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Properties and testing of a hydraulic pulse jet and its application in offshore drilling

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Abstract: Offshore drilling has attracted more attention than ever before due to the increasing worldwide energy demand especially in China. High cost, long drilling cycles, and low rate of penetration (ROP) represent critical challenges for offshore drilling operations. The hydraulic pulse generator was specifically designed, based on China offshore drilling technologies and parameters, to overcome problems encountered during offshore drilling. Both laboratory and field tests were conducted to collect the characteristics of the hydraulic pulse generator. The relationships between flow rate and pressure amplitude, pressure loss and pulse frequency were obtained, which can be used to optimize operation parameters for hydraulic pulse jet drilling. Meanwhile a bottom hole assembly (BHA) for pulse jet drilling has been designed, combining the hydraulic pulse generator with the conventional BHA, positive displacement motor, and rotary steerable system (RSS) etc. Furthermore, the hydraulic pulse jet technique has been successfully applied in more than 10 offshore wells in China. The depth of the applied wells ranged from 2,000 m to 4,100 m with drilling bit diameters of 311 mm and 216 mm. The field application results showed that hydraulic pulse jet technique was feasible for various bit types and formations, and that ROP could be significantly increased, by more than 25%.

Key words: Pulse jet, offshore drilling, parameter test, oilfield application, rate of penetration

1 Introduction

Improving offshore drilling rates nowadays encounters great challenges. Drilling hydraulics may affect the rate of penetration (ROP) in offshore drilling (Folsta and Martins, 2012; Jerez et al, 2013; Nagib et al, 2011; Taufiqurrachman and Tanjung, 2013). Especially the heavy, high-density drilling fluids used for deepwater drilling to control formation pressure may reduce ROP significantly (Cheng et al, 2011; Mohamed et al, 2009). Many efforts have been made to improve offshore drilling rates, because offshore drilling is generally considered to be high cost and high risk due to high offshore platform investment, the harsh natural environments and complex downhole hazards (Cheng et al, 2013; Poedjono et al, 2007, Patel et al, 2011; Ranieri et al, 2013). In China, the costs of offshore drilling on drillships and platforms have now reached 1 billion dollars and the daily rate reached from $200,000 to $500,000. Offshore drilling is still going in despite of the difficulties like high cost, high risk and low penetration rates, because the well could be productive. The challenges found in offshore drilling have forced oil industry researchers to develop new technologies to improve the ROP and achieve cost control in offshore drilling (Guan et al, 2012; Rocha et al, 2003).

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In the early 1980s, Johnson et al (1982) proposed the self-resonant cavitating pulse water jet theory and designed a nozzle with a structure to generate an acoustic self-resonant cavitating jet. Ghalambor et al (1988) developed an intermittent jet nozzle with a rotating disc to change drilling fluid velocity. Biianti (1990) designed a pulse jet nozzle which could change the port area and increase jet impact force by 124% and power by 400%. Subsequently, Shen and coworkers (Shen, 1987) carried out theoretical and experimental research in self-resonant cavitating pulse water-jet technology. On the basis of hydro-acoustics principles and fluid-transient theory, Li and Shen designed a new efficient self-resonant cavitating nozzle and verified its high efficiency by numerical simulation and field experiments (Li and Shen, 1991).

In the 1990s, Kolle and Marvin (1999) developed hydropulse, a negative pressure pulse tool installed with a self-circulating lift valve and improved it in the early 21st century. Waltech in Canada designed a negative pressure pulse tool (Wang, 2005). Based on fluid transient theory, researchers in China developed several types of bottom hole pulse drilling tools, such as the down hole mechanical-pulse generator (Chen et al, 2000), the low-pressure pulse jet modulator (Yang et al, 2003), and the down hole hydropulse vibration drilling tool (Ni et al, 2006a; 2006b).

However, these tools were not applied widely because they were not fully reliable. To improve drilling rate further, Li and coworkers have developed a novel tool, a hydraulic pulse generator, on the basis of pulse jet theory to improve ROP (Fu et al, 2012; Li et al, 2009; 2008; 2010). Moreover, the hydraulic pulse generator has been applied widely in onshore drilling and the average ROP was increased by 17%-105% (Shi et al, 2010; Wang et al, 2009). In order to better apply the hydraulic pulse generator to offshore drilling, we have conducted tests on the hydraulic parameters in order to optimize them for offshore drilling. Hydraulic pulse generators are used with different bottom hole assemblies (BHAs) in several offshore oilfields in China to improve the ROP.

2 Hydraulic pulse jet drilling

Hydraulic pulse jet drilling is a new drilling technology. This technology improves the ROP by a hydraulic pulse generator installed upon the bit during drilling. This generator consists of a housing, a flow guide device, an impeller assembly and a resonant chamber which is also called a cavity resonator, etc., as shown in Fig. 1.

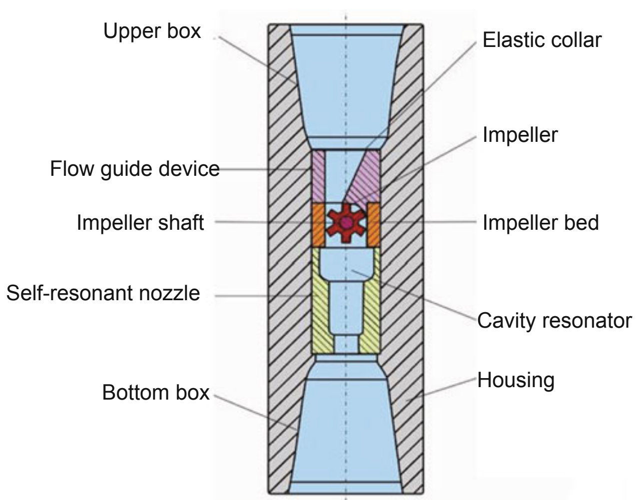


Fig. 1 Structure of the hydraulic pulse generator

The generator is classified according to different outer diameters of the body or the housing where the flow guide device is installed. One of the most important parts of the flow guide device is the contracted flow channel, which may change the flow direction and velocity of the drilling fluid, and then tangential force is generated to make the impeller rotate continuously at a high speed, thus producing pressure pulses. The impeller assembly consists of the body, an impeller, an impeller shaft and a shaft sleeve. The impeller is installed on the shaft, and sits on the impeller bed through the connection of a shaft sleeve to the both sides of the shaft and the bed. Hydraulic pulses generated by the impeller assembly form the pulsing source to the resonant chamber. The chamber is placed at the bottom of the housing to amplify the pulsing signal of the drilling fluid and generate fluid resonance. When the steady drilling fluid flows through the contracted cross-section of the resonant chamber, pressure fluctuation occurs and then it is reflected and fed back to the chamber. When the frequency of the pulse pressure matches the natural frequency of the resonant chamber, acoustic resonance of fluids is generated and pressure pulses are amplified in the chamber. Thus intense pulsing turbulent vortex rings are formed at the outlet and impact on the bottom hole.

3 Tests of hydraulic pulse jet properties

3.1 Laboratory testing

Test apparatus used in laboratory included: a hydraulic pulse generator whose outer diameter is 120 mm, 4 pressure sensors with a measuring range from 0 to 5 MPa, a data acquisition system made in the US., a BQ700 pump with a maximum flow rate of 650 L/min and a maximum discharge pressure of 60 MPa. Water was used as the flow medium in this test. The flow chart of the laboratory test is shown in Fig. 2.

A photograph of the hydraulic pulse generator is shown in Fig. 3. In this test, the sampling interval was 0.005 s, the

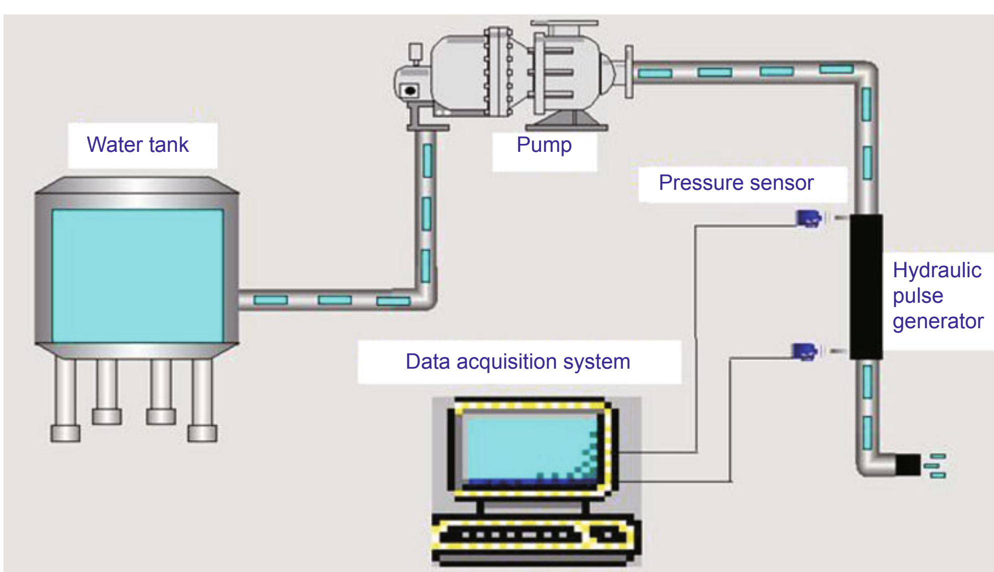


Fig. 2 Flow chart of the laboratory test

inlet and outlet pressures of the generator were then measured at different flow rates and pressure amplitudes, pulse frequency and pressure loss were also measured. The pressure amplitudes at the generator inlet and outlet were 0.45-0.92 MPa and 0.50-1.20 MPa, respectively. Both the inlet and outlet pressure amplitudes show a quadratic dependence on flow rate, as shown in Fig. 4. The pressure loss was 0.58-1.60 MPa, showing a quadratic relationship with flow rate, as shown in Fig. 5. The pulse frequency was 4.65-8.00 Hz, showing a linear relationship with flow rate, as shown in Fig. 6.

Fig. 3 Photograph of the hydraulic pulse generator

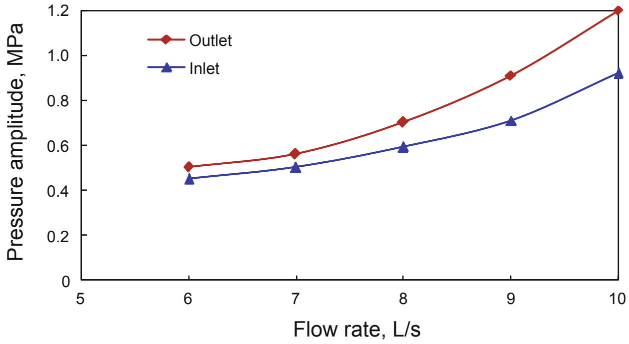


Fig. 4 Inlet/outlet pressure amplitudes at different flow rates

3.2 Field testing

Field tests were conducted in Well 11-18 in the Shengli Oilfield, China. The test equipment included a drilling pump (3NB1300), a pressure sensor, a digital data acquisition system and a computer. The BHA in the test was: Φ215 mm polycrystalline diamond compact (PDC) bit + Φ178 mm hydraulic pulse generator + Φ158 mm drill collar (DC) × 2 + Φ127 mm drill pipe (DP) × 1 + a kelly.

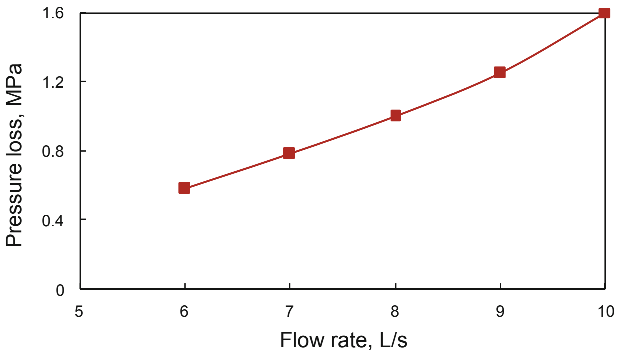


Fig. 5 Pressure loss at different flow rates

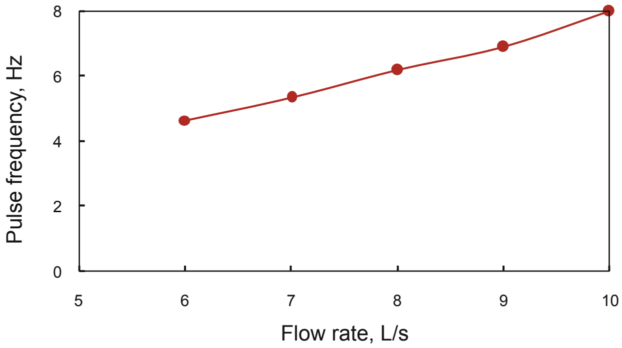


Fig. 6 Pulse frequency at different flow rates

The schematic of the site test device is shown in Fig. 7.

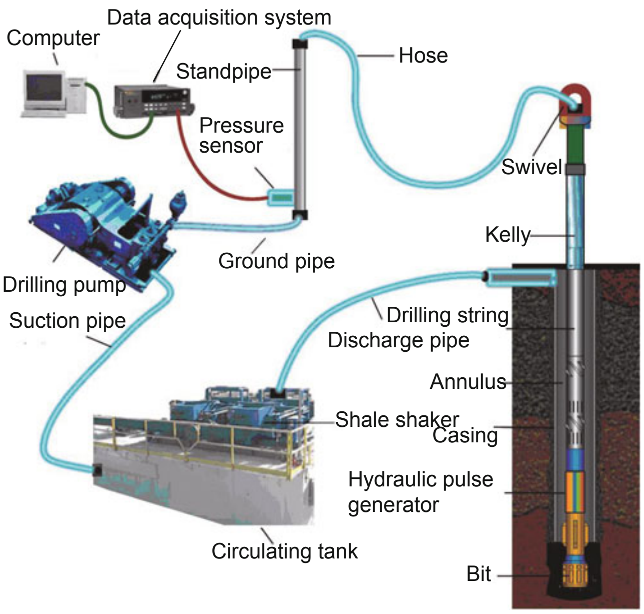


Fig. 7 Field test apparatus for the hydraulic pulse generator

The parameters of the hydraulic pulse generator used in field tests are listed in the Table 1 and the drilling fluid properties are shown in the Table 2.

Table 1 Hydraulic pulse generator used in the field test

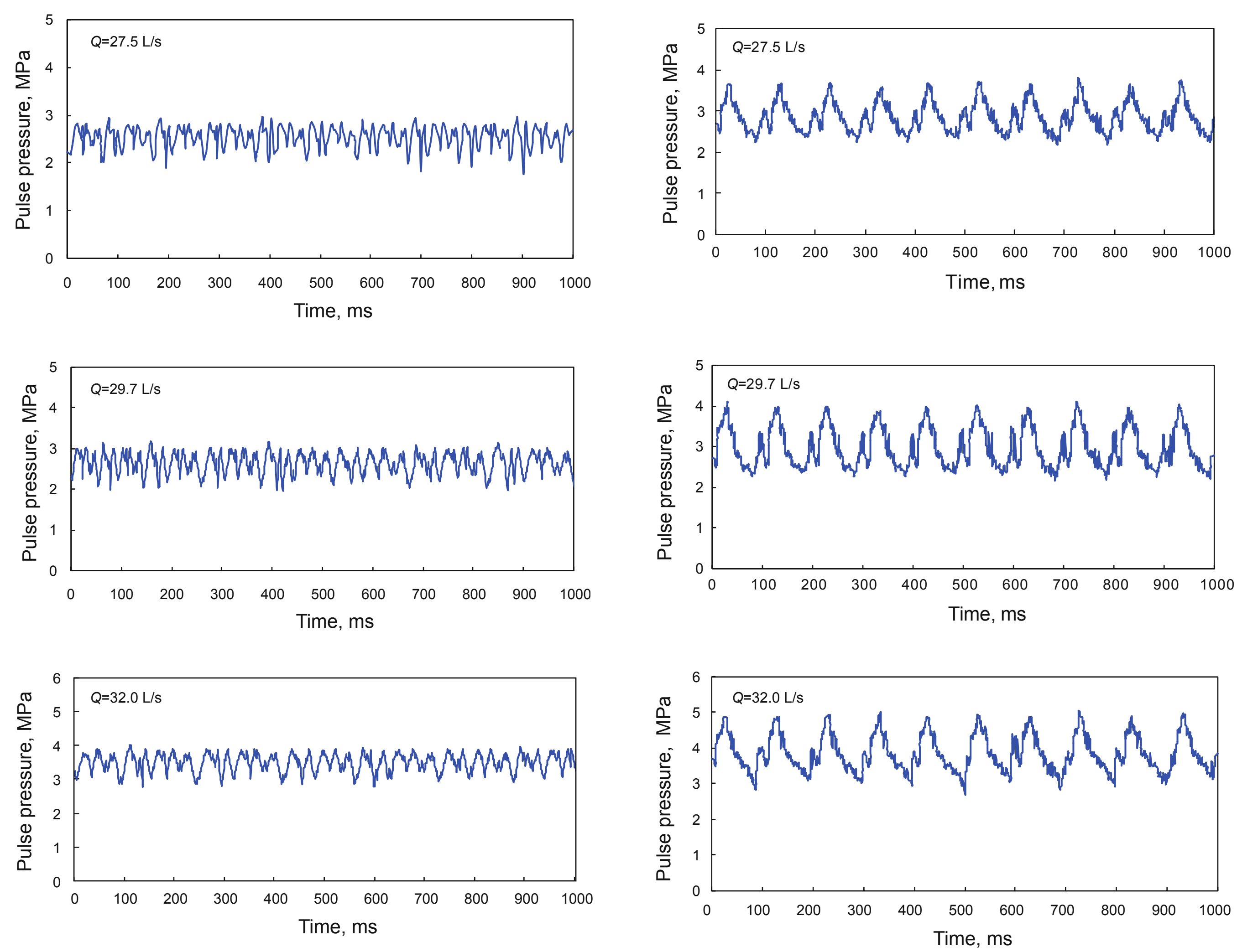
Main parameters	Prototype size
Flow guide device outlet (length × width, mm)	50×28
Impeller (outside diameter × length, mm）	Φ50×50
Square hole of the impeller seat (length × width, mm)	69×50
Resonant chamber (inside diameter × height, mm)	Φ80×50 ＋ Φ40×20

Table 2 Properties of the drilling fluid

Rotational viscometer readings at 3, 6, 100, 200, 300, 600 rpm	Density g/cm^3	Plastic viscosity mPa·s	Yield point Pa	Gel strength 10sec/10min, Pa	API filtrate mL/30min	pH value	Cake thickness mm	Funnel viscosity s
3, 5, 21, 25, 32, 42	1.20	10	8	3/6	5	8.0	0.5	45

The pulse pressure, pulse frequency and pressure loss at different flow rates were investigated by surface tests, in which the real-time standpipe pressure was recorded in conventional drilling and hydraulic pulse jet drilling, respectively, as shown in Fig. 8.

When the flow rates were 27.5, 29.7 and 32.0 L/s, the corresponding pulse pressure amplitudes were 1.5, 2.1 and 2.2 MPa, and the pulse frequencies were 8.5, 9.3 and 10.1 Hz. Compared with conventional drilling, the hydraulic pulse generator produced remarkable pulse pressure and its



(a) Without the pulse generator (b) With the pulse generator

Fig. 8 Influence of the pulse generator on the amplitude of pressure fluctuation amplitude increased as the flow rate increased.

4 Applications of hydraulic pulse generator in offshore drilling

Hydraulic pulse generators have been applied in more than 10 offshore wells in China, combined with a conventional BHA, a positive displacement motor, and a rotary steerable drilling system.

4.1 Combined with the conventional BHA

The hydraulic pulse generator combined with the conventional BHA has been applied at a depth of 2,008.5-2,033.0 m (tested interval) in Well LHV13-2-1S1 in the Bohai Oilfield, China.

The conventional BHA applied in this well was as follows: Φ215 mm roller bit + Φ178 mm hydraulic pulse generator + Φ158 mm DC + Φ215 mm centralizer + Φ158 mm float valve (F/V) + Φ158 mm DC × 17 + Φ158 mm flexible joint (F/J) + cross over sub (X/O) + Φ139 mm high weight drill pipe (HWDP) × 11.

Control intervals in Well LHV13-2-1S1 with depths of 2,418.0-2,469.0 m and 2,469.0-2,508.4 m, were drilled out with the same drill tools except without installing the hydraulic pulse generator. The drilling parameters for both the tested and control intervals are shown in Table 3.

Table 3 Drilling parameters when combined with conventional BHA in Well LHV13-2-1S1

Weight on bit kN	Rotary speed r/min	Flow rate L/min	Pump pressure MPa
50-150	40-60	1500-1600	6-9

Field test results indicated that the length was 24.5 m at the tested interval from 2,008.5 m to 2,033.0 m in Well LHV13-2-1S1. The net drilling time was 10 h and the average ROP was 2.45 m/h, with an improvement of 59% compared with the control intervals. The details are shown in Table 4.

Table 4 Comparison of the ROP between the tested and control intervals in Well LHV13-2-1S1

Well interval	Depth m	Length m	Drilling time h	ROP m/h	Improvement %	Average improvement %
Tested interval	2008.5-2033.0	24.5	10.0	2.45		
Control interval	2418.0-2469.0	51.0	33.8	1.50	63.3	59
	2469.0-2508.4	39.4	24.3	1.60	53.1	

4.2 Combined with the positive displacement motor (PDM)

The hydraulic pulse generator combined with PDM was applied at the depth of 2,600.0-2,899.0 m in Well CFD18-1N-1 in the Bohai Oilfield, China.

The designed depth of Well CFD18-1N-1 (located in the west of the Bohai Sea) was 3,010 m (the third section of the Dongying Formation). The tested interval was from 2,600.0 m to 2,899.0 m. The formation lithology was predominately sandy conglomerate and pebbly sandstone. The formation drillability was poor and the ROP was extremely low in this interval.

The BHA with a positive displacement motor applied was as follows: Φ215.9 mm PDC bit + Φ178 mm hydraulic pulse generator + X-over + Φ177 mm PDM (0.75°) + Φ215.9 mm stabilizer (STB) + Φ165 mm F/V+ Φ165 mm DC × 8 + Φ165 mm (F/J+JAR) + Φ127 mm HWDP × 14 + Φ127 mm DP.

The BHA including bits and nozzles in the adjacent interval of 2,900.0-3,006.0 m was the same as that in the tested interval except without the installation of the hydraulic pulse generator. The drilling parameters are shown in Table 5.

Table 5 Drilling parameters when combined with the positive displacement motor in Well CFD18-1N-1

Weight on bit kN	Rotary speed r/min	Flow rate L/min	Pump pressure MPa	Density g/cm^3	Funnel viscosity s
20-50	80-95	1500-1900	13-16	1.28-1.29	50-65

The length of the tested intervals was 299.0 m, from 2,600.0 m to 2,899.0 m in Well CFD18-1N-1. The net drilling time was 14.25 h. The average ROP was 21.0 m/h, with an improvement of 58% compared with the adjacent interval of 2,900.0-3,006.0 m. The details are shown in Table 6. A plot of drilling time per meter versus well depth measured in Well CFD18-1N-1 is shown in Fig. 9.

Table 6 Comparison of the ROP between the tested and adjacent intervals in Well CFD18-1N-1

Well interval	Depth m	Length m	Drilling time h	ROP m/h	Improvement %
Tested interval	2600.0-2899.0	299.0	14.3	20.98	
Adjacent interval	2900.0-3006.0	106.0	8.0	13.25	58.34

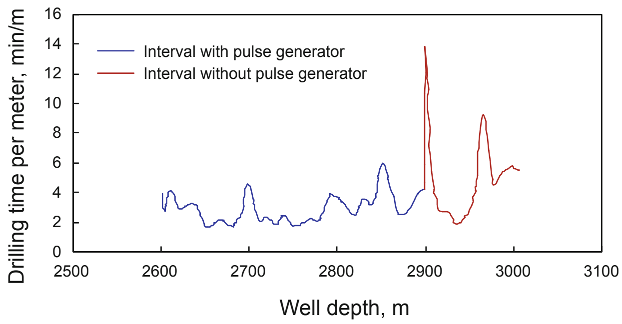


Fig. 9 Drilling time per meter in the tested and adjacent intervals in Well CFD18-1N-1

4.3 Combined with the rotary steerable system

A rotary steerable system (RSS) is mainly used in directional drilling where the specialized bottom hole equipment is utilized to replace the conventional directional drilling tools such as the positive displacement motor. They are generally programmed by the measurement while drilling (MWD) engineer or directional driller who transmits commands using surface equipment using either pressure fluctuations in the mud column or variations in the drill string rotation which the tool understands and gradually steers towards the desired direction. Smooth wellbore drilled by an RSS can reduce the risk of stuck pipes, 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.

The hydraulic pulse generator combined with the RSS was applied at the interval of 2,348.0-2,365.0 m in Well LHV13-2-1S1 in the Bohai Oilfield, China.

The BHA including the RSS combined the generator in the test was as follows: Φ215 mm PDC bit + Φ178 mm hydraulic pulse generator + X/O + Φ171 mm power driver + Φ171 mm measurement while drilling (MWD) + Φ158 mm nonmagnetic drilling collar (NMDC) + Φ158 mm DC × 9 + Φ158 mm (F/J+JAR) + X/O + Φ139 mm HWDP + Φ139 mm DP.

The BHA used in the adjacent intervals (2,338.0-2,347.0 m and 2,366.0-2,418.0 m) for comparison were the same as the tested interval except without installing the hydraulic pulse generator between the bit and X-over.

The drilling parameters used in the tested and adjacent intervals in Well LHV-13-2-1S1 are listed in the Table 7. The length of the tested interval was 17.0 m, from 2,348.0 m to 2,365.0 m in Well LHV13-2-1S1. The net drilling time was 6.0 h. The average ROP in the tested interval was 3.0 m/h, with an improvement of 25%-131% compared with the adjacent intervals. The details are listed in Table 8. A comparison of drilling time per meter between the tested and adjacent intervals is shown in Fig. 10.

Table 7 Drilling parameters when combined with the RSS in Well LHV-13-2-1S1

Well interval	Depth m	Weight on bit kN	Rotary speed r/min	Flow rate L/min	Pump pressure MPa
Tested interval	2348.0-2365.0	50-120	100-120	1700-1800	9-11
Adjacent interval	2338.0-2347.0	20-110	100-125	1500-1800	9-11
	2366.0-2418.0	90-160	50-80	1700-1800	9-11

Table 8 Comparison of the ROP between the tested and adjacent intervals in Well LHV13-2-1S1

Well interval	Depth m	Length m	Drilling time h	ROP m/h	Improvement %
Tested interval	2348.0-2365.0	18.0	6.0	3.0	
Adjacent interval	2338.0-2347.0	10.0	4.2	2.4	25.0
	2366.0-2418.0	53.0	40.8	1.3	130.7

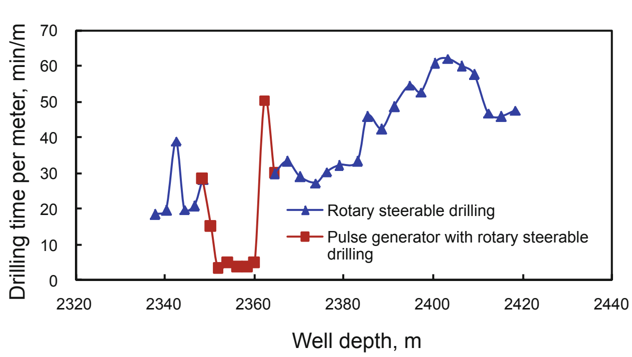


Fig. 10 Drilling time per meter in the tested and adjacent intervals in Well LHV13-2-1S1

5 Conclusions

1) Laboratory test results showed that when the flow rate was 6-10 L/s, the pressure amplitude at the outlet of the hydraulic pulse generator was 0.5-1.2 MPa, the pressure loss was 0.6-1.6 MPa, and the frequency was 4.65-8.00 Hz. The pulse pressure amplitude and pressure loss showed a quadratic relationship with the flow rate, while the pulse frequency showed a linear relationship with the flow rate.

2) In order to verify the high efficiency of the hydraulic pulse jet drilling technology in different types of bits, formations and drilling fluid densities, field tests were conducted using the hydraulic pulse generator combined

with the conventional BHA, positive displacement motor and RSS. Field results showed that hydraulic pulse jet drilling could increase the ROP by at least 25% and had favorable applicability in offshore drilling.

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