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The Asymptotic Rheological Model of Anomalously Viscous Oil

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Abstract: A math modelling of viscosity/temperature properties of anomalous non-Newtonian oilis of great interest, both from as the point of view of fundamental research well asoperation tasks of pipeline transportation of oil. Thermohydraulic calculations, determining the time of safe stop and starting characteristics of non-isothermal pipelines for highly paraffin and heavy oil require the use of reliable models that could accurately describe the actual flow laws in a wide range of temperatures and rates. It is in detail considered the shortcomings of existing equations for describing the flow parameters of non-Newtonian fluids, also is proposed the new rheological model and algorithm for automating the calculation of its parameters. The results of the accuracy estimation of the proposed method are compared with Balkley-Herschel equation.

Key words: Rheological model, non-Newtonian fluids, anomalously viscous oil, modeling, Balkley-Herschel, estimation

INTRODUCTION

The high content of paraffins, resins and asphaltenes in oil complicates the processes of its extraction, field collection and transportation (Tashbulatov and Karimov, 2017; Kh and Bakhtin, 1999). Anomalous viscosity and high pour point lead to loss of oil fluidity increase a value of hydraulic resistance of pipeline, operation costs. A non-Newtonian anomalous character of flow complicates the calculation of viscosity-temperature properties of oil in the range operating temperature and rate (ASTM D7152-11, 2016). The authenticity and accuracy of a model used determines the calculated values of the viscosity and initial shear stress necessary to calculate the predicted modes, the time of safe stops and the starting parameters of flow on non-isothermal pipelines transporting viscous and solidifying oils (Golovanchikov and Kidalov, 2014; Anonymous, 2009). A value of the relative error in pumping volume depending on predicted value of kinematic viscosity calculated by the adopted model varies in a wide range for Laminar mode:

$$\frac{\Delta Q}{Q} = -\frac{\Delta v}{v} \tag{1}$$

For turbulent flow conditions in the zone of hydraulically smooth pipes:

$$\frac{\Delta Q}{Q} = -\frac{1}{7}\cdot\frac{\Delta v}{v} \tag{2}$$

For turbulent flow conditions in the zone of mixed friction:

$$\frac{\Delta Q}{Q} = -\frac{0{,}123}{1{,}877}\cdot\frac{\Delta v}{v} \approx -\frac{1}{15}\cdot\frac{\Delta v}{v} \tag{3}$$

It follows from Eq. 1-3 that the relative error in calculating the throughput of pipeline is directly proportional to the value of the viscosity in the laminar regime and can be from 6-14% of the pumping volume for different turbulent regime zones (Tashbulatov and Karimov, 2017).

MATERIALS AND METHODS

By Kh and Bakhtin (1999) 15 flow different rheological models proposed by various researchers are considered on the basis of which the recommendations are given on a choice of the model from the results of experimental data. Especially, distinguished are the following types of models, most often used in practice: Newtonian viscous liquids:

$$\tau = \mu\dot{\gamma} \tag{4}$$

Shvedov-Bingham for visco-plasticliquids:

$$\tau = \tau_0 + \mu\dot{\gamma} \tag{5}$$

Ostwald de Waal for pseudo-plastic liquid:

$$\tau = K\dot{\gamma}^n \tag{6}$$

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Universal approximation equation of Balkley-Herschel for nonlinear pseudo-plastic fluids:

$$\tau = \tau_0 + K\dot{\gamma}^n \quad (7)$$

Investigation of the rheological properties of high-viscosity and solidified oil is carried out by rotational viscosimetry methods, concluding in obtaining of flow curves from the instrument readings data representing the dependence of the shear stress τ on the velocity gradient γ' (Tkharn *et al.*, 2015; Fuchs, 2003).

To describe a flow of a Newtonian fluid, it suffices to have just one experimental Eq. 8 determining the slope's character of the straight line emerging from the origin of the co-ordinate, then the tangent of this angle will be equal to the value of the dynamic viscosity (Chernikin, 2010; Kusakov, 1936). A flow curve of a visco-plastic fluid is described by at least two Eq. 9 and 10. In both cases, the experimental flow curves are quite easily approximated by the method of least squares:

$$\mu = \frac{\sum_{i=1}^{1} \dot{\gamma}_i \tau_i}{\sum_{i=1}^{1} \dot{\gamma}_i^2} \quad (8)$$

$$\tau_0 = \frac{\sum_{i=1}^{1} \tau_i \sum_{i=1}^{1} \dot{\gamma}_i^2 - \sum_{i=1}^{1} \dot{\gamma}_i \sum_{i=1}^{1} \dot{\gamma}_i \tau_i}{1\sum_{i=1}^{1} \dot{\gamma}_i^2 - \left(\sum_{i=1}^{1} \dot{\gamma}_i\right)^2} \quad (9)$$

$$\mu = \frac{1\sum_{i=1}^{1} \dot{\gamma}_i \tau_i - \sum_{i=1}^{1} \dot{\gamma}_i \sum_{i=1}^{1} \tau_i}{1\sum_{i=1}^{1} \dot{\gamma}_i^2 - \left(\sum_{i=1}^{1} \dot{\gamma}_i\right)^2} \quad (10)$$

The presence of the nonlinear anomalous zone of viscosity at low velocities, manifested in the pseudo-plastic fluids, quite complicates the computation of the parameters of the model used Eq. 6 and could be similarly calculated after the linearization of the model:

$$K = \exp\left(\frac{\sum_{i=1}^{1} \ln \tau_i \sum_{i=1}^{1} \ln^2 \dot{\gamma}_i - \sum_{i=1}^{1} \ln \dot{\gamma}_i \sum_{i=1}^{1} \ln \dot{\gamma}_i \ln \tau_i}{1\sum_{i=1}^{1} \ln^2 \dot{\gamma}_i - \left(\sum_{i=1}^{1} \ln \dot{\gamma}_i\right)^2}\right) \quad (11)$$

$$n = \frac{1\sum_{i=1}^{1} \ln \dot{\gamma}_i \ln \tau_i - \sum_{i=1}^{1} \ln \dot{\gamma}_i \sum_{i=1}^{1} \ln \tau_i}{1\sum_{i=1}^{1} \ln^2 \dot{\gamma}_i - \left(\sum_{i=1}^{1} \ln \dot{\gamma}_i\right)^2} \quad (12)$$

The universality of the Balkley-Herschel equation lies in the fact that due to the variation of the parameters it allows one to describe any of the above models (Eq. 4-7). The parameters of the approximation equation could be determined in two different ways, requiring certain math skills which complicates the process of constructing the model manually.

In the first method, the Balkley-Herschel equation is linearized in the following way (Golovanchikov and Kidalov, 2014):

$$\ln(\tau - \tau_0) = \ln K + n \ln \dot{\gamma} \quad (13)$$

The parameters K, n are determined by the method of least squares according to Eq. 11 and 12 and the value of the initial shear stress is determined iteratively at which the sum of the squares of the deviations will take the minimum value:

$$f(\tau_0) = \sum_{i=1}^{1} \left(\tau_i - \left(\tau_0 + K\dot{\gamma}^n\right)\right) \rightarrow \min \quad (14)$$

In the second method (Eq. 13*), the variable γ' is replaced to the γ^n, the parameters K, n are obtained by the least-squares method according to Eq. 9 and 10 and n is determined iteratively at which the sum of the squares of the deviations, Eq. 10 will take the minimum value.

From the point of view of practical use of different models it is important to know that the more parameters used, the more precisely they describes the experimental data. However with increasing complexity of the rheological model, measurement errors and excursion of conditions, imperceptible in the interpolation interval, could significantly change the behavior of the flow curve during the forecasting stage (outside the measurement range). This means that the model is overridden that is the number of parameters is unreasonably overestimated. The process of a identification the true model from the obtained experimental data with a limited sample size linked with problem of correctly correlating the complexity of that model with the amount and level of error of the available data (Kh and Bakhtin, 1999).

For example, Kh and Bakhtin (1999), Tkharn *et al.* (2015), Fuchs (2003), Chernikin (2010), Kusakov (1936), Golovanchikov and Kidalov (2014) and Anonymous

(2009), the choice of flow models is determined by two criteria the mean square deviation (as the functional of empirical risk) and the medium risk function. The mean square deviation is determined by Eq. 15:

$$I_0(a) = \frac{1}{1}\sum_{i=1}^{1}\left(y_i - F(x_i, a)\right)^2 \quad (15)$$

Where:

a = Model parameter
I = Sample size

The functional of the average risk should be evaluated using the following parameter:

$$I_m(a) = \left[\frac{I_0(a)}{1-\sqrt{\frac{n(\ln(1)+1)-\ln(\eta)}{1}}}\right]_\infty \quad (16)$$

$$[z]_\infty = \begin{cases} z, z \geq 0 \\ \infty, z < 0 \end{cases} \quad (17)$$

Where:

n = Number of model parameters
η = Probability that the risk will be less than or equal to its estimate

Another one model that deserves interest from the point of view of the universality of its usage is the Shulman rheological model:

$$\tau^{\frac{1}{n}} = \tau_0^{\frac{1}{n}} + \left(\mu_{pl}\dot{\gamma}\right)^{\frac{1}{m}} \quad (18)$$

where n, m-coefficients of nonlinearity. Last model also assumes non-linearity of ductility and viscosity. It includes most of the used rheological equations is a generalization of the currently used models: Newton (τ_0 = 0, m = n = 1), Shvedov-Bingham (m = n = 1), Ostwald (τ_0 = 0) and Balkley-Herschel (n = 1). The above model has found considerable application in the description of non-Newtonian systems but even that so-called universal model does not allow approximation whole flow curve over the entire rate rangeat constant coefficients n, m.

Despite the universality use of the above described flow models, variable values of dimensions of the coefficients used indicate the absence of a physical meaning of the latters. Moreover, as the shear rate is increased, the proposed universal Eq. 7 and 8 do not correspond to the real character of the flow and theoretical rheological notions of the asymptotic approaching value of viscosity to the called consistency of fluid (Karimov and Mastobaev, 2012; Bakhtizin *et al*., 2016).

RESULTS AND DISCUSSION

Because previously described models are not rheological laws as such and used because of their convenient form to the regression analys of experimental data (values of dimensions have no physical meaning) for describing the flow law of anomal-viscousity liquids over the entire range of shear rates it is proposed to use the following equation obtained by extrapolating rectilinear portion of the experimental flow curve for the following boundary condition (Fig. 1):

$$\lim_{\dot{\gamma}\to\infty(\text{at }\dot{\gamma}\geq\dot{\gamma}_p)} f(\dot{\gamma}) = \tau_d + \mu\dot{\gamma} \quad (19)$$

The proposed equation has the following form:

$$\tau = \tau_d + \mu\dot{\gamma} - \frac{(\tau_d - \tau_s)\dot{\gamma}_{\Delta\tau/2}}{\dot{\gamma} + \dot{\gamma}_{\Delta\tau/2}} \quad (20)$$

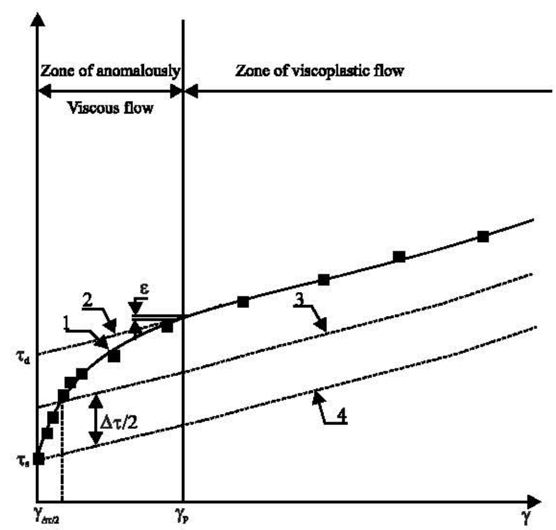

Fig. 1: Asymptotic rheological model (1-dependence of transient shear stress τ relative to γ; 2-asymptotic line; 3-middle auxiliary line; 4-auxiliary line passing through τ_s value; τ-shear stress; γ-shear rate; τ_d-dynamic stress; τ_s-static stress; γ_p-transient shear rate; Δτ-difference between dynamic and static shear stress; $\gamma_{\Delta\tau/2}$-shear rate at which the value of the shear stress is equal to half the difference between the dynamic τ_d and static τ_s stresses; ϵ-stress deviation from viscoplastic flow at the boundary of zones)

where, $\gamma_{\Delta\tau/2}$ shear rate at which the value of the shear stress is equal to half the difference between the dynamic τ_d and static τ_s stresses.

The parameters τ_d and μ are determined by the least squares method according to Eq. 9 and 10 by extrapolating the straightline part of the curve corresponding to the plastic viscosity to the intersection with the ordinate axis (stress).

To determination transition boundaries between plastic and viscous flow zone, experimental data sampling I_j obtained by decreasing the terms of the sampling I is determined from the following conditions:

$$\mu_{1\text{-}j} \leq \mu_{1\text{-}(j\text{-}1)} \quad (21)$$

$$Se_{\tau(1\text{-}j)} \leq Se_{\tau(1\text{-}(j\text{-}1))} \quad (22)$$

$$Se_{\tau(1\text{-}j)} = \sqrt{\frac{1}{1\text{-}j\text{-}2}\sum_{i=1}^{1\text{-}j}\left(\tau_i\text{-}\tau_d\text{-}\mu\dot{\gamma}\right)^2} \quad (23)$$

Where:

Se_τ = Standard error for estimating τ with linear approximation of data sampling (i-j)

j = Number of excluded points

According to Eq. 23, the deviations of the shear stresses from the values, calculated for the straightline continued part $\tau_d+\mu\gamma$ are described by the Eq. 24:

$$\Delta\tau = \frac{\left(\tau_d\text{-}\tau_s\right)\dot{\gamma}_{\Delta\tau/2}}{\dot{\gamma}+\dot{\gamma}_{\Delta\tau/2}} \quad (24)$$

To estimate the parameters τ_s, $\gamma_{\Delta\tau/2}$ in the transition anomalus-viscous zone performs the following transformations:

$$\frac{1}{\Delta\tau} = \frac{1}{\left(\tau_d\text{-}\tau_s\right)\dot{\gamma}_{\Delta\tau/2}}\dot{\gamma}+\frac{1}{\left(\tau_d\text{-}\tau_s\right)} \quad (25)$$

After the following replacement of variables:

$$\dot{\gamma}_{\Delta\tau/2} = \frac{B}{A} \quad (26)$$

$$\tau_s = \tau_d\text{-}\frac{1}{B} \quad (27)$$

$$T = \frac{1}{\Delta\tau} \quad (28)$$

As a result, we get:

$$T = A\dot{\gamma}+B \quad (29)$$

The values of the coefficients A and B are also determined by the method of least squares according to Eq. 9 and 10.

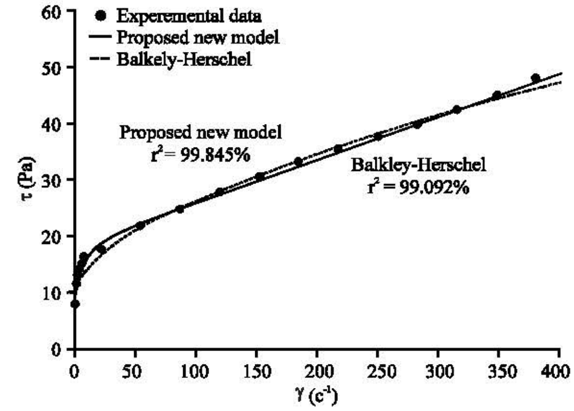

Fig. 2: The results of the approximation of the proposed model for high-viscosity oil in comparison with the Balkley-Herschel Model

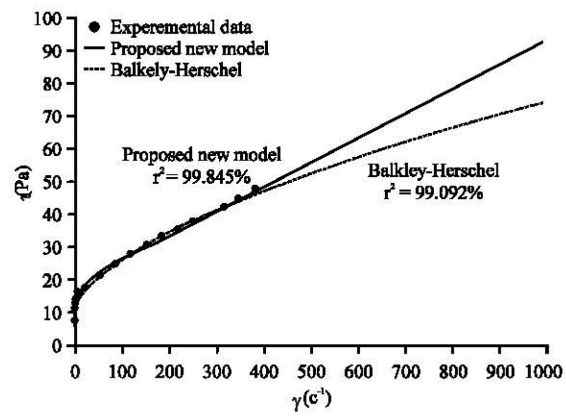

Fig. 3: The forecast of a change in the nature of the flow in comparison with the Balkley-Herschel Model

To identify the transition point between steeply curved and straightlined zones, it should be introduced the variable γ_p corresponding to the rate at which the deviation of the model from the asymptote exceeds a certain value ε:

$$\dot{\gamma}_p = \frac{\left(\tau_d\text{-}\tau_s\right)\dot{\gamma}_{\Delta\tau/2}}{\varepsilon}\text{-}\dot{\gamma}_{\Delta\tau/2} \quad (30)$$

If assume ε equals the value of root-mean-square deviation of the linear approximation of the visco-plastic flow zone, then Eq. 23 could be defined by 4 parameters in the anomal-viscous zone and by 2 parameters-in the visco-plastic flow zone. So, the number of parameters should be calculated by the following formula:

$$n = \frac{2\dot{\gamma}_p\text{-}4(\dot{\gamma}_{max}\text{-}\dot{\gamma}_p)}{\dot{\gamma}_{max}} \quad (31)$$

Figure 2 and 3 presents results of comparison of the approximation of the experimental flow curve a high paraffinic oil by proposed new model and the known Balkley-Herschel Model.

CONCLUSION

Thus, the accuracy of the proposed model, estimated by the coefficient of determination is comparable (actually 1% more accurate) to the wide known universal Balkley-Herschel Model while further increasing the shear rate, it fully corresponds to the asymptotic character of the flow law, approaching the value of certain liquid consistency which allows . It is used in the entire range of rates without changing the constants of that model. To calculate the latters, the researchers have developed a special algorithm that makes it possible to automate the process of constructing a model from the readings of shear rate and stress data measured by rotational viscometer.

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