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A COMPREHENSIVE HYDRAULIC CALCULATION METHOD OF NON-NEWTONIAN FLUIDS USED FOUR-PARAMETER MODEL

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Accurate predictions of hydraulic parameters are essential for drilling operations. A comprehensive method of hydraulic parameter calculation is presented for a four-parameter rheological model. Based on the Rabinowitsch-Mooney equation, the explicit equation between the wall shear stress and volumetric flow rate of this model for pipe was obtained. When modeled as a slot, the equation for annular flow is also obtained. A new generalized flow index and effective diameter for annular flow were defined through theoretical analysis based on Metzner & Reed's study. The new generalized effective diameter accounts for the effects both of annulus geometry and fluid rheology. Based on the definition of Fanning friction factor, the general expression of generalized Reynolds number for both annulus and pipe were derived in view of the fact that the generalized flow index is non-constant. We show the calculation method for generalized flow index and a utility pressure losses calculation model. The predictions of this method have been compared with an extensive set of data from literature. The comparisons of pressure loss show excellent agreement over laminar and turbulent flow regimes.

Keywords: comprehensive method, hydraulic calculation, four-parameter model, generalized effective diameter, solution for n'.

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Introduction

The determination of frictional pressure losses in the circulating system has been an objective of technology for almost as many years as rotary drilling has been in existence. As deeper well are being drilled in search of new crude oil and natural gas reserves, the prediction and control the rheology of drilling fluid and the hydraulics of drilling become increasingly important. Especially, with the implementation and promotion of the management pressure drilling (MPD) technology, the role of accurately predicted hydraulic parameters becomes vital portion of drilling operation, which provided technical support for engineering decisions to ensure high-quality fast drilling [1,2].

Pivotal to the drilling hydraulic calculation is the rheology model used to characterize the flow behavior of the drilling fluid and cements. Earliest the Bingham plastic [3] and power law model [4] are often used for drilling hydraulic calculation, which have gained widespread acceptance within the petroleum industry because of their simplicity. Herschel & Bulkley [5] presented a yield power law model and then Cementing research section [6] published their papers to discuss the application of this model. Casson [7] presented an improved two-parameter model, which was discussed by Chen [8]. Robertson and Stiff [9] presented a new rheological model and then the application of this model was described in detail by Liu and Huang [10, 11]. Nowadays, with many wells drilled deep, slim or horizontal on the shore and off shore using more complex drilling fluids, as yet no single rheological model is able to accurately represent the behavior of all them over the full spectrum of shear rates [12]. And a new powerful rheological model was proposed to describe the drilling fluid flow behavior by Fan et al., which called four-parameter model [13]. And so in this article a comprehensive hydraulic calculation method for this model both in pipe and annuli was proposed.

1. Four-parameter model

The Four-parameter model proposed by Fan et al. is shown in Eq. (1) [13]:

$$\tau = \tau_0 + a\gamma + b\gamma^c \qquad (1)$$

Where: τ is shear stress, Pa;

τ_0 is yield stress, Pa;

γ is shear rate, s^{-1};

a is coefficient of viscosity, Pa·s;

b is consistency coefficient, Pa·s^c;

c is the flow behavior index, dimensionless.

As seen in Eq. (1), this model is the combination of Bingham and Power-law model, based on which the apparent viscosity μ_{app} can be given by:

$$\mu_{app} = \frac{\tau_0}{\gamma} + a + b\gamma^{c-1} \qquad (2)$$

From Eq. (1) and Eq. (2) we can see using this model can described both the yield value and infinite apparent viscosity of drilling fluid.

2. Comprehensive hydraulic method

2.1 Flow equation in pipe and annuli

2.1.1 Flow equation of pipe flow

The geometry of pipe flow is shown in figure 1. As for the steady state laminar flow of any time-independent purely viscous fluid in pipe, Herzog &

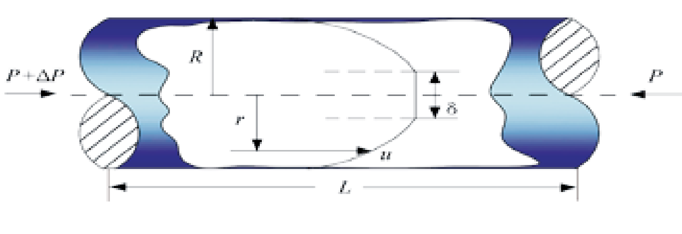

Fig.1. Illustration of the four-parameter fluid flow in pipe

Weissenberg first developed an equation called pipe flow rate equation that relate the pipe flow rate to the wall shear stress [14]:

$$Q=\frac{\pi R^3}{\tau_w^3}\int_0^{\tau_w}\tau^2\gamma d\tau \qquad (3a)$$

Where: Q is flow rate, m^3/s;

R is the radius of pipe, m;

τ_w is the wall shear stress, Pa.

The Eq. (3a) is generalized flow rate equation for the viscous fluid flow in pipe. And for the fluid with a yield stress, the integration interval of Eq. (3a) will be [τ_0, τ_w], then the flow rate equation could be rearranged as the following:

$$Q=\frac{\pi R^3}{\tau_w^3}\int_{\tau_0}^{\tau_w}\tau^2\gamma d\tau \qquad (3b)$$

Substituting Eq.(1) into Eq.(3b) and integrating it, then the flow rate equation for four-parameter fluid in pipe can be derived as following:

$$Q_p=\frac{\pi R^3}{\tau_w^3}\left(\frac{\tau_0^2 a\gamma_w^2}{2}+\frac{2\tau_0 a^2\gamma_w^3}{3}+\frac{a^3\gamma_w^4}{4}+\frac{c}{c+1}\tau_0^2 b\gamma_w^{c+1}+\right.$$
$$+\frac{c+1}{c+2}2\tau_0 ab\gamma_w^{c+2}+\frac{c+2}{c+3}a^2 b\gamma_w^{c+3}+\frac{2c}{2c+1}\tau_0 b^2\gamma_w^{2c+1}+$$
$$\left.+\frac{2c+1}{2c+2}ab^2\gamma_w^{2c+2}+\frac{c}{3c+1}b^3\gamma_w^{3c+1}\right) \qquad (4)$$

Where the subscript "p" represents the variable in pipe, γ_w is the wall shear rate, s^{-1}.

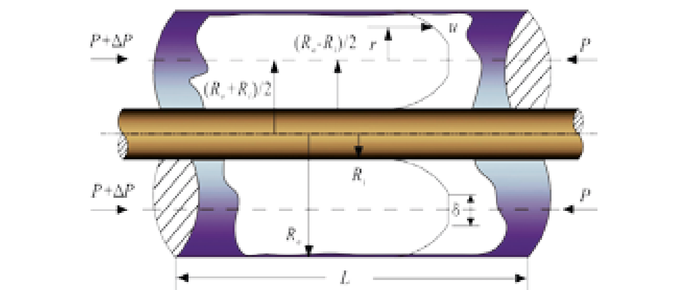

Fig.2. Illustration of the four-parameter fluid flow in annuli

2.1.2 Flow equation of annular flow

The geometry of four-parameter fluid flow in annuli as a slot is depicted in figure 2, where R_i and R_o are the radii of the inner and outer cylinders. There is a central core of the fluid which moves as a rigid plug if the shear stress levels are smaller than the yield stress of the fluid, the thickness of central core is δ.

For annular flow, as the slot model is reasonably accurate as long as the ratio $R_i/R_o > 0.3$ [15,16], therefore the slot model will be used for the Four-parameter rheological model flow in annuli. We take two thin ring elements in annuli, the radius of one ring element is $(R_o+R_i)/2+r$ and the radius of the other is $(R_o+R_i)/2-r$, both of their thickness is dr. Assuming the velocity is u at r, and so the flow rate equation may be expressed as:

$$Q=\int_0^{\frac{R_\delta}{2}}2\pi\left(R_o+R_i\right)udr=$$
$$=2\pi\left(R_o+R_i\right)\left(ur\Big|_0^{\frac{R_\delta}{2}}-\int_0^{\frac{R_\delta}{2}}r\frac{du}{dr}dr\right) \qquad (5)$$

Where R_δ is the annular clearance ($R_\delta=R_o-R_i$), m.

Since $u = 0$ when $r = R_\delta/2$ (no slip at the wall), hence $ur\Big|_0^{\frac{R_\delta}{2}}=0$. Then the Eq. (5) can be simplified to:

$$Q=2\pi\left(R_o+R_i\right)\int_0^{\frac{R_\delta}{2}}r\left(-du/dr\right)dr \qquad (6)$$

For a yield fluid such as four-parameter fluid, since $-du/dr = 0$ when $r < \delta/2$, so the Eq.(6) may be expressed as:

$$Q=2\pi\left(R_o+R_i\right)\int_{\frac{\delta}{2}}^{\frac{R_\delta}{2}}r\left(-du/dr\right)dr \qquad (7)$$

Based on the simple force balance principle, the shear stress of the fluid layer at r can be taken the form [9, 17]:

$$\tau=\frac{\Delta Pr}{L} \qquad (8)$$

Where ΔP is the pressure loss, Pa.

Similarly, the annular wall shear stress τ_w can be written as:

$$\tau_w=\frac{\Delta PD_{hy}}{4L}=\frac{\Delta PR_\delta}{2L} \qquad (9)$$

Where D_{hy} is annular hydraulic diameter, $2R_\delta$, m.

Combined Eq.(8) and Eq. (9), then the following formula can be obtained:

$$\frac{\tau}{\tau_w}=\frac{2r}{R_\delta} \qquad (10)$$

Eq.(10) may be rearranged and then the following equations can be derived:

$$r=\frac{R_\delta}{2\tau_w}\tau \quad \text{and} \quad dr=\frac{R_\delta}{2\tau_w}d\tau \qquad (11)$$

The solution of Eq. (7), utilizing the condition that $\gamma = (-du/dr) = f(\tau)$, combining Eq. (7) and Eq. (11), and substituting the foregoing for r and dr, we obtain:

$$Q=\frac{\pi\left(R_o+R_i\right)R_\delta^{\;2}}{2\tau_w^2}\int_{\tau_0}^{\tau_w}\tau\gamma d\tau \qquad (12)$$

And following similar approach as pipe flow, substituting Eq.(1) into Eq.(12) and integrating them, the annular flow rate equation for four-parameter model can be derived as following:

$$Q_a=\frac{\pi(R_o+R_i)R_\delta^2}{4\tau_w^2}\left(a\tau_0\gamma_w^2+\frac{2}{3}a^2\gamma_w^3+2b\frac{c}{c+1}\tau_0\gamma_w^{c+1}+\right.$$
$$\left.+2ab\frac{c+1}{c+2}\gamma_w^{c+2}+b^2\frac{2c}{2c+1}\gamma_w^{2c+1}\right) \qquad (13)$$

Where the subscript "*a*" represents the variable in annuli.

The flow rate equations show that the volumetric flow is function of wall shear rate, shear stress and rheological parameters. For a given flow rate, the flow equation of pipe or annuli viz. Eq.(4) and Eq.(13) can be solved using numerical method, and then γ_w and τ_w will be obtained.

2.2 Generalized Flow Index

2.2.1 Generalized flow index for pipe flow

Metzner & Reed defined a generalized flow index n_p' based on the Rabinowitsch-Mooney equation for pipe flow, the definition formula of n_p' is expressed as [18]:

$$n_p'=\frac{d\ln\tau_w}{d\ln\left(8v/D\right)} \qquad (14)$$

Where: n' is the generalized flow index, dimensionless;

v is the mean velocity, m/s;

D is the diameter of pipe, m.

And then they rearranged the Rabinowitsh-Mooney equation as following form:

$$\gamma_{w,a,n} = \frac{12v}{D_{hy}} \tag{15}$$

2.2.2 Generalized flow index for annular flow

Kelessidis et al. gave the concentric annuli Newtonian wall shear rate $\gamma_{w,a,n}$ expression formula which modeled as a slot as following form [19]:

$$\gamma_{w,p} = \frac{3n_p'+1}{4n_p'}\left(\frac{8v}{D}\right) \tag{16}$$

Rabinowitsch [20] & Mooney [21] introduced the pipe flow characteristic parameter $8v/D$. Follow them we could also rewritten Eq.(16) as $\gamma_{w,a,n} = 8v\Big/\left(\tfrac{2}{3}D_{hy}\right)$ so that the annular shear rate can be put into the same form as the shear rate of Newtonian pipe flow. The volumetric flow rate of concentric annuli could also be written as:

$$Q = \pi(R_0 + R_i)\, R_\delta v \tag{17}$$

Combining Eq. (12) and Eq. (17), the following equation can be derived:

$$\frac{8v}{\tfrac{2}{3}D_{hy}}\tau_w^2 = 3\int_{\tau_0}^{\tau_w} \tau\gamma \, d\tau \tag{18}$$

Eq. (18) may be rearranged and differentiated with τ_w:

$$\gamma_{w,a} = \frac{2}{3}\left(\frac{8v}{\tfrac{2}{3}D_{hy}}\right) + \frac{1}{3}\frac{d\left(8v/\tfrac{2}{3}D_{hy}\right)}{d\tau_w}\tau_w \tag{19}$$

The Eq. (19) is the wall shear rate formula of annular flow. Following the generalized flow index n_p' for pipe flow, a new generalized flow index for Four-parameter fluid flow in annuli viz. n_a' can be defined as:

$$n_a' = \frac{d\ln\tau_w}{d\ln\left(8v/\tfrac{2}{3}D_{hy}\right)} \tag{20}$$

Introducing the above relation expression to Eq.(19) and simplifying, the following equation for $\gamma_{w,a}$ can be obtained:

$$\gamma_{w,a} = \frac{2n_a'+1}{3n_a'}\left(\frac{8v}{\tfrac{2}{3}D_{hy}}\right) \tag{21}$$

2.2.3 Solution of generalized flow index

Eq.(15) and Eq.(21) are the simplified formula of the four-parameter fluid wall shear rate in pipe and annuli, which is the function of the generalized flow index and the Newtonian wall shear rate. For a given flow rate, if the values of wall shear rate obtained in the section 2.1 use numerical method and then inserted them into Eq.(15) and Eq.(21), then the generalized flow index of four-parameter fluid both in pipe and annuli can be computed easily.

2.3 Generalized effective diameter

Reed & Pilehvari defined an "effective diameter" so that the wall shear rate of pipe can be put into the same form as the shear rate for Newtonian pipe flow, the effective diameter $D_{eff,p}$ for pipe flow is [22]:

$$D_{eff,p} = \frac{4n_p'}{3n_p'+1}D \tag{22}$$

Where D_{eff} is the generalized effective diameter, m.

For four-parameter fluid annular flow, we followed Reed & Pilehvari and defined a new effective diameter $D_{eff,a}$ for annular flow as:

$$D_{eff,a} = \frac{2n_a'}{2n_a'+1}D_{hy} \tag{23}$$

Based on the generalized effective diameter, the wall shear rate both pipe and annuli can be put into the same form as the shear rate of Newtonian pipe flow:

$$\gamma_w = \frac{8v}{D_{eff}} \tag{24}$$

2.4 Generalized Reynolds number

The Fanning friction factor for the steady, stabilized, laminar flow defined as $f = 2\tau_w/\rho v^2$ [18]. The wall shear stress formula of pipe flow can be obtained from a force balance principle, viz. $\tau_w = (\Delta pD)/(4L)$, and the formula for annular wall shear stress was given by Eq. (9).

Then we combined the wall shear stress formula with Fanning friction definition formula, viz. $f=2\tau_w/\rho v^2$. And referenced to the formula relate friction factor to Reynolds number for Newtonian pipe flow, viz. $f = 16/Re$, the generalized Reynolds number for four-parameter fluid can be obtained:

$$Re_{g,p} = \frac{\rho D v}{\left(\frac{3n'+1}{4n'}\right)\tau_w\Big/\gamma_w} = \frac{\rho\left(\frac{4n'}{3n'+1}\right)Dv}{\tau_w/\gamma_w} = \frac{\rho D_{eff,p}v}{\tau_w/\gamma_w} \tag{25a}$$

$$Re_{g,a} = \frac{\rho\left(\frac{2}{3}D_{hy}\right)v}{\left(\frac{2n_a'+1}{3n_a'}\right)\tau_w\Big/\gamma_w} = \frac{\rho\left(\frac{2}{3}\frac{3n_a'}{2n_a'+1}D_{hy}\right)v}{\tau_w/\gamma_w} = \frac{\rho\left(\frac{2n_a'}{2n_a'+1}D_{hy}\right)v}{\tau_w/\gamma_w} = \frac{\rho D_{eff,a}v}{\tau_w/\gamma_w} \tag{25b}$$

Where Re_g is generalized Reynolds number, dimensionless.

Reed & Pilehvari gave the expression of apparent viscosity as $\mu_{w,app} = \tau_w/\gamma_w$ [22]. And then the generalized Reynolds number for both pipe and annuli can be rewrite as:

$$Re_g = \frac{\rho D_{eff}v}{\mu_{w,app}} \tag{26}$$

In summary of the preceding paragraphs it can be seen that both of pipe and annular flow for four-parameter fluid can be linked to the Newtonian fluid pipe flow based on the generalized effective diameter and generalized Reynolds number.

2.5 Pressure loss calculation

The next step in the mathematical development is to relate the Reynolds number to the Fanning friction factor (f) after obtained n', Re_g and D_{eff}. As mentioned previously, the laminar flow Fanning friction factor for both pipe and annuli can be expressed as the following formula:

$$f = \frac{16}{Re_g} \tag{27}$$

Where f is Fanning friction factor, dimensionless.

For turbulent flow, we can use the friction factor equation that Dodge & Metzner [23] proposed for smooth pipe and the equation that Reed & Pilehvari [22] proposed for rough pipe.

For smooth pipe:

$$\frac{1}{\sqrt{f}} = \left(\frac{4}{n'^{0.75}}\right)\log_{10}\left(Re_g f^{(1-n'/2)}\right) - \frac{0.395}{n'^{1.2}} \qquad (28)$$

For rough pipe:

$$\frac{1}{\sqrt{f}} = -4\log_{10}\left\{\frac{0.27\varepsilon}{D_{eff}} + \frac{1.26^{(n')^{-1.2}}}{\left[Re_g f^{(1-0.5n')}\right]^{n'^{-0.75}}}\right\} \qquad (29)$$

Where ε is the absolute roughness, m.

Thus, the pressure loss is calculated by the following equation:

$$\Delta P = \begin{cases} 2f\dfrac{\rho v^2}{D}L & \text{pipe flow} \\ 2f\dfrac{\rho v^2}{D_{hy}}L & \text{annular flow} \end{cases} \qquad (30)$$

Where ρ is the density of fluid, kg/m^3.

3. Results and discussion

The accuracy of the predictions of this comprehensive method has been determined by comparing with experimental data from works reported previously. The first experimental data used is from work by Okafor [24]. These data were two different drilling fluids flowing in different size pipe and annuli, all conduit section were 10.973 m long and effectively smooth. The second source of experiment data is the published work by Subramanian, who measured pressure drops for a wide of drilling fluids in a large flow loop operated by Amoco [25].

In figure 3, the comparison of predictions with fluid A in 2in pipe laminar flow experimental results of Okafor's is shown. Very good match is seen for the laminar flow prediction data with measure data. The prediction of the different fluid and pipe is shown in figure 4, which shows that the results used this comprehensive method have a very good match for both laminar and turbulent flow in pipe. Figure 5 and figure 6 show the comparison of laminar predictions for different fluid in different annuli, the predicted values of Four-parameter hydraulic model match the experimental data closely in annuli.

Figure 7 through 9 compare predicted and experimental pressure drops from the Subramanian's study. Experimental data of figure 7 was measured in both laminar and turbulent flow regimes for Bentonite 1 mud in smooth pipe. The agreement is satisfactory in both laminar and turbulent regimes. Figure 8 shows the Bentonite 2 mud in rough pipe over laminar and turbulent, the comparison of predicted and experimental are matched so good. Figure 9 shows results of a mixed-metal-hydroxide (MMH) mud in concentric annuli. Similarly,

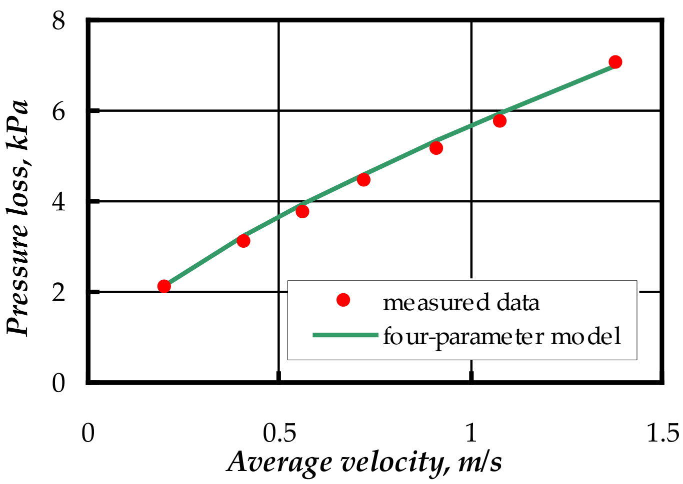

Fig.3. Comparison of predictions with measurements of fluid A in 2in pipe

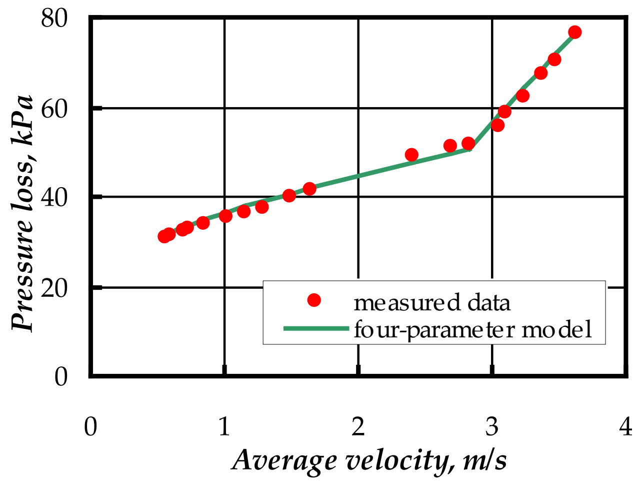

Fig.4. Comparison of predictions with measurements of fluid B in 1in pipe

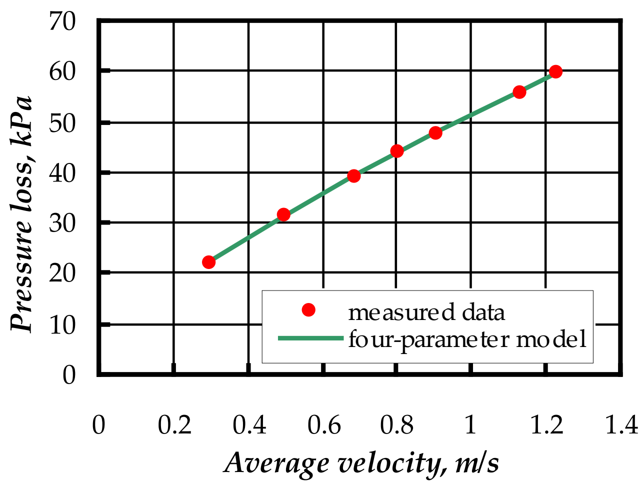

Fig.5. Comparison of predictions with measurements of fluid A in annuli (3×2in)

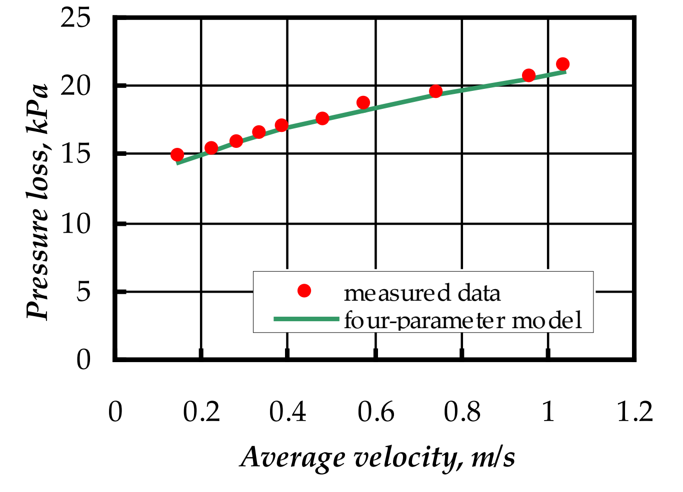

Fig.6. Comparison of predictions with measurements of Fluid B in annuli (3×1in)

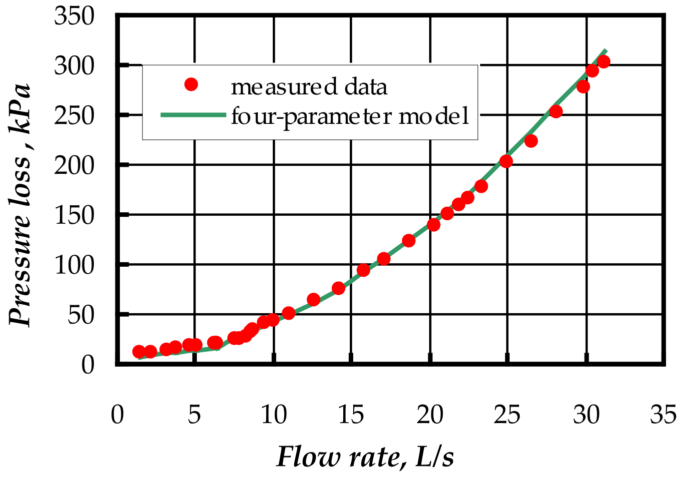

Fig.8. Comparison of predictions with measurements of Bentonite mud 2 in rough pipe

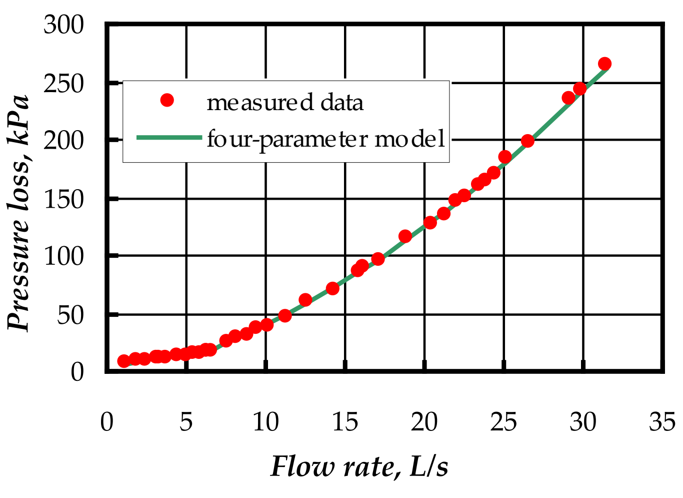

Fig.7. Comparison of predictions with measurements of Bentonite mud 1 in smooth pipe

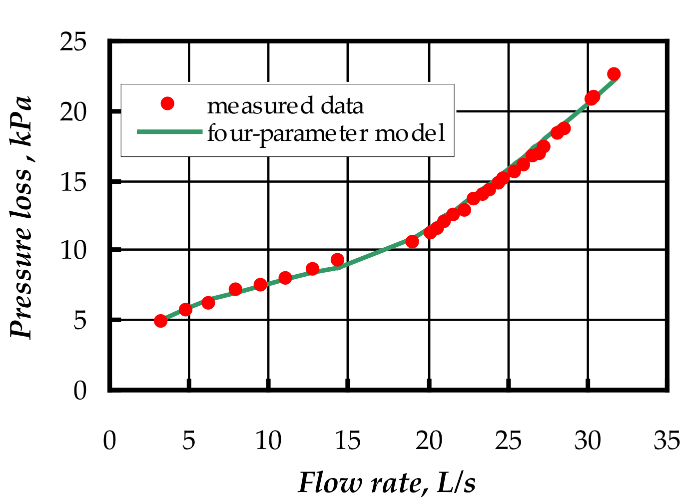

Fig.9. Comparison of predictions with measurements of MMH mud in annuli

there is good agreement between predicted and experimental values.

There is excellent match with the experimental results of both laminar and turbulent flow in different pipe and annuli, because of the laminar flow pressure loss obtained by accurate flow equation and the four-parameter model can describe the drilling fluid rheological properties excellently. For the turbulent flow, the pipe and annular flow pressure loss can be calculated use unified empirical formula through the generalized Reynolds number Re_g and generalized flow index n'. Obviously, the calculated pressure losses are also match with the measured results excellently.

4. Conclusions

Based on the pipe flow equation the accurate flow equation of Four-parameter model was derived and modeled as a slot the flow equation of annuli was obtained too. Then the comprehensive hydraulic model which predicts the pressure drop covering both the laminar and turbulent of Four-parameter rheological fluids in pipe and annuli had been presented. Followed the Metzner & Reed's study of pipe flow, we defined the generalized flow index for annular flow. Especially, a new generalized effective diameter for annuli was defined through theoretical analysis, and then the expression of the generalized Reynolds number was derived through which we relate the Four-parameter fluid flow in pipe and annuli to the Newtonian fluid in pipes. The excellent application results show that the model can precisely calculate pipe and annular flow pressure loss of different drilling fluid.

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Обобщенный метод гидравлического расчета неньютоновских жидкостей с использованием 4-х параметрической модели

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Реферат

При буровых операциях очень важны точные прогнозы гидравлических параметров. В статье представлен обобщенный метод расчета гидравлических параметров 4-х параметрической реологической модели. Основываясь на уравнении Рабиновича-Муни, было получено уравнение в явном виде, связывающее напряжение сдвига на стенке и объемный расход жидкости рассматриваемой модели в трубе. Также, было получено уравнение для кольцевого потока. Путем теоретического анализа, основываясь на исследованиях Метцнера и Рида, были определены новый обобщенный показатель текучести и эффективный диаметр для кольцевого потока. Для кольцевой геометрии и реологии жидкости рассчитан новый обобщенный эффективный диаметр. Основываясь на определении коэффициента трения Фэннинга, выражение обобщенного числа Рейнольдса как для кольцевого пространства, так и для трубы было получено с учетом не постоянного обобщенного индекса текучести. Представлен алгоритм вычислений падения давления. Результаты показали отличную согласованность ламинарных и турбулентных режимов течения.

4-parametrli modeldən istifadə edərək qeyri-nyuton mayelərin ümumiləşdirilmiş hidravlik hesablama üsulu

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Xülasə

Qazma əməliyyatları aparılarkən hidravlik parametrlərin dəqiq proqnozu çox mühümdür. Məqalədə 4-parametrli reoloji modelin hidravlik parametrlərinin ümumiləşdirilmiş hesablama üsulu təqdim olunur. Rabinoviç-Muni tənliyinə əsaslanaraq divarboyu sürüşmə təzyiqi və baxılan modelin boruda həcmli maye sərfi arasında dəqiq tənliyi əldə edilmişdir. Halqavari axın üçün tənlik də alınmışdır. Metsner və Ridin tədqiqatlarına əsaslanaraq, yeni ümumləşdirilmiş axın göstəricisi və halqavari axın üçün effektiv diametr nəzəri təhlil yolu ilə müəyyənləşdirilmişdir. Yeni ümumiləşdirilmiş effektiv diametr halqavari həndəsə və maye reologiyası üçün də hesablanıb. Feninqin sürüşmə əmsalınının müəyyənləşdirilməsinə əsaslanaraq, ümumləşdirilmiş Reynolds rəqəminin ifadəsi həm halqavari sahə, həm də borular üçün daimi olmayan ümumiləşdirilmiş axın indeksi nəzərə alınaraq müəyyən edilmişdir. Təzyiq düşməsinin hesablanması alqoritmi təqdim olunur. Göstəricilər axınının laminar və turbulent rejimlərinin əla uyğunluğunu göstərir.