2013 WJTA-IMCA Conference and Expo
September 9-11, 2013 • Houston, Texas

Paper

MECHANISM OF HYDRAULIC PULSED AND CAVITATING JET IMPROVING ROP AND APPLICATION IN CHINA OFFSHORE DRILLING

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ABSTRACT

Offshore drilling has attracted much more attention than ever before due to the increasing worldwide energy demand especially in China. The issues challenge offshore drilling are cost control, shorter drilling cycle, and speed up the drilling process. First of all, the mechanism of pulsed and cavitating jet improving ROP had been studied in this paper, which include: 1) negative pressure pulse changes the flow field at the bottom hole and lowers the rock breaking strength; 2) negative pressure pulse can accelerate rock debris to break away from the bottom hole; and 3) self-resonating cavitating jet can improve the rock breaking efficiency. Secondly, the hydraulic pulsed and cavitating jet generator was designed based on the China offshore drilling technologies and parameters and then the generator's characteristics was collected through the laboratory and field tests. At the same time the paper designed hydraulic pulsed and cavitating jet drilling technique parameters and bottom hole assemblies matching with drilling collar, positive displacement motor, and rotary steerable system, etc. The last, application of the hydraulic pulsed and cavitating jet technique has been successfully conducted in more than 10 offshore wells in China offshore drilling. The depth of the applied wells ranges from 2000-4100 meters with wellbore diameters of 311 mm and 215 mm. The field application results show that hydraulic pulsed and cavitating jet techniques have good applicability to bit types and formations, and significantly improve the ROP by more than 25%.

1. INTRODUCTION

In recent years, offshore drilling has attracted much more attention than ever before due to the increasing worldwide energy demand although the offshore area is considered as a high cost and high risk environment. The offshore drilling has the characteristics of high cost and high risk because of the harsh natural environment, high offshore platform investment and complex downhole hazarders. The challenges found in offshore drilling have forced the oil industry to develop new significant technologies and techniques to improve the ROP of offshore drilling (Luiz Alberto S. Rocha et al. 2003, Guan et al. 2012).

Petroleum researchers all around the world have been trying to study and develop the new drilling methods. The drilling hydraulics in offshore wells has its own characteristics and hydraulic parameter is one of the most important factors, which affect the ROP in offshore drilling. Research and testing shows improving ROP by hydraulic pulsed and cavitating jet drilling technology is an effective method (Li et al. 2003, 2005 and 2008).

2. HYDRAULIC PULSED AND CAVITATING JET DRILLING TECHNOLOGY

Hydraulic pulsed and cavitating jet drilling technology is a new drilling technology which combines pulsed jet and cavitating jet. The technology achieves improving ROP by the hydraulic pulsed and caviting jet generator which is installed upon the bit in the drilling process.

2.1 Structure of Generator

The hydraulic pulsed cavitating jet generator consists of a housing, a flow guide device, an impeller assembly and a resonating chamber, etc. As shown in **Figure 1**.

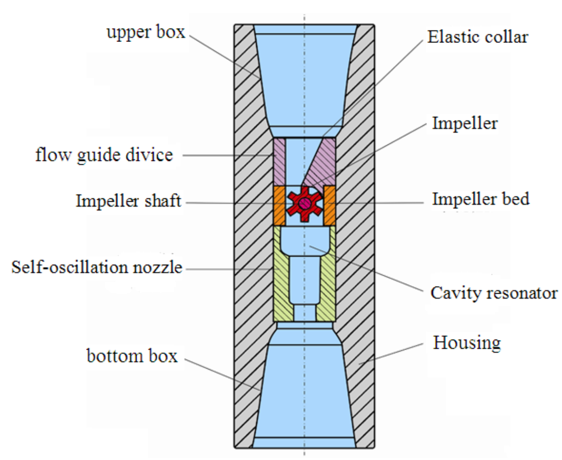


Figure 1. Structure of Hydraulic Pulsed Cavitating Jet Generator

2.2 Operating Principle of Generator

Flow guide device is placed at the top in the housing. The important structure of the flow guide device is sloping flow channel, which can change the flow direction and velocity of the drilling fluid, and generate the tangential force that can make impeller revolving continuously at a high speed and generate the pressure pulse. Impeller assembly consists of the body, impeller, impeller shaft and shaft sleeve. The impeller is installed on the shaft, and sits on the impeller bed by a shaft sleeve.

Hydraulic pulse generated by the impeller assembly is the pulsing source to the resonating chamber. The chamber is placed at the bottom in the housing to amplify the pulsing signal of drilling fluid and generate the fluid resonance. When the steady drilling fluid flows through the contracted cross-section of resonating chamber, the resonating pressure fluctuation occurs. Then it will be reflected and feedback to the chamber. When the frequency of the pulsating pressure match the natural frequency of resonating chamber, the fluid acoustic resonance is generated and pressure oscillation is amplified in resonating chamber. Thus the intense pulsating turbulent vortex rings are formed at the outlet and the pulsating pressure impact on the bottom hole.

2.3 Mechanisms of Improving ROP

The hydraulic pulsed and cavitating jet drilling technology couples fluid oscillation and cavitating effects, which can modulate the steady drilling fluid to be the self-resonating cavitating jet. Hydraulic pulse can improve flow field at the bottom hole, enhance the cuttings cleanout efficiency, and reduce pressure holds and regrinding. Cavitating erosion can improve

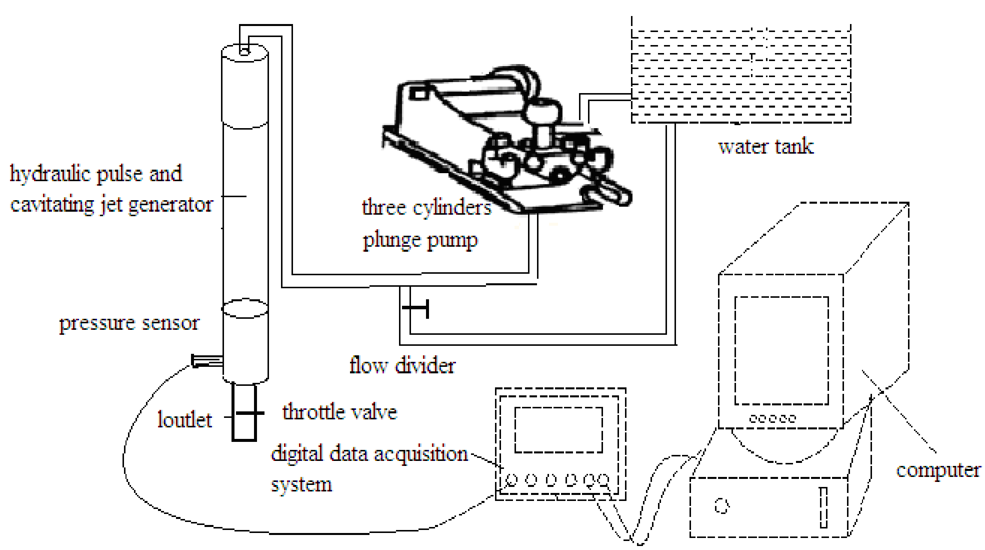


Figure 2. Schematic Device Experimental Diagram

the rock breaking efficiency. Instantaneous negative pressure causes local instantaneous under balance, which can change the stress state of rock and make it easier to break. Hydraulic pulsed and cavitating jet can reduce the chip hold down effect caused by annulus pressure. The mechanism is similar to the underbalanced drilling and drilling speed can be improved greatly (Li et al. 2009).

3. HYDRAULIC PERFORMANCE TESTS OF HYDRAULIC PULSED CAVITATING JET GENERATOR

3.1 Laboratory Tests

The laboratory tests were conducted in the Research Center of High Pressure Jet in China University of Petroleum (East China). The experimental equipments consisted of three cylinder plunge pump, water tank, pressure sensor (4~20Ma), voltage regulator (8-20V), digital data acquisition system, computer, etc.

Schematic of laboratory experimental device flow diagram is shown in **Figure 2**. Hydraulic pulsed and cavitating jet generator prototype parameters are shown in the **Table 1**.

Table 1. Hydraulic Pulsed and Cavitating Jet Generator Prototype Parameters in the Laboratory

Main parameters	**Prototype size in laboratory**
Flow guide device outlet (length × width, mm)	50×7
Impeller (outside diameter × length, mm)	Φ60×50
Square hole of impeller seat (length × width, mm)	61×50
Resonating chamber (inside diameter × height, mm)	Φ36×50 + Φ20×20

Laboratory tests results show that when the flow rate is less than a certain value the pressure fluctuation generated by the hydraulic pulsed and cavitating jet generator is not obvious. Pressure fluctuation increases as the flow rate increases, shown as **Figure 3**.

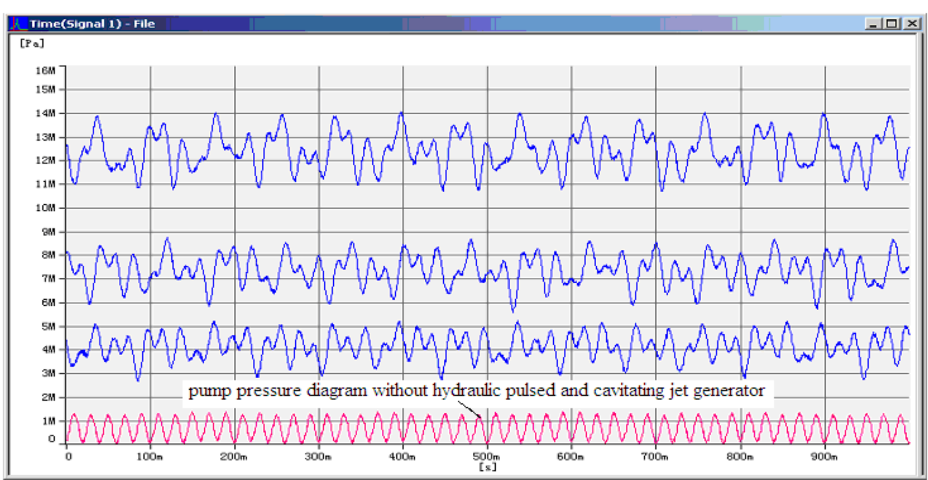


Figure 3. Diagram of Hydraulic Pulsed and Cavitating Jet Generator Pressure Fluctuation

At the same time, with the increasing of flow rate, pressure loss increases. When flow rate is the constant the generator will have its natural frequency. When the flow rate up to 6.0 L/s the frequency is 14 Hz and pressure fluctuation is about 3 MPa.

3.2 Drilling Site Test

The field tests were conducted in the Well 11-18, Shengli Oil Field, in China. The experimental equipments consisted of drilling pump (3NB1300), pressure sensor, digital data acquisition system, computer, etc. The bottom hole assembly is as follows: Φ215 mm bit (PDC) + Φ178 mm hydraulic pulsed and cavitating jet generator +Φ158 mm DC × 2 +Φ127 mm DP×1 + kelly. Schematic of site test device flow diagram is shown in **Figure 4**.

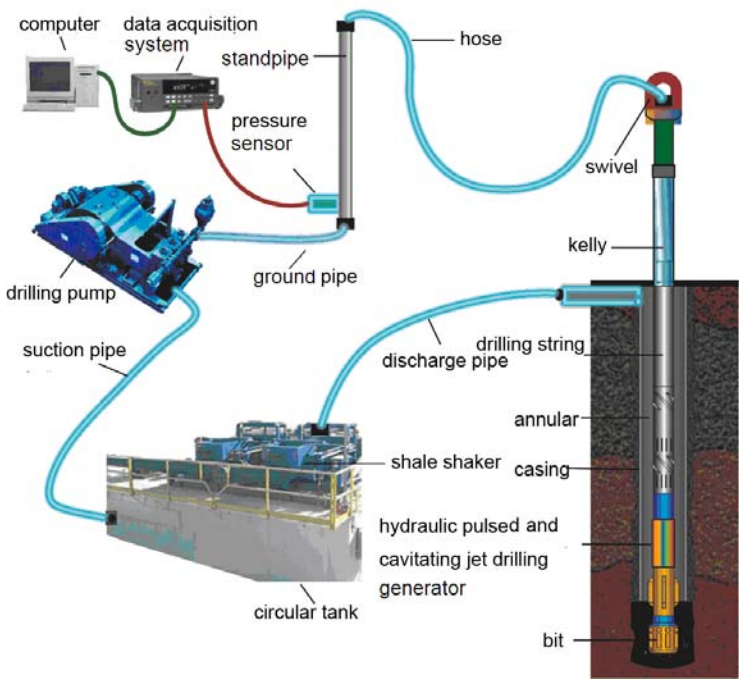


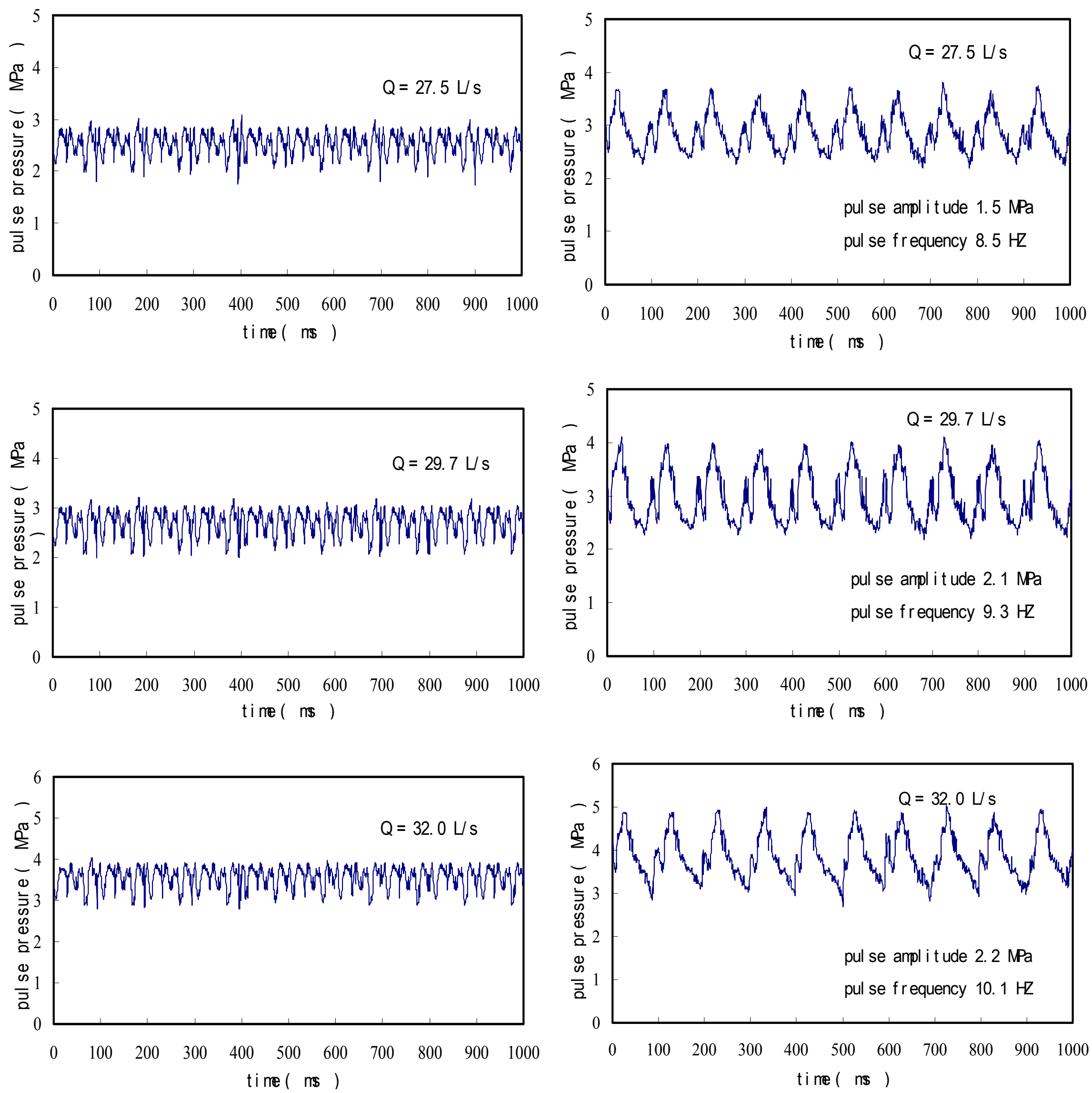
Figure 4. Drilling Site Test Apparatus for Hydraulic Pulse and Cavitating Jet Generator

Hydraulic pulsed and cavitating jet generator prototype parameters are shown in the **Table 2**. Drilling site test mud parameters are shown in the **Table 3**.

Table 2. Hydraulic Pulsed and Cavitating Jet Generator Prototype Parameters in the Field

Main parameters	**Prototype size in field**
Flow guide device outlet (length × width, mm)	50×28
Impeller (outside diameter × length, mm)	Φ50×50
Square hole of impeller seat (length × width, mm)	69×50
Resonating chamber (inside diameter × height, mm)	Φ80×50 + Φ40×20

The pulse pressure, pulse frequency and pressure loss with different flow rate were investigated by the surface test which recorded the curves of stand pipe pressure and time in conventional drilling and hydraulic pulsated cavitating jet drilling. The drilling site test results diagrams are shown in **Figure 5**.



(a) Without the tool (b) With the tool

Figure 5. Diagram of Hydraulic Pulsed and Cavitating Jet Generator Pressure Fluctuation

When the flow rate is 27.5~32.0L/s, hydraulic pulsed cavitating jet generator produces obvious pulsing pressure (1.5~2.2MPa) and the amplitude increases as the flow rate increases.

Table 3. Mud parameters in the drilling site tests

Rotational viscometer count	Φ3	Φ6	Φ100	Φ200	Φ300	Φ600
	3	5	21	25	32	42
Density (g/cm^3)	1.20		**PH**		8	
Plastic viscosity (mPa•s)	10		**Filtration (mL)**		5	
Yield point (Pa)	8		**Cake thickness (mm)**		0.5	
Gel strength 10s/10min (Pa)	3/6		**Funnel viscosity (s)**		45	

The pulse frequency of hydraulic pulsed cavitating jet generator increases slowly as the flow rate increases. When the flow rate is 32.0L/s, the pulse frequency is about 10Hz.

When the flow rate is between 27.5~32.0L/s, the pressure loss of hydraulic pulsed cavitating jet generator is about 0.56~0.60MPa.

4. APPLICATIONS OF HYDRAULIC PULSED AND CAVITATING JET DRILLING TECHNIQUE IN BOHAI SEA OIL FIELD

Hydraulic pulsed and cavitating jet drilling technique matching general bottom hole assembly, hydraulic motor, and rotary steerable drilling system, had been applied more than 10 offshore wells in China offshore drilling.

4.1 Matching with General Bottom Hole Assembly

Hydraulic pulsed and cavitating jet drilling technique which matched with the general bottom hole assembly had applied in the LHV13-2-1S1 well from 2008.5 m to 2033.0 m in the Bohai sea oil field in China.

Field applied bottom hole assembly of matching with general bottom hole assembly: Φ215 mm bit (roller bit) + Φ178 mm Hydraulic pulsed and cavitating jet generator + Φ158 mm DC×1 +Φ215 mm STB+Φ158 mm F/V(RING)+Φ158 mm DC×17+Φ158 mm(F/J+JAR)+X/O+Φ139 mm HWDP×11.

The bottom hole assembly including bits and nozzles in the adjacent intervals 2418.0-2469.0 m and 2469.0-2508.4m are the same with the experimental intervals except without installing hydraulic pulsed and cavitating generator.

Matching with general bottom hole assembly applied drilling parameters are as shown in the **Table 4** and the same with adjacent intervals.

Table 4. Matching with General Bottom Hole Assembly Drilling Parameters

Weight on bit (KN)	Rotate speed (r/min)	Flow rate (L/min)	Pump ressure (MPa)
50 ~ 150	40 ~ 60	1500 ~ 1600	6 ~ 9

Result of application

Applied drilling well intervals footage from 2008.5 m to 2033.0 m is 591.0 m in the LHV13-2-1S1 well. Net drilling time is ten hours. Average ROP is 2.45 m/hour. Average ROP improved 58.9% than adjacent wells' section. The details are shown in **Table 5**.

Table 5 Applied and Adjacent Intervals Comparison of ROP in the LHV13-2-1S1 Well

Type	Interval (m)	Footage (m)	Drilling time (h)	ROP (m/h)	Improving (%)	Average improving (%)
Applied interval	2008 ~ 2033	25	10.0	2.45		
Adjacent interval	2418 ~ 2469	51	33.8	1.50	63.3	58.9
	2469 ~ 2508	39	24.3	1.60	53.1	

4.2 Matching with Positive Displacement Motor (PDM)

Hydraulic pulsed and cavitating jet drilling technique which matched with the positive displacement motor had applied in the CFD18-1N-1 well from 2600.0 m to 2899.0 m in the Bohai sea oil field in China.

Design depth of the CFD18-1N-1 well is 3010 m (third section of Dongying Formation). Tectonic position is located in the west of Bohai sea. Applied interval from 2600.0 m to 2899.0 m is the third section of Dongying formation. The formation lithology based on the sandy conglomerate and pebbly sandstone. The formation drillability is poor and ROP is low.

Field applied bottom hole assembly of matching with positive displacement motor: Φ215.9 mm bit (PDC)+ Φ178 mm hydraulic pulsed and cavitating jet generator + X-over+Φ177 mm PDM (0.75°) + Φ215.9 mm STB +Φ165 mm F/V+ Φ165 mm DC×8+Φ165 mm (F/J+JAR)+ Φ127 mm HWDP×14+Φ127 mm DP.

The bottom hole assembly including bits and nozzles in the adjacent interval 2900.0-3006.0 m are the same with the applied interval except without installing hydraulic pulsed and cavitating generator.

Matching with positive displacement motor applied drilling parameters are as shown in the **Table 6** and the same with adjacent intervals.

Table 6. Matching with Positive Displacement Motor Applied Parameters

Weight on bit (KN)	Rotate speed (r/min)	Flow rate (L/min)	Dump pressure (MPa)	Density (g/cm^3)	Viscosity (s)
20 ~ 50	80 ~ 95	1500 ~ 1900	13 ~ 16	1.28 ~ 1.29	50 ~ 65

2600.0-2899.0 m applied well intervals footage is 299.0 m in the CFD18-1N-1 well. Net drilling time is 14.25 hours. Average ROP is 20.98 m/hour. Average ROP improved 58.34% than adjacent 2900.0-3006.0 m intervals. The details are shown in **Table 7**.

Table 7. Applied and Adjacent Intervals ROP Comparison Table in CFD18-1N-1 Well

Type	Intervals (m)	Footage (m)	Net drilling time (h)	ROP (m/h)	ROP improving (%)
Applied interval	2600 ~ 2899	299	14.3	20.98	
Comparison interval	2900 ~ 3006	106	8.0	13.25	58.34

The comparison diagram of the CFD18-1N-1 well is shown in **Figure 6**.

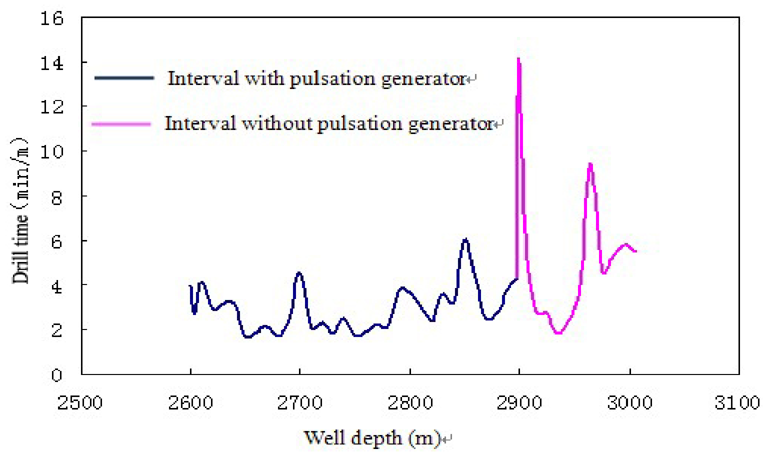


Figure 6. Drilling Time per Meter Comparison Diagram of the CFD18-1N-1 Well

4.3 Matching with Rotary Steerable System

Rotary steerable system is a drilling technology used in directional drilling. It utilizes specialized bottom holes equipments to replace conventional directional tools such as positive displacement motors. They are generally programmed by the MWD engineer or directional driller who transmits commands using surface equipment which the tool understands and gradually steers into the desired direction using either pressure fluctuations in the mud column or variations in the drill string rotation. The smoother wellbores drilled with the rotary steerable system reduce the risk of stuck pipe, make tripping and casing running easier, and reduce drilling fluid and cement cost. Smooth, horizontal holes are significantly easier to complete, particularly in multistage fractures.

Hydraulic pulsed and cavitating jet drilling technique matching with the rotary steerable system had applied in the LHV13-2-1S1 well from 2348.0 m to 2365.0 m in the Bohai sea oil field in China.

Field applied bottom hole assembly of matching with rotary steerable system: Φ215mm Bit(PDC) + Φ178 mm hydraulic pulsed and cavitating jet generator +X/O+Φ171mm Power Driver+ Φ171mm MWD+Φ158mm NMDC+Φ158mm DC×9+Φ158mm (F/J+JAR) + X/O + Φ139mm HWDP+Φ139mm DP.

Table 8. Drilling Parameters in the Applied and Adjacent Intervals in the LHV-13-2-1S1 Well

Type	Intervals (m)	Weight on bit (T)	Rotating speed (r/min)	Flowrate (L/min)	Pump pressure (MPa)
Applied interval	2348 ~ 2365	5 ~ 12	100 ~ 120	1700 ~ 1800	9 ~ 11
Adjacent interval	2338 ~ 2347	2 ~ 11	100 ~ 125	1500 ~ 1800	9 ~ 11
	2366 ~ 2418	9 ~ 16	50 ~ 80	1700 ~ 1800	9 ~ 11

The bottom hole assembly including bits (FM×553Z) and nozzles (14 mm×5) in the adjacent intervals 2338.0-2347.0 m and 2366.0-2418.0 m are the same with the experimental intervals except without installing hydraulic pulsed and cavitating generator between the bit and X-over. Hydraulic pulsed and cavitating jet drilling technique's drilling parameters matching rotary steerable system in the applied and adjacent intervals are as shown in the **Table 8** in the LHV-13-2-1S1 well.

Table 9. Applied Intervals and Adjacent Intervals ROP in the LHV13-2-1S1 Well

Type	Intervals (m)	Lithology	Footage (m)	Net drilling time(h)	ROP (m/h)	Improving (%)
Applied interval	2348~2365	Mudstone and sandy conglomerate	18	6.0	3.0	
Adjacent interval	2338~2347		10	4.2	2.4	25.0
	2366~2418		53	40.8	1.3	130.7

234.8-2365 m test well intervals footage is 18.0m in the LHV13-2-1S1 well. Net drilling time is 6.0 hour. Average ROP is 3.0 m/h. Average ROP improved 25.0%-130.7% than adjacent wells' similar intervals. The details are shown in **Table 9**. The drilling time per meter comparison diagram of applied intervals with adjacent intervals can be shown in **Figure 7**.

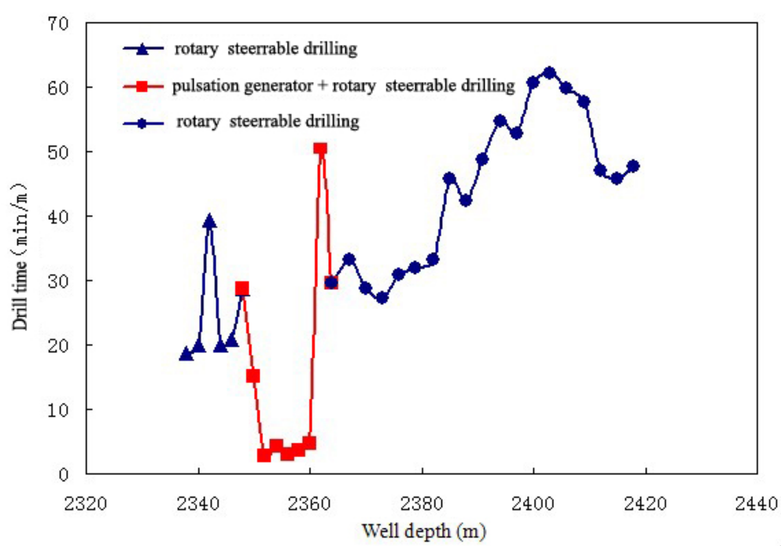


Figure 7. Drilling Time per Meter Comparison Diagram in the Applied and Adjacent Intervals

5. CONCLUSION

(1) The hydraulic pulsed cavitating jet drilling technology can decrease rock strength and improve the cuttings cleanout efficiency from the bottom, and can also reduce the repeat cutting and chip hold down effect. Therefore, the improvement of ROP can be achieved eventually.
(2) In terms of different bit types, formation, and drilling fluid densities, four wells' tests of hydraulic pulsed cavitating jet drilling technology matching with normal BHA, hydraulic motor BHA, and rotary steerable system are carried out. The results show that hydraulic pulsed cavitating jet drilling technology has good adaptability.
(3) Hydraulic pulsed cavitating jet generator has a lot of advantages, such as stability performance, reliable quantity, and it's enough life-time. Hydraulic pulsed cavitating jet drilling technology can afford an effective approach to improve ROP in offshore drilling.

ACKNOWLEDGMENTS

The authors express their appreciations to National Key Basic Research and Development Projects of China (No. 2010CB226700) for the financial support of this work.

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NOMENCLATURE

ROP = rate of penetration
PDC = polycrystalline diamond compact
DP = drilling pipe
DC = drilling collar
NMDC = nonmagnetic drilling collar
MWD = measurement while drilling
STB = stabilizer
F/J = flexible joint
F/V = float valve
X/O = cross over sub