Research on Key Technologies of Abrasive Jet Micro-hole Sidetracking Used in Geothermal Drilling

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ABSTRACT

Complex fracture networks can promote the production of geothermal resources, but it's difficult to gain a wide range of complex fracture networks due to its heterogeneity and crustal stress distribution; multi-branch hydraulic fracturing can improve the shape of the fractures. Conventional sidetracking technology is too expensive to be applicated, while the radial jet drilling has the possibility of applying in this area, which is economic and environmentally friendly. However, the radial jet drilling technology can't break the granite with water jet only, so abrasive jet is introduced to the radial jet drilling technology to improve the rock breaking capacity. Due to the strong abrasive erosion, the conventional radical jet drilling technology has been improved such as the director, the feeding string, and the rock breaking nozzle. This paper proposed a sidetracking drilling technology based on the radial jet drilling, which aims to make an arc-shaped hole in the formation and extend a distance in the near horizontal section. The existing research difficulties of this technology are proposed, and many experiments are done to try to solve these difficulties. The main difficulties are the diverter, feeding pipe, and abrasive nozzle. The diverter is designed, processed and experimentally optimized. The feeding resistance test and deformation measurement are used to optimize the feeding pipe. The key of the abrasive jet nozzle is the impeller which directly affects the flow field shape, some flow field tests are done to obtain a more suitable nozzle structure. Finally, a set of downhole tool strings consists of feeding pipe; diverter and abrasive nozzle is suggested. The hydraulic sidetracking technology is dedicated to drilling multiple branches to increase the control area to improve the fracturing effect, ignoring the heterogeneity and crustal stress distribution.

1. INTRODUCTION

The radial drilling technology for micro-holes was first proposed by the Los Alamo National Laboratory in the United States in 1994. Subsequently, the US Department of Energy funded a number of micro-holes research projects to promote the commercial application of the technology and the adaptability of the horizontal micro-holes technology. It can improve the drilling efficiency and greatly reduce the drilling cost. It is an effective method to transform and increase the production of old wells. It has been fully applied in the United States, Canada, Argentina, Russia and other countries with good results[1-3]. China began to promote high-pressure water jet drilling technology in 1978, and conducted high-pressure hydraulic jet drilling tests in Liaohe Oilfield, Shengli Oilfield, Daqing Oilfield and other oilfields, which promoted the development of micro-hole radial horizontal well technology[4-6]. The China University of Petroleum's (Beijing) High Pressure Water Jet Laboratory has been committed to promoting the application of micro-hole radial horizontal well technology. Huang Zhongwei et al. Verified the feasibility of water-jet side drilling radial micro-well technology through field experiments. The technology has been systematically studied in terms of guiding devices, rock-breaking nozzles, energy consumption, etc[7-10].

Abrasive jets have been used in many fields such as cutting glass[11], perforation, casing cutting and drilling[12-14]. Sand perforation has been proven as having longer perforating distance and wider perforating hole, an abrasive jet is a more simple tool to cut the case without running into other mill tools, and abrasive jet technology has been applicated in many oil fields[15]. Nozzles are designed to match the technology as the key tool, and some numerical simulations has been done to analyze the properties of abrasive jetting[16, 17]. And some Abrasive jet rock breaking refers to a method of improving rock breaking efficiency by mixing calcium carbonate or quartz particles in high-pressure water, and accelerating the particles by high-speed water flow to make the particles hit the rock surface with certain kinetic energy. Thus, forming cracks, combined with water jet impact and water pavilion, rock breaking characteristics and experimental applications of abrasive jet have been studied by predecessors, and abrasive jet has been proven to be an efficient rock breaking method. The combination of abrasive jet and micro-hole radial drilling technology provides inspiration for the abrasive jet sidetracking technology proposed in this paper.

Radial drilling technology for small boreholes refers to the technique of drilling one or more horizontal micro-holes in the horizontal turning side within 0.3m, using high-pressure hose for feeding and pure hydraulic energy for rock breaking drilling, which is suitable for drilling in Softer rocks. For hard rock, Zhongwei Huang and others proposed the drilling method of rock breaking with hydraulic + abrasive, but the original key tools such as drilling micro-holes, pipe strings, nozzles, and diverter are no longer applicable. On the basis of drilling technology, a new type of sidetracking technology for micro-holes based on abrasive jet drilling is proposed.

2. ABRASIVE JET MICRO-HOLES SIDETRACKING TECHNOLOGY

Abrasive jet micro-hole sidetracking is mainly an advanced technology that can be used to drill one or more slant holes in thicker reservoirs. It is an advanced technology that integrates casing milling and formation drilling, and has the advantages of increasing the communication area of the oil well, improve production and recovery ratio, etc. The technology can also be used to drill multi-branch micro-hole in horizontal wells, forming fish bones, greatly increasing the control reserves of single wells and increasing the economic benefits of single well. Abrasive jet micro-hole sidetracking can overcome the current technical problems of pure hydraulic jet radial horizontal wells. Such as, the flexible tube is not wear-resistant and cannot be used for abrasive jets, the nozzle pure water

hydraulically can hardly break hard rock, and the self-promotion force is insufficient. And the technology is suitable for thick, soft to hard oil and gas reservoirs, and has good application prospects for fracture-cavity oil and gas reservoirs in Tahe Oilfield.
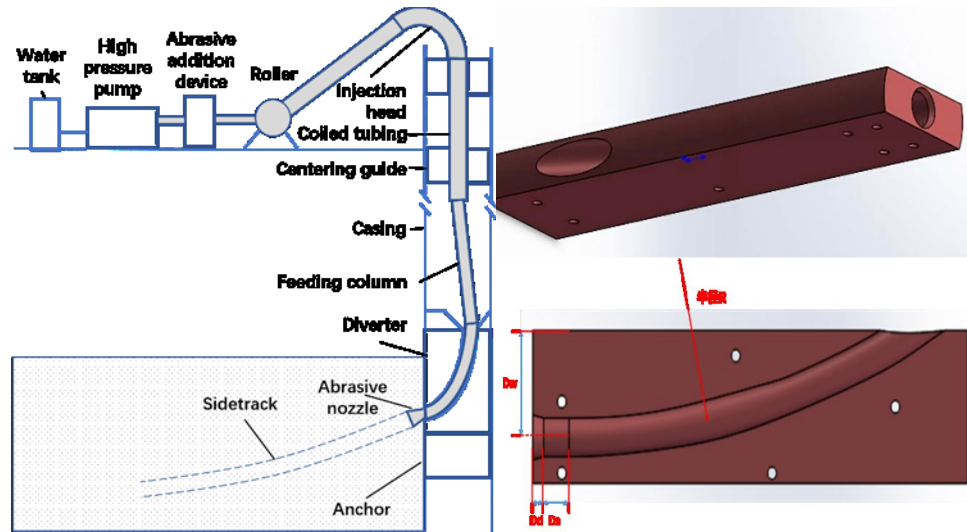

Fig. 1 Abrasive jet micro-hole sidetracking technology   Fig. 2 Diverter

The ground equipment of abrasive jet micro-hole sidetracking technology mainly consists of a coiled tubing machine, high-pressure pump, water tank for sand mixer (also named as abrasive addition device), etc. Downhole pipe string is composed of abrasive nozzles, feeding pipe and diverter, and various joints of anchoring devices shown as Fig.1, the specific processes are as follows:

1) Run the diverter anchoring device into the designated position of the formation through tubing transmission, fix the orientation, and anchor the diverter;

2) Connect the downhole tubing string to the tubing at the surface, and use the coiled tubing to feed the length, load display to determine whether the nozzle enters the diverter. When the tubing load suddenly shows a decrease, it indicates that the abrasive nozzle is in place;

3) Turn on the high-pressure pump on the ground, turn on the abrasive addition device after a period of stable operation, and finely control the feeding speed of the pipe string by the coiled tubing;

4) Pull out the drill string, pull out the diverter and the anchoring device, re-anchor the position and orientation, repeat the above process for the second experience side drilling;

5) Complete micro-hole sidetracking of predicted bearing prediction horizon.

Abrasive jet micro-hole sidetracking technology has the following advantages:

1) The ground equipment is simple and the operation is easy. The drilling mud includes water and quartz particles or calcium carbonate particles, which is are environmentally friendly;

2) It can be used for drilling in heterogeneous rock and interlayer formations, the effect of abrasive jet rock breaking is greatly better than ordinary hydraulic;

3) It can be realized that the integration of casing milling and drilling, reduces the number of lifting and lowering of the pipe strings, and saves money.

Abrasive jet microbore drilling technology is urgently needed to be resolved before field application. These problems such as diverter, rock breaking tool, and feeding pipe are related to the success of this process. Rigid pipe is different from flexible pipe, it has a higher yield strength ratio, is not easy to bend and has less elastic deformation, and easy plastic deformation so the structural parameters of the diverter need to be redesigned and processed; There is a small plastic deformation after sliding out the device, so that the feeding pipe can gradually turn to the horizontal after extending out of the diverter and extend a distance in the near horizontal section. The pipe also should be hard enough to withstand abrasive erosion; the key factors of abrasive jet nozzle such as, rock breaking efficiency and anti-wear ability, should also be considered when drilling.

3. DIVERTER
The SolidWorks software is used to model the three-dimensional track of the diverter. By stretching, scanning, and mirroring the 2D sketch of the diverter, a three-dimensional model of the steering gear track is generated. The whole diverter track is mainly composed of three parts: the guiding section, the straight pipe section and arc section shown as Fig.2. the guide section is used to lead the feeding pipe into the diverter and then into the formation; The straight pipe section is used to ensure that the feeding pipe enters the diverter and there is a straight section to avoid a large deformation when entering the arc section; The arc-shaped section is used to pull the

feeding pipe to change the exit angle. It is the main part of the diverter, and the turning radius of the arc R is the key image-like factor that affects the steering of the feeding pipe. In the design process of the diverter, for the same steering angle, it was found that the track width Dw affects the turning radius R. The larger the turning radius, the smaller the curvature and the greater the steering resistance, so the eccentric design is adopted.

Four diverters with steering angles of 20 °, 25 °, 30 °, and 40 ° are designed as shown in Fig.3, and four potentially feasible rigid pipes are selected for resistance test experiments. The experimental results are shown in Table 1. The Fig.4 shows that the max resistance and stable resistance all increase with the steering angle. When the beginning of the pipe slides out of the diverter, the passing resistance becomes stable, the resistance remaining consistent is called stable resistance. From Table 1, it can be concluded that when the steering angle of the diverter reaches up to 30 °, the resistance of the four kinds of pipes will exceed 8KN which is the top of experimental equipment range, and this resistance value is also a large resistance in field applications, so the steering gear angle is designed to be 25 °. The angle of the pipe after turning out of the diverter is about 19 °.
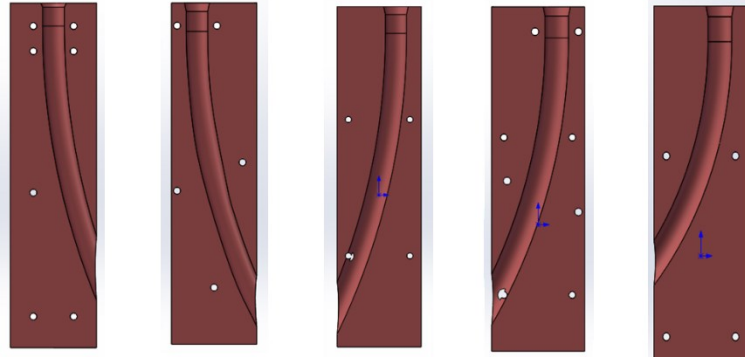

Fig. 3 Schematic diagram of 20 °, 25 °, 30 °, 40 °diverter

The pipe feeding inside the diverter always slides forward against the outer track, when the feeding pipe starts to be in force, it starts to contact the inside of the track and gradually deforms, at the same time, the feeding pipe starts to be stressed at the entrance. There will still be forces acting in three places shown as Fig.5 until the front of the feeding pipe exits from the diverter, and the acting position of the track force remains unchanged after exiting the diverter.
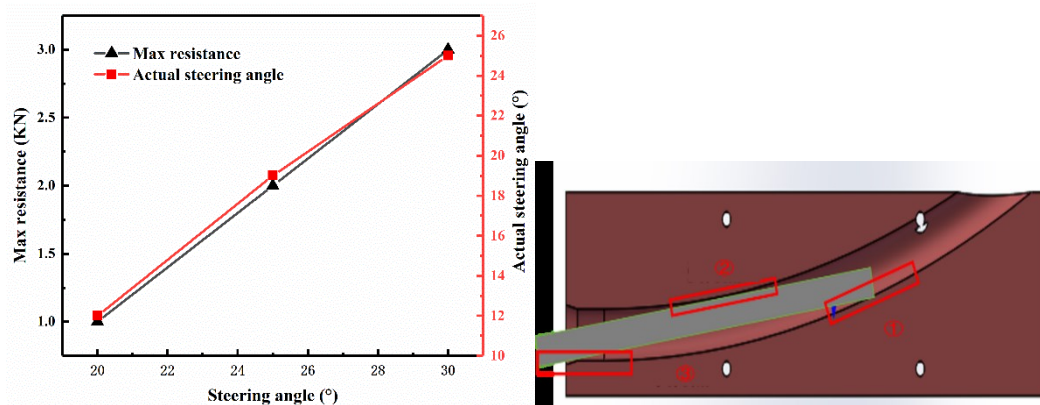

Fig.4 The relationship between steering angle and resistance Fig 5. Column force in the diverter position

4. FEEDING PIPE

It is necessary to consider whether the pipe is wear-resistant, and whether the yield strength of the pipe can match the 25 ° diverter when choosing the pipe material. Ideally, the feeding pipe has a small plastic deformation after passing through the diverter, and can maintain the plastic deformation for a certain distance after exiting the diverter. After reaching the horizontal state, it can continue to extend a distance in the near horizontal position. Many resistance force tests are done to choose the more suitable pipe, the author chooses beryllium copper, titanium alloy, pure titanium, pure aluminum, 304 stainless steel, 316 stainless steel and ordinary steel as the test pipe. The degree of deformation of the pipe string is measured and the length of the feeding pipe transferred into the horizontal section is calculated through resistance force testing.

4.1 The influence of pipe wall thickness on passing resistance

In this group of experiments, three materials of 304 stainless steel, 316 stainless steel, and pure titanium are selected as the test pipes. The outer diameter of the pipe is 25mm. The maximum passing resistance and smooth resistance are analyzed. As shown in Fig.6, the pipe passing resistance increases linearly with the wall thickness. According to the experimental results, among the three test pipes, pure titanium has the largest passing resistance, 304 stainless steel pipe is in the second place, and 316 stainless steel pipe has the smallest passing resistance. From the comparative analysis of maximum resistance and stable resistance, the resistance change is not obvious when the pipe string passes through the steering gear, which proves that the pipe is prone to plastic deformation.
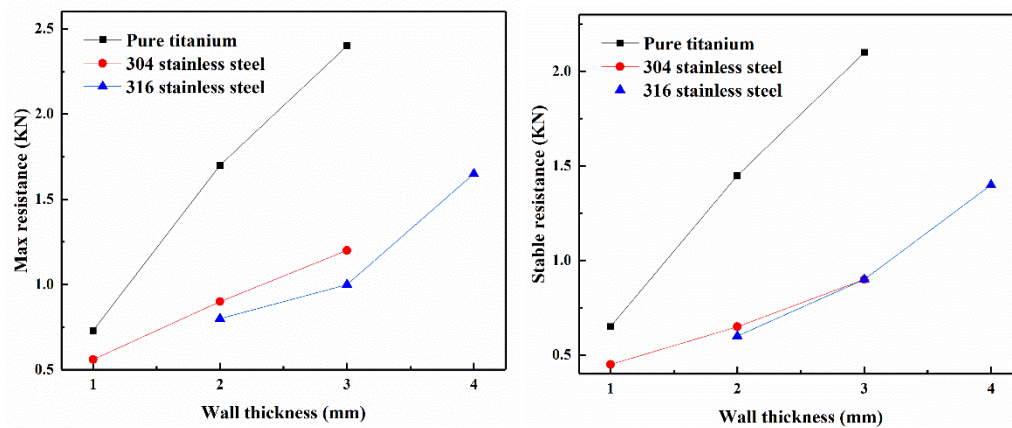

Fig.6 Relationship between wall thickness and resistance

4.2 The influence of pipe type on passing resistance and plastic deformation

In this paper, various pipes with a wall thickness of 3mm are selected for passing resistance test, and the extension to the horizontal distance is estimated. As Fig.7 shows, Titanium, 304 stainless steel, and 316 stainless steel have lower passing resistance, and the three materials also have the shorter distance extended to horizontal, and shorter distance can't meet the basic requirement. Correspondingly, titanium alloy and beryllium copper have the lowest degree of plastic deformation, and the other four pipes have higher plastic deformation. Except for ordinary steel, the other pipes show a positive correlation between plastic deformation and passing resistance.
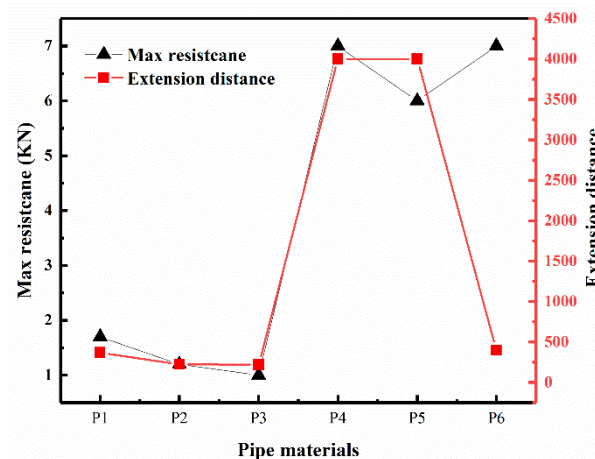

Fig.7 Influence of pipe materials on resistance and extension distance(P1 represents Pure titanium, P2 represents 304 stainless stee, P3 represents 316 stainless steel, P4 represents Copper, P5 represents Titanium alloy, P6 represents Ordinary steel)

4.3 Pipe selection and treatment

From the above discussion, we can see that pure aluminum, pure titanium, 304 stainless steel, 316 stainless steel, and ordinary steel as the feeding pipe, all undergo large plastic deformation and it is calculated that they will complete horizontal extend distance within 3m, and then start to upturn, which can't meet the requirements for pipe selection. Beryllium copper undergoes pure elastic deformation when passing through the diverter, and its density is relatively high, which does not meet the requirements for pipe selection. In summary, the preliminary selection of titanium alloy is used as the material of the material of feeding pipe.

At the same time, through comprehensive consideration of the passing resistance of feeding pipe, the resistance of the fluid through the pipe and the size of the diverter track, a 25mm outer diameter titanium alloy pipe string was finally selected as the outer diameter

of the formation. After selecting the feeding pipe, it is necessary to further determine the parameters such as the wall thickness of the pipe model. In this paper, two types of titanium named pipe 1 and pipe 2 are selected for the resistance test. The test results are shown in Table 2.

Titanium alloy type	Outer diameter/ （mm）	Wall thickness/ （mm）	Diverter degree/ （°）	Max resistance / （KN）	Minimum resistance/ （KN）	Actual steering angle / （°）	Extend to horizontal length / （m）
Pipe 1	33	3	25	7	2	18	2.5
Pipe 1	25	1.5	25	2	1.1	18	6.6
Pipe 2	25	3	25	2	1.1	18	3.6

Table 2 Test results of resistance of different types of titanium alloy pipes passing through the diverter

In field applications, it is required that the resistance of the pipe through the diverter is as low as possible. The resistance reduction test is based on the selected 25 ° eccentric diverter, the material treatments are chosen as the resistance reduction method. The experimental data shows a good effect, and it can ensure that the plastic deformation of the pipe after passing through the diverter is within the required range. In this paper, two treatment methods are selected, which are referred to as Treatment 1 and Treatment 2. Experimental results are shown in Table 3.

Titanium alloy type	Treatment method	Wall thickness/ （mm）	Max resistance / （KN）	Steady resistance/ （KN）	Actual steering angle / （°）	Angle after exit （°）
Pipe 1	Treatment 1	1.5	1.63	1.05	21	7
		2.0	2.51	1.54	18	7
	Treatment 2	1.5	1.60	1.41	18	0
		2.0	2.62	1.70	18	2

Table 3 Resistance test results of titanium alloy pipes treated by different treatment methods

From the experimental data, it is clear that Treatment 2 is more in line with the requirements. In summary, the titanium alloy named Pipe 1 treated by Treatment2 is selected as the feeding pipe, the outer diameter is 25 mm, and the wall thickness is 2 mm.

5. ABRASIVE JET NOZZLE

Abrasive jet drilling has high rock breaking efficiency, it is necessary to consider the reaming capacity, and the structure of the nozzle needs to be simpler to avoid some unnecessary problems. Conical nozzles can't generate a hole which can allow the feeding pipe to slide into; Multi-orifice nozzle can't generate a regular hole[10, 18], and the unregular hole can increase the resistance force which is not expected; The rotating multi-orifice can generate a regular hole by rotating the nozzle cap, while the structure is too complex to guarantee the normal working condition with abrasives. It is easy to find that the rotating bearing will become stuck when the particle flows into the gap, between the rotating bearing and the rotating outer wall. Straight swirl mixing nozzle has the advantages of straight jet and rotating jet[19, 20], can effectively expand the diameter of the hole, and has the potential to be used in drilling technology in tiny wellbore water. And its structural parameters, rock breaking characteristics, and fluency analysis have been analyzed and studied by previous scholars, and the fluid flow through the nozzle can generate a fan jetting field; the main structure is the impeller which directly influences the flow field. In this paper, the method of abrasive jet is used to break rock, and its hole-expanding performance is particularly important. This paper mainly studies the effect of impeller rotation angle on the jet hole-expanding performance.
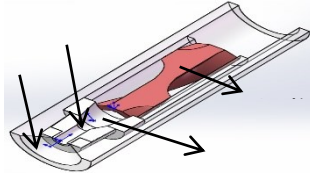
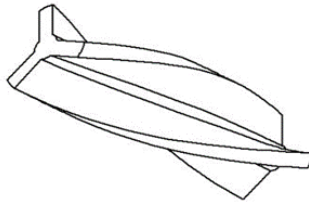**Fig. 8 Structure of straight swirling mixing nozzle**   **Fig. 9 3D printed impeller**

The abrasive jet nozzle selected in this paper is a straight swirling mixing nozzle. The geometric modeling using SOLIDWORKS software is shown in Fig.8. The impeller is printed using 3D printing technology as shown in Figure 6. The rotation angle of the impeller is set to be 180 °, 270 ° and 360 ° as shown in Fig.9. From the analysis of the experiment, the appropriate abrasive jet nozzle is selected, and the direct observation method is used for analysis. The flow field of three different nozzles are shown as Fig.10.

It can be seen from the figure that when the impeller rotation angle reaches 360 °, it has a good hole expansion effect and can meet the operation requirements. The degree of smooth dispersion is positively related to the impeller rotation angle. An abrasive jet nozzle with an impeller rotation angle greater than or equal to 360 ° is suggested.
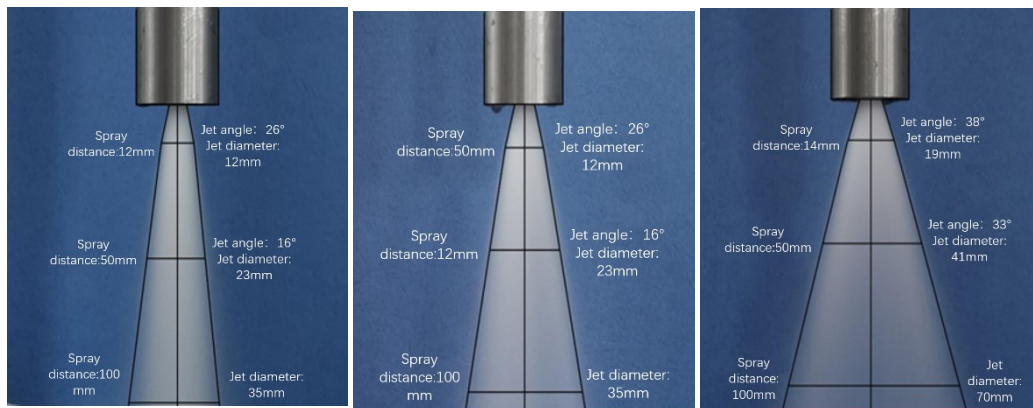

Figure 10. Flow field at different impeller rotation angles

6. CONCLUSION

This paper proposes a technology that can increase the production of harder reservoirs. Micro-hole sidetracking is performed with relatively simple ground equipment, and then one or more small branch holes are drilled, thereby increasing the control area of a single well and increasing production. The technology is also environmentally friendly and non-polluted. however, there are key issues such as steering, feeding pipe, and rock breaking efficiency that need to be resolved.

Aiming at the steering problem of abrasive jet microbore sidetracking technology, this paper develops an eccentric 25 ° diverter suitable for rigid pipe, that is set as the feeding pipe.

In view of the problem of abrasive jet micro-hole sidetracking technology feeding, and the use of abrasive jets, the author recommends using rigid tubes as the feeding pipe, and after experimentation, the titanium alloy named Pipe 1 with treatment method 2 is finally recommended. The outer diameter is 25mm. The wall thickness is 2mm, and the maximum resistance through the diverter is 2KN.

Based on the previous research on nozzles and abrasive jets, the author selects straight swirling mixing jet nozzles, and conducts experimental research on the problem of hole expansion. Finally, a direct-selection mixed nozzle with an impeller rotation angle of 360 ° is recommended as the rock-breaking nozzle of this process.

Above all, a set of technologies suitable for drilling small holes in hot dry rocks are basically presented, aiming to drill multi-branches to improve the fracturing effect ignoring the heterogeneity and crustal stress distribution, when the technology is used in geothermal drilling and fracturing.

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APPENDIX

Pipe	Diverter degree/ （°）	Passability (yes or no)	Actual steering angle / （°）	Angle after exit / （°）	Max resistance / （KN）	Minimum resistance/ （KN）
Copper	20	yes	12	0	3	1
	25	yes	19	0	7	2
	30	no	——	——	——	——
	40	no	——	——	——	——
	90	no	——	——	——	——
Titanium alloy	20	yes	12	0	3	1
	25	yes	19	3	6	2

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	30	no	——	——	——	——
	40	no	——	——	——	——
	90	no	——	——	——	——
Ordinary steel pipe (17mm outer diameter)	20	yes	12	6	1	0.5
	25	yes	19	12	2	0.8
	30	yes	25	18	3	1
Ordinary steel pipe (1 inch outer diameter)	20	yes	12	——	6	2
	25	yes	19	12°	7	2
	30	no	——	——	——	——

Table 1. Results of steering angle optimization experiment