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Increasing Drilling Speed by Absorption and Hydraulic Supercharging of Drill String in Formation Containing Hydrogen Sulfide: A Case Study

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Abstract: Increasing drilling speed and shortening the well construction period are the goals of the drilling field. The use of downhole speed-up tools has been noted for its advantages such as no additional cost, no change in drilling equipment and no impact on normal drilling operations. However, conventional downhole speed-up tools cannot meet the needs when the drilled formation contains hydrogen sulfide. Then, the technology test on increasing drilling speed by absorption and hydraulic supercharging of drill string in hydrogen sulfide formation was carried out in well Wanweiye1 (WWY1), Anhui Province, China. The results show that: firstly, the speed-up device by absorption and hydraulic supercharging of drill string can be used in the formation containing hydrogen sulfide, and can still perform normal drilling operations with a hydrogen sulfide concentration of 567 ppm; secondly, the speed-up technology by absorption and hydraulic supercharging of drill string has a significant speed-raising effect in the region containing hydrogen sulfide and can raise the speed by 62.5% to 92.05%; thirdly, the speed-up device by absorption and hydraulic supercharging of drill string can meet the needs of high density killing fluid. Once the well WWY1 suffered an overflow, the device did not affect the killing operation when the killing fluid density reached 2.2 g/cm3 and killing time reached 104.8 h.

Keywords: hydrogen sulfide; the speed-up technology by drill string absorption and hydraulic supercharging; well WWY 1; downhole speed-up tools

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1. Introduction

With the increase in the development of oil and gas resources in deep formations, the number of deep and ultra-deep wells in new and old exploration areas is increasing, and the drilling depth is getting deeper and deeper, which makes the problem of slow drilling speed of deep wells become one of the most important problems faced by drillers [1,2]. Although a variety of techniques and methods have been developed to improve drilling speed, such as high-pressure jet drilling, underbalanced drilling, optimized drilling etc, the downhole speed-up tools have still attracted attention because they do not increase excessive additional costs, do not change drilling equipment, and do not affect normal drilling operations. So far, researchers have developed many speed-up tools, mainly including downhole dynamic drilling tools, rotary impact drilling tools, downhole pulsed cavitation jet generators, downhole torsion impact drilling tools etc. [3–19]. These tools have played their positive role, improving drilling speeds. However, they have shown deficiencies and problems in the process of increasing drilling speed in formations containing hydrogen sulfide. In this paper, the speed-up technology by drill string's absorption and hydraulic supercharging is proposed to improve drilling speed in hydrogen sulfide formation, and the experiment is carried out in Well WWY1, the results show that the speed increase effect is obvious.

2. Requirements for Speed-Up Tools in Formations Containing Hydrogen Sulfide

(1) The hydrogen sulfide environment requires speed-up tools to be resistant to corrosion. Hydrogen sulfide is dissolved in water to form a weak acid, which can corrode metals and rubber, mainly in the form of electrochemical corrosion, stress corrosion and "hydrogen embrittlement". The harm to rubber materials is that it can accelerate its aging and shorten its service life. In summary, the hydrogen sulfide environment requires the use of corrosion-resistant metal materials and hydrogen sulfide-resistant rubber materials. Additionally, since rubber materials are more susceptible to be damaged, the amount of using rubber should be reduced as much as possible. The above basic requirements cannot be met by most of the existing tools [20].

(2) The hydrogen sulfide environment requires speed-up tools to withstand drill string vibration. In conventional formation drilling, if the drill string itself is not corroded, it is highly resistant to vibration hazards. However, when the drill string is corroded, excessive vibration can cause damage to the drill string, which can lead to downhole accidents and even greater drilling risks. That requires that the speed-up tool has the ability to alleviate vibration or absorb and utilize vibration.

(3) Drilling in hydrogen sulfide formation requires that the downhole speed-up tools can meet the needs of well killing and even plugging. When drilling in formations containing hydrogen sulfide, in order to control hydrogen sulfide to enter the wellbore or reach the ground along the wellbore, it is necessary to carry out well killing or well-killing plugging operations, which requires speed-up tools to meet the needs of large displacement and high-density well killing. When killing and plugging the well, the speed-up tools must be able to meet the requirements for the passage of the plugging material.

(4) The speed increase in deep hydrogen sulfide formation requires sufficient energy of speed-up tools. No matter what kinds of tools, they take energy to do their job. If the energy source cannot be guaranteed, it will be difficult for the speed-up tools to work properly. It is found that although the common tools used in the field have different speed-up mechanisms, most of them have a common characteristic that the energy source for the tools to perform their functions comes from the drilling circulating medium. Drilling practice shows that with the increase of well depth, the pressure loss of drilling circulation medium increases, and even in extremely deep wells, the circulation medium can only meet the requirement of circulating rock carrying without other energy. It is conceivable that in such wells, the working conditions of the tools or devices mentioned above will be greatly affected, and it is very likely that they will not work or even affect the progress of drilling operations. How to make further use of hydraulic energy or to find and utilize new underground energy is one of the difficulties in current research.

(5) Whether the downhole speed-up tools work normally or not, they cannot affect the normal circulation of drilling fluid. Drilling operations, risk prevention and control in bottom hole need to be controlled by drilling fluid circulation. Once the drilling fluid cannot be recycled, the consequences will be very serious. Constant circulation of drilling fluid is even more important in formations containing hydrogen sulfide, which requires bottom hole circulation can still continue even if the downhole tool fails or is damaged.

(6) As the drilling resistance of rock increases and the drilling rate decreases with the increase of well depth, it is required that the effect of the speed-up tools should be enhanced with the increasing of well depth. If it cannot be strengthened, it should at least not deteriorate.

Based on the above six factors, it can be seen that all kinds of speed-up tools powered by drilling fluid cannot fully meet the needs of drilling in formation containing hydrogen sulfide at present. It is a new attempt to explore drilling speed-up technology using drill string vibration as energy source for efficient drilling in such formation.

3. The Speed-Up Technology by Drill String's Absorption and Hydraulic Supercharging and Its Characteristics

The high frequency and large variation of weight on bit (WOB) directly acting on the bit will cause the bit's cutters to be subjected to tremendous impact force instantly, which will cause the cutters to break. A spring and damping structure are installed in the middle of the drill string and the upper part of the drill bit to transfer the WOB through the spring and damping structure. Then the fluctuation of WOB will be transformed into elastic potential energy and damping work of the spring. On the one hand, the fluctuation range of WOB will be greatly attenuated, and on the other hand, the action time of impact force will be prolonged. The reaction of the internal liquid pressure of the plunger pump is used as the damping to attenuate the fluctuation of WOB, and the damping work can be converted into the internal liquid pressure of the plunger pump, so as to realize the increase of the discharge liquid pressure of the plunger pump.

(1) The speed-up device by drill string's absorption and hydraulic supercharging

Based on the above concepts, Guan Zhichuan and Liu Yongwang from China University of Petroleum (East China) put forward the idea of high-pressure jet generation based on drill string vibration, and designed a downhole speed-up device by drill string's absorption and hydraulic supercharging [21–32], as shown in Figure 1. The device transfers the energy of drill string vibration to all drilling fluids in the circulation, achieving the purpose of pressurization for circulating drilling fluid pulse. The device is shown in Figure 2.

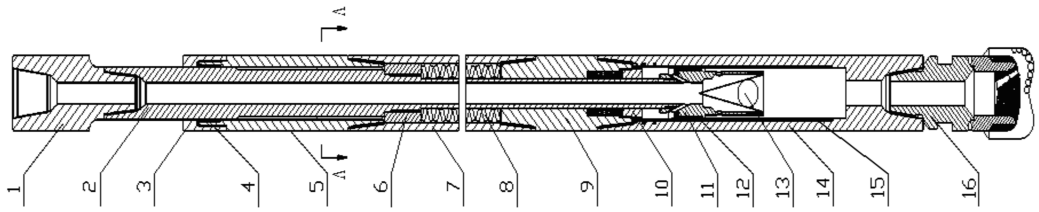

Figure 1. Schematic diagram of the structure of the speed-up device by drill string's absorption and hydraulic supercharging. Tool upper joint: 1. The spindle; 2. Upper seal assembly gland; 3. Upper seal assembly; 4. The external spline; 5. The limit body; 6. Protection tube; 7. Spring; 8. Joint in tool; 9. Lower seal assembly; 10. Plunger head; 11. Sliding seal assembly; 12. Control check valve; 13. Plunger cylinder outer cylinder; 14. Plunger liner; 15. Pressurization chamber; 16. Drill bit.

Figure 2. Physical of the drill string vibration reduction, pressurization and speed-up device.

The device uses the reaction of internal liquid pressure of the plunger pump structure to act as a damping to attenuate WOB fluctuation and convert the damping work into internal liquid pressure of the plunger pump structure, thereby realizing the increase of the hydraulic pressure discharged by the plunger pump. The device includes drill string linkage body and drill string split body. The former includes a tool upper joint, a mandrel and a limiting body sleeved outside the middle part of the mandrel. While the latter includes a plunger cylinder outer tube, a drill bit, a spline outer tube sleeved on the upper part of the mandrel, and a tool center joint connected with the spline outer tube.

The process of generating high-pressure pulse jets by the device is as follows. When the drill string vibrates downwards, that is, when WOB increases, the drill string linkage body moves downwards relative to the split body, the volume in the plunger cylinder decreases, the elastic reset element compresses and accumulates energy, and the movement speed of the plunger head increases first and then decreases. When such movement speed is greater than the flow rate of the drilling fluid in the plunger cylinder, the one-way valve for control is closed. At this time, the drilling fluid in the plunger cylinder and the elastic reset element work together to share the increase of drilling pressure, and the drilling fluid pressure in the plunger cylinder increases. When the movement speed is less than the flow rate of the drilling fluid in the plunger cylinder, the one-way valve for control is opened, and the drilling fluid flows into the bit at normal pressure and sprays.

When the drill string vibrates upward, that is, when WOB decreases, the plunger head moves upward relative to the plunger cylinder, the elastic reset element releases energy and accelerates the reset of the tool, the one-way valve for control is opened, and the drilling fluid enters the plunger cylinder. Due to the cross-sectional effect of the flow channel, the pressure in the plunger cylinder is lower than the normal pressure, and the jet whose pressure increases and decreases periodically is the pulse jet.

(2) The features of the device are as follows:

i. The device can effectively perform periodic compression and pressurization of all bottom hole drilling fluids, can realize the transfer of drill string vibration energy and the generation of pulse jets, can realize the pulse jet modulation of bottom hole jets, and the pulse amplitude is relatively high.
ii. The pressure generated by the pulsed jet is generally higher than that without the device, and the rock crushing and rock carrying capacity is significantly enhanced.
iii. The energy source of the tool increases with the increase of well depth, and the tool is more effective.
iv. The pulsed jet generated by this device has no special requirements for the applied bit, and the large pulsation generated at the bottom of the hole can alleviate the bit balling. The speed increase is particularly obvious in the case of low drilling rate caused by difficulty in increasing displacement.
v. When the device is not drilling, the entire flow channel is open, allowing circulation to continue even if the tool fails.
vi. There are only a few seals inside the device, most of which are made of metal and have high corrosion resistance.

It can be seen that the speed-up device by drill string's absorption and hydraulic supercharging can meet the application conditions of efficient drilling in hydrogen sulfide formation, and it is very necessary to carry out actual drilling test.

4. Application of the Speed-Up Technology by Drill String's Absorption and Hydraulic Supercharging in the Speed-Up Process of WWY1 Well

In order to test the application effect of the speed-up technology by drill string's absorption and hydraulic supercharging in improving drilling rate in hydrogen sulfide formation, a drilling test was carried out in well WWY1 as shown in Figure 3.

Figure 3. Device downhole experiment.

(1) Overview of well WWY1

Well WWY1 is located near Fengxu Village, Shenxiang Town, Jiujiang District, Wuhu City, Anhui Province, China. Its structural location is in the northeast of Dougouba sub-sag, Wuwei Sag, Yanjiang Depression, lower Yangtze Basin. It is a parametric and straight well, with a design depth of 3500 m. The purpose of drilling is to explore the gas content of Permian shale in Wuwei Sag of Yanjiang Depression of Lower Yangtze, and to strive to make breakthroughs; to understand the structure, lithology, lithofacies development and change laws of the target interval; to obtain various geological parameters for evaluating shale gas in the target interval and evaluate the resource potential. The principle of drilling completion is to drill through the Permian target layer to achieve the geological goal. If the target layer is drilled earlier than the designed depth, it will continue to drill to the designed depth to verify the geological properties of the geophysical data. The geological stratification is shown in Table 1.

Table 1. Geological stratification of well WWY1.

Stratum				Designing Hierarchical Data		Major	Real Drill Stratification		Real Drill Design Bottom Boundary Comparison	Real Drill Design Thickness Comparison
System	Series	Formation	Code Name	Bottom Depth	Thickness	Target Stratum	Bottom Well Depth	Thickness		
				(m)	(m)	/				
Quaternary	/	/	Q	70	70	/	59	59	−11	−11
Neogene	/	/	N	510	440	/	533	474	23	34
Paleogene	/	Shuangtasi	$E_{1-2}sh$	1335	825	/	1294	761	−41	−64
Upper Cretaceous	/	Chishan	K_2c	2020	685	/	1972	678	−48	−7
Triassic	Upper	Huangmaqing	T_2h	2100	80	/	/	0	/	−80
	Upper	Zhouchongcun	T_2z	2200	100	/	2350 Unpierced	/	/	/
	Upper	Nanlinghu	T_2n	2590	390	/	/	/	/	/
	Lower	Helongshan	T_1h	2950	360	/	/	/	/	/
		Yinkeng	T_2y	3200	250	/	/	/	/	/
Permian	Upper	Dalong	P_3d	3260	60	Shale gas layer	/	/	/	/
		Longtan	P_3l	3400	140	Shale gas layer	/	/	/	/
	Middle	Gufeng	P_2g	3480	80	Shale gas layer	/	/	/	/
		Qixia	P_2q	3500	Finish drilling		/	/	/	/

Outstanding problems in well WWY1 drilling:

i. The drilling speed in the triassic system decreased significantly, with the average rate of penetration (ROP) lower than 2 m/h;
ii. The mud loss is complicated. After the second opening, there is permeability loss and two other well losses occur;
iii. There is high pressure overflow in the drilling process, and the overflow fluid contains a lot of hydrogen sulfide. Prior to this well test, there was an overflow with hydrogen sulfide concentration of 268 ppm, and no other types of speed-up tools could be applied after this overflow.

(2) Test situation of the speed-up technology by drill string's absorption and hydraulic supercharging

In the second spudding, the drilling of well WWY1 was completed at a depth of 2212 m. In the third spudding, it was drilled to 2244 m by conventional drilling tools and roller bit with sweeping plug. After drilling out, the speed-up device by drill string's absorption and hydraulic supercharging was run down the hole for speed-up operation.

i. Drilling assembly: Φ215.9 mm PDC (FL1665 JH) + Φ165 mm Speed up Device by Drill String's Absorption and Hydraulic Supercharging + 411 * 410 Float Value + 411 * 4 A10 + Φ159 mmNDC * 1 + 4 A11 * 410 + Φ212 SmmTB + 411 * 4 A10 + Φ159 mm SDC * 9 + 4 A11 * 410 + Φ127 mm HWDP * 5 + Φ165 mm Drilling Jar + Φ127 mm HWDP * 19 + Φ127 mm DP.
ii. Drilling fluid properties: density 1.24 g/cm3, viscosity 44 s, sand content 0.2%, mud cake 1 mm, PH 11.
iii. Drilling parameters: WOB 60–80 kN, RPM 75 r/min, displacement 32 L/S, pump pressure 11 Mpa.
iv. Test conditions of wellhead before entering: wellhead displacement 20 L/s, pressure drop 1 MPa.

(3) Analysis of the using effect

Since WWY1 is a geological parameter well, there is no adjacent well data for comparison and no comparability for wells far apart. Therefore, the upper and lower adjacent sections of WWY1 and the drilling conditions of the same formation are selected for comparison. The well was drilled to 1972 m and entered the Zhoucunchong Formation of the Middle Triassic. It was drilled to 2398 m without penetration and the main lithology is gray-white gypsum rock and gray marl. The test section was 2244~2350.6 m, the footage was 106.6 m, and the downhole operation lasted 168 h, of which the pure drilling time was 30.54 h.

i. Comparison of drilling speed

The ROP of well 2214–2244 M drilled with conventional drilling tools was 1.76 m/h, and the ROP of well 2244–2350 m drilled with drill string absorption, hydraulic supercharging and speed-up technology was 3.38 m/h, a relative increase of 92.05%. Compared with the PDC bit used in the lower part, the ROP increased by 62.50% and 31.01%, respectively, when the drilling tool assembly and drilling parameters are basically the same, and the average value of ROP increased by 33.87% compared with that using PDC bit in the latter two runs, as shown in Figure 4 and Table 2.

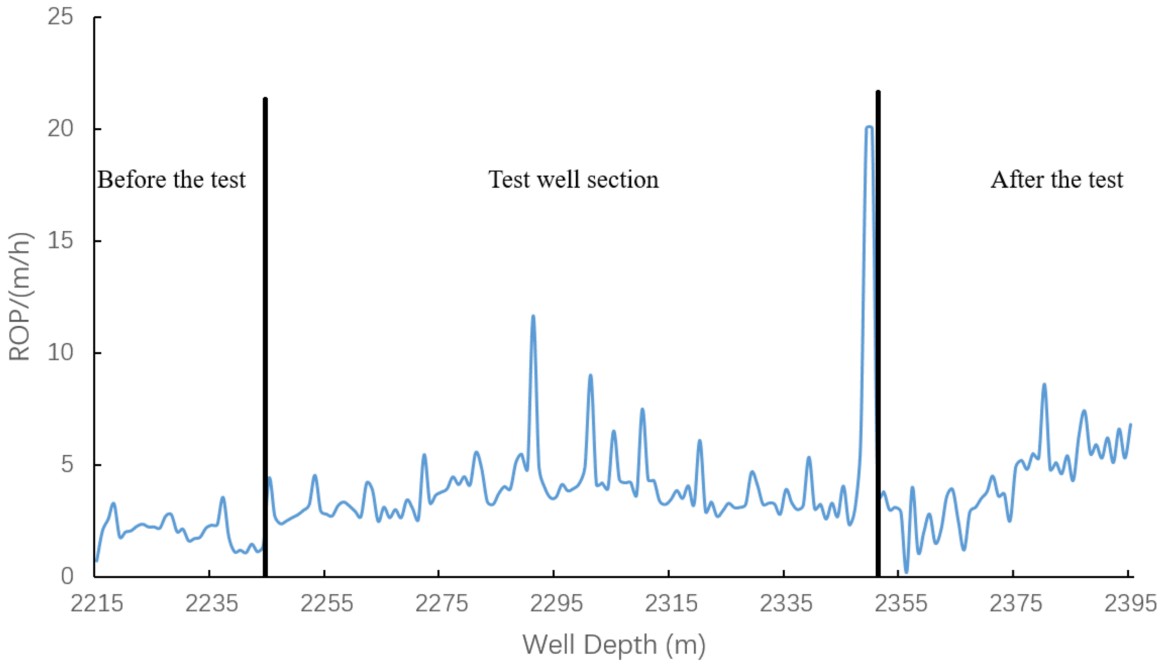

Figure 4. Drilling records of WWYl section (2244–2350 m) using drill string absorption & hydraulic supercharging & speed-up technology.

Table 2. ROP and drilling parameters.

Bit Size/mm	Bit Type	Drilling Section/m		Drilled Formation	Drilling Depth/m	Drilling Time/h	ROP /(m/h)	Bit Weight/ kN	Rotating Speed/ rpm	Displacement /(L/s)	Pump Pressure /MPa	Increased ROP/%	Remark
		Start	End										
215.9	HJ517G	2214	2244	T	30	17.05	1.76	10/40	65	32	10	92.05	
215.9	FL1665JH	2244	2350.6	T	106.6	31.54	3.38	60/80	65	32	15	0.00	Use absorption & hydraulic supercharging tools
215.9	FL1665JH	2350.6	2353.89	T	3.29	1.58	2.08	60/80	65	32	13	62.50	
215.9	FL1665JH	2365.28	2398	T	32.72	12.68	2.58	70/130	75	30	16.5	31.01	

The device protects the bit, and the exit bit is shown in Figure 5.

ii. Situation of controlling well deviation

Well WWY1 is a vertical well and a geological parameter well, so it has higher requirements for well deviation control. The pointing pendulum drill assembly [33] was adopted in this experiment, and its specific combination is shown in Table 3. Oblique measurement data at a single point during the experiment: depth: 2280 m, inclination: 1.81°, bearing: 121.87°. The deviation measurement results meet the requirements of drilling design, which proves that the technology can play a role in well deviation control with special drilling assembly.

Figure 5. Photos of exit bit.

Table 3. Situation of drilling assembly in wellbore of Φ215.9 mm of WWY1 in the third spudding.

Well Section/m	Drilling Tool Combination	Purpose
2214.00–2244.00	Φ215.9 Cone + 430 * 410 + Φ162 Float value + Φ212 stabilizer + 411 * 4A10 + Φ159 Spiral drill collars * 9 + 4A11 * 410 + Φ127 Heavy weight drill pipe * 4 + Φ165 Drilling jar + Φ127 Heavy weight drill pipe * 20 + Φ127 drill pipe * 200 + 133 kelly	Drilling in third spudding
2244.00–2350.60	Φ215.9PDC + Φ165 Drill string vibration reduction, pressurization and speed-up device + Φ162 Float value + 411 * 4A10 + Φ159 non-magnetic drill collar + 4A11 * 410 + Φ212 stabilizer + 411 * 4A10 + Φ159 Spiral drill collars * 9 + 4A11 * 410 + Φ127 Heavy weight drill pipe * 4 + Φ165 Drilling jar + Φ127 Heavy weight drill pipe * 20 + Φ127 drill pipe * 210 + 133 kelly	Drilling in third spudding (experimental well section)
2350.60–2353.89	Φ215.9PDC + 430 * 410 + Φ162 Float value + 411 * 4A10 + Φ159 Spiral drill collars * 3 + 4A11 * 410 + Φ127 Heavy weight drill pipe * 11 + Φ165 Drilling jar + Φ127 Heavy weight drill pipe * 13 + Φ127 drill pipe * 217 + 133 kelly	Drilling in third spudding
2365.28–2398.00	Φ215.9PDC + 430 * 410 + Φ162 Float value + 411 * 4A10 + Φ159 non-magnetic drill collar + Φ159 Spiral drill collars * 9 + 4A11 * 410 + Φ127 Heavy weight drill pipe * 4 + Φ165 Drilling jar + Φ127 Heavy weight drill pipe * 20 + Φ127 drill pipe * 215 + 133 kelly	Drilling in third spudding

iii. Hydrogen sulfide resistance of the device

At 6:50 on 9 December 2019, well WWY1 overflowed, accompanied by hydrogen sulfide and the highest casing pressure of 20 MPa. It is the well which has the highest shut-in casing pressure and the highest concentration of hydrogen sulfide among more than 40,000 wells constructed in Jiangsu, Anhui and Zhejiang working areas in China. Until the well killing was successful at 15:40 on 13 December, the drill string vibration reduction, pressurization and speed-up device was still normal on the aspect of exit performance after being soaked for 144 h with overflowing of hydrogen sulfide, whose highest concentration was 567 ppm.

(4) Suitable for well killing operations

In order to control the overflow in well WWY1, 130 m^3 of 2.0 g/cm^3 heavy slurry was prepared on 11 December 2019, and 82.3 m^3 of heavy slurry was pushed into the well by the horizontal push killing method. Such method was stopped until the casing pressure dropped to 10 MPa. At 20:00 on December 12, the casing pressure dropped to 1 MPa. At 13:30 on December 13, 2019, the mud density in the tank was increased to 2.20 g/cm^3, and the ground circulation was even. The throttling cycle killing method was adopted to push 86 m^3 of heavy mud whose injection density was 2.20 g/cm^3. The time to treat the overflow loss was totally 104 h 50 min and the drill string vibration reduction, pressurization and speed-up device was still in the well without any impact on the killing operation.

5. Conclusions and Cognition

(1) The speed-up device by drill string's absorption and hydraulic supercharging can meet the requirements for being used in formations with high hydrogen sulfide content, and can still perform normal drilling operations in an environment with hydrogen sulfide concentration of 567 ppm.
(2) The speed-up technology by drill string's absorption and hydraulic supercharging has a significant speed increase effect in areas containing hydrogen sulfide, and the drilling speed can be increased by 62.5–92.05% under the same conditions.
(3) The speed-up device by drill string's absorption and hydraulic supercharging can meet the needs of high-density drilling hydraulic wells. When the overflow occurred in well WWW1, in which the killing fluid density reached 2.2 g/cm^3 and the killing time was 104.8 h, the drill string absorption, hydraulic supercharging and speed-up device did not affect the whole process of killing well construction.
(4) The speed-up test of technology by drill string absorption and hydraulic supercharging studied in this paper provides a new method for speed increase in formations with high hydrogen sulfide content in well WWY1.
(5) The future research direction should be tested in different rock formations, and the speed-up technology by drill string's absorption and hydraulic supercharging should be applied to most hydrogen sulfide bearing formations.

6. Patent

Chinese National invention patent. No. ZL2017 1 0035169.4.

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