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Research Article

A Mathematical Approach Using Thermoporoelastic Model for Reamer While Drilling Efficiency Analysis and Closeness

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Abstract: The main objective of this research is to predict the proper bit/reamer size ratio based on the rock strength weakening zone around the wellbore. Nowadays, the Reaming While Drilling (RWD) technology is gaining more and more acceptance in the petroleum industry by means of reducing drilling time and Non-Productive Time (NPT), which results in significant cost saving. The importance of this research is analyzing scenarios in which RWD would add benefit to the operation, given that the reaming process is often fraught with much inefficiency. Thus, through the process of estimation optimum reamer/size ratio, by coupling three key parameters in geo mechanics: thermo-poro-elastic, a model of rock strength is developed to analytically assess how rock strength distribution changes around the wellbores and in particular below the reamer in drilling environments. An analytical model of thermoporoelastic is used with published data (for rock properties usage purposes) in order to develop a model of rock strength below the reamer to show in how far some specific rock could be a good candidate for reamer usage. This in turn allows finding proper candidates for effective RWD applications and also can assist to determine the maximum reamer/bit size ratio for certain rock characteristics in order to optimize the drilling system. From the analysis performed, which was carried considering two different groups in terms of formation permeability, it is be conclusive that for low-permeable formation the size of reamer is function of exposure time of wellbore after making pilot hole while the reamer size for enlargement operation through the permeable formation due to fast diffusion rate is not a time dependent parameter.

Keywords: Drilling efficiency, pore pressure, reamer, rock strength, thermoporoelastic, temperature

INTRODUCTION

Drilling a well and simultaneously opening it up to the target diameter by use of a hole opening device, Regardless of whether an eccentric reaming tool or a concentric under-reamer are utilized, are all considered Reaming While Drilling (RWD). There are generally three RWD techniques used in addition to conventional rotary drilling. These are Casing-While-Drilling (CWD), Dual Body Bit (DBB) and using reamer and bit simultaneously.

One of the most important applications of RWD is CWD. It is well documented that CWD technology has great impact to decrease drilling time and reduce cost. Apart from hazard mitigations associated with CWD, on the other hand, its capability to eliminate the casing running process begin immediately after reaching targeted depth and in addition, fast retrieving and running a bit via wireline instead of conventional method to change BHA. This approach removes non-productive time (NPT) from the drilling curve, improve drilling efficiency. Reducing time for drilling operations also can lead to enormous cost savings, especially for offshore.

In addition, DBB as another application of RWD has huge effect on drilling cost. With the dual-body bit concept, which consists basically of a core bit (rim) and a drill plug, the operator has enough flexibility to

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exchange from coring to full-hole drilling and vice-versa, with the benefit of eliminating a round trip. This is achieved by selecting proper bit from the surface with utilizing a conventional wire line assembly. Furthermore, if the objective is full-hole drilling, the dual-body bit approach allows the possibility to significantly improve the bit performance by replacing the drill plug for another one that is more suitable for drilling conditions. By replacing the drill plug, the characteristics of the bit (profile, hydraulics, cutting structure, etc.) can be altered (Bencic *et al*., 1998; De Sousa *et al*., 1999).

A proper marriage between bit and reamer is essential in optimizing BHA performance and optimizing BHA durability. Over the years, bit and reamer selection have been done independently and they are not considered as an integrated drilling string system. For many years, a trial-and-error method has been used by the drilling industry to determine what reamer size and type drilled best with a certain PDC bit. This concept has proven to be less efficient and in many cases has led to sever vibration related problems such as: large amount of NPT, drilling tools failures and financial impact, especially in deep-water drilling operation (Barton, 2010; Ho *et al*., 2013). It is well known that minimizing drilling time is an important topic in drilling operations. Cost issues are not only caused by the drilling operation itself, it also includes rig daily rate, various services and equipment's etc. Currently offshore rig costs are in excess of $1 million per day (Radford *et al*., 2010). Saving such a huge amount will drastically help the economics of the drilling industry.

RWD technology is gaining more and more acceptances in the petroleum industry as a means of significantly reducing the overall drilling time and costs. This acceptance is increasing as RWD research activities increase and viable solutions for the many drawbacks that hindered the frequent use of this technology in the past are arising. Research on weight on bit/reamer distribution torque on bit/reamer (Meyer-Heye *et al*., 2010; Ma *et al*., 2012) and string vibrations, etc. has significantly contributed to enhance the confidence of the operators for using RWD technology.

To understand the performance improvements that can be achieved using the RWD compared to conventional full hole bits, it is important to first understand the effects of drilling a well into rock. When a drill bit penetrates the formation, the stress state as well as pore pressure and temperature of the rock surrounding the bit and the wellbore become significantly altered from their original in situ state. In effect, the rock becomes stress relieved; however most conventional drill bits gain little advantage from this effect (Teasdale *et al*., 2014).

Unlike full whole drill bits, RWD system effectively uses this stress alteration to its advantage due to its design. In fact, the pilot hole which is initially drilled by the pilot section of the RWD is much in the same way as a conventional bit; nevertheless as a result of its smaller diameter, lower volume of rock is required to be removed. The smaller pilot leads to providing a slight improvement in rate of penetration in comparison to a larger diameter bit. After making this pilot hole, the stress state, pore pressure and temperature, in the surrounding rock, change due to the stress relaxation effect, drilling fluid diffusion and thermal diffusion. Consequently, when the succeeding reamer section continues to make the hole bigger, it does so through this stress-relaxed rock and in some formations type weakened rock. The consequence of this effect is that the reamer section requires less power to destroy the remaining rock to full hole diameter, which leads to a further improvement in ROP.

The increased usage of RWD and related hole opening tools separately from the drill bit, essentially has created the need to understand the interaction between the drill bit and the hole opening tool itself as well as the wellbore rock. As documented before, problems that can result from improper matching include sever vibration, inability to open the hole, mechanical damage to string components or to the bit and sub-optimal drilling performance. Such dysfunction may be created by improper matching of pilot and reamer bit. This study investigates rock property aspect of the wellbore to estimate weakening zone and finally predicts whether a formation is a good candidate for RWD and to establish an estimation of optimum bit/reamer size ratio. Therefore, in line with these objectives, the pore pressure profile around the wellbore is explored by using thermoporoelastic theory. Then apparent rock strength around the wellbore for different scenarios is estimated. It also considers reamer -pilot size ratio and relates this ratio to apparent rock strength around the wellbore.

LITERATURE REVIEW

Bencic *et al*. (1998) innovated new approach in the dual-body bit concept which included the use of slim hole continuous coring bottom-hole-assembly (BHA), with the outer bit part (rim) being assembled on the outer tube and also an internal portion (plug). The plug can be recovered by using a conventional wireline system. Finally, the authors concluded that the potential of this concept is to decrease tripping time and associated cost by more than 50%.

Therefore the most important applications of this approach might be seen in drilling an exploration well. Because for this type of drilling, the necessity of coring operations in the case of multi-layered reservoirs, this concept facilitates a very fast and efficient method change from coring to full hole drilling mode, without coring of non-targetsection, or tripping out the coring assembly and tripping in the drilling assembly. Their tests concentrated on the use of different pieces of bits, either individually or in different sets in four rock types.

De Sousa *et al*. (1999) conducted extensive laboratory work to describe the steps towards the optimization of several slim-hole dual-body bits. The authors suggested that in order to make easier field operations, the ratio of rim and drill plugs' total flow areas should be nearly one. The optimum ratio of total flow areas depended on the formation and this parameter while drilling in soft rocks was more important than in hard ones. Furthermore, the authors concluded that generally, bit performance does not depend on the distance between rim and plug. The behavior of the bits changed according to the type of rock being drilled. They did not discussed rock mechanics aspects interaction with DBB.

Teasdale *et al*. (2014) tested a DBB in lab and field. Their examination of the results showed that the dual-diameter bit (without the option of changing pilot with wire line), although less aggressive in terms of blade and cutter count, outperforms the more aggressive conventional bit across the full range of WOB. Additionally, specific energy showed higher efficiency compare to same test with a conventional bit.

The authors concluded that the higher drilling efficiency than conventional PDC bit is highly related to the stress relieving effect created by the dual-diameter design and in fact, stresses around the wellbore change markedly impaired from their original in situ state. Finally, the rock weakens; nevertheless, the majority of conventional drill bits derive little benefit from this alteration.

Meyer-Heye *et al*. (2010) developed bit aggressiveness which facilitates the assessment of the influences of drilling diameters and cutting structures separately on the load distribution. This model helps the optimization of cutter layout and density for a given bit and reamer size ratio by calculating the weights distribution on each tool. In addition, a higher aggressive reamer with 20% larger diameter than a pilot bit (tapered profile reamer) requires less weight as WOB.

Ma *et al*. (2012) introduced a dual factor method for calculating weight distribution in reaming while drilling by substituting depth of cut per bit rotation ratio in specific energy definition:

$$W_b = \frac{C_0 A_b}{1+\frac{120\pi k_b}{C_0}} \tag{1}$$

In the same way weight on reamer is defined and then weight distribution factor can be solved as:

$$f_w = \frac{W_r}{W_b} \tag{2}$$

According to this equation, a ratio of the weight on the reamer to the total weight applied from the surface can be derived:

$$F_r = \frac{W_r}{W_r+W_b} = \left(1-\frac{1}{f_w+1}\right)\times 100\% \tag{3}$$

f_w is influenced by drilling tool's geometry, its sharpness and formation stress. Although the geometry parameter is a constant, the other two factors, sharpness and formation stress, may change with different conditions. So the two factors were seen as the main variables that influencing weight distribution in RWD.

There have been no previous studies, so far, which have discussed reamer/bit size ratio in relation to rock mechanic and geomechanic properties of formation.

MATERIALS AND METHODS

By digging into the Mohr-Coulomb criteria and Kirsch's equation, it will be able to shed important new light on to the Reamer/Pilot size ratio's guide line (Fig. 1).

The Mohr-Coulomb failure criterion (Fig. 2) describes the shearing resistance to the contact forces and friction, to the physical bonds (cohesion) that exist between the grains. The failure envelope is determined from many Mohr circles and this failure criterion is illustrated by its envelope. The result of each tri-axial test is showed by a circle. Tri-axial test refers to when a rock's sample is subjected to the lateral confinement ($\sigma_2 = \sigma_3$) and the axial stress (σ_1) is increased until failure (Aadnoy and Looyeh, 2010; Fjaer, 2008).

Then stability can be analyzed by calculations of the normal and shear stresses for a given condition. The Mohr-Coulomb linear envelope in terms of σ_1, σ_3 (Mohr-Coulomb Criteria):

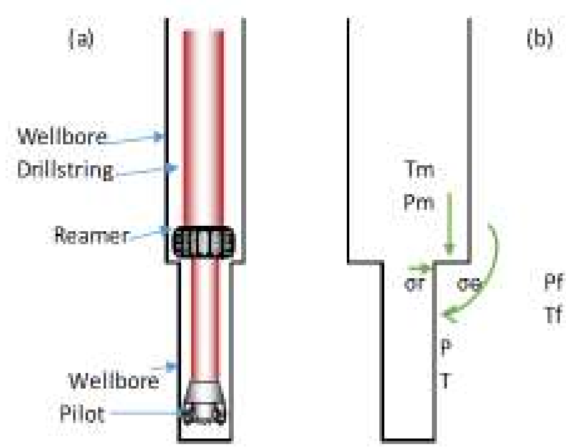

Fig. 1: Simplified depiction of (a): Reamer and pilot; (b): stresses below reamer

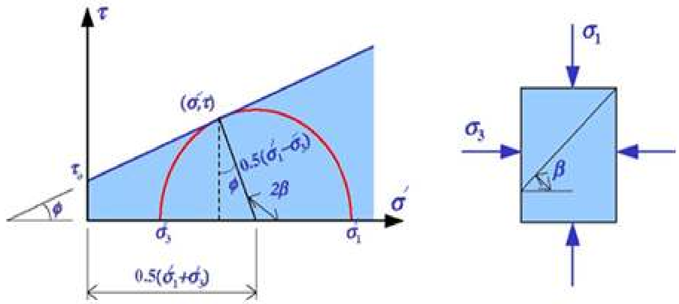

Fig. 2: Mohr-Coulomb criteria (Aadnoy and Looyeh, 2010)

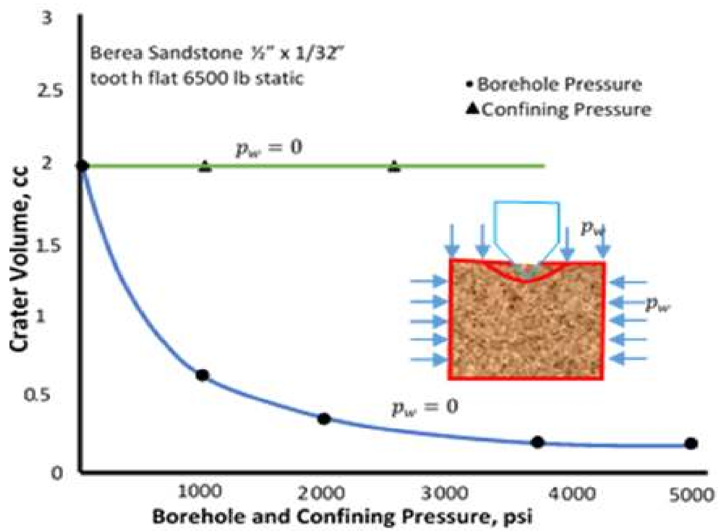

Fig. 3: Effect of normal and tangential stress on single-tooth crater volume (Maurer, 1965)

$$|\tau| = S_0 + \mu \quad (4)$$

Or,

$$\acute{\sigma}_1 = C_o + \acute{\sigma}_3 \tan^2 \beta \quad (5)$$

The reason why effective stress is used in Mohr-Coulomb Criteria is due to the fact that the ductility, strength, sonic velocity and volumetric properties of the porous formation depends not only on the exterior body stresses, but also on the interior pore stresses. While the pore pressure is a tensile stress, it decreases the rock frame stress created by an exterior compression. (Conventionally in petroleum rock mechanic tensile stresses are defined as negative and compressions are positive.) By combining these two parameters into a single parameter, the effective stress is considered for the combined effect of a change in either or both of the other parameters (Warren and Smith, 1985). Therefore, the effective stress is given as $\sigma_e = \sigma - \alpha P_f$, in which α is the Biot's coefficient and for the most common cases can be assumed to be one.

In Eq. 5, $\acute{\sigma}_1$ is the maximum effective stress which causes rock failure at a certain confined stress ($\acute{\sigma}_3$). In another words, the maximum effective stress ($\acute{\sigma}_1$) is Apparent Rock Strength (ARS) at a specified confined stress.

It is well-known that the strength of a rock is controlled largely by the minimum principal stress. Maurer (1965) reported impact of single-tooth tests (Fig. 3) by means of measuring the crater volume at different stress conditions. His results revealed that the crater volume is remarkably decreased once the mud pressure rises above the pore pressure. On the other hand, if the difference between mud and pore pressure is keptstable, but the horizontal stresses parallel to the rock surface are raised, crater volume is constant (Warren and Smith, 1985). Yang and Gray (1967) reported a slight grow in crater volume as the horizontal stresses are raised. These tests are in line with this idea that the ARS and the drilling rate are mainly controlled by the minimum principal stress and the high stresses parallel to the bottom of the hole has little effect on them. Therefore, Apparent Rock Strength (ARS) can be determined according to M-C criteria:

$$ARS = C_o + \acute{\sigma}_3 \tan^2 \beta \quad (6)$$

There is a widely practiced and accepted rock mechanics method for calculating ARS of a rock.

Calhoun *et al*. (2005) combined two methods and introduced a new method for various range of porosity as follow by Eq. (3), (4) and (6):

$$if\ \varphi \geq 0.2 \ --\rightarrow$$
$$ARS_1 = C_0 + (p_w - p_f)\frac{1+\sin\emptyset}{1-\sin\emptyset} \quad (7)$$

$$if\ 0.05 \geq \varphi \ --\rightarrow$$
$$ARS_2 = C_0 + \left(p_w - \left(p_f - \frac{\sigma_v - p_w}{3}\right)\right)\frac{1+\sin\emptyset}{1-\sin\emptyset} \quad (8)$$

$$if\ 0.2 > \varphi > 0.05 \ --\rightarrow$$
$$ARS_3 = \frac{ARS_1(\varphi-0.05)}{0.15} + \frac{ARS_2(0.2-\varphi)}{0.15} \quad (9)$$

The main difference between these equations is related to pore pressure and the minimum effective stress calculation procedure. Since the formation consisting of an elastic solid matrix and fluid filled pores is subjected to the deformation, the diffusion and the thermal perturbations, the mechanical response must be characterized by coupled thermo-poro-elastic. The fluid diffusion, deformation and as well as the temperature variations will cause the solid and fluid volumes to change, thereby disturbing stress and pore pressure equilibria. The pore pressure calculations depend on the formation's permeability and the filter cake's quality. For the sake of brevity, the process of deriving the pore pressure solutions is not reiterated in this study and the final equations only were mentioned for each case from different references (Cui *et al*., 1997; Li *et al*., 1998; Abousleiman *et al*., 1999; Caicedo *et al*., 2005a, 2005b).

For permeable formations with permeable filter cake due to hydraulic diffusion (10):

$$p_{hyd} = \frac{p_m - p_f}{\ln\left({}^{r_e}/_{r_w}\right)}\ln\left({}^{r_e}/_{r}\right) = -A_p\ln\left({}^{r_e}/_{r}\right), and A_p = -\frac{p_m - p_f}{\ln\left({}^{r_e}/_{r_w}\right)} \quad (10)$$

For Permeable formations with permeable filter cake p = 0.

For Low Permeable formations with permeable filter cake due to hydraulic diffusions and temperature changes (11 and 12, respectively):

$$\tilde{p}_{hyd} = \frac{(p_w - p_f)}{s}\frac{K_0(\xi)}{K_0(\beta)} \quad (11)$$

$$\tilde{p}_{thermal} = \frac{c_{ft}}{1 - {}^{c_f}/_{c_T}}\frac{(T_m - T_f)}{s}\left[\frac{K_0(\xi)}{K_0(\beta)} - \frac{K_0(\xi_T)}{K_0(\beta_T)}\right] \quad (12)$$

For low permeable formation with impermeable filter cake due to thermal effect (13):

$$\tilde{p}_{thermal} = \frac{c_{ft}}{1 - {}^{c_f}/_{c_T}}\frac{(T_m - T_f)}{s}\left[\frac{K_0(\xi_T) - \sqrt{\frac{c_f}{c_T}}K_0(\xi)\frac{K_1(\beta_T)}{K_1(\beta)}}{K_0(\beta_T)}\right] \quad (13)$$

Induced pore pressure due to far filed stress deviator which is employ for all type of formations is given by Tao and Ghassemi (2007):

$$\tilde{p} = \frac{S_0\cos 2(\theta - \theta_r)}{s}\left\{\frac{B^2(1-v)(1+v_u)^2}{9(1-v_u)(v_u - v)}C_1K_2(\xi) + \frac{B(1+v_u)C_2}{3(1-v_u)}\left(\frac{r_w}{r}\right)^2\right\} \quad (14)$$

where, the overbars represent the Laplace transform, C_1 and C_2 are constants obtained from boundary conditions:

$$C_1 = -\frac{12\beta(1-v_u)(v_u - v)}{B(1+v_u)(D_2 - D_1)} \quad (15)$$

$$C_2 = \frac{4(1-v_u)D_2}{(D_2 - D_1)} \quad (16)$$

$$D_1 = 2(v_u - v)k_1(\beta) \quad (17)$$

$$D_2 = \beta(1-v)k_2(\beta) \quad (18)$$

These results can be superposed together to obtain the pore pressure in a realistic situation.

Due to the complexity of the integrands involved in conducting Laplace inversions, the pore pressure components in the time domain have to be obtained numerically by applying approximate numerical schemes. The Stehfest method which has received high marks for its accuracy, efficiency and stability (Detournay and Cheng, 1988), is used. The Stehfest formula is:

$$f(t) = \frac{\ln 2}{t}\sum_{n=1}^{N} C_n\tilde{f}\left(n\frac{\ln 2}{t}\right) \quad (19)$$

With the coefficient C_n is given by:

$$C_n = (-1)^{n + {}^{N}/_{2}}\sum_{j=\left[{}^{(n+1)}/_{2}\right]}^{min(n,{}^{N}/_{2})}\frac{j^{{}^{N}/_{2}}(2j)!}{({}^{N}/_{2} - j)!j!(j-1)!(n-j)!(2n-j)!} \quad (20)$$

The number of terms N in the series is even and a selection of N = 8 generally gives satisfactory results.

RESULTS AND DISCUSSION

Considering all the information presented and explained throughout this study, it is suggested that the usage of reamers in the BHA is not always recommended since in some cases it is not beneficial for the drilling activity, but actually would cause some drawbacks outweighing the benefits.

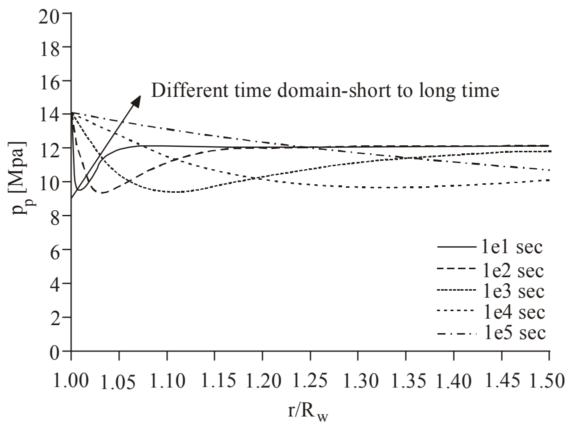

Fig. 4: Low permeable formation: Pore pressure

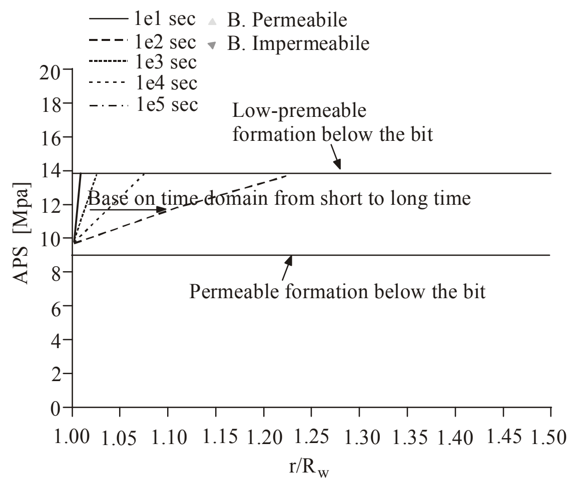

Fig. 5: Low permeable formation: Apparent rock strength

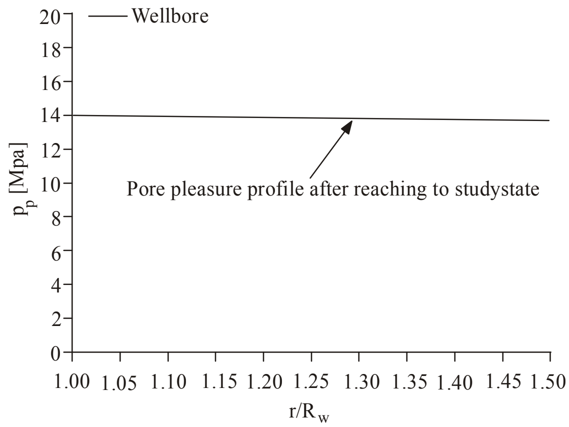

Fig. 6: Permeable formation: Pore pressure

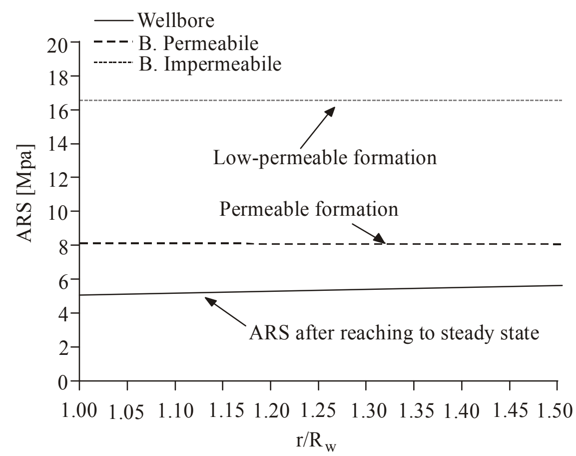

Fig. 7: Permeable formation: Apparent rock strength

In the first step, data from the literatures were collected and employed in the models presented in order to verify and exemplify how the apparent rock strength profile would change due to stresses alteration; change in pore pressure and change in temperature follow by different scenarios of mud diffusion into the formation. It is possible to estimate the weakening zone around the wellbore, which in turn can be used to predict proper bit/reamer size ratio.

The simulations are run for two different scenarios base on the permeability of formation: Group 1- Low-permeable, Group2- High permeable.

Figure 4 and 5 represent the simulation run for the group 1. The results emphasize the pore pressure and the rock strengths profile in low permeable formation respectively.

The wellbore is cooled down by the drilling fluid in this example; therefore, a negative (decreased) thermally induced pore pressure is created for both permeable and low-permeable boundary conditions. In addition, at early times and due to the Skempton effects, the pore pressure falls below the formation initial pressure, and, as time progresses, the pore pressure reaches equilibrium. Finding from Fig. 4 is in line with this concept. In this figure the pore pressure variations are presented from the instant of fluid exposure to the rock formation for different time sets due to exposure to drilling fluid and stress relaxation.

The result of ARS simulation for different time domain versus distance from the wellbore is given in the Fig. 5. As a means of providing comparison between ARS of the wellbore within situ rock just below the bit, minimum and maximum of ARS for permeable and impermeable formation (according the method is presented by Calhoun *et al*. (2005) are plotted on the same figure (top and bottom bold line). Teasdale *et al*. (2014) suggested that the stress relaxation zone around the wellbore is in line with the results of this graph. The conclusion drawn from this figure is that the weakening zone extension is a function of time. (time as a result of Laplace transformation comes to play). Therefore in early time after drilling pilot hole reamer size should be just a little bigger than pilot bit in order to gain benefit of the weakening rock. However, if the subsequent hole enlargement process proceeds after longer time, then the weakening zone will be extended as a consequence of hydraulic and thermal diffusivity. This allows bigger

Table 1: Formation characteristics (These data were obtained from Chen and Ewy (2004) and Tao and Ghassemi (2007) for tests performed on permeable and low permeable formation)

Property	Shale (low-permeable)	Sand (permeable)
Max. horizontal stress, $\boldsymbol{\sigma_H, MPa}$	18.00	20.3
Min. horizontal stress, $\boldsymbol{\sigma_h, MPa}$	17.00	20.3
Pore pressure, $\boldsymbol{P_p, MPa}$	12.00	12.43
Wellbore pressure, $\boldsymbol{P_m, MPa}$	14.00	13.95
Temperature difference, $\Delta\boldsymbol{T}$, ℃	-25.00	-25.00
Biot's coefficient, $\boldsymbol{\alpha}$	0.97	0.99
Drained poisson's ratio, $\boldsymbol{v}$	0.22	0.30
Undrained poisson's ratio, $\boldsymbol{v_u}$	042	0.46
Skempton's coefficient	0.92	0.92
Thermal diffusivity [m2/s]	1.6e-6	7.15e-7
Fluid diffusivity [m2/s]	6e-8	7.15e-3
Coupling coefficient [MPa/C]	0.17	0.31
UCS	5.00	5.00
Friction angle	20.00	20.00
Wellbore radius [in]	8.50	8.50
Drainage radius [in]	-	60.00

reamer size, since it may actively use this change in rock strength to its advantage.

The simulation run for group 2 is much in the same way as the group 1 except the run for group 2 includes hydraulic diffusion, which is considered a dominant factor, causing the pore pressure to vary very fast. This would make the simulations to be very complex to analyze. In this way, the results for the permeable formations are not detailed considering different time-ranges but a steady-state condition can be achieved in about 30 min (Chen and Ewy, 2004, 2005) for typical high permeable sandstone.

Figure 6 and 7 illustrate the simulation results for the permeable formation. It is possible to see that the apparent rock strengths always fall below the rock strength just below the bit, confirming to be a good candidate for reamers. Further, the bit/reamer size ratio is not an issue for this case.

The formation characteristics in play for the simulations are detailed in the Table 1.

CONCLUSION

Reamer technology has been in use for a long time in the industry but with not much details on the rock weakening/strength surrounding the wellbore with respect to reamer/bit size ratio and distance between the reamer and the bit.

This study discusses a methodology to properly select the environment in which the utilization of a reamer could be beneficial to the operation. Based on thermoporoelastic models, it is possible to simulate how the apparent rock strength changes in relation to time and pore pressure for different scenarios after making a pilot hole and exposing it to the drilling fluid, accounting for differences in permeability.

From the analyses of the two groups, which have been analyzed, the following conclusions could be drawn:

- Thermoporoplastic model of ARS can reveal weakening zone around the wellbore and can be used to select optimum reamer/bit size ratio in order to gain advantage of rock weakening around the wellbore.
- The results from the calculations show that for the low-permeable formation under investigation, 10% bigger reamer requires less energy to destroy a specific rock; this is a result of rock weakening process.
- For a high-permeable formation, size ratio is not an issue to gain advantage of the weakening zone.
- According to the literature, the results drawn from this approach presented fit well with suggestions found in other publications.
- Although a lot of work and laboratory tests, remain to be performed, this method and the results show that the concept can be used as a guidance for drilling engineering to select the reamer-bit system of best choice for a specific scenario.

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NOMENCLATURE

k_b	: Bit sharpness
$\acute{\sigma}_1$	: Maximum effective stress
$\acute{\sigma}_3$	: Confined or minimum effective stress
B	: Orientation of the failure plane
C_o	: Unconfined Compressive Strength (UCS)
φ	: Porosity
k_0, k_1 and k_2	: The second kind of Bessel functions with zero, one and two order, respectively
A_b	: Bit area
W_b	: Weight on bit
W_r	: Weight on reamer
$\emptyset$	: Internal friction angle
p_w	: Wellbore pressure
p_f	: Formation pressure
σ_v	: Vertical stress
α	: Biot's factor

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