Enhancement of Hydrodynamic Processes in Oil Pipelines Considering Rheologically Complex High-Viscosity Oils

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Abstract
This paper describes a mathematical model of flow-related hydrodynamic processes for rheologically complex high-viscosity bitumen oil and oil-water suspensions and presents methods to improve the design and performance of oil pipelines.

1. Introduction
Production of high-viscosity and paraffinic oils has been steadily increased in the Russian Federation over last two decades, which relates to the deterioration in petroleum supply condition and significant depletion of high-yield fields. Paraffinic oils are produced in promising oil regions in the north of European Russia, Republic of Komi, Yamalo-Nenets and Khanty-Mansi Districts, Western Siberia. Mature fields of Kazakhstan and Turkmenistan are developed in a similar manner.

The process of involving more alike fields into the development is constrained by necessity of searching non-conventional engineering solutions and significant expenditures for production of high-viscosity oils and delivery them to the customers. Primarily, such energy requirements are associated with the need to overcome the viscous friction forces. For that purpose, temperature heating of oils is widely used to reduce their effective viscosity. At the same time, high-viscosity paraffinic oils are rheologically complex fluids frequently exercising pseudo plastic characteristics. This offers challenges to control effective oil viscosity and considerable reduction in friction of piping due to flow share rate.

Intensifiers as regular configurable discrete pipe roughness or inserts different in size are usually used for flow shearing. Such authors as Ye.M. Khabakhpasheva, B.S. Petukhova, G.A. Dreitzer, G. Astarita, G. Marucci, Yu.G. Nazmeyeva, A.Ye. Bergls, O.V. Mitrofanova and others, who study the effects to reduce flow friction in channels with intensifying devices when flowing in viscous as well as pseudo plastic fluids, describe in their papers that vortex intensifiers, e.g. vane, screw, belt vortex generators or those in the form of helical pipes are sufficiently efficient for such flows. Selection of the optimal shape and design parameters of intensifiers depends on many factors – the rheological and thermophysical characteristics of the service environment, climate conditions, extended sections, etc., which requires multivariate calculations and comparative analytical researches [4]. In such circumstances, the processes should be mathematically modelled.

The problem of determining the laws of the hydrodynamic characteristics of abnormally viscous oils flowing in the oil pipelines and active channels is complex and requires systematisation. Although, it is a problem of great engineering importance, there were not enough researches
conducted so far, and the present study is aimed to find solution to the identified problem through mathematical modelling. The problem statement is as follows:

We consider the steady laminar isothermal flow of oil in the pipeline with vortex generators [5]. The flow temperature $t_0$ in the zone of interest is assumed constant; while the averaged flow temperature varies in the range from $t_0 = 10^\circ C + 20^\circ C$.

2. The research object

The objectives of the study are set from the standpoint of classical hydrodynamics and with the definition of the components of the velocity vector in a helical coordinate system if the flow integrity, constant oil flow and boundary conditions of flow adhesion on the pipe wall are imposed (velocity $V_{\text{limit}} = 0$) [2].

The main problem at the solution of objectives associated with study of a convective heatmass transfer in channels special complexity is hydrodynamic calculation. The solution of the system of hydrodynamic equations includes the equations of movement and continuity makes by the Galerkin’s approximation [4].

Let’s find the created speed profile at a laminar flow of nonlinear viscoelastic liquid in the channel with a screw knurl. Although the tensor of tension in a timepoint $t$ described by nonlinear symmetric tensor functionality from history of deformation and decays in a row Taylor in the vicinity $t=0$ on N-orders kinematic tensors of Whyte-Mettsner $B_N$ [6]:

$$B_{N+1} = \frac{d}{dt}(B_N) - (B_N \cdot \nabla V^T) - (\nabla V \cdot B_N), \quad (1)$$

$$B_1 = 2D, \quad (2)$$

where $D = \frac{(\nabla V + \nabla V^T)}{2}$ - the deformation speeds tensor.

Generally view of the set of equation describing this objective and including the equations of movement and continuity:

$$(V \cdot \text{grad} = -\frac{1}{\rho} \text{grad}P + \frac{1}{\rho} \text{div}(T^0), \quad (3)$$

$$\text{div}(V) = 0, \quad (4)$$

$$V|_\Gamma = 0, \quad (5)$$

where $T^0$ – deviator of the stress tensor.

All the borders of taken channel can be provided by family of screw surfaces. A screw channel regardless of cross-section profile possesses one-parametrical group of screw symmetry. As a result required speed field can be considered independent of system of coordinates directed on a channel axis.

To determine the rheological oil characteristics, a differential type model is used, in which the stress tensor relates to the strain rate tensor through a nonlinear function of the effective viscosity dependent on the second invariant of the strain rate tensor.

The stress tensor is defined as:

$$T = -pI + \phi_1 \cdot (I_2) \cdot B_1, \quad (6)$$
where $I_2 = 4 \cdot tr \cdot D^2 = tr \cdot B_1^2$.

The material magnitude $\varphi_1$ can be characterised by sufficiently complex $I_2$ functions. One of these functions for viscosity ($\varphi_1(I_2)$) is the Kutateladze-Khabakhpasheva model:

$$\varphi_p = \exp(-\tau_p),$$

where $\varphi_p = (\varphi_\infty - \Phi)/(\varphi_\infty - \varphi_0)$,

$$\tau_p = \theta (\tau - \tau_1)/(\varphi_\infty - \varphi_0)$$

where $\tau = \varphi_1(I_2) \sqrt{I_2}/2; \Phi = 1/\varphi_1(I_2), \varphi_0, \varphi_\infty - yield$.

To present temperature dependences $\varphi_1$, exponential dependence of primary rheological parameters $\varphi_\infty, \varphi_0, \theta, \kappa$ on temperature $t$ is used:

$$\varphi_\infty = A_\infty \cdot \exp(-B_\infty t/(Rt));$$

$$\varphi_0 = A_0 \cdot \exp(-B/(Rt));$$

$$\theta = \theta_\infty \cdot \exp(-B_\infty t/(Rt));$$

$$\kappa = \kappa_0 \cdot \exp(-C t/(Rt)),$$

where $A_\infty, A_0, \theta_0, \kappa_0$ - pre-exponentials;

$B_\infty, B_0$ - activation energy of viscous flow at $\tau \to 0, \tau \to \infty$.

$C$ - constant similar to $B_\infty, B_0$;

$R$ - gas constant.

System of hydrodynamic equations with boundary condition $V|_r = 0$ has to correspond to an integrated ratio:

$$\iint_L \{ \rho (\nabla V \cdot \tilde{h}) - (\text{div}(\rho V^0) \cdot \tilde{h}) + (\nabla P \cdot \tilde{h}) \} dL = 0,$$

where $\tilde{h}$ - any element of space of solenoidal vector functions $H_2^1(\Omega)$.

Boundary condition is satisfied for element $\tilde{h}$ ($\tilde{h}|_r = 0$). For sequence of basic functions $h^{(1)}, h^{(2)}$, ..., $h^{(n)}$, belongs to space $H_2^1(\Omega)$, has to correspond:

$$\iint_\Omega \{ \varphi_1 B_1(V^{(n)}):D(h^{(k)}) + \varphi_2 B_2(V^{(n)}):D(h^{(k)}) +$$

$$+ (\rho(V^{(n)} \nabla V^{(n)}) + \nabla P)h^{(k)} \} d\Omega = 0.$$
This system represents the functional operator $L_0$, defined as $(L_0 V, h) = 0$, can be described through the operators $L_1, L_2$ for which ratios are carried out $(L_1 V, h) = 0, (L_2 V, h) = 0$.

Thus:

$$
(L_1 V, h) = \int_{\Omega} \varphi_1 \left[ \frac{\partial V}{\partial q^1} \frac{\partial h}{\partial q^1} + \left( \frac{\partial V}{\partial q^2} \frac{\partial h}{\partial q^2} + \frac{A}{q^3} \frac{\partial V}{\partial q^3} \right) \frac{\partial h}{\partial q^1} + \left( \frac{2}{q^2} \right) \frac{\partial}{\partial q^1} \left( V^2 + k V^3 + \frac{\partial V}{\partial q^2} \frac{\partial h}{\partial q^1} \right) \right] d\Omega = 0,
$$

Taking into account screw symmetry of a current can say that $\frac{\partial \rho}{\partial q^3} = C = \text{const.}$

$$
\frac{\partial \rho}{\partial q^2} = - \frac{1}{q} \int_{\Omega} \varphi_1 \left[ \left( A \frac{\partial V}{\partial q^1} + k (q^1)^2 \frac{\partial V}{\partial q^1} \right) \frac{\partial V}{\partial q^2} + \left( A^2 \frac{\partial V}{\partial q^2} \frac{\partial h}{\partial q^1} \right) \frac{\partial V}{\partial q^1} + \frac{2k}{q^1} V_1 \frac{\partial V}{\partial q^1} \right] d\Omega = 0.
$$

3. Conclusions

A twisted tape insert and helical round-shaped wall ledges are taken as intensifying vortex generators. The parameters of vortex generators vary between $S/D = 2-10; d/D = 0.6-0.95$ ($D =$ pipe ID, $d =$ reduced diameter of pipe flow area with vortex generator, $S =$ twisting step) [3].

Analysis of studying pseudo plastic flow used in the petrochemical industry, can be expected to reduce the effect of the pipe friction for isothermal flows of viscoplastic oils only through a localised impact on the flow at the level of 10-15%.

References

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