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Mechanisms and Application for Hydraulic Pulsed Cavitating Jet Generator

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Abstract

To improve the rate of penetration (ROP) further, based on analysis of the jet modulating mechanism, a new drilling tool is designed which couples the advantages of both pulsed jet and cavitating jet. When drilling fluid flows through the tool in drilling process, the fluid is modulated to pulsed and cavitating jet by impellers and in self-resonant chamber. Thus, pulsed cavitating jet is formed at the outlet of the bit nozzle. Because of jet pulsation, cavitating erosion and local negative pressure effect, bottom cuttings cleaning efficiency is enhanced and the ROP is improved. The hydraulic pulsed cavitating jet generator has been applied in 8 oil fields and more than 100 wells in China. The results indicated that the maximum density of test drilling fluid was 1.70 g/cm^3, the maximum test well depth was 6,162 m. The generator could work over 230 h, and the maximum operation time was above 520 h. As the result, the average ROP had been increased by 10.1% to 104.4%. The generator has the characteristics of simple structure and long operation time, and has a well adaptability to the existing drilling equipments, technological parameters, which provides a safe and efficient new drilling technology for deep well.

Key words: Hydraulic pulsation; Cavitating jet; Penetration rate; Generator; Mechanism; Experiment; BHA

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INTRODUCTION

Drilling is the key procedure and method to oil and gas exploration and development. A survey[1] carried out by USA indicates that drilling time takes up a third of well construction period, almost half in deep well. Thus, it's very important to improve the rate of penetration (ROP) and reduce drilling time. The drilling experiences show that reasonable utilization of hydraulic energy and introducing a new type of jet which can assist to break rocks and clean bottom cuttings, is one of the feasible ways nowadays to effectively improve the ROP in deep well without any increase of ground equipment capacity. Cavitating jet and pulsed jet are studied intensively and obtained some achievements on research.

At the beginning of 1980s, researchers A. F. Conn and V. E. Johnson and so forth from American Tractor fluent company first brought up the idea of self-resonant cavitating water jet theory, they carried out researches on it and designed two typical nozzle structures of acoustic self-resonant cavitating jet[2]. Subsequently, academician Shen Zhonghou carried out theoretical and experimental researches on self-resonant cavitating water jet technology in a systematic way. Designing model of self-resonant cavitating nozzle was established and new types and efficient self-resonant cavitating nozzles were designed based on principle of hydro-acoustics and theory of fluid transients. The nozzle is applied in drilling process, which brings significant economic benefits[3-5]. Other scholars and experts coming up one after another also carried out theoretical and experimental researches on cavitating water jet and nozzle[6-9].

Overseas researches on pulsed jet drilling started from 1990s, Tempress company designed self-circulating lift valve based on the principle of fluid transients and created negative pressure pulsed tool-Hydropulse[10]. Waltech company of Canada designed negative pressure pulsed tool based on the principle of wall jet[11]. According to different modulating methods of pulsed jet, domestic scholars have designed kinds of types of bottomed hole pulsed drilling tool[17-19], such as hydraulic plate valve[12], LPMS-I pulsed modulating tool[13], SLPMC hydraulic pulsed drilling tool of mechanical blocking type[14], pulsed oscillation drilling tool of ball valve type[15], pulsed drilling tool of bit chamber rotor modulating type[16].

For various reasons, above tools are either not widely used or the increase margin of penetration rate has met its limitation at current condition. To improve penetration rate further, professor Li Gensheng successfully designed hydraulic pulsed cavitating jet generator which couples advantages of both pulsed jet and cavitating jet. A new hydraulic pulsed cavitating jet drilling technology was formed which has a good performance on field application.

1. HYDRAULIC PULSED CAVITATING JET GENERATOR

1.1 Structure Design

The hydraulic pulsed cavitating jet generator consists of up and bottom box sub, body, elastic collar, diverting device, impeller bed, impeller shaft, impeller and shaft wearing sleeve, cavity resonator(resonant chamber) and slef-resonant nozzle[20] as shown in Figure 1.

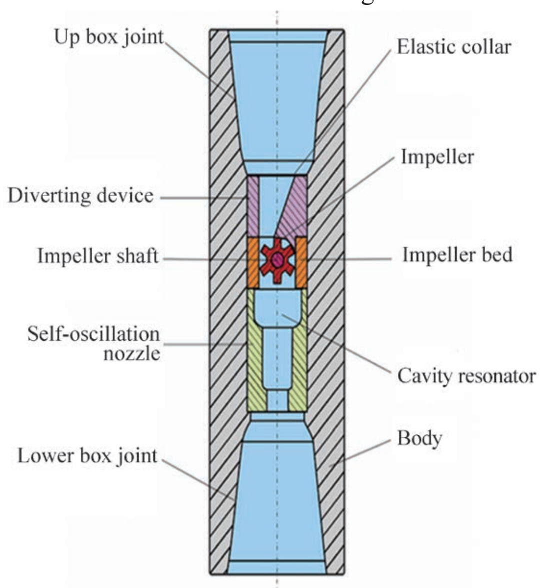

Figure1
Structure of Hydraulic Pulsed Cavitating Jet

Diverting device changes the flow direction and velocity of drilling fluid, so strong erosion resistance is required; Hydraulic pulse of drilling fluid generated by the impeller assembly is the pulsing source to the resonant chamber; Self-resonant chamber is designed in accordance with self oscillation resonator of organ-pipe. Basic parameters of hydraulic pulsed cavitating jet generator are as follows, model: HPCDT-178 and HPCDT-228, length: 500 - 605 mm, well depth: ≤ 7,000 m, flow rate: 20 - 60 L/s, pressure lose: 0.5 - 1.5 MPa, pulsing pressure: 2.0 - 3.0 MPa.

1.2 Jet Modulating Mechanism

The key parts of hydraulic hydraulic pulsed cavitating jet generator which can modulate jet are impeller assembly, self-resonant chamber and nozzle[21]. Methods of modulating jet to pulsation include piston oscillation, mechanical oscillation blocking, wall jet diversion, organ-pipe and Helmholtz acoustic resonance[22]. From the view of mechanism, the former three methods are pressure wave modulations which are based on the principle of transient fluid, the latter two methods fall into the category of shear wave rectification of wave-vortex coupling mechanism. Cavitating jet is generated by three types cavitating initiations, namely detour flow, shear and oscillation.

The slope flow channel of diverting device can change the flow direction and velocity of drilling fluid, and generate tangential impacting force which can make impeller revolve continuously at a high speed that changes the flow aisle areas continuously and generates impulse finally. Based on the principle of transient flow, continuous jet is modulated to pulsed jet when passing through impeller assembly. When pulsed jet flows into bottom resonant chamber and flows through the contracted cross-section of resonant chamber, the resonant pressure fluctuation occurs. Then it will be reflected and feedback to the chamber and feedback pressure oscillation occurs. When the frequency of the pulsating pressure matchs the natural frequency of resonant chamber, the fluid acoustic resonance is generated and feedback pressure oscillation is amplified in resonant chamber. Thus the intense pulsating turbulent vortex rings are formed at the outlet and self-resonant cavitation occurs, then the jet coupling vortex ring jet and self-resonant cavitating jet is formed.

2. MECHANISM TO IMPROVE ROP OF HYDRAULIC PULSED CAVITATING JET

The hydraulic pulsed cavitating jet generator is installed between the bit and drill collar or helicoids hydraulic motor, which couples fluid oscillation and cavitating effects and can modulate the steady flowing drilling fluid into pulsed cavitating jet. It generates three kinds of effects at bottom hole: hydraulic pulse, instantaneous negative pressure, cavitating erosion. The combination of hydraulic pulsed jet and cavitating jet can changes the flow filed at bottom hole and rock stress state so as to enhance rock-breaking and cuttings cleanout efficiency and improve penetration rate of deep drilling.

2.1 Hydraulic Pulse

The intermittent water hammer impacting pressure of pulsed jet that acts on target surface is much larger than the stagnation pressure of continuous jet, which can decrease the rock-breaking specific energy dramatically. The resonant chamber amplify the pressure oscillation generated by hydraulic pulsed tool and generate the fluid resonance, then the pulsed jet out of bit nozzle can improve flow field at bottom hole and enhance rock-breaking and cuttings cleanout efficiency.

2.2 Instantaneous Negative Pressure

Pulsed jet and pressure oscillation produce relatively instantaneous negative pressure at the bottom and cause local instantaneous underbalance, which can reduce the chip hold down effect caused by annulus fluid column pressure and improve penetration rate greatly.

Continuous low pressure can not maintain the initial negative pressure on the layer to be broken because of the pressure diffusion in the bottom rocks. However, pulsed low pressure can establish the negative pressure on the layer to be broken repeatedly. Researches indicate that the period of negative pulsation is 20 - 40 ms and it can be maintained for 1 - 2 ms, so the negative pressure effect can be ensured[23].

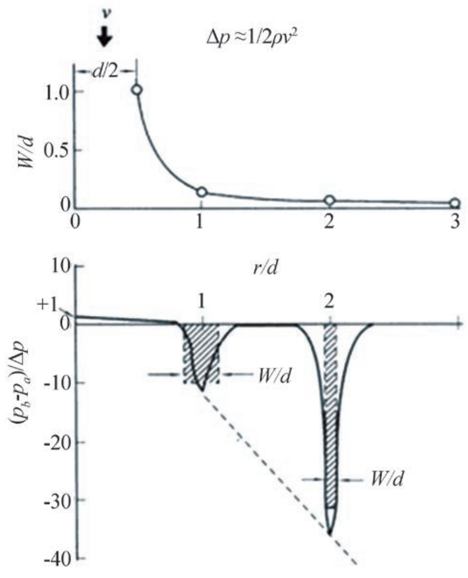

Figure2
Instantaneous Boundary Pressure Distribution at Bottom Hole

2.2.1 Change the Stress State of Rock and Decrease Breaking Strength of Rocks

The hydraulic pulsed cavitating jet can produce instantaneous negative pressure difference ΔP_n (Figure 2) at bottom hole, which can periodically decrease the local static fluid column pressure P_b as well as normal principle stress σ^e_n. The diameter of stress Mohr circle increases instantaneously and transcends shear resistant envelope curve. Consequently, the plasticity and strength of rock are decreased, which makes the rock easy to break and enhances rock breaking efficiency.

2.2.2 Improve Flow Field at Bottom and Make Cuttings Separate From Bottom Promptly

When negative pressure pulsation ΔP_n is produced, in the area where ΔP_n acts, the horizontal thrust needed to separate cuttings from bottom decreases with the drop of total hold down pressure ($P_b+\Delta P_m+w-P_p-\Delta P_n$), which makes the cuttings separate from bottom promptly and cutting cleaning efficiency improved as well as avoid regrinding.

2.3 Cavitating Erosion

When pressure pulsation occurs, it is easy to produce air bubbles near the bottom due to pressure reducing, which helps cavitation occur. The impacting pressure of cavitating jet is 8.6 - 124 times as large as stagnation pressure of continuous jet, it enhances rock-breaking and cuttings cleanout effects significantly so as to improve drilling speed.

3. TOOL TEST AND PARAMETER OPTIMIZATION

After the prototype of hydraulic pulsed cavitating jet generator was developed, in order to check its working reliability and have a good understanding of structure design parameters, laboratory and field tests were carried out first. The characteristics and rules of pressure oscillation and pressure frequency were obtained. Then researches of parameter optimization were carried out in laboratory.

3.1 Laboratory Test and Filed Test

3.1.1 Laboratory Test

Laboratory test was carried out in water jet research center of china university of petroleum (east china). The power was supplied by Triplex plunger pump, the maximum flow rate was 5.8 L/s during the test.

Laboratory tests indicated that the amplitude of pulsing pressure and pressure lose produced by hydraulic pulsed cavitating jet generator increased as the flow rate increased. The pulse frequency of hydraulic pulsed cavitating jet generator was invariable when the flow rate remained constant. When the flow rate was 5.8 L/s, the pulse frequency was about 14 Hz, the pulsing pressure amplitude was about 2.5 MPa (Figure 3).

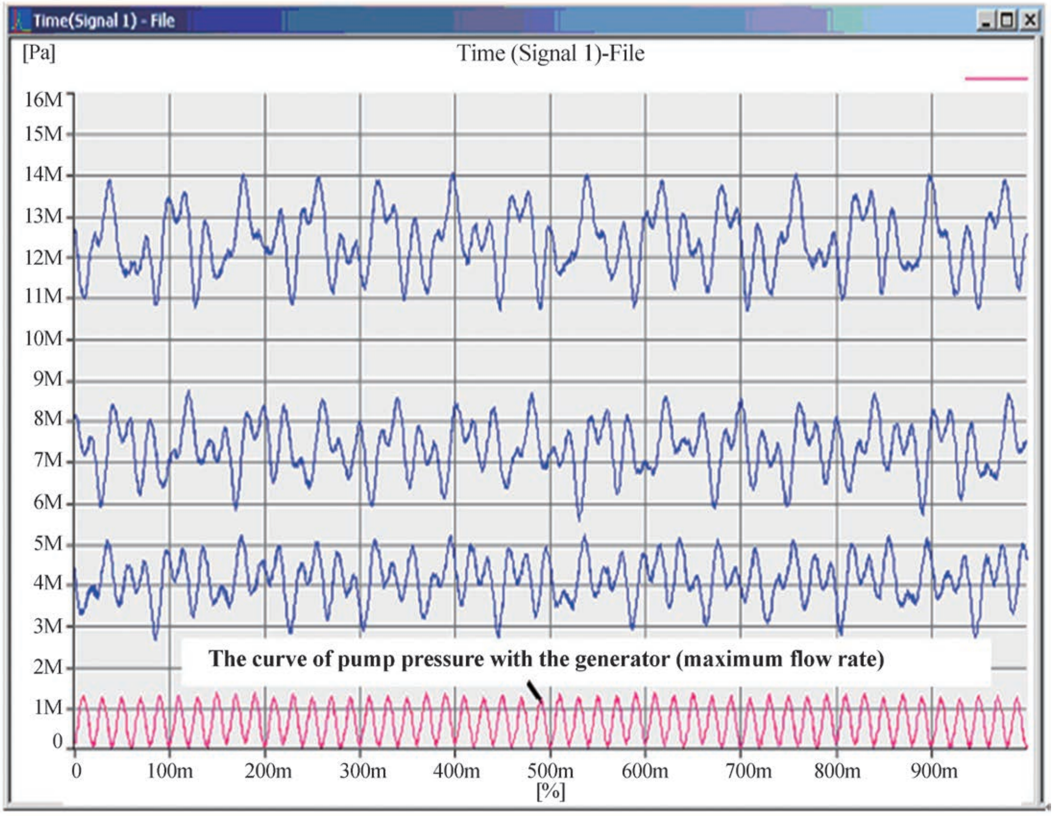

Figure 3
Laboratory Test Results

3.1.2 Field Test

Field tests were finished on Xin 11-Gengxie 18 well which was constructed by 32,577 drilling crew of yellow river drilling fifth branch company of Shengli Petroleum Administration. The testing drilling assembly was: bit+ hydraulic pulsed cavitating jet generator+2 joints 6¼ drill collar+1 joint 5" drill pipe + Kelly. Bit nozzle pressure were tested under two circumstances-with and without hydraulic pulsed cavitating jet generator. When the flow rate was between 27.5 - 32.0 L/s, the pulsing pressure amplitude was 1.00 - 1.70 MPa, pressure lose was 0.56 - 0.60 MPa, the pulse frequency was about 9.5 Hz (Figure 4).

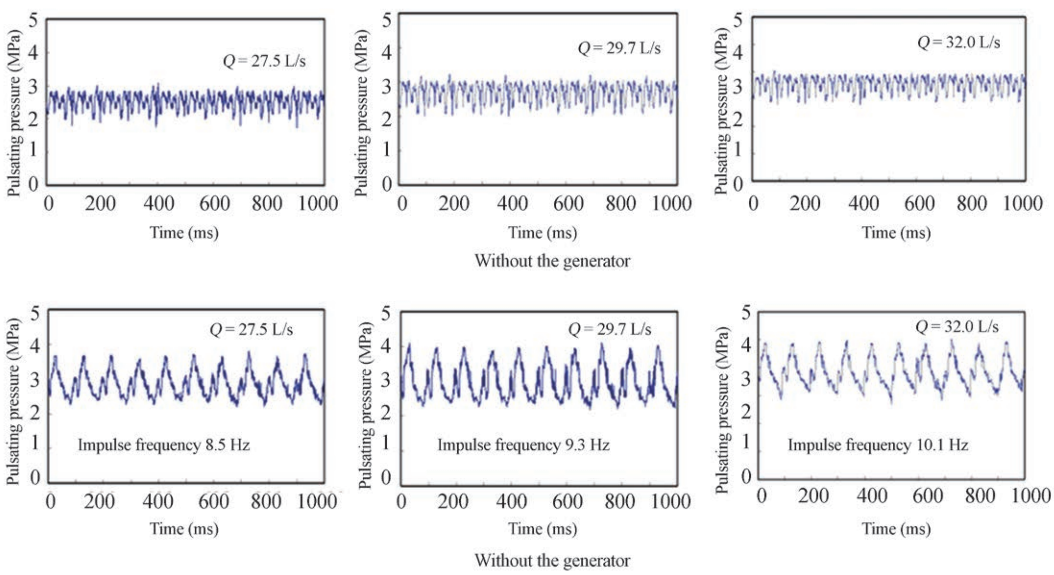

Figure 4
Field Test Curve

3.2 Parameter Optimization Research in Laboratory

In order to optimize the parameters of hydraulic pulsed cavitating jet generator, small size hydraulic pulsed cavitating jet generator was used to carry out laboratory experiments. Theoretical researches indicate that the pressure pulsation of hydraulic pulsed cavitating jet generator is mainly affected by flow rate, number of impeller blade and structure of resonant chamber and nozzle. Experiments lay emphasis on the influence of the number of impeller blade and flow rate on pressure oscillation. Pump flow rate was in the range of 11 - 14 L/s, the number of impeller blade was chosen at 0 (pressure pulsation is merely generated by resonant chamber), 3, 4 and 6 at the condition that the height and width of each blade is same[24].

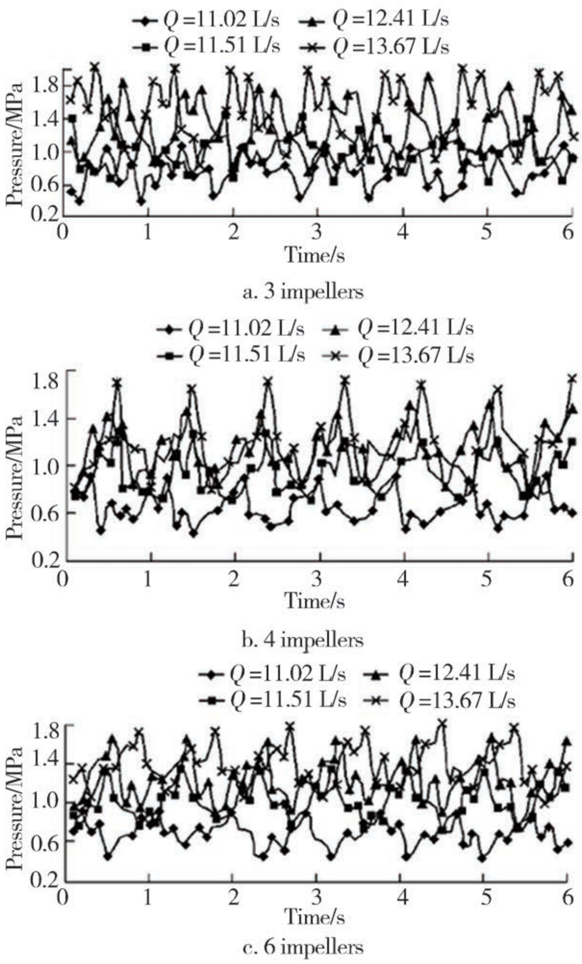

Figure 5
Pressure Oscillation Changes With Time in the Condition of Different Flow Rate and Impellers

3.2.1 Influence of Pump Flow Rate on Pressure Oscillation

As we can see from the Figure 5, the average pusation pressure and the amplitude of pressure oscillation increase as the flow rate increases. Take the generator with three impellers for example, when the flow rate is 13.67 L/s, the average pressure is 1.25 MPa, the amplitude of pressure oscillation is 1.1 MPa; when the flow rate is 11.02 L/s, the average pressure is 0.48 MPa, the amplitude of pressure oscillation is 0.57 MPa. Because the fluid velocity increses as the flow rate increases, so the tangential impacting force of fluid acting on impellers becomes bigger and impellers revolve faster, which produces larger pressure oscillation.

3.2.2 Influence of Impeller Number on Pressure Oscillation

As we can see from Figure 6, the average pusation pressure doesn't change a lot with regard to generators with different impeller number when the flow rate is fixed. The amplitude of pressure oscillation of generator with 3 impellers is the largest among all the generators. Considering the generator with 3 impellers, when the flow rate is 13.67 L/s, the average pressure is 1.25 MPa, the amplitude of pressure oscillation is 1.1 MPa; As to the generator with 4 impellers, the average pressure is 1.25 MPa, the amplitude of pressure oscillation is 0.9 MPa; As to the generator with 6 impellers, the average pressure is 1.24 MPa, the amplitude of pressure oscillation is 0.7 MPa; As to the generator without impellers(pressure pulsation is merely generated by resonant chamber), the average pressure is 1.26 MPa, the amplitude of pressure oscillation is 0.55 MPa. At the laboratory condition, pressure oscilltion coupled by 3 impeller blades and resonant chamber is most favorable, the amplitude of pressure oscillation is the largest.

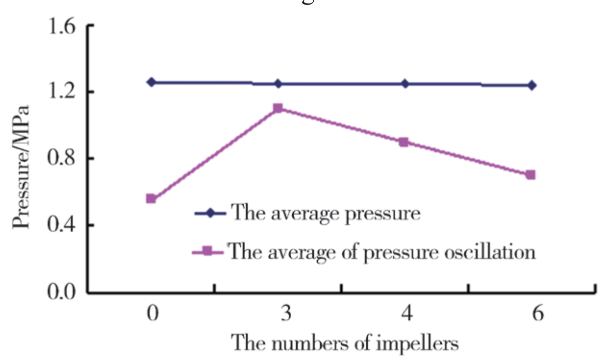

Figure 6
The Curve of Pressure Oscillation and Impeller Number

4. FIELD TEST AND RESULT ANALYSIS

Regarding to the problems of low ROP, high cost and so forth in ulta-deep and deep well drilling, a large number of filed tests of hydraulic pulsed cavitating jet drilling technology had been applied in 8 oil fields with multiple blocks, intervals, formations and combinations, such as Tarim oilfield, Xinjiang oilfield, Daqing oilfield, Sichuan oilfield, and so forth.

The field tests that carried out in 16", 121/4", 81/2" wellbore showed good applicability of the tool mating with PDC bits and cone bits to conventional drilling assembly, helicoid hydraulic motor, underbalance drilling assembly and Power V system. The maximum test well depth was 6,162 m and the life-time of the tool was over 230 h, the maximum life-time was over 520 h, which can meet the field requirements on reliability and life-time. As the result, the average ROP was enhanced by 10. 1% to 104. 4%. Hydraulic pulsed cavitating jet can afford an effective and safe approach to improve ROP in deep well.

4.1 Conventional Hydraulic Pulsed Cavitating Jet Drilling

Conventional hydraulic pulsed cavitating jet drilling is a method which installs the hydraulic pulsed cavitating jet generator between the bit and drill collar, which can modulate the continuous flowing driiling fluid in drill collar to pulsed cavitating jet, so as to improve ROP by changing bottom flow field and enhancing rock-breaking and rock-cleaning efficiency. A large number of filed tests of hydraulic pulsed cavitating jet drilling technology mating with PDC bits and cone bits had been accomplishedin different blocks of different oil fields, such as Kela, Yingmai, Tazhong, Lunnan blocks in Xinjiang Tarim oilfields, Yuanba block in Sichuan oilfield, Yitong block in Jilin oilfield, and so forth[25-26].

(a) BHA

Bit + hydraulic pulsed cavitating jet generator + drill collar + drill pipe

(b) Test results analysis

The size of well bore was 16", $12^1/_4$", $9^1/_2$", $8^1/_2$" and so forth. The well depth ranged from 1,500 to 6,162 m, the drilling fluid density was between 1.06 - 1.70 g/cm^3. Table 1 includes test parameters of some test wells, Table 2 includes ROP comparison of conventional hydraulic pulsed cavitating drilling tests with adjacent intervals. Drilling time comparison of test well and adjacent well is presented in Figures 7 and 8. Test results indicated that the ROP of test well was enhanced by 10% - 85% comparing to contrast wells. As a result, the hydraulic pulsed cavitating jet generator is compatible with conventional drilling and has a good adaptability to field drilling parameters.

Table 1
Test Parameters of Conventional Hydraulic Pulsed Cavitating Jet Drilling Well

Well name	Bit type	Bit size (mm)	Interval depth (m)	WOB (kN)	Rotate speed (rpm)	Flow rate (L/s)	Drilling fluid Density (g/cm^3)
KL 2-6	ST936RS	406.4	2,499 - 2,705	90	130	52-55	1.47-1.50
Zhonggu 171	M1355SG	215.9	4,193 - 6,036	60	80	28	1.15
Yitong 61	HJT517	215.9	2,121 - 2,686	180	85	30	1.19 - 1.27
TK1294	DS653AB	241.3	5,403 - 5,993	60	L+85	30	1.28 - 1.33
Yue 2-12	M1355	215.9	2,318 - 2,919	50	65	30	1.21
Yuanba 12	HJT537GK	311.2	4,100 - 4,141	240	40	40	1．55

Table 2
The ROP Comparison of Conventional Hydraulic Pulsed Cavitating Jet Drilling Tests and Adjacent Intervals

Well name	Interval (m)	Footage (m)	Drilling time (h)	ROP (m/h)	Correlation interval (m)	ROP (m/h)	ROP increased (%)	The average ROP increased (%)
Kela 2-6	2,500 - 2,705	205	65.10	3.13	2,400 - 2,500	1.94	61.34	48.95
					2,705 - 2,800	2.26	38.50	
Zhonggu 162	4,631 - 5,502	871	259.90	3.35	Zhonggu 16	1.72	94.70	53.10
					Zhonggu 17	3.00	11.67	
Zhonggu 171	4,193 - 6,036	1,843	596.25	3.09	Zhonggu 16	1.83	68.85	44.80
					Zhonggu 17	2.56	20.70	
					Xing 34	2.38	8.00	
					Xing 39	2.20	16.80	
Lungu 351	4,312 - 4,737	425	111.16	3.82	Lunnan 631	3.38	13.01	10.40
					Lungu 392	3.61	5.80	

To be continued

Continued

Well name	Interval (m)	Footage (m)	Drilling time (h)	ROP (m/h)	Correlation interval (m)	ROP (m/h)	ROP increased (%)	The average ROP increased (%)
TK1296	4,903 - 5,185	282	76.32	3.70	TK1244	3.13	18.20	16.20
					S94-1	3.24	14.20	
TK1294	5,403 - 5,993	590	227.70	2.60	TK1283	2.28	14.00	38.18
					TK1266	1.77	46.90	
					TK1205	1.98	31.30	
					TK1264	1.62	60.50	
TK1090	5,349 - 6,162	813	265.99	3.06	TK1066	2.04	50.00	57.54
					TK1005	1.99	53.70	
					TK1067	1.97	55.30	
					TK1013	1.72	77.90	
Yuanba 12	4,100 - 4,121	21	21.17	0.99	4,083 - 4,099	0.71	39.40	30.20
	4,121 - 4,141	20	23.32	0.86			21.10	

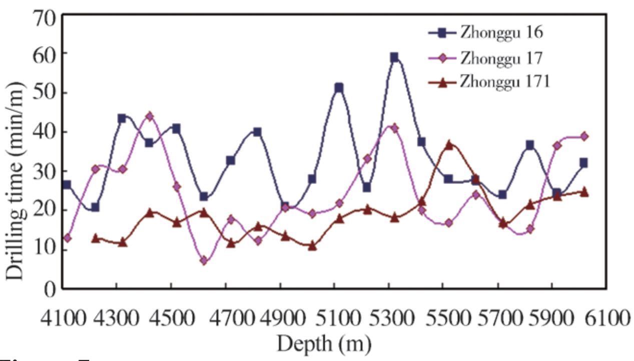

Figure 7
Drilling Time Comparison of Zhonggu 171 and Adjacent Well

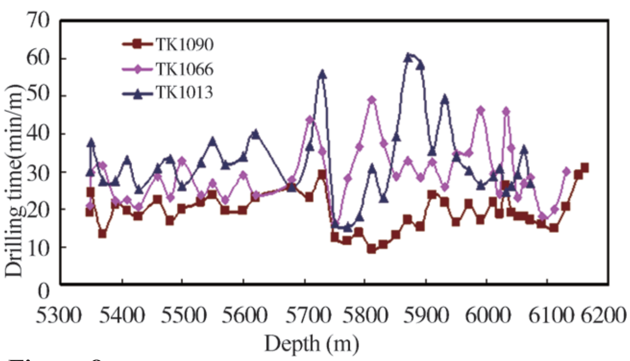

Figure 8
Drilling Time Comparison of TK1090 and Adjacent Well

4.2 Field Tests of Hydraulic Pulsed Cavitatiing Jet Compound Drilling

Hydraulic pulsed cavitating jet compound drilling is a new method which installs the hydraulic pulsed cavitating jet generator between the bit and helicoid hydraulic motor. Hydraulic pulsed cavitating jet can improve bottom clean-up efficiency by changing bottom flow field and stress state of bottom rocks. The compound drilling with the combination of mechanical energy and hydraulic energy can achieve optimum effect of improving ROP.

A large number of filed tests of hydraulic pulsed cavitating jet compound drilling technology mating with PDC bits and cone bits had been accomplished in different blocks of different oilfields, such as Yingmai, Tazhong, Lunnan blocks in Xinjiang Tarim oilfield, Tahe block in Xinjiang oilfield, Hailaer block in Daqing oilfield, and so forth[27-28].

(a) BHA

Bit + hydraulic pulsed cavitating jet generator + helicoid hydraulic motor +drill collar + drill pipe

(b) Test results analysis

The size of well bore was $12^1/_4$", $9^1/_2$", $8^1/_2$" and so on. The well depth ranged from 1,800 to 4,100 m. Table 3 includes test parameters of some test wells, Table 4 includes ROP comparison of conventional hydraulic pulsed cavitating jet drilling tests with hydraulic pulsed cavitating jet compound drilling in adjacent intervals. Drilling time comparison of test well and adjacent well were presented in Figures 9 and 10. Test results indicated that the ROP of test well was enhanced by 13.4% - 104.4% comparing to contrast wells. As a result, the hydraulic pulsed cavitating jet drilling has a good adaptability to helicoid hydraulic motor compounding drilling.

Table 3
Test Parameters of Hydraulic Pulsed Cavitating Jet Combined Drilling Well

Well name	Bit type	Bit size (mm)	Interval depth (m)	WOB (kN)	Rotate speed (rpm)	Flow rate (L/s)	Drilling fluid Density (g/cm^3)
Wu 34	HJT547	215.9	3,015 - 3,083	120	L+50	30	1.13
Zhonggu 162	FS2563BG	311.2	2,555 - 3,390	40	L+40	40	1.10
Zhonggu 171	FS2563BG	311.2	2,580 - 3,349	30	L+40	40	1.07
YM 41	FS2653BG	311.2	1,799 - 3,480	60	L+40	45	1.15
TK1093	GS605F	241.3	1,274 - 3,919	50	L+50	40	1.18

Table 4
The ROP Comparison of Hydraulic Pulsed Cavitating Jet Combined Drilling Tests and Adjacent Intervals

Well name	Interval (m)	Footage (m)	Drilling time (h)	ROP (m/h)	Correlation interval (m)	ROP (m/h)	ROP increased (%)	The average ROP increased (%)
Wu 34	3,015 - 3,083	68	24.64	2.80	2,957 - 3,015	2.42	15.70	15.70
Zhonggu 162	2,555 - 3,390	835	78.95	10.58	Zhonggu 16	8.18	29.30	78.40
					Zhonggu 17	4.65	127.50	
Zhonggu 171	2,580 - 3,349	769	63.45	12.12	Zhonggu 16	8.18	48.10	104.40
					Zhonggu 17	4.65	160.60	
Yingmai 41	1,799 - 3,123	1,324	73.23	18.10	Yingmai 323	14.70	22.60	46.90
					Yingmai 38	10.57	71.20	
TK1093	1,274 - 3,919	2,645	68.70	38.50	TK1027	19.70	95.40	68.90
					TK1017	28.39	35.60	
					TK1005	18.94	103.20	
					TK1067	27.29	41.00	

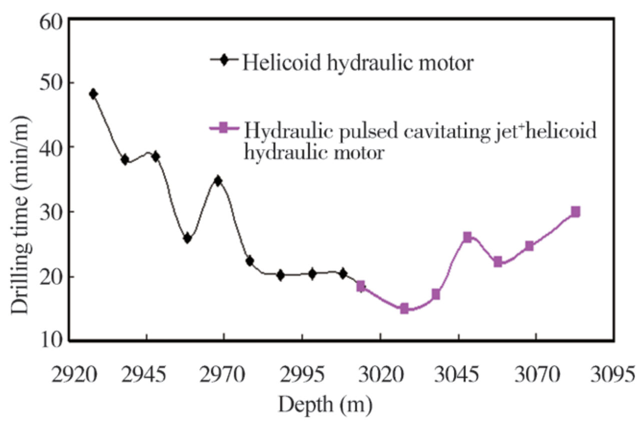

Figure 9
Drilling Time Comparison of Wu 34 and Adjacent Well

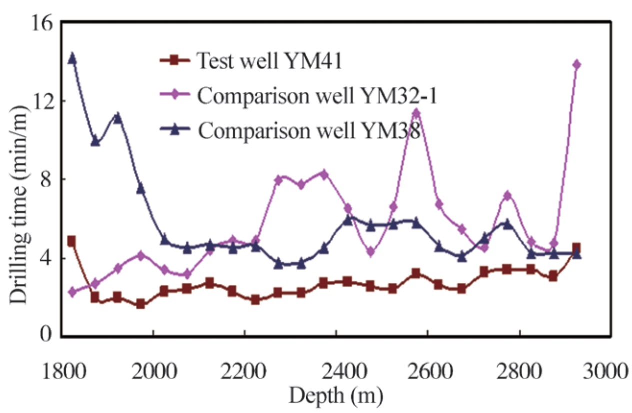

Figure 10
Drilling Time Comparison of Yingmai 41 and Adjacent Well

4.3 Field Tests of Hydraulic Pulsed Cavitating Jet With Underbalance Drilling

Field tests of hydraulic pulsed cavitating jet with underbalance drilling were carried out in Jinlong 3 well of Xinjiang oilfield[29]. The test interval is characterized by hard formation, high abrasivity and low ROP. Underbalance drilling was adopted to improve ROP in the interval of 2,485 - 2,591 m. The negative pressure value had been maintained as 1.0 MPa and the average ROP is 1.02 m/h. The hydraulic pulsed cavitating jet with underbalance drilling combined with cone bit was adopted in the interval of 2,591 - 2,759 m and the average ROP is 1.19 m/h. The hydraulic pulsed cavitating jet generator combined with cone bit and helicoids hydraulic motor was applied in the interval of 2,655 - 2,759 m and the average ROP was 1.91 m/h. Table 5 includes test parameters of Jinlong 3 wel. Table 6 includes ROP comparison of hydraulic pulsed cavitating jet with underbalance drilling with conventional underbalance drilling tests in adjacent intervals. Drilling time comparison of Jinlong 3 well with adjacent well is presented in Figure 11. Test results indicated that the average ROP of two test intervals were enhanced by 16.7% and 87.3% comparing to adjacent interval respectively. As a result, the hydraulic pulsed cavitating jet drilling has a good adaptability to underbalance drilling.

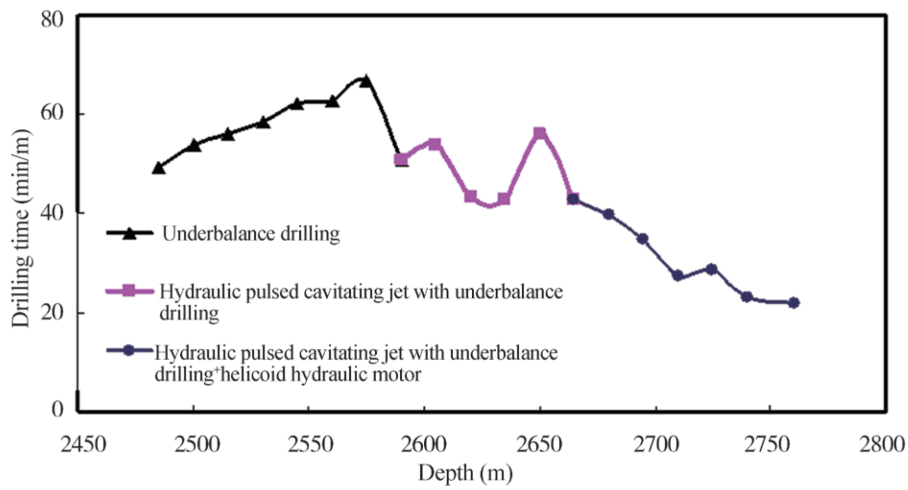

Figure 11
Comparison of Jinlong 3 Well Test Interval and Adjacent Interval

Table 5
On-Site Construction Parameters of Test Interval and Correlation Interval in Jinlong 3 Well

Interval (m)	Operational mode	Weight on bit (kN)	Rotate speed (r/min)	Flow rate (L/s)	Pump pressure (MPa)	Drilling fluid density (g/cm^3)
2,485 - 2,591	Underbalance drilling	220	65	26	18.5	1.18 - 1.21
2,591 - 2,655	Hydraulic pulsed cavitating jet with underbalance drilling	220	65	26	19.0	1.18 - 1.21
2,655 - 2,760	Hydraulic pulsed cavitating jet with underbalance drilling＋Helicoid hydraulic motor	160	65+ Helicoid hydraulic motor	26	20.0	1.18 - 1.21

Table 6
On-Site Construction Parameters of Test Interval and Correlation Interval in Jinlong 3 Well

Interval type	Operational mode	Interval (m)	Footage (m)	Drilling time (h)	Average ROP (m/h)	ROP increased (%)
Correlation interval	Underbalance drilling	2,485 - 2,591	106	104.29	1.02	-
Test interval	Hydraulic pulsed cavitating jet with underbalance drilling	2,591 - 2,655	64	53.62	1.19	16.70
Test interval	Hydraulic pulsed cavitating jet with underbalance drilling＋Helicoid hydraulic motor	2,655 - 2,760	105	54.92	1.91	87.30

4.4 Field Tests of Hydraulic Pulsed Cavitating Jet With Power V System

Fengcheng 1 well locates in the Junggar Basin in western uplift Wuxia fracture belt of Xinjiang oilfield. The angle of bedding is 12°W by S. The formation ROP is low and it is easy to deviate. So, hydraulic pulsed cavitating jet combined with Power V system was adopted. On one hand, well deviation can be controlled so as to ensure the well bore quality of highly deviated formation and release drill pressure, on the other hand, bottom flow field and rock stress state can be changed and chip hold down effect can be reduced by hydraulic pulsed cavitating jet generator so as to improve ROP and reduce drilling cost, which can promote the application of Power V technology[30].

The hydraulic pulsed cavitating jet generator combined with Power V technology was applied in the interval of 2,976 - 3,009 m and the average ROP was 1.12 m/h which was increased by 19% comparing with the average ROP 0.94 m/h achieved merely by Power V technology in the interval of 2,885 - 2,975 m. The well deviation was also well controlled. Table 7 includes test parameters of Fengcheng1 well. Table 8 includes ROP comparison of hydraulic pulsed cavitating jet combined Power V system with Power V drilling tests in adjacent intervals. Drilling time comparison of Fengcheng 1 well with adjacent well is presented in Figure 12. As a result, the hydraulic pulsed cavitating jet drilling has a good adaptability to Power V system, which reduces the operation time of Power V system and drilling cost.

Table 7
On-Site Construction Parameters of Test Interval and Correlation Interval in Fengcheng 1 Well

Interval (m)	Operational mode	Weight on bit (kN)	Rotate speed (r/min)	Flow rate (L/s)	Pump pressure (MPa)	Drilling fluid density (g/cm^3)
2,885 - 2,975	Drilling with Power V system	350	70	50	20	1.19
2,976 - 3,009	Hydraulic pulsation-cavitating jetdrilling with Power V system	300	65	50	20	1.19

Table 8
On-Site Construction Parameters of Test Interval and Correlation Interval in Fengcheng 1 Well

Interval type	Operational mode	Interval (m)	Footage (m)	Drilling time (h)	Average ROP (m/h)	ROP increased (%)
Correlation interval	Drilling with Power V system	2,885 - 2,975	91	96.76	0.94	-
Test interval	Hydraulic Pulsation-cavitating generator with Power V system	2,976 - 3,009	34	30.36	1.12	19.1

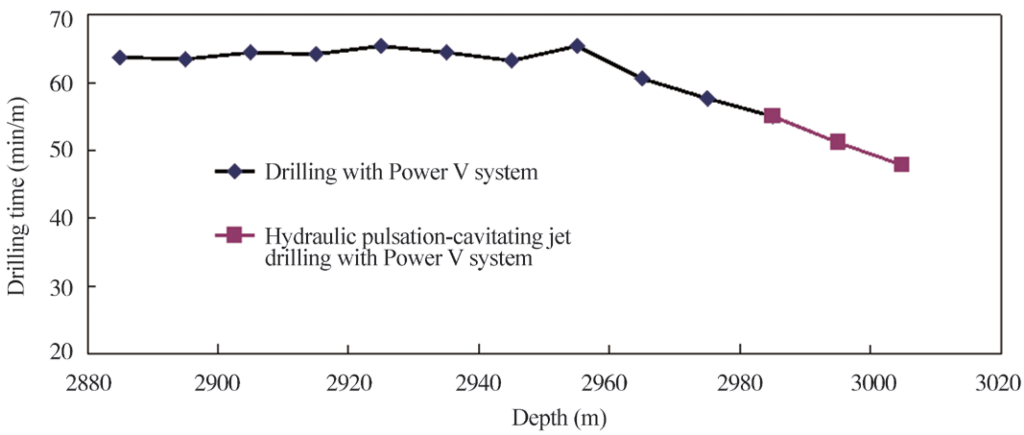

Figure 12
Comparison of Fengcheng 1 Well Test Interval and Adjacent Interval

CONCLUSION

(a) The modulating mechanisms of hydraulic pulsed cavitating jet generator include pressure wave modulation and shear wave rectification. The tangential impacting force of fluid can make impeller revolve continuously, which changes the flow aisle area periodically and generates the impulse finally. The feedback pressure oscillation is amplified in resonant chamber and fluid acoustic resonance and self-resonant cavitation are generated. Thus, pulsed cavitating jet is formed.

(b) The hydraulic pulsed cavitating jet generator is installed between the bit and drill collar or helicoids hydraulic motor, which can modulate the steady flowing drilling fluid to pulsed cavitating jet. It generates three kinds of effects at bottom hole: hydraulic pulse, instantaneous negative pressure, and cavitating erosion. The combination of hydraulic pulsation jet and cavitating jet can change flow filed at bottom hole and rock stress state so as to enhance rock-breaking and cuttings cleanout efficiency and improve penetration rate of deep drilling.

(c) Both laboratory and field tests of hydraulic pulsed cavitating jet generator indicate that the amplitude of pressure oscillation and pressure lose increase as the flow rate increases. When the flow rate is fixed, the pulse frequency is invariable. Under the condition of parameter optimization test, the amplitude of pressure oscillation of generator with 3 impellers is largest among all the generators at the same flow rate.

(d) A large number of field tests of hydraulic pulsed cavitating jet drilling technology with multiple drilling assembly had been applied. The maximum test well drilling fluid density was 1.70 g/cm^3, the maximum test well depth was 6,162 m and the life-time of the tool was over 230 h, the maximum life-time was over 520 h. As the result, the average ROP was enhanced by 10. 1% to 104.4%. Test results indicate that hydraulic pulsed cavitating jet generator has the characteristics of simple structure, operation convenience, long operation time and strong reliability, which makes a good adaptability to the existing drilling equipments and technological parameters.

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