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Effective Mechanical Specific Energy: A New Approach for Evaluating PDC Bit Performance and Cutters Wear

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Abstract

Predicting the PDC bit performance during drilling operation is important for the cost effectiveness of the operation. The majority of PDC bits are assessed based on their performance that are relative to offset wells. Determination of mechanical specific energy (MSE) in real time and compare it with the known MSE for a sharp bit to assess the bit life has been utilized by several operators in the past. However, MSE still cannot be used to predict the bit performance in exploration wells and also it cannot assess the bit efficiency in the inner and outer cones.

A more precise approach needs to be devised and applied to improve the prediction of bit life and the decision when to pull the bit out of the hole. Effective mechanical specific energy (EMSE) developed in this work is a new wear and performance predictive model that is to measure the cutting efficiency based on number of cutters, which contact the rock as a function of weight on bit (WOB), rotary speed (RPM), torque, and depth of cut (DOC). This model modifies the previous MSE model by incorporating such parameters and including detailed design of the bit, number of blades, cutter density, cutter size, and cutting angle. Using this approach together with the analysis of rock hardness, a level of understanding of how the drilling variables influence the bit performance in the inner and outer cone is improved, and a convenient comparison of the bit condition in the frame of the standard bit record is achieved. This work presents a new simple model to predict the PDC cutters wear using actual data from three sections drilled in three oil wells in Libya. It is found that the obtained results are in well agreement with the actual dull grading shown in the bit record.

Keywords: Mechanical specific energy, PDC bit performance, PDC bit wear, depth of cut, bit profile

1. Introduction

The demand for running PDC bits in oil and gas drilling requires a predictive tool to evaluate the cutting elements and the involved drilling parameters to reduce the cost per foot. Bit life and rate of penetration become the primary factors in the calculation of the cost per foot for any candidate drilling bit. However, the principal factors that need to be considered in forecasting the wear are the bit design, drilling parameters, and rock properties (Ersoy and Waller, 1995).

Few approaches of predicting drilling performance are available in the literature and generally were described by the Mechanical Specific Energy (MSE). The concept of MSE was developed by Teale (1965) who defined MSE as the work required to remove a given volume of rock. MSE is introduced by the following equation:

$$\text{MSE} = \frac{\text{Energy}}{\text{Volume of rock removed}} \quad \ldots\ldots (1)$$

Teale performed an experimental test under atmospheric conditions to estimate the bit efficiency when he discovered that the value of MSE was equivalent to the value of compressive strength of the rocks. Teale (1965) stated that the process of drilling is basically consisting of combination of two mechanism actions: “indentation”, by which the bit cutters are continuously pushed by weight into the formation to create a Depth of Cut (DOC); “cutting”, by which the bit is dragged laterally to cut the formation as a function of torque. Teale (1965) developed an equation, i.e. Eq. 2, to measure the MSE in a laboratory-scale based on the resultant WOB and torque.

$$\text{MSE} = \frac{\text{WOB}}{\text{A}} + \frac{2\pi \times \text{T} \times \text{RPM}}{\text{A} \times \text{ROP}} \quad \ldots\ldots (2)$$

The depth of cut per revolution is defined as shown in Eq. 3 (Sinor et al., 2001, Teale, 1965).

$$\text{DOC} = \frac{\text{ROP}}{\text{RPM}} \quad \ldots\ldots (3)$$

MSE as a function of DOC can be expressed as follows.

$$\text{MSE} = \frac{\text{WOB}}{\text{A}} + \frac{2\pi \times \text{T}}{\text{A} \times \text{DOC}} \quad \ldots\ldots (4)$$

Where MSE (psi), WOB (lbs), T (lbs-ft), RPM (rev/min), A is the bit cross-sectional area (in^2), ROP (ft/hr), and DOC (in).

The approach was applied by Dupriest and Koederitz (2005) to reduce the drilling cost by increasing ROP. However, the predicted ROP was more than three times the actual ROP. Dupriest and Koederitz (2005) used the concept on the rig site by adjusting MSE values so that the values of rock strength would be approximately similar, in the range of 30-40% as followed in Eq. 5.

$$\mathrm{MSE_{adj}} = \mathrm{MSE} \times \mathrm{EFF_m} \quad \dots \quad (5)$$

Where $\mathrm{MSE_{adj}}$ is the adjusting MSE (psi), and $\mathrm{EFF_m}$ is the efficiency factor which is equal to 0.35 (unitless) (Dupriest and Koederitz, 2005).

During drilling, the bit is only able to deliver 30-40% of the energy to the formation because of the ineffective or unnecessary torque and also because of the friction loss between the bit components. This was studied by Pessier and Fear (1992) who compared different bits efficiency and proved that while the PDC bits may require less WOB to drill than rock bits. The PDC bit responded partially with torque and both types of bits end up with 30% efficiency. The influence of differential pressure on the PDC bit drilling performance in laboratory scale conditions was studied by (Andersen and Azar, 1993). The results indicate that within normal drilling condition, the differential pressure will reduce the bit efficiency due to bit balling or chip hole down effects underneath the bit.

Checkina et al. (1996) investigated the PDC wear experimentally in contact with two different types of rock deformation: elastic deformation and crushing. The method revealed the impact of the bit wear on characteristics of the cutting process. Mensa-Wilmot (2001) investigated the impact of formation hardness, abrasiveness and hole size to evaluate the PDC bit efficiency. He concluded that outer region wears should be higher than in inner during drilling in abrasive formation, while in application of hard formation; inner cutters should expect higher wear than outer region.

Van Quickelberghe et al. (2006) proposed an experimental procedure to analyse the results of wear test obtained by measuring the applied forces and cross-sectional area of the cutting that computed by laser – profiled the grooves.

Hareland et al. (2009) developed a cutting efficiency factor which is defined as the ratio of the volume of rock removed by a single cutter to the force needed to remove that volume of rock.

He stated that the factor is based on the back-rack angle, DOC, and the rock strength. While Che et al. (2012) stated that more attention should be paid to the comprehensive cutting mechanism and rock removal theories to evaluate the cutting efficiency. Azar et al. (2013) developed a more convenient cutter (conical shaped polycrystalline diamond element- CDE) to improve ROP and prevent impact wear that caused by vibration while dining in interbedded formations.

A ROP method combined with an analytical model to predict the PDC bit wear was developed based on a geometric correlation between cutters height loss and volume loss of cutters which assumed to be in linear proportional with WOB (Liu et al., 2014). Yang et al. (2019) introduced a model to indicate when to pull the bit out of hole and predict the Kymera PDC bit cutters wear. His model considered the mechanical specific energy, principal component analysis, and wavelet analysis. Mazen et al. (2019) investigated the effect of rock strength, bit design, rock-cutter interface, and bit hydraulic on PDC bits to predict the bit performance and the abrasive cutters wear on the inner and outer bit cones.

Glowka (1987) confirmed that the PDC bit profile must be considered if the evaluation of bit efficiency is the main objective. However, he assumed that the cutter wear, rock removed, and energy is the same for all cutters fixed on the bit blades. Wang et al. (2018) stated that each cutter mounted in the blade has a particular location as a function of radial distance to the bit centre. He also reported that the rock removed is not similar for all cutters as the bit is rotating in different circular path.

The axial force or WOB acting on the bit face is distributed on the cutters among the bit profile. The MSE consumed by cutters which are in contact with the rock is not the same for all cutters fixed on the bit face. To bridge this gap, a new predictive tool is required to evaluate the bit performance and wear for cutters in both the inner and outer cones to match the standard dull grading format.

2. Methodology

Once the bit reached the bottom of the hole and contact the rock; WOB is applied. As a result, the cutters penetrate the formation to create a DOC that is affected by bit size, bit design, and formation strength. When the bit start rotating to crush the rock, the projected cutting area of each cutter may differ because of the number, size, and location of cutters (Hareland and Rampersad, 1994).

The cutter pushed to the rock to obtain DOC is based on the applied WOB and cutting angle (Hareland et al., 2009). This has been proved by Tian et al. (2015) who stated that the bit efficiency is significantly dependant on the cutting angle and the bit wear.

The response of the torque to the applied WOB can be employed as an index to assess how the cutters are aggressive to the formation, so the higher torque to WOB ratio, the more aggressive the cutters. Accordingly, the bit is considered to be efficient if the required energy to drill is minimum (Sinor et al., 2001).

Good hole cleaning was suggested for most of the proposed models in the past such as: (Gouda et al., 2011, Pryhorovska, 2017, Wojtanowicz and Kuru, 1993). Optimum bit hydraulic efficiency to ensure perfect hole cleaning can easily be obtained in the case of drilling with PDC bit with proper size of nozzles, sufficient mud weight, and flow rate. In this work, the effect of mud hydraulic is neglected.

Based on that, the new EMSE tool is first developed to predict the bit performance and cutters wear in the inner and outer cones (see Fig. 1) by including the drilling variables recorded on the rig site such as WOB, RPM, ROP, cutting angle, and torque. It simplifies the model in order to make the model more convenient to be applicable on rig site compared with MSE model that was developed based on single cutter theory and presented by Dupriest and Koederitz (2005) (see Eq. 5).

Fig. 1 PDC Profile - Inner and Outer Cones.

Chen et al. (2014) used a modified equation to determine DOC as follows:

$$\mathrm{DOC} = \frac{\mathrm{ROP}}{5 \times \mathrm{RPM}} \qquad (6)$$

Eq. 6 suggests using a constant number that might be referred to the number of blades as the cutting elements. The bit blades extended azimuthally from the bit body and a number of cutters are disposed on every blade (see Fig. 2). However, a plurality of cutters engage to create DOC and cut the rock with different results and effectiveness (Jones, 1990). Therefore, the bit performance should basically be evaluated according to the length of effective blades that consist of cutters which actually face the rock to drill. The reduction in effective cutting rate will lead specific energy to increase due to loss of energy on friction which may result in replacing the bit because of the increment in cutters wear (Teale, 1965).

Fig. 2 Updated diagram - PDC bit drill through formation by shearing the rock (Drilling, 2017)

In this model, Eq. 6 is correlated to develop a new idea by including the effective blade (EB) as proposed in Spread (2017). The modified DOC is determined in both cones as follows:

$$DOC_{inner} = \frac{ROP}{RPM \times N_b \times EB_{inner}} \quad (7)$$

$$DOC_{outer} = \frac{ROP}{RPM \times N_b \times EB_{outer}} \quad (8)$$

Where, N_b is the number of blades.

EB is defined as the ratio of total cutters width that is involved in drilling to the length of the blade as follows (see Fig. 3):

$$EB_{inner} = \frac{Ct_{inner}}{Lb_{inner}} = \frac{C_{inner} \times Nc_{inner}}{Lb_{inner}} \quad (9)$$

$$EB_{outer} = \frac{Ct_{outer}}{Lb_{outer}} = \frac{C_{outer} \times Nc_{outer}}{Lb_{outer}} \quad (10)$$

Where, C_t is the total cutters width (in), Nc_{inner} and Nc_{outer} are the number of cutters in the inner and outer cones respectively. C_{inner} and C_{outer} are inner cutters width and outer cutters width respectively, and Lb is the blade length (in).

Lb, as shown in Fig. 3, can be determined in both cones using Eqs. 11 and 12.

$$Lb_{inner} = [(r_{inner})^2 + (h_c)^2]^{0.5} \quad (11)$$

$$Lb_{outer} = [(r_{outer})^2 + (h_c)^2]^{0.5} \quad (12)$$

Fig. 3 shows the inner and outer cone and how can be calculated as a function of bit radius (r_b) as suggested by Brandon et al. (1992). (see Eqs. 13 and 14).

$$r_{inner} = \frac{2}{3} \times r_b \quad (13)$$

$$r_{outer} = \frac{1}{3} \times r_b \quad (14)$$

Fig. 3 A schematic diagram of PDC drill bit blade: bit radius, blade length, cone height, and cutting angle

Where, r_b is the bit radius (in), r_i is the inner cone radius (in), and r_o is the outer cone radius (in).

Fig. 4 illustrates several bit profiles and guides how the cone height h_c can be calculated.

Fig. 4 Updated bit selection chart (Bourgoyne et al., 1986).

PDC bit can be designed with various profiles (see Fig. 4). Two 8.5" PDC bits which are designed with shallow cone profiles and one 16" PDC which is designed with a parabolic profile in the medium cone are selected. According to the options as shown in Fig. 4, the cone height will take the range of ($1/8\ D_b < h_c$) for 8.5" PDC bits, and ($1/8\ D_b \leq h_c \leq 1/4\ D_b$) for the 16" PDC bit. In this work, h_c is assumed to be equal to 3 inches for the 8.5" PDC bits, and 4 inches for the 16" PDC bit.

Glowka (1985) reported that the cutting area is significantly dependant on DOC and cutter arc length. Glowka (1989) concluded that the shape of the cutting area is based on the previous cut made by adjacent cutter. While Chen et al. (2014) concluded that every cutter has a particular shape of arc, and the arc of cutters located on the outer cone may differ to those in the inner cone. Accordingly, in this work, the cross-sectional area of the cutting is suggested to be calculated as a function of cutter width for both cones as shown in Eqs. 15 and 16.

$$Ac_{inner} = DOC_{inner} \times C_{inner} \quad (15)$$

$$Ac_{outer} = DOC_{outer} \times C_{outer} \quad (16)$$

Where, C_{inner} is the inner cutters width (in), and C_{outer} is the outer cutters width (in).

Where cutters width is assumed to be constant in both cones (see Fig. 5).

Fig. 5 Cutting cross sectional area and total of cutters width.

The cross-sectional area of PDC cutter can also be determined as a function of cutting angle as proposed by Gouda et al. (2011).

$$Ac_{inner} = WOB \times \cos \emptyset_{inner} / \delta \quad (17)$$

$$Ac_{outer} = WOB \times \cos\emptyset_{outer} / \delta \quad \text{.......... (18)}$$

Where $\emptyset$ is the cutting angle (degrees), and δ is the rock hardness (psi).

Rock hardness characterizes the rock resistance to be scratched or drilled. An increase of rock hardness would result in increasing mechanical energy, as more energy needed to cut the rock. Jogi and Zoeller (1995) introduced Eq. 19 to estimate the rock hardness.

$$\delta = \frac{1}{Drillability} = \frac{WOB \times RPM}{ROP \times D_b} \quad \text{.......... (19)}$$

Where, δ (psi), and D_b is the bit diameter (in).

Number of cutters is not the same for inner and outer cones, so Eqs. 17 and 18 are developed in this model as follows:

$$DOC_{inner} \times C_{inner} \times Nc_{inner} = WOB \times \cos\emptyset_{inner} / \delta \quad \text{.......... (20)}$$

$$DOC_{outer} \times C_{outer} \times Nc_{outer} = WOB \times \cos\emptyset_{outer} / \delta \quad \text{.......... (21)}$$

Determination of cutter width is suggested as follows in Spread (2017). In this work, the cutter width is estimated for both cones as follows:

$$C_{inner} = 2 \times [DOC_{inner} \times (D_{cutter} - DOC_{inner})]^{0.5} \quad \text{.......... (22)}$$

$$C_{outer} = 2 \times [DOC_{outer} \times (D_{cutter} - DOC_{outer})]^{0.5} \quad \text{.......... (23)}$$

Where D_{cutter} is the cutter diameter (in).

Solving Eqs. 20 through 23, DOC and C for both cones can be calculated.

The obtained values of EB_{inner} and EB_{outer} are used to calculate DOC for both cones using Eqs. 7 and 8. Then Eqs. 7 and 8 are substituting into Eq. 3. To obtain Eqs. 24 and 25 for determination of EMSE in inner and outer cones, respectively.

$$EMSE_{inner} = \frac{WOB}{A_{inner}} + \left(EB_{inner} \times N_b \times \frac{2\pi \times T \times RPM}{A \times ROP}\right) \quad \text{.......... (24)}$$

$$EMSE_{outer} = \frac{WOB}{A_{outer}} + \left(EB_{outer} \times N_b \times \frac{2\pi \times T \times RPM}{A \times ROP}\right) \quad \text{.......... (25)}$$

Where A_{inner} and A_{outer} are the inner and outer bit area (in^2), respectively.

Volume of rock removed as a function of ROP can be determined as presented by Jogi and Zoeller (1995) by use of Eq. 26.

$$V_r = A \times \frac{ROP}{RPM} \ldots \ldots (26)$$

While Hareland and Rampersad (1994) reported that the volume of rock removed can be defined as proposed in Eq. 27

$$V_r = 2\pi \sum_{i=n}^{i} Ac \times R \ldots \ldots (27)$$

Where Ac is the cutting area of the cutter (in^2), and R is the distance from cutter to bit centre (in).

By substituting Eq. 27 into Eqs. 24 and 25, new Eqs. 28 and 29 are developed to compute the effective mechanical specific energy in both inner and outer cones.

$$EMSE_{inner} = \frac{WOB}{A_{inner}} + \left(EB_{inner} \times N_b \times \frac{T}{Ac_{inner} \times R_{inner} \times Nc_{inner}}\right) \ldots \ldots (28)$$

$$EMSE_{outer} = \frac{WOB}{A_{outer}} + \left(EB_{outer} \times N_b \times \frac{T}{Ac_{outer} \times R_{outer} \times Nc_{outer}}\right) \ldots \ldots (29)$$

3. Model Assumptions

In this model, the following assumptions are made:

- The model assumes normal drilling conditions and ignores the impact damage that might be caused while drilling through interbeded formation due to bit whirl.
- All cutters located in both the inner and outer cone have equal cutter width, depth of cut, and consume the same mechanical energy.
- The model is applicable for PDC cutters as round in shape.
- Bit blades assumed to be straight and have the same length (see Fig. 3).
- Good hole cleaning is assumed at the bottom hole of drilling formation.
- Radial location of cutters fixed in the inner cone (R_{inner}) is equal to the average distance between the cutter position at the middle of the cone to the bit centre ($\frac{r_{inner}}{2}$). (R_{outer}) is measured by the distance between the cutter position at the middle of the outer cone to the bit centre ($\frac{r_{outer}}{2} + r_{inner}$).

4. Results and Discussions

4.1 Well 1

A heavy set of 8.5" PDC bit designed with 9 blades and 13 mm cutters drilled the production zone from 3,205 ft to 3,445 ft in 31.6 hours through Dahra C and Rabia Shale formation. The bit reached the final depth and dulled for 2 – 0 (i.e. 2 mm height lost on inner cone out of 8 mm and no wear recorded in the outer cone).

As can be seen from Fig.6, ROP trend behave inversely with EMSE in both cones, the bit will need less energy if the bit is aggressive with high ROP. However, the bit will struggle to drill and require more energy if ROP is dropped because of the increase in the hardness (see Fig. 8a). The real bit dulling in the bit record showed damage of 2 mm cutters height lost in the inner cone and no damage in the outer cone. The predicted bit efficiency and cutters wear as reflected by EMSE agrees with the actual bit dulling as shown in Fig. 6 and Fig.8c, where EMSE inner is greater than EMSE outer during drilling the whole section, which demonstrates the bit wear occurred in the inner cone. This is shown in Fig. 7, where the effective blades for the inner cone is greater than the effective blades for the outer cone. The inner effective blades are obtained as a result of having more inner cutters in contact with the rock due to the effect of the cutting angle and the distribution of the cutters among the blades. Accordingly, the inner cutters are more subjected to wear and that agrees with the actual dull grading recorded in the bit record.

Fig. 6 Prediction of bit performance in the inner and outer cone versus depth for well 1 and comparison with ROP.

Fig. 7 Prediction of effective blades in the inner and outer cone versus depth for well 1.

The adjusted mechanical specific energy trend suggested that the bit cutters were starting to wear at depth of 3,275 ft (see Fig. 8b) while the sharp increase of adjusting MSE at depth of 3,365 ft could indicate severe damage of the bit cutters. This agrees with the rising trend of the EMSE inner as shown in the red curve in Fig. 8c matching the actual bit wear occurred in the inner cone.

A quick glance at the trends of hardness, adjusting MSE, and EMSE, could reveal that there is a good agreement between all trends and even the values are similar at several depths. Once WOB is applied on the 9 blades bit, the weight is distributed to the cutters that penetrate into the rock to create DOC. Based on the model equations, and the results shown in Fig. 7, the average effective blades that are calculated in the inner and outer cone indicate low rock-cutter interaction response (13% and 8%, respectively). This is because the required bit energy (MSE and EMSE) is quite similar to rock hardness as shown in Fig.8, consequently, only about 3 ft/hr as an average ROP is obtained during the whole interval.

The adjusting MSE trend behaves similarly to the trend of hardness. However, EMSE trend shows a more matching with hardness trend when compared to the adjusting MSE curve along the whole interval. For example, from depth 3,300 to 3,325 ft, and from 3,425 to 3,435 ft, adjusting MSE trend displays some reduction in the trend as compared with the hardness trend where EMSE curves show a good matching.

In general, the results emphasized the fact that ESME approach is more convenient as it can be compared to the standard dull grading and used for predicting the bit performance in the inner and outer cone. To confirm the accuracy of this technique, the same computations as above are applied for the other two candidate's wells.

Fig. 8 Trends of Hardness, MSE adj and EMSE trends along the depth of well 1.

4.2 Well 2

The 16" PDC bit in well 2 drilled 1,522 ft from 2,014 ft to 3,536 ft with 6 blades – doubled rows and 16 mm cutters through Miocene, Oligocene, and Upper Eocene formation, and made 18 ft/hr average ROP. The bit pulled out with severe damage at the outer cone and dulled for 1–4 (i.e. 1 mm height was lost in the inner and 4 mm lost in the outer cone out of 8 mm).

The same procedures of computations were performed for this well to better understand the prediction of bit efficiency during drilling. EMSE in both cones are inversely proportional with ROP trend from the first bit run till the final depth. However, Fig. 9 shows that the EMSE values for the outer cone is greater than the obtained in the inner cone. The PDC required more energy to drill using the outer cone cutters due to the high number of active cutters that mounted in the outer cone as compared to cutters in the inner cone as shown in Fig. 10. Using the model equations, the average effective blades in the outer cone is estimated to about 61% compared to 29% in the inner cone. As a result, the cutters width has a strong influence on the cutting area and volume of rock removed in the outer cone compared to the one obtained by the cutters fixed in the inner cone. Accordingly, wear is more expected to be recorded in the outer cutters.

Fig. 10 illustrates the effective blades in both cones, which reflect the dullness, or that the wear of the outer cutters is rising compared to the wear that occurred on the cutters located in the inner cone.

Fig. 9 Prediction of bit performance in the inner and outer cones versus depth for well 2 and comparison with ROP.

Fig. 10 Prediction of effective blades in the inner and outer cone versus depth for well 2.

The second attempt for predicting the bit cutters wear is by using the analysis of the hardness curve. It is clearly observed from Fig. 11 that the EMSE like as the adjusting MSE curves are matching hardness curve at most depths. However, hardness and ESME values show more agreement compared to the values of MSE adj. Values of adjusting MSE are less than hardness values which could explain that the bit struggled to drill which not reflected with the obtained ROP.

At 3,475 ft as shown in Fig. 9, the ROP dropped from 3.4 to only 1.9 ft/hr, and bit start struggling to drill as rock hardness trend is gradually increased to reach its peak at depth of 3,534 ft (see Fig. 11a) indicating an abrasive wear occurred to the outer cone (see the trend in orange colour in Fig. 11c).

EMSE concept is likely to be more efficient as a predicting tool than the specific energy technique, thus it will be applied for the third well to observe its accuracy and reliability as a trending tool to assess the bit efficiency.

Fig. 11 Trends of Hardness, MSE adj and EMSE trends along the depth of well 2.

4.3 Well 3

The candidate 8.5" PDC bit drilled the pilot hole from 6,713 ft to 7,046 ft. The PDC was designed with 7 blades and 13 mm cutters. The PDC drilled through Kheir formation which mainly consists of clay, dolomite, and some traces of shale. The bit pulled out green and dulled for 0 – 0 (i.e. no wear on both inner and outer cones).

Fig. 12 illustrates the close matching in values between both EMSE inner and EMSE outer, while ROP trend responds inversely along with the whole interval. At the depth of 6,865ft, the rock hardness increases to reach its peak, estimated at 270,000 psi. Keeping the same applied WOB and RPM, ROP dropped form 1.9 ft/hr to 1 ft/hr (see Fig. 12) which means the bit requires more energy in order to the cutters to penetrate the rock. EMSE in both the inner and outer cone reaches its peak and are calculated according to model equations to be 647,671 and 552,700 psi, respectively.

Fig. 13 shows the effective blades for both inner and outer cones that actually response proportionally with ROP, and also represented in the calculation of the cutting area of the cutters. Although, the rock hardness is low as shown in Fig. 14a, both cones indicate low effective blades that reflect the obtained low ROP values among the whole interval. This is because of the received WOB by every cutter due to the number of blades - size of cutters of the selected PDC bit.

Fig. 12 Prediction of bit performance in the inner and outer cone versus depth for well 3 and comparison with ROP.

Fig. 13 Prediction of effective blades in the inner and outer cone versus depth for well 3.

In Fig. 14, it can be seen that there is a very good matching between adjusting MSE and EMSE trends with hardness curve. However, hardness values are less than values of adjusting MSE and EMSE (see Fig. 14a) that can reveal that the formation is drillable by the candidate durable 8.5" PDC bit. This concludes that the bit continued to drill once the adjusting MSE and EMSE in both cones exceed the hardness but with aggressiveness and low efficiency. To improve ROP, more WOB is needed or a 5 - 6 blades PDC bit should be run to drill this section.

Furthermore, the interpretation for this reflects the good condition of the bit when it is being pulled out of the hole with no wear recorded in both cones. Again, as shown in Fig. 14c, EMSE inner and EMSE outer are very similar with inconsiderable difference that matches the actual dull grading for the PDC bit. The results prove the reliability of the effective mechanical specific energy technique.

Fig. 14 Trends of Hardness, MSE adj and EMSE trends along the depth of well 3.

5. Conclusion

- A new method has been developed to forecast the bit efficiency when different cutting area overlap because of different radial rotation and cutting angle. The model accounts for the effective cut depth that is obtained by cutters located at each cone.
- Drillability or rock hardness allows EMSE to indicate it in more convenient way the performance of bit compared with adjusting MSE.
- By using this new model and effective blade determination technique, cutters wear can be predicted in both cones with reasonable accuracy. The concept can easily be adjusted for any PDC bit size and design as energy estimated will not be changed.
- The EMSE tool defines the required energy to drill in more accuracy, thanks to this model where EMSE in both cones can be detected to match the standard bit dull grade.
- EMSE trends in wells 1 and 2 achieve 20% and 65% accuracy to match the hardness trends compared to MSE trends as shown in Figs. 8 and 11.

- The model can be applied to optimize drilling parameters and bit selection. This concept can also guide the future design of the PDC bits.
- Future developments and improvements are required to investigate the effect of using mud motor on EMSE.

Nomenclature

A = Bit area, in^2

Ac_{inner} = Cutting area of any cutter in the inner cone, in^2

Ac_{outer} = Cutting area of any cutter in the outer cone, in^2

C_{inner} = cutters width of any cutter in the inner cone, in

C_{outer} = cutters width of any cutter in the outer cone, in

Ct_{inner}= Total of cutters width for cutters located in the inner cone, in

Ct_{outer}= Total of cutters width for cutters located in the outer cone, in

D_b = Bit diameter, in

DOC = Depth of cut, in

DOC_{inner} = Depth of cut of cutters located in the inner cone, in

DOC_{ouer} = Depth of cut of cutters located in the outer cone, in

EB_{inner} = Effective blades for the inner cone, unitless

EB_{outer} = Effective blades for the outer cone, unitless

EFF_m= Efficiency factor, unitless

$EMSE_{inner}$ = Effective mechanical specific energy in the inner cone, psi

$EMSE_{outer}$ = Effective mechanical specific energy in the outer cone, psi

g = Gage height, in

h_c = Cone height, in

Lb_{inner}= Inner blade length, in

Lb_{outer}= Outer blade length, in

MSE = Mechanical specific energy, psi

$MSE_{adj.}$ = Adjusted mechanical specific energy, psi

N_b = Number of blades, unitless

Nc_{inner} = Number of cutters in the inner cone, unitless

Nc_{outer} = Number of cutters in the outer cone, unitless

R = Distance from cutter to bit centre, in

r_b = Bit radius, in

r_{inner} = Inner cone radius, in

R_{inner} = Inner radial distance, in

r_{outer} = Outer cone radius, in

R_{outer} = Outer radial distance, in

ROP = Rate of penetration, ft/hr

RPM = Rotation per minute, rpm

T = Torque, lbs − in

V_r = Volume of rock removed, in^3

WOB = Weight on bit, lbs

$\emptyset_{inner}$ = Cutting angle of the cutters in inner cone, degree °

$\emptyset_{outer}$ = Cutting angle of the cutters in outer cone, degree °

δ = Hardness or the cutting force per unit area, psi

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List of figures