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Research/Technical Note

Study and Application of Hydraulic Jet Radial Drilling in Carbonate Reservoirs

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Abstract: The hydraulic jet radial drilling technology is a low-cost production and completion technology for effectively developing low-permeability marginal reservoirs, thin-bed reservoirs with edge and bottom water, and depleted oil and gas fields. It has been successfully and widely applied in sandstone, coalbed methane, and heavy oil reservoirs. In order to explore its application in carbonate reservoirs, specially economically and efficiently develop low-permeability thin-layer carbonate reservoirs, the pilot of hydraulic jet radial drilling technology in the carbonate reservoir application was successfully completed through the research on the principle, advantage, existing problems and application condition of radial jet drilling, economic productivity was got, and cost-effective development was achieved, this pilot provided a method for the development of low permeability thin layer carbonate reservoir. This research shows that the hydraulic jet radial drilling technology has its unique technical advantages, which can enable some reservoirs to increase production or injection, but it is not suitable for every well, it has certain applicable conditions, such as the depth, thickness, and temperature of the target zone, and the conditions of well inclination, casing and wellbore have certain requirements too. The hydraulic jet radial drilling technology can achieve the expected target based on the zone and well selection, in selecting layers, as far as possible, homogeneous oil layers with good reservoir physical properties should be selected; the key of its successful implementation is the depth and azimuth control, wellbore diameter and operation safety control. The application of hydraulic jet radial drilling in carbonate reservoirs will make the spray hose wear large due to its high Young's modulus the high hardness, which affects the treatment footage; the use of acid in jet drilling can increase the radial drilling footage, but on the other hand can also produce impurities affecting the operation. The working fluid for jetting must meet the requirements of no solid phase.

Keywords: Hydraulic Jet, Radial Drilling, Carbonate Reservoir, Technological Advantages, Technological Process

1. Introduction

Radial drilling technology is a drilling technology that uses high-pressure water jet to drill multiple radial horizontal branch boreholes in one or multiple layers of a reservoir, which is a completion and stimulation technology for oil and gas fields [1-2]. This technology can effectively prevent water cones and gas cones. It can be used both for the development of new drilled wells and for the stimulation of old wells, and is favorable for the stimulation of thin layer reservoirs, low-permeability oil and gas reservoirs and coal bed methane, and is an effective means for water well stimulation as well. The technology uses magnetic positioning and natural gamma logging to determine the window cutting depth of radial drilling in the casing. The gyro inclinometer is then used to determine the orientation of the radial drilling. A milling bit is run to drill a hole with a diameter of 1in on the casing. The high-pressure pump is used to pressurize the solid-free drilling fluid and pump it through the coiled tubing to the downhole. The high-pressure potential energy of the drilling fluid is converted into kinetic energy by the jet bit to generate high-speed jet. The jet penetrates the formation with momentum. A horizontal wellbore with a depth of more than 100m and a diameter of 1~3in can be drilled [3]. There are three technical and economic indicators for radial drilling: first, the diameter of the borehole, that is, the size of the horizontal wellbore; second, the extent that the radial drilling can reach, that is, the maximum horizontal displacement; and third, the drilling rate. Among them, the borehole diameter and drilling rate are determined by the rock breaking ability of the water jet bit. The maximum horizontal displacement of the wellbore is closely related to the hydraulic feeding capacity of the power system [4].

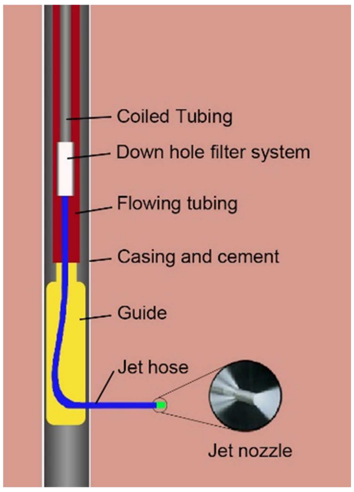

Figure 1. *Schematic diagram of hydraulic jet radial drilling technology.*

The radial drilling system successfully developed by the American company Petrolphysics in the 1970s and 1980s is a representative of early radial drilling technology. Petrolphysics' radial drilling system could drill a horizontal section with the length of more than 60 m, the borehole diameters drilled could exceed 100 mm in unconsolidated reservoirs, and up to 24 radial boreholes at the same depth could be drilled. In the practical applications, four radial wellbores with the length about 20 m were usually drilled at the same depth. But, before radial drilling, casing milling and borehole reaming were needed [5-6]. Currently, companies such as RDS Company, Blast Company, and WES Company have developed new radial drilling technology. Compared with traditional radial drilling technology, the essential difference of the new radial drilling technology lies in the use of new guide without the need of time-consuming casing milling and borehole reaming. Instead, equipment and tools are directly used to drill holes in the casing and cement sheath, and then drills the radial borehole. The operating efficiency of the new radial drilling technology has been greatly improved because of the elimination of casing milling and borehole reaming [7-8].

The initial researches on radial drilling technology were aimed at the development of shallow heavy oil. Applications in stimulation, water injection and coalbed methane development in some countries had shown good prospects. China began research on radial drilling in 1992 [9]. In August 1997, the first radial drilling well was completed. Subsequently, field tests on radial drilling technology were conducted in Liaohe Oilfield, Shengli Oilfield, Nanyang Oilfield, Jiangsu Oilfield, Jilin Oilfield, Qinshui and Fuxin Coal Mine [4, 10]. Applications were mainly focused in the fields of low permeability sandstone reservoir, heavy oil reservoir, and coalbed methane. The early radial drilling length was about 20m, and now it is mostly 50-100m. Radial drilling in coalbed is relatively longer, mostly about 200-400m because of the lower mechanical strength compared to that of clastic rocks, shallowly buried depth, and low density. Subject to cleat developed in the coal bed, the arrangement of hydraulic jet radial drilling well should consider the direction of the crustal stress and the orientation of the cleat system. By making the radial drilling wellbore perpendicular to the cleat, the more effective connected network could be formed to maximize the drainage and pressure reduction of the branch wellbore [11-13].

2. Main Process Flow and Operation key Points

The main process flow of hydraulic jet radial drilling technology is: running guide, casing window cutting and radial drilling [14].

1. Running guide: Before radial drilling operation, the guide is run into the well by tubing through workover rig. The guide azimuth is determined by a gyroscope or other instrument. The guide azimuth adjustment is completed by rotating the tubing by the workover rig. The main equipment includes guide, centralizers, directional joints, and depth correction pup joint.

2. Casing window cutting: The milling bit and the cardan shaft are guided by the guide from vertical to the horizontal direction, making the milling bit drilling perpendicular to the casing. The ground high-pressure pump is started to pump the high-pressure drilling fluid to the downhole motor by coiled tubing, so as to starts to drill the casing. With the milling of the casing and cement sheath, the ground control system runs the coiled tubing back and completes the window opening process of the casing and cement sheath. The main equipment includes downhole motor, cardan shaft and milling bit.

3. Radial drilling: The coiled tubing unit runs the nozzle and jet hose into the tubing. Start the high-pressure pump on the ground. The nozzle uses high-speed jet erosion to achieve breaking rock, drilling in the formation and completing the radial drilling. The main equipment includes nozzles and jet hose.

There are two key points of the operation of hydraulic radial drilling technology [15]:

1. Depth and azimuth control. Depth and azimuth are the keys to increase production after the operation. The radial drilling depth of the hydraulic jetting is strictly in accordance with the design depth. At each change of azimuth, the positioning measurement is conducted using the base point, and the azimuth angle measurement is conducted by the gyroscope to ensure the tool is run to the designed depth and orientation.

2. Wellbore diameter and operation safety control. When the jet drill bit enters the oil layer, the flow rate, pressure and

lifting system are kept stably and continuously. High pump pressure and high pump rate are recommended to maintain a high drilling rate without drilling accidents.

3. Technology Advantages

The advantages of radial drilling technology can be understood from its technical principle:

(1) Smaller casing damage compared to conventional sidetrack drilling.

(2) No-rotation of the drill string and drill bit reduces downhole complexity.

(3) The non-solid-phase jetting fluid and short operation time minimize formation damage.

(4) An alternative for perforation and building up along oil and gas channel.

(5) Improvement of the layout of well patterns in reservoir enlarges oil supply area and increases the oil drainage area.

(6) The control of the layers could finely address conflicts of oil and water wells.

(7) Optimized well pattern and enhanced oil recovery of residual oil.

(8) For heavy oil reservoir, radial drilling smoothes the steam injection channel and consequently increases the steam injection volume.

(9) The radial hole can be used to guide the fracture propagation. Fracturing is performed after the radial drilling in the severe sanding well then the artificial fracture is filled with filler to prevent sand plug in the hole and increase the production cycle.

(10) Compared with other stimulation techniques, the radial drilling technology has its own advantages: For example, the penetration depth of the composite perforation is limited; The fracturing and acidizing can effectively penetrate the formation, but the fracture orientation cannot be controlled, and a large amount of liquid required, which is unfavorable for the thin oil layer with bottom water; Horizontal well drilling needs large investment, long operation time and is prone to formation damage.

4. Existing Problems

In terms of engineering technology:

(1) Since the radial drilling pushes the drill bit forward only with the backward jet without direction control, which leads to great uncertainty in the radial drilling. The radial drilling wellbore is easy to run out of the thin oil layer.

(2) The length of the radial drilling wellbore may not reach the designed length. The main reason is due to the slow running of the coiled tubing, the weight of the high-pressure hose, and the insufficient forward push of jet bit because of the enlarged borehole by severe erosion of jetting.

(3) Large pressure loss due to liquid pressure transmission in long coiled tubing leads to insufficient pressure at the jet bit and a decrease of collimation and strength of high pressure hose's steel.

(4) The ability to open casing window is limited, which is mainly subject to casing diameter, grade, and thickness. The casing diameter determines the size of the guide shoe.

(5) Downhole tools have limited fatigue life, including coiled tubing, downhole motor, cardan shaft, milling bit, nozzles, high-pressure hose and guide shoe.

(6) Due to the short radius of curvature of the radial drilling well, conventional well completion methods are no longer applicable. Under current technology conditions, only screen gravel pack completion or open hole completion can be used, which presents less reliability.

Application of geological conditions and well conditions:

(1) The required thickness of the target reservoir is limited because the radial drilling is prone into the soft formation, whose direction cannot be controlled.

(2) The jet drilling in formation is limited within certain lithologies like sandstone, coal bed, mud shale, carbonate rock and argillaceous siltstone. It is difficult to drill formations with high mechanical strength.

(3) There is a general requirement for porosity, which is above 5% for coal bed, above 10% for oil layer (suitable for low porosity formations). There is also a general requirement for permeability, which is above 1mD for coal bed and is suitable for low permeability formations.

5. Applicable Conditions

Applicable formation and well condition: The formation thickness should be greater than 1m, with good plane homogeneity, good potential for stimulation, definite distribution of oil, gas, and water and not serious sanding, the target zone should develop upper and lower barrier layer, clear faults distribution and depth of less than 3500m. The wellbore has a single-layer casing (4 1/2”~7”) with the wellbore inclination of less than 35°. The formation temperature should be lower than 120°C.

Applicable wellbore conditions: No severe casing deformation to ensure the guide passes through the wellbore. The operating string should be clean and oil-free. Wiper trip should be conducted before running the working string. The wellbore is required to be washed before the operation to ensure the wellbore cleanliness. The wellbore pocket space should be long enough to conduct the jetting operation.

6. Case Study

6.1. Selection of Well and Layer

The radial drilling test was targeting the A2 layer of Well T-1 in the TK carbonate structure. The thickness of A2 layer in Well T-1 is relatively large (Figure 2), which is preferable for operation. According to the seismic data, the A2 layer is intact with a gentle structure. The pay zone contrast also indicates that the A2 layer in Well T-1 has better developed physical properties than the offset Well T-4 and Well T-5. The well log shows that there is a continuous oil and gas display section of about 10m at the top of the A2 layer, and the oil layer distribution is relatively stable.

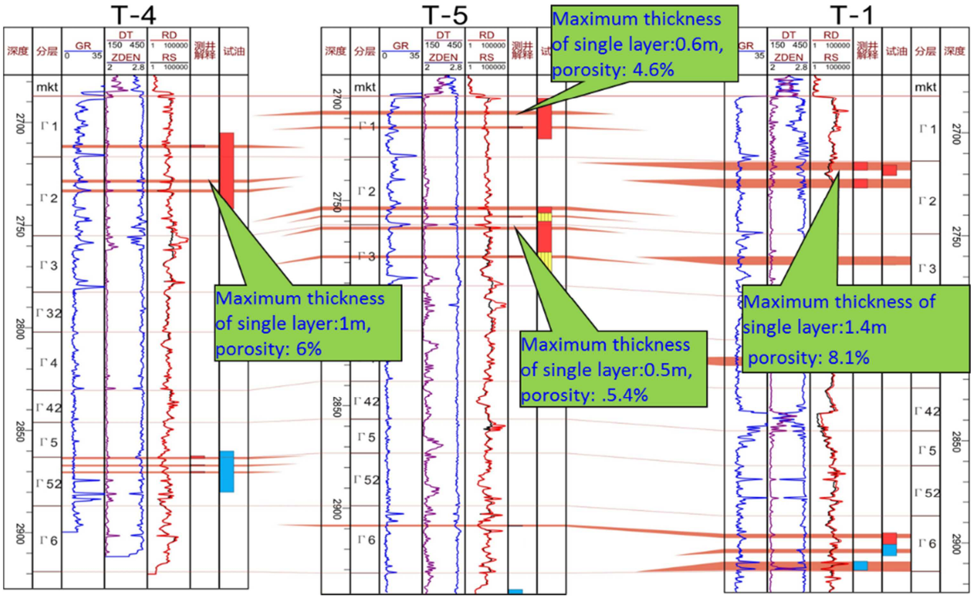

Figure 2. *A2 oil layer comparison.*

Well logging interpretation showed that: the 2715.8m-2717m and 2719.2m-2720.8m two sections of A2 layer in Well T-1 showed as oil layers with the thickness of 1.2m and 1.6m respectively. There is no bottom water and gas cap in the reservoir. The experiments of cores of offset wells showed that the target layer has low clay content, weak sensitivity and consequently low requirement for working fluid.

The target layer is completed with 168, 3mm 90SS casing, and the cementing quality is qualified. The hydraulic jetting radial drilling technology is applicable.

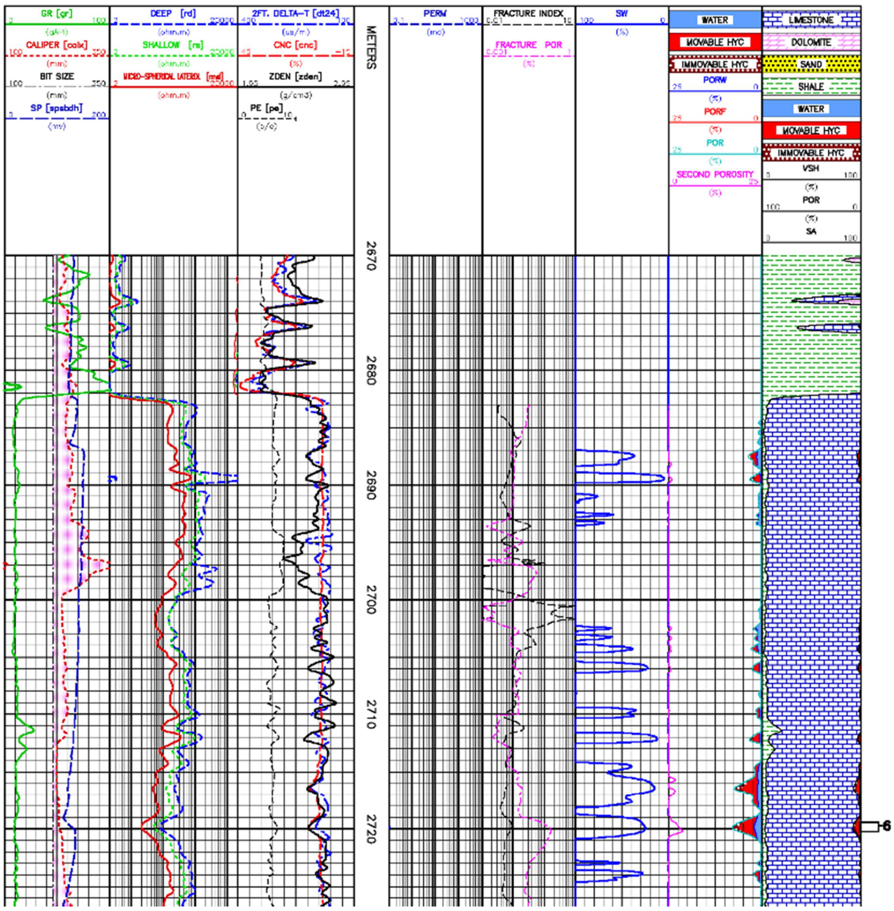

Figure 3. *Well logging interpretation result of the A2 layer in Well T-1.*

Table 1. *Well logging interpretation results of the A2 layer in Well T-1.*

Well Name	Layer	Top depth	Bottom depth	Thickness (m)	Effective Thickness (m)	POR (%)	K (mD)	So (%)	Φf (%)	Kf (mD)	Explanation of conclusions	Reservoir type
	A2	2715.8	2717	1.2	0.6	8.4	0.48	81	0.15	46.7	Oil	Fracture-pore type reservoir
T-1	A2	2719.2	2720.8	1.6	0.8	8.1	0.4	69.4	0.13	40.6	Oil	Fracture-pore type reservoir
	A2	2746.7	2747.8	1.1	0.5	7.5	0.27	48.9	0	0	Oil and water	Pore type reservoir

6.2. Radial Drilling Plan

The basic plan is to conduct high-pressure hydraulic jet radial drilling in the 2715.8m-2717m and 2719.2m-2720.6m two sections. For each section, 3 branch wellbores with the length of 50-100m and a phase angle of 120° are drilled at the same depth. The lower layer was first drilled and the 6 branch holes had a spaced phase angle of 60° from each other.

6.3. Operation Process and Results

The operation flow chart is shown in Figure 4. The 12 days operation completed six radial drilling 30-40mm diameter boreholes with single-hole footage of 45-56m, an average footage of 50.5m. During the operation of drilling the six holes, the first, fourth and fifth holes were drilled with fresh water; the second, third and sixth holes were drilled with 2 m^3 10% hydrochloric acid for each hole. The six holes were milled using water.

The specific operating parameters and results are shown in Table 2. It can be seen from the table that the pressure and time for milling each hole with water are similar. In the horizontal drilling stage, the jetting pressure and time are almost the same. The average footage of the three holes drilled with water jet is 47m. The average footage of the three holes drilled with acid is 54m, which is 15% longer than that using water.

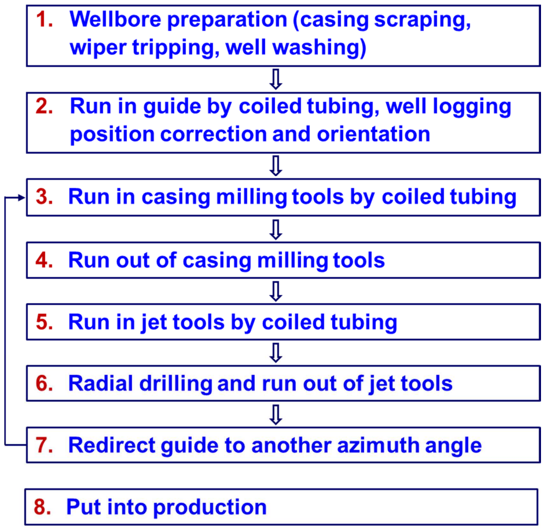

Figure 4. *Flow chart of radial drilling in Well T-1.*

Table 2. *Radial drilling operation parameters and results of Well T-1.*

No.	Milling pressure (MPa)	Milling time (min)	Jet pressure (MPa)	Jet time (min)	Footage (m)	Jet fluid
1st branch	5-8	60	30	30	48	Water
2nd branch	5-8	60	30-32	30	53	Acid
3rd branch	5-10	60	30-35	30	53	Acid
4th branch	5-8	65	30	30	45	Water
5th branch	5-10	50	30	30	48	Water
6th branch	5-8	60	30	30	56	Acid

After finishing radial drilling, the coiled tubing was used to conduct gas-lift production. The coiled tubing was run to the depth of 2700m. The initial daily production liquid was 16 m^3, including 12.57 m^3 oil and 3.43 m^3 water. The stimulation performance is great compared to zero oil production before the operation.

6.4. Complex Situation Analysis

1. Residual impurities found in the downhole motor rotor

During the motor maintenance after finishing milling the third hole and running out of the hole, the rotor was a little stuck. The interior of the rotor was found been clogged with powdery impurities. The motor rotor worked well after the first two holes milling. The rotor stuck was still observed during the maintenance of the motor after milling the fourth hole.

Causes analysis: (1) Hydrochloric acid with a concentration of 10% was used to drill the second hole and the third hole. The powdery impurities should be the reaction products by hydrochloric acid and the rust of the pump tank, high-pressure line and coiled tubing. Milling of the first and the second hole did not show the scenario. (2) Solid phase impurity accumulation in the operation using water.

The impact of powdery impurities on jetting is greater than milling. The impact on jetting restrains the length of the drilling footage. Hydrochloric acid jetting produced more impurities than water jetting, and was more likely to cause nozzle blockage.

2. Jet drilling length just reached expectations

In the process of jetting drilling, it is necessary to maintain a constant pump pressure. The downhole tool is more likely to have problems if the pump pressure changes during jetting (3-5 MPa or more, not operation intended). To ensure the safety, drilling operation should be stopped. The radial horizontal drilling footage failed to achieve the designed 100m target mainly because a significant pressure change was observed on the ground when the first branch was drilled to

45m. A fluctuation of 2-5MPa of the jetting pressure was observed during drilling the second and the third branches to the length of 50m. Considering the operation safety, the safety drilling footage of the hydraulic jet radial drilling technology in the carbonate reservoir was determined to be about 50m this time.

Causes analysis: (1) Carbonate reservoirs has serious heterogeneity, high Young's modulus and high hardness. The hose was subject to a great degree of curvature in the carbonate formation, which is likely to cause wear and damage to the hose. After the drilling was completed, significant wear was observed on the hose. (2) The liquid purity and the ground liquid filtration system did not meet the requirement, and the diameter of the nozzle is only 0.7mm, the nozzle was likely to be blocked at high pressure for a long time, making the jet drilling failed to move in a straight line. (3) The operation rate was small and cannot be accurately measured by the pump equipment. The coiled tubing equipment cannot measure the running speed, the measurement of hanging weight was not precise enough, and these all had a certain influence on the operation.

7. Conclusion

Radial drilling is a well completion technology with the function of stimulating production, which can make some reservoirs to increase production or injection, but it also has some shortcomings and not suitable for every well, it has certain requirements for both reservoir and wellbore conditions. The selection of well and layer is the key to economic benefits. Fine reservoir description is the basis for the successful implementation of radial horizontal wells. In selecting layers, as far as possible, homogeneous oil layers with good reservoir physical properties should be selected.

When running the guide, the depth and the azimuth angle should be calibrated to ensure that the horizontal wellbore enters the right reservoir and run along the designed well path. In the process of radial drilling, it must be ensured that the working fluid has no solid phase (the water quality should reach the standard of 200 mesh filtration). The filtration system must be installed in the pipeline system in order to achieve the requirements for water quality. Flow meters should be installed on the coiled tubing vehicle or pump truck so as to monitor the displacement during milling and jetting so that the working status of the downhole tools can be monitored in time.

In drilling carbonate reservoir, acid can increase the distance of jet drilling, but it is easy to produce impurities that affect the operation. The combination of equipment and tools can be optimized to increase the drilling footage. The heterogeneity, high Young's modulus and high hardness of the carbonate reservoir will accelerate the abrasion of the jetting hose, impacting the footage and treatment performance.

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