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Research Article

Experimental Research on the Technology of Hydra-Jet Sidetracking of Radial Micro-borehole

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Abstract

Ground on line test and field horizontal drilling test in well Jin 17-1 were carried out to prove the feasibility of hydra-jet sidetracking of radial micro-borehole. The pressure loss in the high pressure hose with different flow rates and the self-propelled force of the designed multi-jet nozzle were tested. From the results, the inner pressure loss of the high pressure hose is large. Furthermore, the flow rate, the flow ratio of the front and back nozzle and the borehole diameter has great influence on the self-propelled force. The test results can provide theory basis for design of hydraulic parameters and prediction of pump pressure in construction process. In the ground on line test, casing-opening time is about 15 min and horizontal drilling length reaches 20.6 meters in 97 min, with the average penetration rate of 0.21m/min and the average borehole diameter of 50mm. In the field test, four radial horizontal boreholes have been drilled at the orientation of 90 ° and 180 ° in the two layers at depth of 861.5 m and 864.8 m respectively. The maximum drilling footage is 50m and the average drilling speed is 0.2m/min. The tests above confirm that the technology of hydra-jet sidetracking of radial micro-borehole is feasible, which provides a new technique for reconstruction of old well and well stimulation of low permeability reservoir.

Keywords: hydra-jet, radial horizontal drilling, hydraulic parameters, ground test, field test

1. Introduction

Radial horizontal drilling technology can drill one or more horizontal branch boreholes along the radial direction from the main vertical hole by using the high pressure water jet. Since the turn from vertical to horizontal direction must be achieved within 0.3 meters, the technology of hydra-jet sidetracking of radial micro-borehole is also known as ultra-short radius horizontal drilling [1], [2], [3], [4], [5]. During this operation the energy for high-pressure injection is provided by a high pressure injection pipe, and the water jet bit moves forward to continue the drilling without rotation (Fig 1).

Three main problems should be solved for this technology: first, the borehole diameter caused by water jet, namely the size of the horizontal wellbore. Second, the self-propelled capacity and the maximum horizontal drilling length, that is the maximum horizontal displacement. Last, the rock breaking efficiency that is the proper rate of penetation. The horizontal well diameter is determined by the rock breaking ability of jet bit. The borehole diameter and drilling rate is determined by rock breaking capacity of the jet bit. The maximum horizontal drilling length is closely related to the transfer capability of the steering system [6], [7].

The field experiment has been conducted by applying the self-developed device of hydra-jet sidetracking radial horizontal well [8] based on the parameters of pressure loss of the test fluids in high pressure hose and the self-propelled force of the nozzle. Four well boreholes have been successfully drilled in the field test. This technology of hydra-jet sidetracking of radial micro-borehole need no casing milling and reamer milling, which simplifies the operation process, improves operation efficiency and reduces the construction cost.

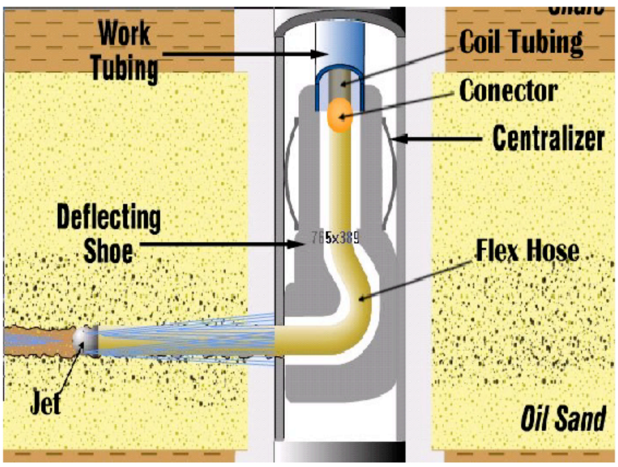

Fig. 1. Voltage Stabilizer Block Diagrem

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2. Design of Hydraulic Parameters

2.1 Design of Multi-jet Bit

The high pressure water jet lab of CUPB has developed a multi-jet bit with high rock breaking ability and self-propelled capacity (Fig 2). The design of multi-jet bit take full advantage of the properties of single jet that it can generate centralized energy and form a deep borehole depth. The multi-jet bit opens more than one nozzle in the front-end of the drilling bit body to generate multiple jets [9],[10]. The single jet can produce a strong impact force within a small area at the bottom of the well to get a good rock-breaking effect. Multiple jets spray into a larger area of the bottom and generates a non-continuous annular region with high impact effect [11],[12]. By combining each jet, a good borehole enlarging effect can be obtained with the Porous nozzle. The rock breaking task is mainly achieved by the central nozzle, while the rest of them assist to rock breaking and expanding the borehole diameter [13],[14]. The main structural parameters are summarized here: backward orifice diameter of the nozzle d_1, backward orifice diffusion angle of the nozzle β, forward center orifice diameter of the nozzle d_2, forward surrounding orifice diameter of the nozzle d_3, and forward orifice diffusion angle of the nozzle α, as shown in Figure 2. Assuming that equivalent diameter of the forward nozzle is d_e, the orifice number of the forward nozzle is n and each orifice has the same diameter. We can calculate d_e using the following equation:

$$md_1^2 = d_{e1}^2 \tag{1}$$

$$(n-1){d_3}^2 + {d_2}^2 = {d_{e2}}^2 \tag{2}$$

where, m is the borehole number of backward nozzle. d_{e1} is the equivalent diameter of backward nozzle. n is the borehole number of backward nozzle; d_{e2} is the equivalent diameter of forward nozzle.

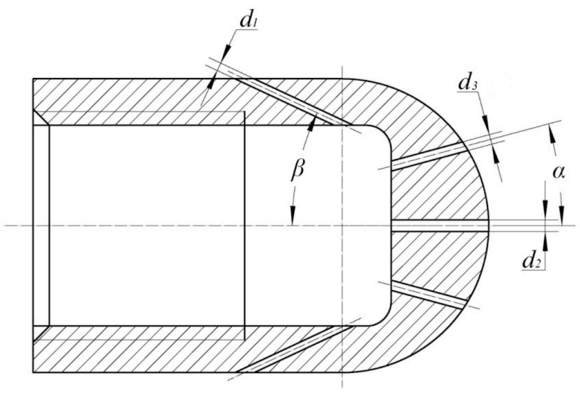

Fig. 2. Structure diagram of multi-jet bit

If the diameter of center borehole and the forward-reverse flow ratio is known, the borehole diameters can be obtained according to equation (1) and (2). From the multi-jet bit laboratory test [15], when diffusion angle β is 20° and n is 6 (5 boreholes around), the rock breaking efficiency achieves better results. Based on the experiment of self-propelled force, the self-propelled force can reach more than 120 N when the forward-reverse flow ratio is 2:3. Therefore, considering the rock breaking efficiency of the nozzle and the magnitude of self-propelled force, the main structural parameters of the nozzle are designed as follows: the borehole number of forward nozzle is 5, the diameter of center borehole d_2 is 1.0mm, and the forward surrounding borehole diameter of the nozzle d_3 is 0.9mm, α is 30°, 8 backward boreholes are uniformly distributed with borehole diameter of 1 mm and β of 20°.

2.2 Steering Gear System

The steering system is mainly composed of diverter, tubing nipple and tubing anchor. The tubing short nipple is used to connect the diverter and tubing anchor. The tubing anchor is used to fasten the downhole tools to the casing wall. The outer diameter of the steering is less than the casing diameter, as shown in Fig 3, two symmetry parts are connected by bolts. The slideway inside the diverter is made up by a straight line segment, a incline line segment and an arc. The casing opening tools and the water jet tools can make turning from vertical to horizontal direction through the slideway with a curve radius of about 0.3 m. The tubing is connected to the diverter to form a high-pressure chamber, which can realize the hydraulic deliver of the flexible drilling tools and help to drill a continuous horizontal borehole.

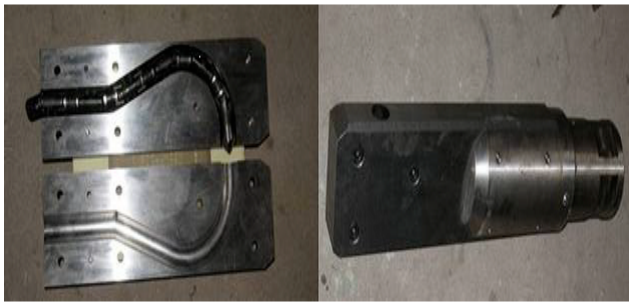

Fig. 3. Structure diagram of multi-jet bit

2.3 Pressure Loss Test along the Manifold

The pressure loss in high pressure hose and coiled tubing was conducted in the field test. The test method is listed as follows: first, the end of high pressure hose is connected with the outlet of the plunger pump equipped with a pressure gage and the other end of the hose is in the atmosphere. The pump pressure, which is the pressure loss of high pressure hose, can be read by pressure gage after pumping started. The pressure loss at different flow rates is tested, so the curve of flow rate and pressure loss can be obtained as shown in the figure 4. It can be concluded that the pressure loss increases linearly with the flow rate increasing. Therefore, the flow rate should not be too large designed in the field test and the pressure loss difference of the high pressure hose between the length of 20m and 10m is increasing under the same flow rate. This is also found in the radial horizontal drilling, the pump pressure increases evidently with the increase of the length of high pressure hose.

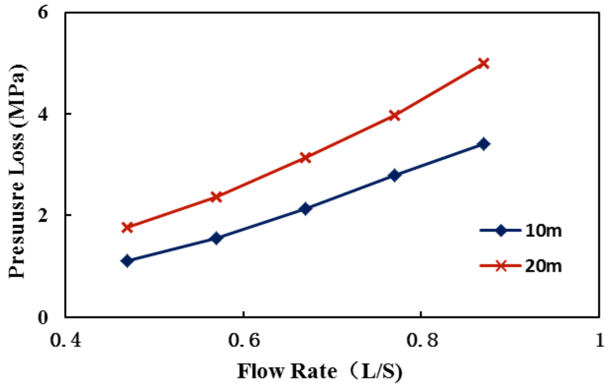

Fig. 4. The change of pressure loss with flow rate in high pressure hose

The pressure loss of the coiled tubing, of which the length is 4000m and the diameter is 25.4mm, was 22MPa when the flow rate was 60L/min.

The curve of pressure loss and flow rate after adding drag reducer is shown in Fig.5. From the figure, the pressure loss decreased sharply after adding drag reducer. The greater the concentration of drag reducer is, the smaller the pressure loss is under the same flow rate. And the decrease of pressure loss becomes slower as the concentration increases. Therefore, adding appropriate amount of drag reducer can lower the pressure loss along the manifold, enhancing the rock breaking efficiency when drilling radial horizontal wells.

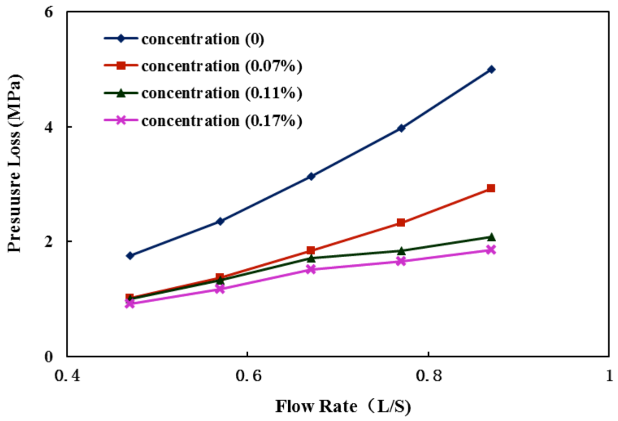

Fig. 5. The change of pressure loss with flow rate under different drag reducer concentration

2.4 Self-propelled Force Test of Multi-jet Bit

When the high-pressure hose is applied as drill pipe in radial horizontal drilling inside casing, it is relatively difficult to run into the hole because the great toughness and weak axial transmission capacity. Thus, high-pressure hose needs to be driven by self-propelled jet bit to continue drilling. The self-propelled jet bit is the key tool of hydra-jet sidetracking of radial micro-borehole, which not only have to break the rocks but also provide the self-propelled force for high-pressure hose moving forward. Generally, the forward and backward boreholes are laid out on self-propelled jet bit. The forward borehole is used for rock breaking to provide the advancing path for the jet bit. The backward borehole generates the forward force for the jet bit and high-pressure hose to move forward by ejecting fluids backward.

The self-developed test device of self-propelled force (as shown in Fig. 6) is used for testing self-propelled force of multi-jet bit. Experiment bench was fixed on the ground to make sure the simulated wellbore wouldn't move or rotate. Simulated wellbore was placed horizontally and was fixed on the experiment bench. Multi-jet bit was connected with high-pressure hose and they are placed inside of the simulated wellbore. The end connector of multi-jet bit is connected to tension meter using tensile test line. And tension meter was fixed on another experiment bench which is as high as the previous one to make sure that tensile test line was horizontal. The function of tension meter was to measure the magnitude of self-propelled force of bit.

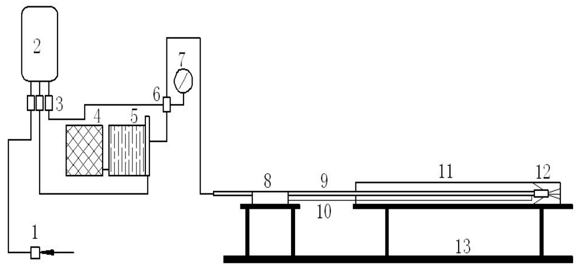

Fig. 6. Experiment apparatus of testing self-propelled force of multi-jet bit(1, entrance gate; 2, water tank; 3, rapid-acting coupling; 4, motor; 5, high-pressure pump; 6, unloading valve; 7, pressure gauge; 8, pull gauge ; 9, high-pressure hose; 10, test lead; 11, simulated wellbore; 12, multi-jets bit; 13, experimental platform.)

(1) Effect of Flow Rate

Because the reverse jet flow of multi-jet bit is bigger than forward jet flow, the jet bit will generate a forward self-propelled force and the forces will increase with the increase of the flow rate. When the forward-reverse flow ratio is designed as 2/3, 1/2, 1/3, 1/6, the jet distance 10 mm and the wellbore diameter is 49 mm, the self-propelled force approximately increases linearly with the flow rate, as shown in Fig.7. Take the forward-reverse flow ratio of 2/3 for example. The change of self-propelled force with flow rate is shown in table 1.

Results show that the self-propelled force increases significantly with the increase of the flow rate. This is because the total momentum of the jet increases a lot as the increase of flow rate, resulting in a greater reverse thrust for the reverse jet and the effect of pressure drop becomes more obvious. When the flow rate ranges from 0.71L/s to 0.99L/s, the range of self-propelled force is from 67.8 to 228.1N in laboratory conditions.

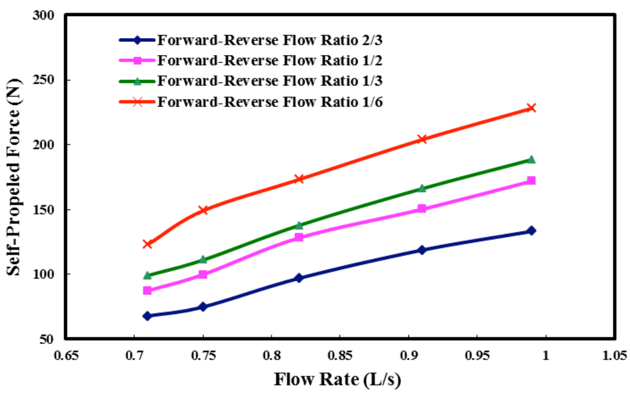

Fig. 7. The change of flow rate with self-propelled force

Table1. The setting of experimental parameters

Parameter types	Values				
Flow rate, L/s	0.71	0.75	0.82	0.91	0.99
Forward-reverse flow ratio	2/3	1/2	1/3	1/6	
Forward jet standoff distance, mm	10	20	30	40	50
Wellbore diameter, mm	30	36	49	62	70

(2) Effect of Wellbore Diameter

The wellbore diameter has influence on the self-propelled force in the following two ways. First, the multiple reverse jet flow with uniform distribution can inject rapidly to produce annular low pressure area at rear of the jet bit, leading a thrust to the jet bit and the high-pressure hose. The pressure drop effect changes with borehole diameters. Second, the reflux generated when the forward jet impact the bottom hole of the well. It can produce a backward thrust to the front face of the jet bit. Different borehole diameters correspond to different reflux velocities. Hence, the thrust on the jet bit is different. In this experiment, the forward jet standoff distance is 10 mm and the forward-reverse flow ratio is 2/3. Figure 8 shows that the self-propelled force first increases and then decreases with the increase of the wellbore diameter. There is an optimal diameter for the wellbore. Take the flow rate of 0.99L/s for instance. The change of self-propelled force with wellbore diameter is shown in table 2.

When the diameter is relatively small, the velocity of the reflux generated by forward jet flow is fast, forming a big backward thrust to the front face of the jet bit. Therefore, the self-propelled force is relatively small. When the wellbore diameter becomes larger, a larger wellbore area weakens isolation ability of the reverse jet. Therefore, the effect of pressure drop reduces and the self-propelled force decreases. When the wellbore diameters are 62 and 70 mm separately, the difference of the self-propelled force between the two can be ignored. When the wellbore diameter reaches 62 mm, the effect of pressure drop of the reverse jet has not been obviously yet. When the wellbore diameter reaches 36-49mm, the self-propelled force is comparatively big. When the wellbore diameter ranges from 36 to 49mm and the flow rate ranges from 0.71to 0.99L/s, the range of self-propelled force is from 51.1 to 136.1N that the forward-reverse flow ratio is 2/3 under laboratory conditions.

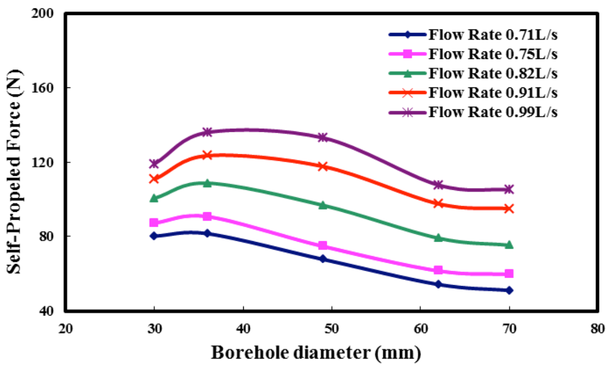

Fig. 8 . The change of borehole diameter with self-propelled force

Table2. The change of self-propelled force with wellbore diameter

Flow rate, L/s	0.99				
Wellbore diameter, mm	30	36	49	62	70
Propelled force, N	119.2	136.1	133.2	107.8	105.2

3. Ground on Line Test

Ground on line test includes casing opening test and hydra-jet drilling test. The purpose of the casing opening test is to examine the reliability of the casing opening device in radial horizontal drilling. The hydra-jet drilling test aims to inspect the performance and stability of the downhole tools when they are grouped together, which can provide technical guidance to field operations.

3.1 Test Devices and Methods

The test system composes of coiled tubing radial horizontal drilling system, high-pressure pump (rated pump pressure 50MPa and rated displacement 120L/min), high-pressure pipelines, brackets, tracks, tubing, pressure gauge, pressure regulator, casing ring (N80 casing and wall thickness 8.7mm) and cement rock samples (uniaxial compressive strength 20MPa). In the casing opening test, the casing ring is installed in the steering lateral, as shown in Fig 9. In the hydra-jet test, high pressure hose and jet bit are connected by the high pressure pipeline. The cement rock samples are placed at the horizontal exit of the steering, as shown in Fig 10.

In the casing opening test, the high pressure pipeline is connected to the drilling motor, flexible drive shaft and milling bit successively. When the bit mills the casing, WOB is imposed to the flexible drive shaft through cuphroe. The drilling motor provides the flexible drive shaft with torque. The hydra-jet test is carried out with jet bit placed horizontally. The air compressor is turned on, after that the high-pressure pump is turned on with pressure adjusted. And after adjusting the pneumatic rotary device, the spray hose and nozzle (80-120 rpm) is turned on and the jetting is started.

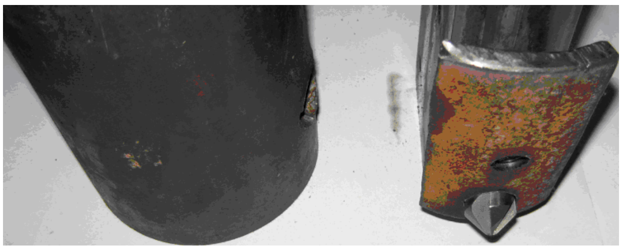

Fig. 9. Drilling test device

Fig. 10. Ground hydrajet test

3.2 Drilling Capacity of the Milling Bit

The pump pressure of the hydraulic milling test is 15 MPa, with the flow rate of 50-60L/min. After milling for 10 minutes, the milling bit drills through the casing. After 15 minutes, the whole milling bit comes out of the casing. Using new milling bits to repeat the experiments, the casing drilling-through time is always about 15 minutes. Drilling capacity of the milling bit can meet the requirement of the field test.

3.3 Rock Breaking Ability of the Multi-jet Bit

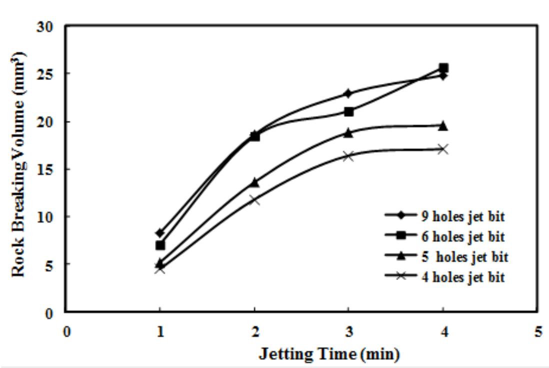

Fig. 11. The change of rock breaking volume with jetting time

The pump pressure of the hydra-jet test is 30 MPa, with flow rate of 70-80L/min. The test uses the pneumatic devices driving the hose in order to achieve rock breaking. The pure drilling time is about 97 minutes, with the horizontal drilling length of 20.6m (drilling through 43 cement rock samples, the length of the sample is 0.48m). The average penetration rate is 0.21m/min, average borehole diameter is 50mm. The relationship cure of rock breaking volume with jetting time is shown in figure 11. With the growth of jetting time, the rock-breaking volume of each jet bit with different boreholes increases shapely at first, and then begins to flatten. These results indicate the stage characteristics of the rock breaking process of the water jet. The rock breaking effect at initial stages is remarkable, while the increase of the effect at later stages is very limited. The test shows the strong rock breaking capacity of the multi-jet bit.

4. Field Test

Jin 17-1 well is located in Shengli Oilfield which is an ordinary heavy oil reservoir in China, with the depth of 866.7m. The designed depth of the target layers are 861.5m and 864.8m. The orientations of the two radial horizontal boreholes in each layer are East and South (i.e., 90 and 180 ° phase).

4.1 Test Devices

Water tankers, square cans, high-pressure pump, coiled tubing equipment, tubing (27/8 "), tubing nipple, coiled tubing radial horizontal drilling system, logging devices for depth correction and orientation measuring, anti-swelling agent, resistance reducing agent, pressure sensors, etc. Equipment connection diagram is shown in Figure 12.

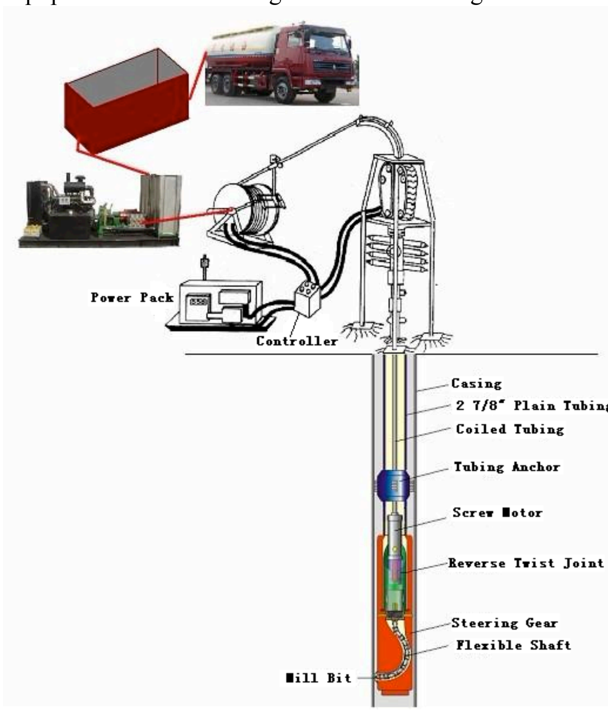

Fig. 12. Equipment connection diagram

4.2 Test Process

1) Trip out the pipe string, salvage sand control string in the well, sand washing, well washing, well passing to the artificial well bottom.

2) Connect the steering, short tubing section, directional connector, tubing anchor, oil column (27/8 ") successively from the bottom to the top, ensuring that the steering depth is 864.8m.

3) Correct the depth, fix the tubing by tubing anchor packer and measure the orientation with gyroscope.

4) Connect the casing opening device, which is composed of milling bit, flexible drive shaft and downhole motor, to the coiled tubing, and lower them into the position of steering through 27/8" tubing.

5) Turn on the pump with the flow rate of 60 L/min, pump pressure of 30MPa. The drilling motor drive the milling bit to open the casing.

6) After milling the casing for about 60 minutes, trip out the coiled tubing and casing-opening devices, and then replace the milling bit.

7) Connect the hydra-jet device to the bottom of the coiled tubing. Turn on the pump and lower the hose to the steering position.

8) Trip out the coiled tubing and hydra-jet device after one borehole is completed. Then replace the nozzle.

9) Unset the tubing anchor, rotate the column and change the steering position to 90 °. Repeat the above process.

10) Lift up the coiled tubing to the depth of 861.5 m and repeat the process of hydra-jet drilling twice.

4.3 Test Results

Four radial horizontal boreholes have been drilled at the orientation of 90 ° and 180 ° in the two layers at depth of 861.5 m and 864.8 m respectively according to the designation. The parameters of the radial horizontal boreholes are shown in Table 3.

According to the ground test, the time needed to drill through the casing by the milling bit is about 15 minutes. The casing milling time is designed to be 60 min to ensure that the casing can be drilled through due to the complex downhole condition. In the ground test, the rate of penetration is about 0.2m/min, so the lowering speed of coiled tubing (i.e., penetration rate) is controlled to be 0.2m/min. Because this is the first time for field test of coiled tubing radial horizontal drilling, the horizontal well 1# was drilled with length of 20 m, hydra-jet time of 87 min and the average penetration rate of 0.23m/min. The length of well #2, #3, #4 is 50 m. The hydra-jet time for well #2 is 236 minutes and the average rate of penetration is 0.21m/min. The hydrajet time for well #3 is 259 minutes and the average rate of penetration is 0.19m/min. The hydrajet time for well #4 is 248 minutes and the average rate of penetration is 0.20m/min.

Table3. Parameters of the radial horizontal borehole

Well number	Depth/m	Orientation/°	Casing milling time/min	Hydra-jet time/min	Well length /m
1#	864.8	90	60	93	20
2#	861.5	90	60	236	50
3#	861.5	180	60	247	50
4#	864.8	180	60	229	50

5. Conclusions

The coiled tubing hydra-jet sidetracking of radial micro-borehole technology is applied to the field test for the first time with indigenous technology. The operation process was carried out successfully. The reliability of the downhole tools was verified by the ground test and field test. The tests prove that performance index of each device meets the design requirements.

(1) Under the experimental condition, the pressure loss of high pressure hose in hydra-jet sidetracking of radial micro-borehole almost increases linearly with the increase of flow rate. The self-propelled force of the jet bit becomes larger when the flow rate increases and the forward-reverse flow ratio of the nozzle decrease. The self-propelled force is relatively large when the value of borehole diameter is from 30 to 50 mm.

(2) In the on line ground test, the performance of the casing opening devices and hydra-jet devices is reliable. The casing opening time is about 15 min. A horizontal drilling length of 20.6 m is completed in 97 min with the average penetration rate of 0.21 m/min and the average borehole diameter of 50 mm.

(3) In the field test to the Jin 17-1 well, 4 radial horizontal boreholes were drilled. The length of the horizontal section for one of them is 20m and the other three is 50m respectively. The average penetration rate is 0.2 m/min. The successful application in field test shows that the technology is feasible and can be widely applied.

Acknowledgements

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