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THE ROLE OF DIFFERENT RHEOLOGICAL MODELS IN ACCURACY OF PRESSURE LOSS PREDICTION

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Key words: slimhole drilling, hydraulics, rheological model, drill-in fluid

Abstract

Hydraulics play an important function in many oil field operations including drilling, completion, fracturing, acidizing, workover and production. The standard API methods for drilling fluid hydraulics assume either power law or Bingham plastic rheological model. These models and corresponding hydraulic calculations do provide a simple way for fair estimates of hydraulics for conventional vertical wells using simple drilling fluids, such as bentonite fluids. However, nowdays with many wells drilled deep, slim or horizontal using complex muds with unusual behaviour (such as tested MMH mud), it is necessary to use appropriate rheological model for mathematical modelling of fluid behaviour. Oil and gas reservoirs in Croatia have been under production for quite a while and the probability to discover new deposits of hydrocarbons is rather small. Therefore attempts have been made to maintain the gas and oil exploitation at the present level. One of possible ways to meet this target is re-entry wells drilling. The diameter of such wells in reservoir is smaller than 0,1524 m (6 in). Accurate modelling of annular pressure losses becomes therefore an important issue, particularly in cases where a small safety margin exists between optimal drilling parameters and wellbore stability, what is the case in re-entry wells. The objective of the paper is to show the influence of well geometry and accuracy of fluid rheological properties modelling to the distribution of pressure losses in a slimhole well.

Ključne riječi: izrada bušotina malog promjera, hidraulika, reološki model, drill-in fluid

Sažetak

Hidraulika ima vrlo važnu ulogu pri izvođenju velikog broja postupaka u bušotini uključujući bušenje, opremanje, frakturiranje, kiselinske obrade, održavanje i proizvodnju. Razmatranje hidraulike bušaćeg fluida prema API postupcima podrazumijeva primjenu ili eksponencijalnog ili Bingham plastičnog reološkog modela. Ti modeli i odgovarajući proračuni hidraulike osiguravaju jednostavan način dobivanja podataka prihvatljve točnosti za slučaj primjene u konvencionalnim vertikalnim bušotinama i kod primjene bušotinskih fluida jednostavnog sastava, kao što su bentonitne isplake. Međutim, danas, kada se izrađuje veliki broj dubokih bušotina, bušotina velikog dosega ili malog promjera, koje mogu biti usmjerene ili horizontalne, a za njihovu izradu koriste se fluidi složenog sastava i neobičnog ponašanja (kao što je slučaj s ispitanom MMH isplakom), neophodno je za modeliranje ponašanja fluida primijeniti odgovarajući reološki model. Budući se iz postojećih ležišta u Hrvatskoj nafta i plin proizvode već dulje vrijeme, a vjerojatnost otkrivanja novih ležišta je mala, nastoji se zadržati proizvodnju nafte i plina na današnjoj razini. Jedan od mogućih načina da se to ostvari je i izrada bočnih (“re-entry”) bušotina. Promjer takve bušotine unutar ležišta najčešće je manji od 0,1524 m (6 in). U takvim slučajevima vrlo je važno precizno modeliranje smanjenja tlaka u prstenastom prostoru. Posebno se to odnosi na slučajeve gdje postoji mali sigurnosni zazor između postizanja optimalnih bušaćih parametara i stabilnosti kanala bušotine, kao što je to slučaj kod izrade bočnih bušotina. U radu je prikazan utjecaj geometrije bušotine i preciznosti modeliranja reoloških svojstava fluida na smanjenje tlaka u kanalu bušotine malog promjera.

Introduction

The potential for better economics is the basic reason behind the gaining popularity of slimhole drilling. In last decade, application of slimhole drilling for re-entering from existing wells has provided opportunities to develop reserves of hydrocarbon through horizontal drilling that would otherwise be unprofitable to develop.

Inaccurate prediction of friction pressure loss can cause inaccurate engineering decisions that may cause drilling problems such as loss of circulation, kicks, improper rig power selection etc. These problems become more significant in the area of slimhole drilling. In last decade application of slimhole drilling for re-entering from existing wells has been a boost to development of horizontal drilling. So in slimhole drilling, a more accurate model is required.

The environmental benefits offered by slimhole drilling will also be devalued by the use of traditional drilling fluids, with open-cycle “dump and dilute” mud-conditioning practices, which lead to the discharge of large quantities of whole mud with the drilling cuttings. Furthermore, many conventional drilling fluids have the potential to cause problems with hole cleaning, solids suspension and fluid loss control. A new generation of fluids, collectively known as drill-in fluids, has been developed to overcome these limitations.

Rheological models

Fluids that have a viscosity dependent on shear rate, such as drilling fluids, exhibit non-Newtonian behaviour. This behaviour is difficult to describe with simple model. The description of two different fluids may require the use of two completely different rheological models. In conventional drilling, drilling fluids are modelized with classical rheological models like Bingham plastic or power law model and fluid behaviour is defined with only two points of the rheological relation. These points correspond to higher shear rates. This approach can be justified in the case of conventional drilling. The knowledge of rheological data and methods of predicting pressure losses are the key points to calculate proper pump rate and avoid any obstacle in drilling operation.

Generally, when a drilling fluid flow behaviour deviates from the simple Newtonian, friction pressure loss equation become more complex and less accurate due to many simplifying assumptions. It is believed that one factor that may contribute to the inaccuracies in friction pressure loss calculation in drilling is the particular rheological model used in the development of a given empirical correlation or theoretical expression. One new (old) rheological model that is thought to represent the flow behaviour of drilling fluids very well is the Herschel-Bulkley model or yield power law model. Yield power law model merges the theoretical and practical aspects of Bingham and power law models. A fluid's rheological behaviour is described according to the following equation:

$$\tau = \tau_0 + K \cdot \gamma^n \tag{1}$$

τ – shear stress, Pa
τ_0 – yield point, Pa
K – consistency index, $\mathrm{Pa \cdot s^n}$
γ – shear rate, $\mathrm{s^{-1}}$
n – flow behaviour index, -

The parameters K and n are similar to those of power law model. For fluids having a yield stress, however, the calculated values of n and K will be different from those calculated using power law model. The parameter τ_0 is the fluid's yield stress at zero shear rate (0 rpm). In theory this yield stress is identical to the Bingham plastic yield point (YP), though its calculated value is different. The model is reduce to the Bingham plastic model when n=1, and reduces to the power law rheological model when τ_0=0.

Experimental work

In this section used drilling fluids are evaluated and the equipment used to measure fluid shear stressess is described.

Two drill-in water-based fluids were prepared and tested. The fluids include polymer/calcium carbonate system (named DIF A) and Mixed Metal Hydroxide system (DIF B). The mixed and tested fluids has "typical" formulations using standard drilling fluid chemicals (Table 1.).

Table 1. Tested fluids formulation

Tablica 1. Sastav ispitanih fluida

	TESTED FLUID	
COMPOSITION	**DIF A**	**DIF B**
Water, $\mathrm{dm^3}$	1	1
XC biopolymer, g	6,5	
Wyoming bentonite, g		28,5
Mixed Metal Hydroxide, g		3,3
Filtration control, g	12,5	14,3
Calcium carbonate, g	50	80
KCl, g	45	
KOH, g	1,5	

Specific gravity of prepared fluids was 1050 $\mathrm{kg/m^3}$. The fluid rheology was measured at temperature of 50°C with the Fann 35 viscometer, according to the procedures in API specification 13B. Resulting fluids rheograms are shown on Figure 1.

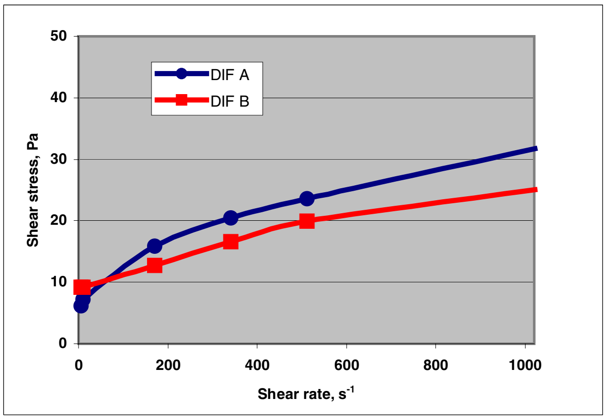

Figure 1. Rheograms of the tested fluids

Slika 1. Krivulje toka ispitanih fluida

Table 2. Bingham's model rheological parameters values of the tested fluids

Tablica 2. Vrijednosti reoloških parametara Binghamovog modela za ispitane fluide

	DIF A		DIF B	
	*A	**F	A	F
Yield point (τ_0), Pa	13,68	16,87	11,533	14,83
Plastic viscosity (μ_p), Pa·s	0,018	0,016	0,014	0,01
Correlation	0,9933	-	0,9779	-

**A –analysis data*
***F –formulas data*

Table 3. Power – law's model rheological parameters values of the tested fluids

Tablica 3. Vrijednosti reoloških parametara eksponencijalnog modela za ispitane fluide

	DIF A		DIF B	
	*A	**F	A	F
Flow behaviour index (n), -	0,339	0,43	0,218	0,329
Consistency index (K), Pa·s^n	2,919	1,611	5,073	2,562
Correlation	0,9959	-	0,9536	-

Table 4. Yield Power law's model rheological parameters values of the tested fluids

Tablica 4. Vrijednosti reoloških parametara modificiranog eksponencijalnog modela za ispitane fluide

	DIF A	DIF B
Flow behaviour index (n_{HB}), -	0,478	0,669
Consistency index (K_{HB}), Pa· s^n	1,007	0,164
Yield point (τ_{0HB}), Pa	4,037	8,46
Correlation	0,9999	0,9966

The Bingham plastic, power law and yield power law models have been applied to the data set reported in the paper. Rheological parameters of specified models are calculated based on data pairs shear rate/shear stress. Linear regression method is used for Bingham plastic model parameters calculation (only data pairs for higher shear rates are included-1022, 511, 340 and 170 s^{-1}) and non-linear regression, using the least squares method, is used for Ppower law and yield power law parameters calculation (all six pairs shear rate/shear stress are included). Bingham and power law model rheological parameters are calculated using standard formulas, too. Results of analysis and calculation with correlation data for every model are shown in Tables 2, 3 and 4.

In Figures 2 (fluid DIF A) and 3 (fluid DIF B) differences between Bingham, the power law and the yieldpower law (Herschel-Bulkley) models estimations can be seen, compared to the actual rheological curve.

It can be seen that yield power law model gives in both cases the best fit of the viscometer data in comparison with the other two rheological models. To evaluate a fluid's carrying capacity, yield stress value calculated by yield power law model is more accurate and useful than the Bingham plastic yield point. Applications of this model have important implications for calculating mud hydraulics and evaluating hole cleaning efficiency.

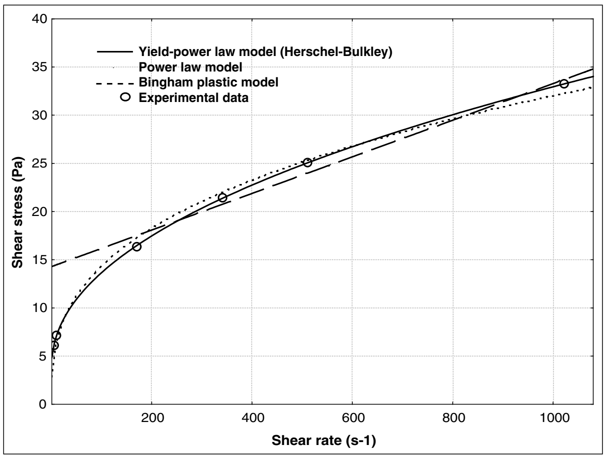

Figure 2. Modelling of rheological behaviour of the fluid DIF A

Slika 2. Modeliranje reološkog ponašanja fluida DIF A

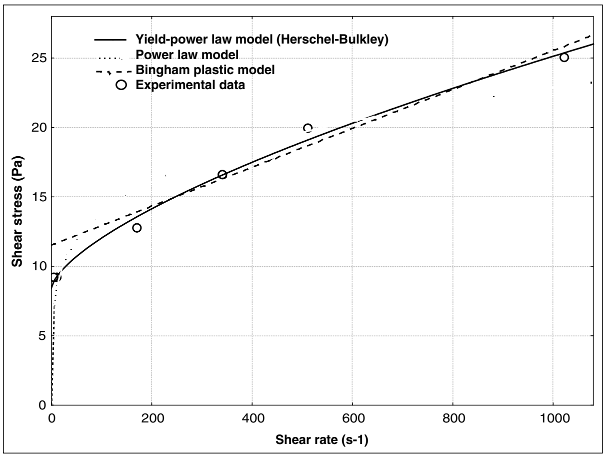

Figure 3. Modelling of rheological behaviour of the fluid DIF B

Slika 3. Modeliranje reološkog ponašanja fluida DIF B

Pressure loss calculations

In conventional drilling the increase in equivalent circulating density (ECD) by annular pressure losses is usually small compared to hydrostatic pressure gradient. So, wellbore stability and efficient hole cleaning can be guaranteed by independent choices of mud density on the one hand and flow properties on the other. Definition of equivalent circulating density is given by:

$$ECD = \frac{\Sigma p_a}{TVD \cdot g} + \rho_m \quad , \quad kg/m^3 \qquad (2)$$

Σp_a - total annulus pressure loss, Pa
TVD - hole or interval true vertical depth, m
g – acceleration due to gravity, m/s^2
ρ_m – mud density, kg/m^3

Slimhole drilling involves fluid flow in narrow annular geometries. Decreasing annular clearance completely modifies the distribution of pressure losses in a well. The use in drilling practice is to express this annulus pressure by ECD. Low hydraulic power transmission to the mud motor and bit is costly in that it can reduce rates of penetration, while high ECD poses a significant threat to hole stability and well control. Annular pressure losses depend on fluid rheology, flow regime and geometry of the annulus.

In slimhole drilling, because of thin clearances used, the estimation of dynamic pressure in the annulus is very sensitive to the choice of the mud model (smaller the annulus clearance - more difficult prediction). Application of model has important implications for calculating mud hydraulics in hole drilling process because Bingham plastic model overestimates and power law model underestimates pressure loss in annulus. The importance of model choice will be illustrated for a practical case of a drilled wellbore. Well geometry is shown in Table 4 and composition of used drillstring in Table 5. Hole pressure losses are calculated for the same flow rate using different rheological models. Both, analysis and formulas data are used in calculations and results are given on Figures 4 and 5. Corresponding ECD for a given well geometry is calculated, too. Results are shown on Figures 6 and 7.

Table 4. Wellbore geometry

Tablica 4. Geometrija kanala bušotine

Characteristic points	Measured depth (m)	True vertical depth (m)
Kick off point	2297	2297
Target	2386,5	2348,5
Total depth	2587	2366,75
Casing shoe	2297	2297

Table 5. Drillstring composition (from the bottom)

Tablica 5. Sastav niza bušaćih alatki (od dna)

Drillstring component	Outer diameter (mm)	Inner diameter (mm)	Length (m)
Bit	117,475	-	0,15
BHA	92,075	-	19,93
Tubing	73,025	55,337	281,67
Drill pipe	73,025	54,6354	28,66
Drill collars	104,775	50,8	77,64
Drill pipe	73,025	54,6354	2178,95

** Inner diameter of casing is 0,124 m.*

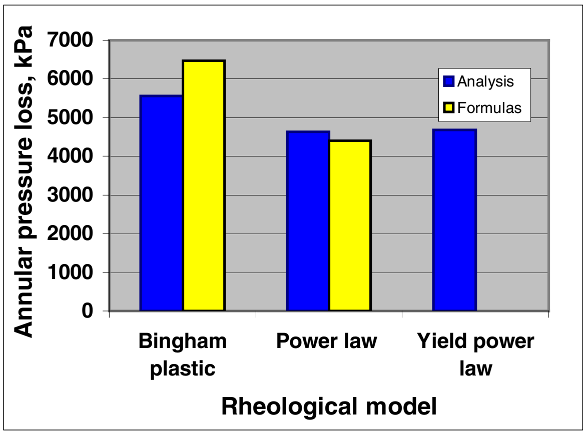

Figure 4. Total pressure loss in the given wellbore geometry during DIF A fluid flow

Slika 4. Ukupno smanjenje tlaka u kanalu bušotine zadane geometrije pri protjecanju fluida DIF A

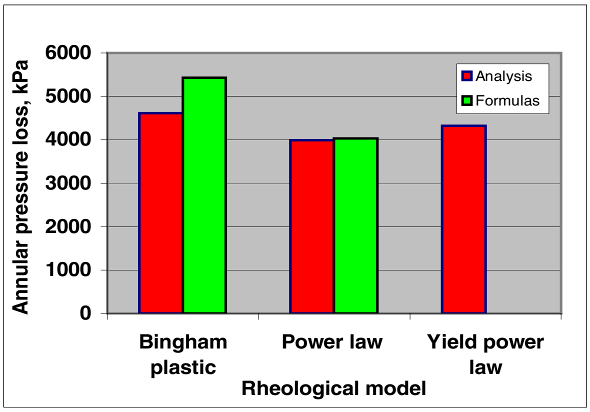

Figure 5. Total pressure loss in the given wellbore geometry during DIF B fluid flow

Slika 5. Ukupno smanjenje tlaka u kanalu bušotine zadane geometrije pri protjecanju fluida DIF B

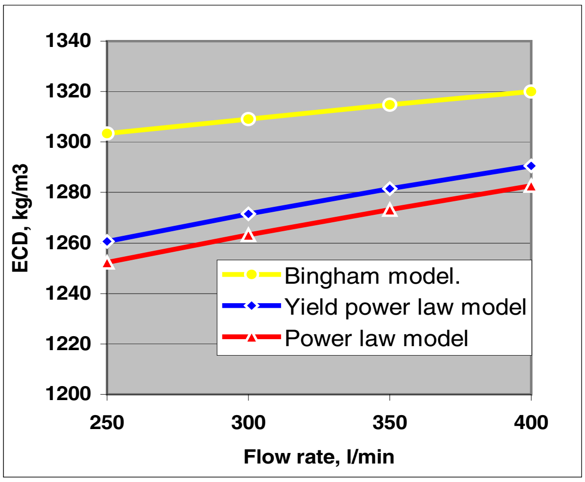

Figure 6. Influence of the choice of mud rheological model on the equivalent circulation densitiy (ECD) of the fluid DIF A

Slika 6. Utjecaj odabranog reološkog modela na ekvivalentnu cirkulacionu gustoću fluida DIF A

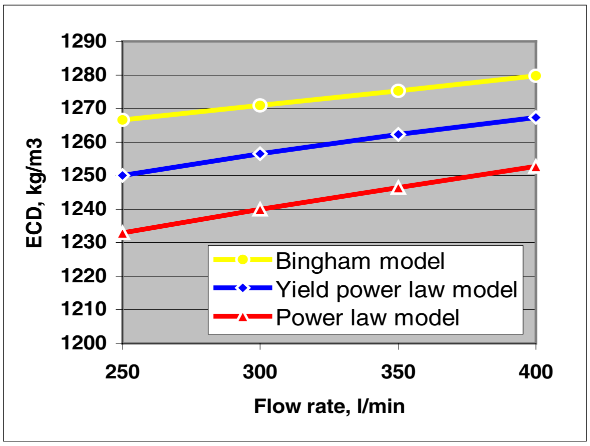

Figure 7. Influence of the choice of mud rheological model on the equivalent circulation densitiy (ECD) of the fluid DIF B

Slika 7. Utjecaj odabranog reološkog modela na ekvivalentnu cirkulacionu gustoću fluida DIF B

Conclusions

- Two completely different drill-in fluids used in slimhole drilling were tested and their rheological behaviour were modelled by Bingham plastic, power law and yield-power law model.
- According to the presented data (Tables 2, 3, 4 and Figures 2 and 3) the yield power law model (Herschel-Bulkley) is most accurate in desribing rheological behaviour of both tested fluids.
- According the literature data (Haciislamoglu, Cartalos, 1994; Langlinais, et al, 1983) Bingham plastic model overestimates and power law model underestimates pressure losses. For the tested fluids it can be seen on the figures 4 and 5.
- The accuracy of the mud modelization in slimhole drilling is essential for accurate predictions of ECD and thus to reach a successful drilling operations. Calculations presented in the paper (Figures 6 and 7) have shown the sensitivity of ECD estimation to the choice of the rheological model.

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