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Modeling Rheological Properties in Blending of Anomalously Viscous Oils

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Abstract: If the oil quality characteres are linearly additive and could be quite easily calculated even with a large number of mixing components, questions of predicting the rheological parameters of the mixtures being formed during the joint pipeline transportation of blended products from fields to destination points are not yet solved. At the same time the relevance that problem, especially in the transport of anomalous high-viscosity and solidifying oils many times increases because of tighten requirements for reliability and energy-efficiency of operating regimes of trunk pipeline system. It is considered vary prediction methods of flowability of oil mix properties and existing blend models, including based on the so-called asymptotic universal model previously proposed by the researchers. The results of approximation for wide known models and high-precision ways of calculation rheological properties for oil blends of various compositions on the basis of analysis of experimental data are presented.

Key words: Rheological model, non-Newtonian oil, anomalously viscous oil, modelling, blend, joint transportation, pipeline run

INTRODUCTION

Domestic as well as foreign experience has presented (Tashbulatov and Karimov, 2017) that the reduction in energy consumption for pipeline transportation could be reached by rheological optimal ratio of blending components in the formation of pipeline run, efficient mixing schemes and regimes of joint transportation of oils, taking into account the features of mixtures being formed (Anonymous, 2009).

From the point of view of the operating energy efficiency, a pipeline run formed by oilscompounded at different operational sections of trunk pipeline systems should have sufficient fluidity over a wide range of temperatures and operating rates, characterized both by low values of effective viscosity and the pour point. In this case, both stationary as well as starting operation conditions after long stops should correspond to the levels of the permissible operating pressures and therefore values and growth rates of the static (initial) shear stress should be minimal in order to allow safe restarting of pumping and reaching on required parameters of the planning operating regimes.

A joint transportation of compounded oils should not lead to an increase in operating costs-the growth of direct (temperature, pressure) and the emergence of additional (indirect) costs (the need for highly expensive “special” methods, increasing the frequency of in-line pigging from asphaltene-resin-paraffin deposits of oil) which is especially important when mixing oil types, different densities where very often rheological effect can not be predicted and the possibility of manifestation of “incompatibility” could bring to the high negative effect (separation of blended oils with precipitation of heavy deposits, losses of oil volume because of “shrinkage” effect) (Golovanchikov and Kidalov, 2014; Fuchs, 2003; Chernikin, 2010; Kusakov, 1936).

The inexpediency of constructing separate own pipelines and often not the possibility of separate transportation of “problem” oils at low volumes of production at remote fields also indicates the need to expand the practice of joint transportation of oils in cases where even usage of “special methods” do not provide the required level of operational reliability and profitability.

Forecasting the character of the flow of oil blends and right selecting of reliable models for describing main rheological properties of fluids co-transported by the same trunk oil pipeline can significantly improve the accuracy of hydraulic calculations at the actual operating conditions of pipelines and allows to predict of expected risks and accidents which makes it possible to make a system of smart controlling of oil blending in order to increase the reliability of technological regimes and reduce operating pumping costs (Sviridov *et al.*, 1970; Tkharn *et al.*, 2015).

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Most of the oil types co-transported in the oil trunk pipeline system under actual existing operating conditions refers to low viscous Newtonian fluids which pumped without using expensive special methods (thermal or chemical treatment). However, on some operational sections of the united trunk pipeline oil system there are intake points of anomalous viscous oils with a high content of resins, asphaltenes and paraffins. Experience has shown that as a result of changes in the world market's conjuncture of oil when main export routes are redirected or the system overall loss of capacity, the proportion of problematic high-viscosity and solidifying oils can significance increase substantially in result is an appearance of non-Newtonian properties reduces the efficiency of operating regimes (Kurnakov, 1938, 1940).

Such changes require the adoption of early preventive actions that aimed at maintaining the required throughput of pumping with taking into account the changed conditions, up to the need to use expensive special methods, the effective usage of which is impossible without taking into account the actual fluid rheological properties which are the complex blends of various oils (ASTM D7152-11, 2016).

Taking into account all the foregoing, the development of new methods for predicting the oil fluidity and universal models for describing rheological laws of complex mixtures exhibiting anomalously viscous non-Newtonian properties are urgent tasks of oil pipeline transportation.

MATERIALS AND METHODS

Method of analysis: In order to establish empirical laws of oil blending processes and evaluating the reliability of various models for describing the character of flow for high viscosity and solidifying fluids the experiments with blends of bitumen and high paraffinic oils together co-pumped through the trunk pipelines have been made.

The results of rheological studies obtained on experimental blends with different ratios of compound oils are presented at Fig. 1. At Fig. 2 a fragment of an anomalous zone concentration range (0-50%) have been singled out separately at which blending of considered oils is leading to appearance of a non-Newtonian properties.

At present to describe the anomalous flow of high viscous oils by indications of a rotational viscometer the Balkley-Herschel approximation equation is generally used:

$$\tau = \tau_0 + K\dot{\gamma}^n \qquad (1)$$

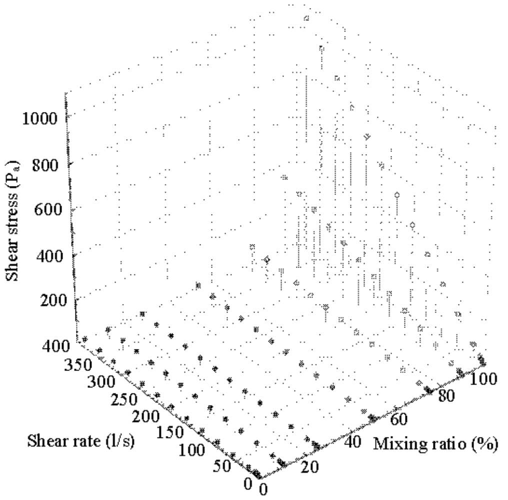

Fig. 1: Experimental values of rheological parameters of binary oil blends (dots describes experimental measurements)

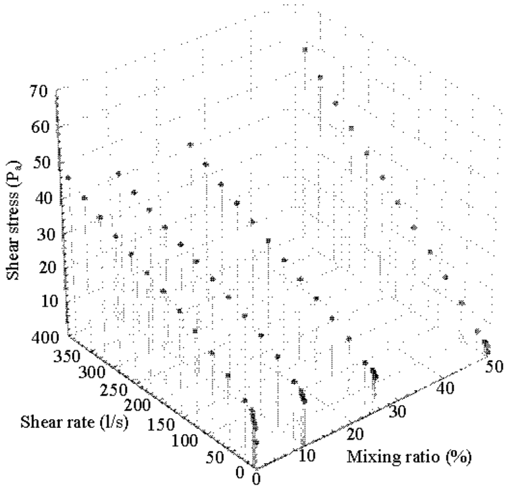

Fig. 2: Anomalous zone, 0-50% mass of bitumen oil solved in high paraffinic oil (dots describes experimental measurements)

Where:

τ_0 = Static (initial) shear stress
K = Coefficient of consistency
n = Index of nonlinearity

That equation in general describes the behavior of a nonlinear viscoplastic fluid and in special cases reduces to a pseudo-plastic fluid flow at $\tau_0 = 0$ (Oswald-de Waal Model), visco-plastic at n = 1 (Shvedov-Bingham Model) and Newtonian viscous flow at $\tau_0 = 0$ and n = 1.

In view of the fact that the considered Balkley-Herschel equation is not a rheological law as such and is used just because of their convenient form of regression processing of experimental data (the dimensions of the used parameters are devoid of real physical meaning), researchers suggest the use of the own universal asymptotic equation for describing rheological properties of any types of oil:

$$\tau=\tau_d+\mu\dot{y}-\frac{\left(\tau_d-\tau_s\right)\dot{y}_{\Delta\tau/2}}{\dot{y}+\dot{y}_{\Delta\tau/2}} \qquad (2)$$

Where:

τ = Static (initial) shear stress

τ_d = Dynamic shear stress

$\dot{y}_{\Delta\tau/2}$ = Shear rate at which the value of the shear stress is equal to half the difference between the values of τ_d and τ_s stresses

Let's make a comparative analysis of the accuracy of using the model developed by the researchers with the widely used Buckley-Herschel equation (Karimov and Mastobaev, 2012; Bakhtizin *et al*., 2016 Tkharn *et al*., 2015) for which purpose we approximate the experimental values of the rheological tests of the mixtures given in Fig. 1 and 2.

The choice of the complexity of the model (determination of the type of flow: Newtonian viscous, visco-plastic, pseudo-plastic, nonlinear visco-plastic) for all the considered variants of mixing was carried out from the condition of a minimum of the average risk functional criteria, according to the methodology described by Kh and Bakhtin (1999). The functional of the average risk should be evaluated using the following parameter:

$$I_m\left(a\right)=\left[\frac{I_0\left(a\right)}{1-\sqrt{\dfrac{n\left(\ln\left(1\right)+1\right)-\ln\left(\eta\right)}{1}}}\right]_{\infty} \qquad (3)$$

$$\left[z\right]_{\infty}=\begin{cases}z, & z\geq 0\\ \infty, & z<0\end{cases} \qquad (4)$$

Where:

n = Number of model parameters

η = Probability that the risk will be less than or equal to its estimate

RESULTS AND DISCUSSION

Table 1: The Results of model approximation of experimental data by using the criterion of the average risk functional

Concentration of bituminous oil in the blend (%)	Rheological model
0	Nonlinear visco-plastic
10	Nonlinear visco-plastic
25	Nonlinear visco-plastic
50	Visco-plastic
75	Newtonian
90	Newtonian
100	Newtonian

The results of model approximation of experimental data using a so-called criterion of "the average risk functional" are presented, described previously (Table 1). Based on the regression analysis carried out, the following dependences of the change in the parameters of the proposed "asymptotic model" equation on the mixing ratio of oils (x) have been obtained. For the dynamic shear stress:

$$\tau_d=\begin{cases}-0.3152x+18.93, & x<60.06\\ 0, & z\geq 60.06\end{cases} \qquad (5)$$

For the plastic (structural) viscosity:

$$\lg\left(\lg\left(\mu_{mix}\right)\right)=\begin{cases}x\lg\left(\lg\left(\mu_1\right)\right)+\left(100-x\right)\lg\left(\lg\left(\mu_2\right)\right)-\\ 0.455x\left(100-x\right)18.93, x<50.00\\ x\lg\left(\lg\left(\mu_1\right)\right)+\left(100-x\right)\lg\left(\lg\left(\mu_2\right)\right)-\\ 1.151x\left(100-x\right)18.93, x\geq 50.00\end{cases} \qquad (6)$$

The difference between the dynamic and static stresses (the parameter characterizing the transition from nonlinear to visco-plastic zone):

$$\Delta\tau_{ds}=\begin{cases}-0.3969x+12.46, & x<31.39\\ 0, & x\geq 31.39\end{cases} \qquad (7)$$

The complex characterizing the change in the area of the anomalous flow zone bounded by spread of experimental points:

$$\dot{\gamma}_p\cdot\Delta\tau_{ds}=\begin{cases}-22.687x+613.21, & x<27.03\\ 0, & x\geq 27.03\end{cases} \qquad (8)$$

The results obtained of approximating the experimental flow curves by using the proposed asymptotic equation are shown at Fig. 3 and 4. According to the results obtainedby the approximation there is a gradual transition of anomalous nonlinear flow (0-30%) to visco-plastic (30-60%) and further to Newtonian (60-100%) with a sharp increase in values of dynamic viscosity.

At Fig. 4 in anomalous viscous range of concentration, upon closer examination, a zone of optimal oil mixing ratio (0-40%) is traced at which shear stresses in blend assumes values even less than in original oils

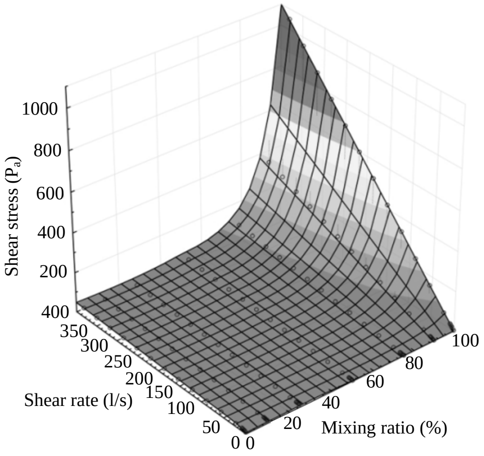

Fig. 3: The results of approximating the experimental flow curves by asymptotic model through at the whole concentration range

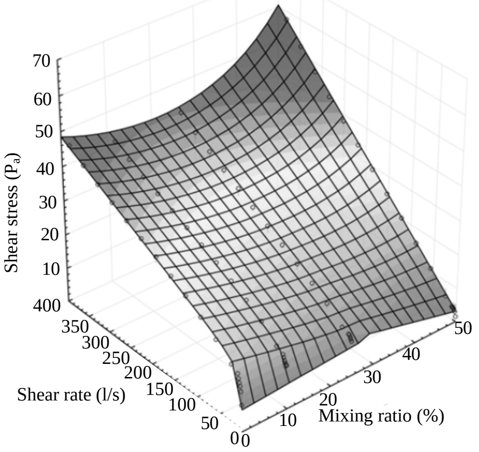

Fig. 4: The results of approximating the experimental flow curves by asymptotic model through at the anomalous viscous zone

before blending. The sum of the squared deviations of this model is 160.6 and the average risk functional is 313.9 which indicates a fairly high reliability of the model used. For the comparative evaluation of the accuracy of the proposed model also carried out by the same way a regression analysis for the approximate equation of wide used the Barkley-Herschel's Model. For the static (initial) shear stress:

$$\tau_0 = \begin{cases} -0.0071x^2+0.2021x+10.72, & x<54.84 \\ 0, & x\geq 54.84 \end{cases} \quad (9)$$

For the coefficient of consistency:

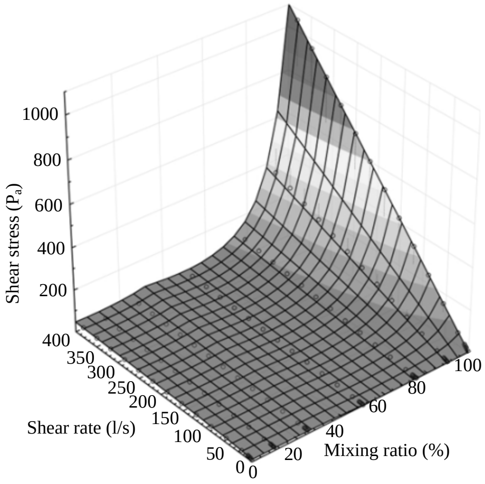

Fig. 5: The results of approximating the experimental flow curves by Balkley-Hershel Model through at the whole concentration range

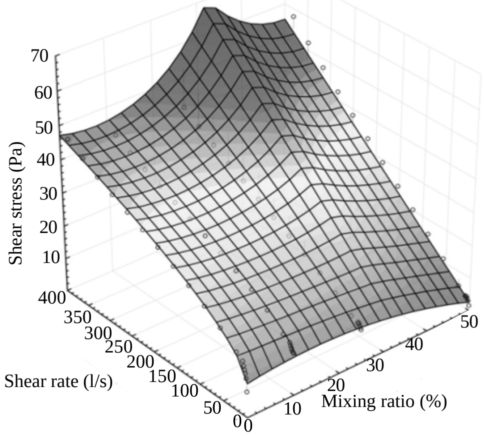

Fig. 6: The results of approximating the experimental flow curves by Balkley-Hershel Model through at the anomalous viscous zone

$$\begin{aligned} &\lg(\lg(K_{mix})) = x\lg(\lg(K_1))+ \\ &+(100\text{-}x)\lg(\lg(K_2))\text{-}4.345x\,(100\text{-}x) \end{aligned} \quad (10)$$

For the index of nonlinearity:

$$n = \begin{cases} 0.0122x+0.606, & x<32.30 \\ 1, & x\geq 32.30 \end{cases} \quad (11)$$

The results obtained by approximation of rheological parameters for experimental blends on the basis of the Balkley-Hershel Model are presented in Fig. 5 and 6. At

Fig. 6, it is pronounced deviations of the experimental values of shear stress in blends from the calculated values based on the Balkley-Herschel Model are clearly visible. In the zone of manifestation of non-Newtonian properties an increase in shear stresses is observed in the concentration range of 30-50% which does not correspond to reality. The jump in the calculated values of the shear stresses is explained by the fact that the dimension of the parameter K (consistency) varies depending on the exponent n which indicates the lack of physical meaning of the latters. For a correct description of the oil blending laws it is necessary to introduce more additional dependencies connecting the values of coefficients. K and n which complicates the approximation way of experimental data by the Balkley-Herschel Model and couldn't be made by the standard methods of regression analysis for description law of variation of the equation coefficients.

The sum of the squared deviations of this model is 778.8 while the average risk function is 1385.9. These parameters turned out to be much less than when using the asymptotic flow model proposed by the authors.

CONCLUSION

Thus, the usage of the asymptotic flow equation developed by the authors in modeling the compounding of non-Newtonian oils makes it possible to avoid large errors in predicting the rheological properties of fluid, having provided the required level of reliability and accuracy of hydraulic calculations of oil pipelines.

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