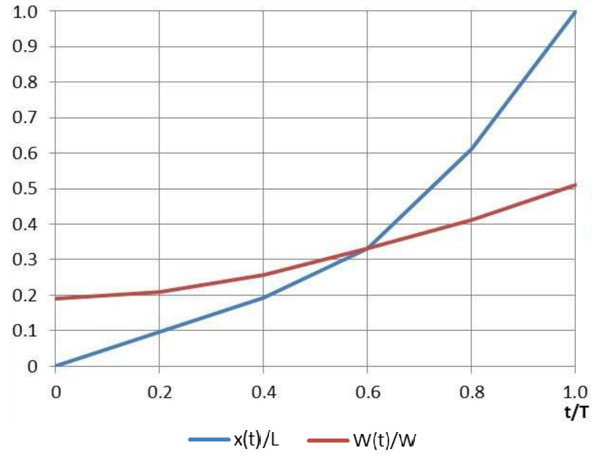
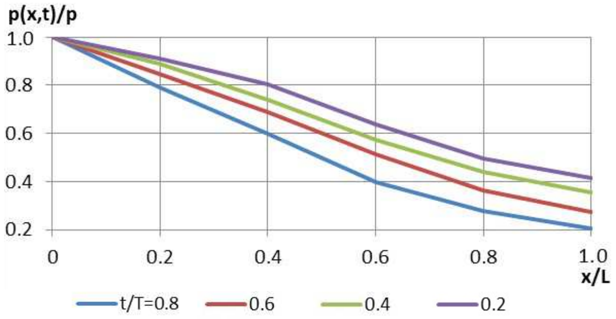
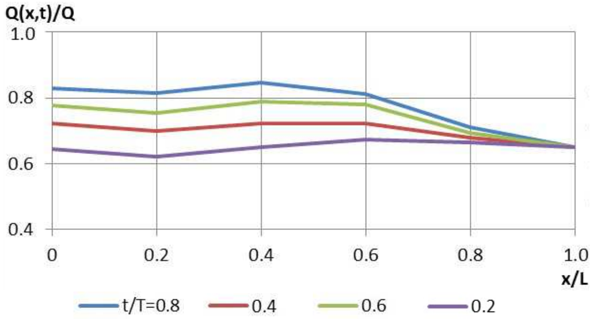


Figure 1 – The motion mode of petroleum product contact and its mixture with ATA



a)



b)

Figure 2 – The variation of petroleum product (a) and pressure loss in the pipeline (b) in length and time

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УДК 622.691.4

Нестаціонарні процеси у нафтопродуктопроводі при використанні протитурбулентних присадок

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Розглядається задача нестаціонарної течії нафтопродукту в трубопроводі з використанням протитурбулентних присадок. Побудована математична модель руху контакту двох рідинних середовищ з різними гідравлічними характеристиками в трубопроводі, реалізація якої дає змогу прогнозувати зміну тиску і витрати нафтопродукту впродовж нестаціонарного процесу заміщення.

Ключові слова: *нестаціонарний процес, протитурбулентна присадка, рухома границя.*