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Research on PDC bit Drilling Rate Equation in Daqing Medium-Deep Well Based on Rock Breaking Experiments by PDC Bit

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Abstract: PDC bit drilling rate equation is one measuring criterion of PDC bit work efficiency. The reasonable PDC bit drilling rate equation could predict the penetration rate and provide guidance for field operation. This paper studied the influences of the parameters on PDC bit drilling rate, such as rock drillability, cutting teeth diameter, specific weight on bit and rotate speed, and regressed the relation equations between the above parameters and drilling rate for cement rock, white sandstone, yellow sandstone, red sandstone and granite based on the laboratory rock breaking experiments. The results showed that the regression equation between specific weight on bit and drilling rate is quadratic polynomial for the soft and intermediate hardness rock, such as cement rock, yellow sandstone and white sandstone. The regression equation is quartic polynomial, the regression equation between rotate speed and drilling rate is quadratic polynomial for the intermediate hardness rock, such as red sandstone. The field data verification results of Daqing Oilfield medium-deep well showed the fractional error in actual drilling speed and forecast drilling speed between 3.03% and 9.23% and the average error is 6.397%. This explained that the modified PDC bit drilling rate equation could describe the drilling law preferably.

Keywords: Daqing Oilfield, drilling rate equation, medium-deep well, PDC bit, rock breaking experiments.

1. INTRODUCTION

PDC bit is a cutting type bit whose main rock breaking method is shear breaking, it could achieve drilling in medium-deep well formation [1, 2]. The research and application of PDC bit drilling rate equation are one of the main tasks in drilling engineering, because the drilling efficiency influences drilling progress and cost directly [3, 4]. The drilling rate of PDC bit is related to bit structural parameters, rock parameters, mechanical parameters, hydraulic parameters and drilling fluid properties parameters [5, 6]. Building the reasonable PDC bit drilling rate equation could predict the penetration rate and provide guidance for field engineers in guiding drilling operation [7-9].

Nowadays, the common drilling rate models are Bingham equation, Young's equation and Eminem equation and so on in drilling engineering. These drilling equations are built by analyzing mechanical parameters and hydraulic parameters on the basic of formation drillability parameters, but they ignored the characteristics of PDC bit rock breaking mechanism [10-13]. Based on the laboratory rock breaking experiments, this paper studied the influences of the parameters on PDC bit drilling rate and built the PDC drilling rate equation of Daqing Oilfield medium-deep well by considering the pressure environment of subsurface formation in Daqing Oilfield.

2. THE PDC BIT ROCK BREAKING EXPERIMENTAL EQUIPMENT AND PARMETERS

When bits are breaking rock, the roller bits mainly produce the axial impact vibration, but PDC bits mainly produce the circumferential torsional impact vibration. So it is very common that PDC bits produce stick-slip phenomenon in real drilling operation. Meanwhile, the main tool of drilling deep formation is PDC bits, and how to improve the rock breaking efficiency of deep wells and reduce the failure of drill wear are also the focus of current researches.

The experimental equipment is shown as Fig. (**1**). The diameters of experimental PDC bit are Φ50 and Φ75, as shown in Fig. (**2**) and Fig. (**3**). The diameters of cutting teeth are 13.5mm, 16.0mm and 19.0mm, their caster angles are all 15°. The samples are cement rock, white sandstone, yellow sandstone, red sandstone and granite, sum to 12 pieces.

The experimental parameters of PDC bit rock breaking experiment are shown in Table **1**.

The rock breaking processes of five kinds of rock samples are shown in Fig. (**4**).

3. THE PDC BIT ROCK BREAKING EXPERIMENTAL RESULTS AND ANALYSIS

3.1. The Influence Analysis of Rock Drillability on Drilling Rate

The rock drillability is an important indicator which describes the degree of difficulty of rock breaking. Applying micro-drilling method in testing drillability grade kd of five kinds of rock samples for evaluating the anti-drilling capability of rock samples, as shown in Table **2**.

The PDC bit rock breaking experiments in different bit weights and rotate speeds with a sum of 5 groups 20 items were conducted. The changing trend figure between drilling rate and drillability grade in different rotate speeds was drawn by the example that bit weight is 15kN and PDC bit diameter is 75mm, as shown in Fig. (**5**).

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Fig. (1). The experimental equipment.

Fig. (2). *Φ*50mm Bit.

Fig. (3). *Φ*75mm Bit.

Table 1. The experimental parameters.

Bit Structure		Lithology	Drilling Parameters	
diameters /mm	Cutting teeth /mm		bit weight /kN	Rotate Speed /rpm
50	13.5,16.0,19.0	cement rock, white sandstone, yellow sandstone, red sandstone, granite	6,10,14	100,150,200
75			9,15,21	

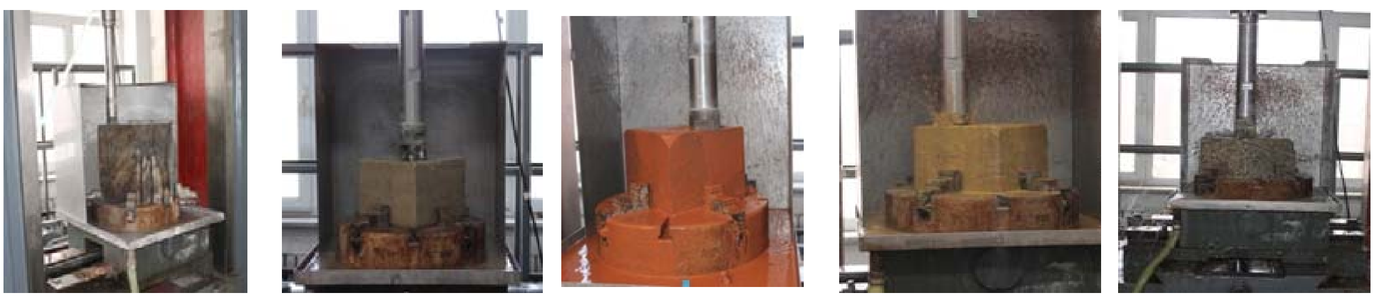

Fig. (4). The rock breaking experiments of PDC bit.

Table 2. The rock drillability grade.

Rock Samples	Actual Drilling time /s				Drillability Grade	Hardness Properties
	1	2	3	Average value		
cement rock	20.55	22.42	21.71	21.56	4.43	intermediate
white sandstone	32.26	30.67	31.72	31.88	4.79	intermediate
yellow sandstone	7.97	8.42	8.45	8.28	3.05	soft
red sandstone	64.32	66.50	66.58	65.80	6.04	intermediate
granite	171.54	182.72	175.74	180.00	7.49	hard

According to Fig. (**5**), the drilling rate decreases with the increase of drillability grade exponentially in different rotate speeds. And the higher rotate speed is the higher drilling rate of PDC bit.

3.2. The Influence Analysis of Cutting Teeth Diameter on Drilling Rate

The cutting tooth is an important structure parameter which influences rock breaking efficiency. The PDC bit rock

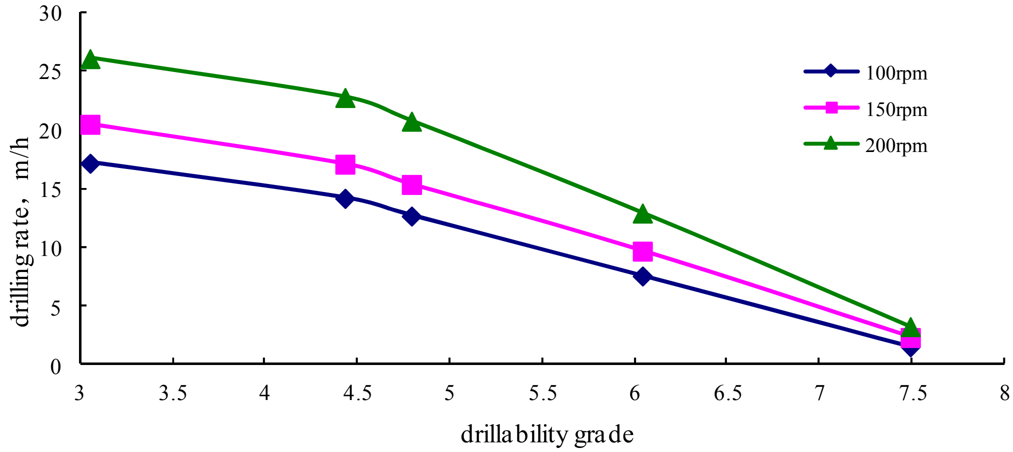

Fig. (5). The relation curve between drilling rate and drillability grade.

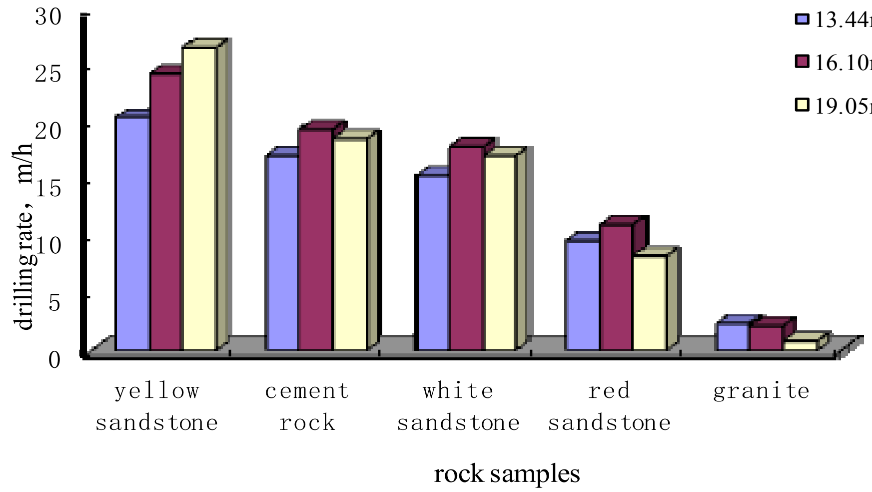

Fig. (6). The histogram between cutting teeth diameter and drilling rate.

breaking laboratory experiments whose caster angles are 15° and cutting teeth diameters are 13.5 mm, 16.0 mm and 19.0mm with a sum of 5 groups and 20 items were conducted. The relation curve between cutting teeth diameter and drilling rate was drawn by the drilling rate data in the condition of bit weight is 15kN and rotate speed is 150rpm, as shown in Fig. (**6**).

According to Fig. (**6**), the drilling rates of different cutting teeth diameters are different in same bit weight, rotate speed and rock sample. This explained that cutting teeth diameters had high influences on PDC bit drilling rate. For yellow sandstone whose drillability grade is lower, PDC bit drilling rate increases with the increase of cutting teeth diameters, for cement rock, white sandstone and red sandstone, PDC bit drilling rate increases firstly and then decreases with the increase in cutting teeth diameters, and for granite whose drillability grade is higher, t drilling rate decreases with the increase of cutting teeth diameters rapidly.

3.3. The Influence Analysis of Specific Weight on Bit on Drilling Rate

The PDC bit rock breaking experiments in different specific weight on bit of different rock samples and rotate speeds with a sum of 5 groups and 20 items. The relation curve between specific weight on bit and PDC bit drilling rate was drawn by the example that cutting teeth diameter is 13.5mm and PDC bit diameter is 75mm, as shown in Fig. (**7**) and Fig. (**8**).

The fitting regression analysis was done by experiment data, and it was made sure that the optimal regression equation was between specific weight on bit and drilling rate by example of white sandstone, as shown in Table **3**.

The laboratory experiment results showed that the relationship between specific weight on bit and drilling rate is polynomial, its correlation coefficient is approximately 1. These results are different from the research results whose relationship between specific weight on bit and drilling rate is considered power function. The regression equation is quadratic polynomial for the soft and intermediate hardness rock, such as cement rock, yellow sandstone and white sandstone, and it is quartic polynomial for the intermediate hardness rock, such as red sandstone, as shown in equation (1) and equation (2).

$$V_s = \mathrm{a}W_\mathrm{p}^2 + \mathrm{b}W_\mathrm{p} + \mathrm{c} \qquad (0 < K_\mathrm{d} \le 6) \qquad (1)$$

$$V_s = \mathrm{a}W_\mathrm{p}^4 + \mathrm{b}W_\mathrm{p}^3 + \mathrm{c}W_\mathrm{p}^2 + \mathrm{d}W_\mathrm{p} + \mathrm{e} \qquad (K_\mathrm{d} > 6) \qquad (2)$$

In the equation, a, b, c, d and e are regression coefficients.

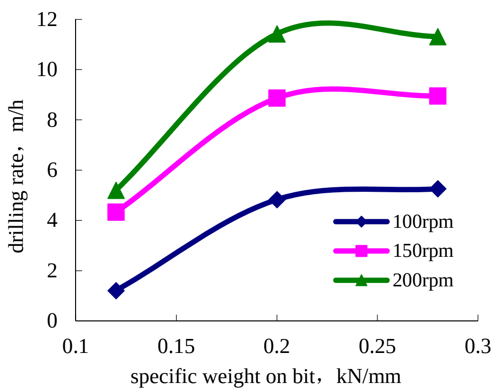

Fig. (7). The 50mm PDC bit in white sandstone.

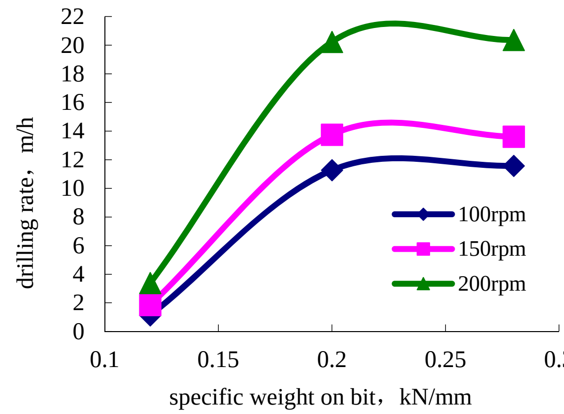

Fig. (8). The 75mm PDC bit in white sandstone.

Table 3. The regression equation between specific weight on bit and drilling rate of white sandstone.

Lithology	Drillability grade	bit diameter /mm	Rotate Speed /rpm	The Optimal Regression Equation	Correlation Coefficient R^2
white sandstone	4.79	50	100	$R = -249.22 W_P^2 + 125\ W_P - 10.201$	≈1
			150	$R = -348.44 W_P^2 + 168.25\ W_P - 0.843$	≈1
			200	$R = -494.53 W_P^2 + 236\ W_P - 15.999$	≈1
		75	100	$R = -768.75 W_P^2 + 372.75\ W_P - 32.53$	≈1
			150	$R = -939.84 W_P^2 + 449.37\ W_P - 8.531$	≈1
			200	$R = -1306.3 W_P^2 + 628.63\ W_P - 3.245$	≈1

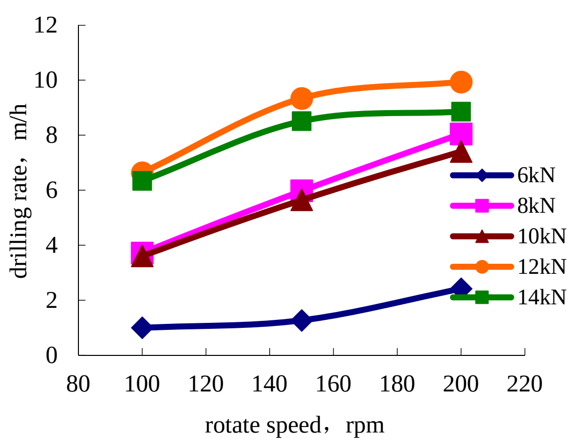

Fig. (9). The 50mm PDC bit in red sandstone.

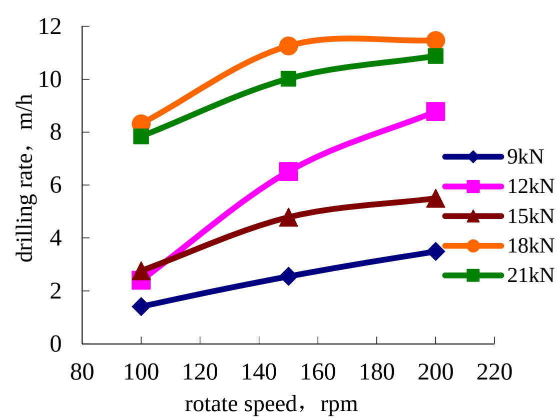

Fig. (10). The 75mm PDC bit in red sandstone.

3.4. The Influence Analysis of Rotate Speed on Drilling Rate

The PDC bit rock breaking experiments in different specific weight on bit of different rock samples with a sum of 5 groups and 20 items were conducted. The relation curve between rotate speed and drilling rate was drawn by the example that cutting teeth diameter is 13.5mm and caster angle is 15°, as shown in Fig. (**9**) and Fig. (**10**).

The fitting regression analysis was done by experiment data, and it was made sure that the optimal regression equation was between rotate speed and drilling rate by example of red sandstone, as shown in Table **4**.

The laboratory experiment results showed that the regression equation between rotate speed and drilling rate is quadratic polynomial, its correlation coefficient is above 0.9947, as shown in equation(3).

$$V_s = an^2 + bn + c \qquad (0 < K_d \le 6) \tag{3}$$

In the equation, a, b and c are regression coefficients.

Table 4. The regression equation between rotate speed and drilling rate of white sandstone.

Lithology	Drillability Grade	bit diameter /mm	Rotate Speed /rpm	The Optimal Regression Equation	Correlation Coefficient R^2
Red Sandstone	6.04	50	6	$R = 0.0002n^2 - 0.0386n + 3.1$	≈1
			8	$R = -4E\text{-}05n^2 + 0.0547n - 1.37$	≈1
			10	$R = -6E\text{-}05\ n^2 + 0.0548n - 1.31$	≈1
			12	$R = -0.0004n^2 + 0.159n - 5.06$	≈1
			14	$R = -0.0004n^2 + 0.1344n - 3.46$	≈1
		75	9	$R = -4E\text{-}05n^2 + 0.0328n - 1.47$	≈1
			12	$R = -0.0004n^2 + 0.1742n - 11.34$	≈1
			15	$R = -0.0003n^2 + 0.1054n - 5.18$	≈1
			18	$R = -0.0005\ n^2 + 0.1953\ n - 5.75$	≈1
			21	$R = -0.0003n^2 + 0.1096n - 0.48$	≈1

4. THE FIELD EXAMPLES ANALYSIS OF PDC BIT DRILLING RATE EQUATION IN DAQING MEDIUM-DEEP WELL

The drilling rate equation is theoretical method of calculating and predicting rock breaking efficiency in different formations, and is foundation of drilling parameter optimization. On the base of laboratory experiments and field drilling data of Liaohe Oilfield and Hebei Oilfield, Petroleum Exploration and Development Research Institute regressed the quartic drilling rate equation, as shown in equation (4).

$$R = KW_p^{\alpha} n^{\lambda} N_c^{f} e^{-\beta \Delta P} \quad (4)$$

In the equation, R is drilling rate; K is colligation coefficient which is relating to lithology; W_p is bit pressure; α is bit pressure coefficient; n is rotate speed; λ is rotate speed coefficient; N_c is bit specific hydraulic horsepower; f is formation hydraulic index; β is colligation coefficient which is related to buried depth and compaction degree of formation; ΔP is bottom hole pressure difference.

According to the above rock breaking experiments, the quartic drilling rate equation was amended, as shown in following equation.

$$R = \begin{cases} K_h (a_1 W_p^2 + b_1 W_p + m_1)(a_2 n^2 + b_2 n + m_2) N_c^f e^{-\beta \Delta P} (0 < K_d \le 6) \\ K_h (a_1 W_p^4 + b_1 W_p^3 + c_1 W_p^2 + d_1 W_p + m_1)(a_2 n^2 + b_2 n + m_2) N_c^f e^{-\beta \Delta P} (K_d \ge 6) \end{cases} \quad (5)$$

In the equation, K_h is colligation coefficient which is related to lithology.

The drilled formation of Daqing medium-deep well is mainly central depression area in Songliao basin. The formations, from shallow to deep in sequences, are MingShui Group, SiFangtai Group, NenJiang Group, YaoJia Group, QingShankou Group and QuanTou Group. It is necessary to build rock drillability grade profile map of central depression area for the application of model in Daqing Oilfield, as shown in Fig. (**11**).

When the data regression, the correlation coefficient R^2 is 0.752, the optimal regression equation is:

$$K_d = 141.0H + 952.6 \quad (6)$$

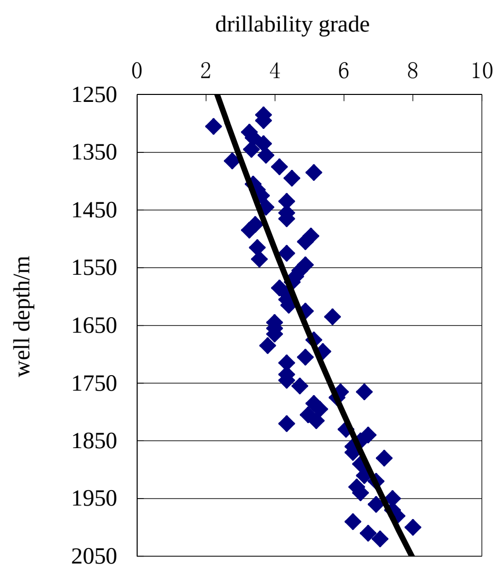

Fig. (11). The rock drillability grade profile map.

The optimal regression equation is based on the correction model data of quartic drilling rate equation. And PDC bit drilling rate equation of central depression area in Songliao basin was taken by multiple regression on the basic of field drilling data in Daqing Oilfield. The formations are shown in Table **5**.

In order to verify the practicability and veracity of PDC bit drilling rate equation, the contrastive analysis was done of field drilling data of 10 horizons in 4wells, as shown in Table **6**.

According to Table **6**, the fractional error between actual drilling speed and forecast drilling speed is between 3.03% and 9.23%, the average error is 6.397%. The variation trend

Table 5. The multiple regression fit coefficient.

Coefficient	K_h	a_1	b_1	c_1	d_1	m_1	a_2	b_2	m_2	f	β
Yaojia Group	3.32	-9.81	1.11	-	-	0.59	0.57	-184.75	16192.93	-0.35	-2.87
Qing One-two horizon	43.53	60.22	17.98	-	-	5.40	-2.97	821.18	-55318.33	1.52	0.77
Qing One horizon	4.88	-1762.02	-130.29	18.71	13.27	5.22	-2.07	564.77	-37502.06	1.35	1.39
Quan Four horizon	30.70	382.96	-32.70	-17.43	-2.56	0.89	-0.48	118.17	-7033.83	-0.25	1.24

Table 6. The verified result of PDC bit drilling rate equation.

Horizon	X27 m/h	D30 m/h	Q79 m/h	C222 m/h	Drilling Speed		Fractional Error %
					Actual m/h	Forecast m/h	
Nen Five horizon	24.3	19.6	35.9	26.6	26.60	28.32	6.47
Nen Four horizon	29.8	19.4	42.8	37.7	32.43	29.88	7.85
Nen Three horizon	32.7	25.6	14.1	47.6	30.00	33.14	7.13
Nen Two horizon	15.7	19.3	14.8	41.6	22.85	20.74	9.23
Nen One horizon	35.2	19.2	40.5	33.3	32.05	34.12	6.46
Yao One horizon	22.1	24.1	32.4	17.8	24.10	27.37	3.03
Qing Two-Three horizon	30.3	9.0	12.2	46.5	24.50	22.86	6.69
Qing One horizon	21.9	9.0	12.3	30.3	18.38	20.52	6.23
Quan Four horizon	25.2	7.0	13.5	23.2	17.23	20.46	4.44
Quan Three horizon	15.1	15.1	12.3	16.5	14.75	16.70	6.44

between actual drilling speed and forecast drilling speed is very close; this explained that the modified PDC bit drilling rate equation could describe the drilling law preferably.

CONCLUSION

1. Studied the influences of the parameters on PDC bit drilling rate, such as rock drillability, cutting teeth diameter, specific weight on bit and rotate speed, by "The simulative and analytic system of rock breaking". The drilling rate decreases with the increase in drillability grade exponentially in different rotate speeds, and increases with the increase of cutting teeth diameters for stone whose drillability grade is lower; and decreases with the increase of cutting teeth diameters rapidly for stone whose drillability grade is higher. And the relationship between specific weight on bit or rotate speed and drilling rate is polynomial and quadratic polynomial independently.
2. The laboratory experiment results, specific weight on bit and drilling rate, showed that the regression equation is quadratic polynomial for the soft and intermediate hardness rock (K_d<6), such as cement rock, yellow sandstone and white sandstone, and it is quartic polynomial for the intermediate hardness rock (K_d>6), such as red sandstone.
3. The laboratory experiment results rotate speed and drilling rate, showed that the regression equation is quadratic polynomial.
4. Regressed the quartic drilling rate equation by experimental analysis results. The field data verification results of Daqing Oilfield medium-deep well showed that the fractional error in actual drilling speed and forecast drilling speed is between 3.03% and 9.23% and the average error is 6.397%. This explained that the modified PDC bit drilling rate equation could describe the drilling law preferably.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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