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Research and Application of Multi-Technology of Air Underbalanced Geothermal Drilling

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ABSTRACT

The underbalanced drilling technology is applied to geothermal Wells with high rate of penetration and reservoir protection. After nearly 10 years of continuous research on the underbalanced drilling technology in deep geothermal wells, the author team summarizes a series of empirical parameters, practices, and measures which are of promoting significance to the development of the industry. This paper will comprehensively introduce the air pressure, air displacement, weight on bit, revolution per minute(rpm), and other drilling parameters applicable to the deep well underbalanced drilling process to guide the air compression equipment and bit selection; Then, elaborate the scheme to deal with large water inflow and formation collapse. Further, disclose the reasonable design of a well structure, correct handling of abnormal conditions, and avoid downhole accidents. Through the publication of this paper, it is expected to lead and drive the application of underbalanced drilling technology in deep Wells.

1. INTRODUCTION

Geothermal reservoirs are often closely associated with geological formations and thus highly fractured. The occurrence of large-scale drilling fluids leaks during geothermal well drilling is the most intractable and costly issue in geothermal drilling, Vivas, C., et al (2020). The reasons include direct loss of drilling fluids and lost circulation materials due to drilling fluids leakage, dealing with drilling fluids leakage greatly increases the non-drilling time, Visser, C. F. et al (2018). Drilling fluids leakage triggers drilling accidents such as downhole stuck or even well blowouts, which further increases the non-drilling time, Magzoub, M. et al (2021). Finally, and most importantly, drilling fluids leakage carries cutting and other solid phase particles into and injures the geothermal reservoir, clogging fractures and reducing production well capacity, Lu L. et al (2009). Moreover, fracture leakage is often vicious, and when the fractures are ⩾1-3 mm, the leakage is difficult to deal with using plugging measures, Sun J. et al (2021), Li Y. et al (2019).

Underbalanced drilling always maintains the bottom-hole pressure lower than the pore pressure of the reservoir, which allows fluids in the reservoir pores to continuously infiltrate or surge into the wellbore, thus avoiding damage to the reservoir, William, C. L. et al (2012). The drilling fluids used in underbalanced drilling include conventional drilling fluids, aerated drilling fluids, stable foam drilling fluids, unstable foam (fog) fluids, and gas drilling fluids such as air. Among them, for air and another gas drilling, the drill bit can be selected from cone bits, PDC bits and air DTH hammers, etc. When the water output of the formation is large, aerated drilling fluids and foam fluid are required.

2. APPLICATION OF UNDERBALANCED DRILLING TECHNOLOGY IN GEOTHERMAL WELLS

2.1 Air Drilling

Air drilling is the use of air as circulating fluids in the drilling of geothermal wells. It is the ultimate process of moving from high-density drilling fluids to low-density drilling fluids. Proper air drilling techniques can increase the rate of penetration, extend bit life, better control through the leakage zone, and improve the efficiency of completion techniques.

When drilling a well in a magmatic formation in Kenya, due to the serious leakage of conventional drilling fluids, the manager switched to air foam drilling technology, which solved a series of difficulties in leakage, high temperature, and low rate of penetration, and not only protected the reservoir, but also shortened the drilling cycle, Lu L. et al (2009).

During the drilling of the Yuanba 121H well, SINOPEC used foam drilling and pure air drilling in the first spud and second spud section, respectively, and reached average rates of penetration of 3.72m/h and 9.41m/h, which were 4.9 and 6.0 times higher than conventional drilling techniques, respectively, and used liquid-phase underbalanced drilling in the third spud section at an average speed of 1.12m/h, which was 1.2 times of the conventional drilling fluids drilling rate. The results show that air drilling can greatly improve the rate of penetration and reduce the incidence of downhole accidents, Zhang H. et al (2014).

2.2 Aerated Fluid Drilling

When aerated fluids are used as the circulation medium, the bottom-hole pressure can be changed by changing the gas volume, which is effective in dealing with the leaking formation.

In the 1980s, aerated mud/water drilling was conducted in the Mak-Ban, Tiwi, and Southern Negros geothermal fields in the Philippines. The advantages are (1) saving time in drilling waiting for water; (2) the ability to monitor cuttings during prolonged leakage; and (3) a cleaner borehole compared to blind drilling, where cuttings tend to return to the formation and may clog the producing layer above the bit.

Several directional wells drilled in the Tres Virgenes geothermal field were drilled with underbalanced fluids with 56% or at least similar drilling efficiency and 20% to 34% lower costs than mud drilling, Jaimes-Maldonado. et al (2006).

The drilling cycle and comprehensive drilling cost of the Xiong'an New Area Rongdong Geothermal 5-1X well increased significantly due to severe leakage and ineffective conventional leak plugging, and the aerated fluids technology was used to achieve significant leak prevention and plugging effects, and drilling was achieved in a short time and at low cost. According to the theory of hydrostatic pressure control zone and friction control zone in gas-liquid two-phase drilling, Liu Yibin et al. pointed out that the bottom-hole pressure tends to decrease and then increase as the gas injection volume increases from 10 m^3/min to 80 m^3/min, Liu Y. et al (2019).

2.3 Air-lift Reverse Circulation Drilling

Airlift reverse circulation drilling is a drilling process to lower the fluid's density inside the drilling string by injecting compressed air into the string, thus changing the differential pressure between the fluid string inside and outside the string, and achieving the inflow of drilling fluids from the outer annulus of the string and the return of fluid from the inner annulus of the string, driven by the differential pressure between the fluid string inside and outside the string, Xu L. et al (2009) .

The Beijing Jingre 164# well was drilled with air-lift reverse circulation from 2760 to 3512m by improving the double-wall drilling pipes, and the rate of penetration was nearly 1.9 times that of the mud positive circulation, with an average pure rate of penetration of about 1.32m/h and a maximum rate of penetration of 3.12m/h, Wang Y. et al (2009).

During the construction of geothermal wells in Dalian Jiaoliu Island, air-lift reverse circulation technology was adopted in the 1306-2200m well section, and good results were achieved in the construction of leaky formations, including reservoir protection, cost reduction, and efficiency improvement, and high-quality well completion, which generated significant economic benefits.

Well D19 in Xiong'an New Area, by improving water intake and other measures, air-lift reverse circulation drilling into complex fractured formations was successful, laying the foundation for the popular application of air-lift reverse circulation drilling in complex formations, Li Y. et al (2019).

3. GAS-LIQUID TWO-PHASE FLOW CUTTING-CARRYING CAPACITY

When no gas is injected, if the fresh water can carry the cuttings independently, the minimum return velocity of fresh water should be not less than the critical velocity of cuttings carried by fresh water and the settling velocity of the cuttings particles, William, C. L. et al (2012). For positive circulation operation, the settling velocity of cuttings particles is estimated in the annulus section with the largest cross-sectional area, and the settling velocity depends on the actual flow of fluid around the cuttings particles in the annulus, i.e., laminar, transition, and turbulent flow. Usually, assuming that the fluid around the cuttings particle is laminar flow, the cuttings settling velocity is calculated using equation (3) and then use equation (5) to calculate the Reynolds number. If the Reynolds number obtained is less than 3, the assumption is correct; if the Reynolds number obtained is greater than 3, the assumption is wrong, and the fluid flow type is transition flow or turbulent flow, and equation (4) should be used to calculate the cuttings settling velocity.

$$v_f \geq v_c + v_t \tag{1}$$

$$v_c = \frac{\kappa}{3600C} \tag{2}$$

$$v_{tl} = \left(\frac{D_c^2}{18\mu}\right)(\gamma_s - \gamma_f) \tag{3}$$

$$\mathrm{v_{tt}} = \left[\frac{4}{3}\left(\frac{\gamma_s - \gamma_f}{\gamma_f}\right)\frac{gD_c}{f_p}\right]^{0.5} \tag{4}$$

$$\mathrm{N}_{Rc} = \frac{D_c v_t}{\mathcal{V}} \tag{5}$$

where v_f-the minimum return velocity of fresh water in annulus, m/s; v_c-critical velocity of fresh water carrying cuttings, m/s; v_t-setting velocity of cuttings particles, m/s; κ-the instantaneous rate of penetration, m/h; C-solid concentration in annular space, usually assumed to be 0.04; v_{tl}-settling velocity of cuttings particles in circumferential laminar flow, m/s; D_c-diameter of cuttings particles, m; γ_s-gravity of cuttings particles, N/m^3;γ_f-water weight, N/m^3; μ -Absolute viscosity of fresh water, N·s/m^2 ; v_{tt}-settling velocity of cuttings particles in annular transition flow and turbulent flow, m/s; g- acceleration of gravity, 9.81m/s^2;f_p-the friction coefficient of solid cuttings particles. $\mathcal{V}$ -Motion viscosity of the circulating fluid, m^2/s.

In Yichun geothermal well drilling process, air-cones technology to cope with the stratum minimum surge is 100.4m^3/h, the maximum surge is 204.6m^3/h. If only considering the cuttings carrying capacity of fresh water, the diameter of the maximum cutting that can be carried by different water volumes is shown in Table 1.

Table 1. Different stratigraphic surges can carry the diameter of the cuttings

Formation water inflow (m³/h)	Maximum annular cross-sectional area (㎡)	Rate of penetration (m/h)	Maximum cuttings diameter that can be carried by fresh water (mm)	Diameter of cuttings collected at the wellhead after gas injection (mm)
100.4	0.0433	4.43	6.3	Maximum diameter 9mm, average diameter 4mm
126.0	0.0433	3.85	10.3	Maximum diameter 25mm, average diameter 5mm
170.0	0.0433	6.82	23.0	Maximum diameter 30mm, average diameter 4mm
204.6	0.0433	4.03	34.5	Maximum diameter 30mm, average diameter 5mm

From the above table, we can see that: the cuttings removal capacity is mainly determined by the minimum return velocity of the formation inflow water in the annulus, and the injection of air will make the cuttings carrying capacity of fresh water further enhanced, and the larger the air injection volume, the stronger the cuttings carrying capacity.

4. APPLICATION OF MULTI-TECHNOLOGY OF AIR UNDERBALANCED DRILLING IN VERY LARGE SURGE GEOTHERMAL WELLS

This section introduces some process measures to achieve underbalanced drilling using air and formation water during the drilling of geothermal wells in Yichun, Jiangxi Province and some parameters for using air to reduce wellbore pressure to drill into oversized gushing formations, coping with a maximum formation output of 204 m³/h.

4.1 Geothermal well project overview

4.1.1 Geological overview

The project is located in Nanmiao Town, Yuanzhou District, Yichun City, Jiangxi Province. The project is located in the south-central part of the Pingxiang-Gao'an concave fold fracture bundle, and the Pingxiang-Guangfeng fracture is close to the south. The sedimentary strata exposed in the work area and its nearby areas are mainly the Lechangxia Group (Z2b-l), which is widely distributed in the east and west of the work area, and a small number of irregular stripes in the mixed rock belt in the south-east of the work area. In the southwest and south of the site, there is a wide range of striped migmatite belts, which were formed in the late Garidonian cycle. There is some migmatite that is not yet granite with shallow accounts, and they are not distinct from granite and are mostly in a transitional form. The main lithology encountered in this geothermal well is this migmatite, and the heat and water control structure is also developed in this formation, which is the target layer for this geothermal resource development.

4.1.2 Wellbore structure

The designed depth of the hot spring well is 1500 m, the designed water output is 1500 m³/d, the designed water output temperature is 40℃, the drilling encountered stratum is mainly bedrock, the designed water extraction section is 1200-1500m, and the total design period is 3 months. According to the *Technical specification for geothermal well drilling*(DZ/T 0260-2014), based on the target depth, well diameter of pump chamber section and completion, stratigraphic sequence, reservoir, and other conditions, combined with the actual site, the wellbore structure is shown in Figure 1.

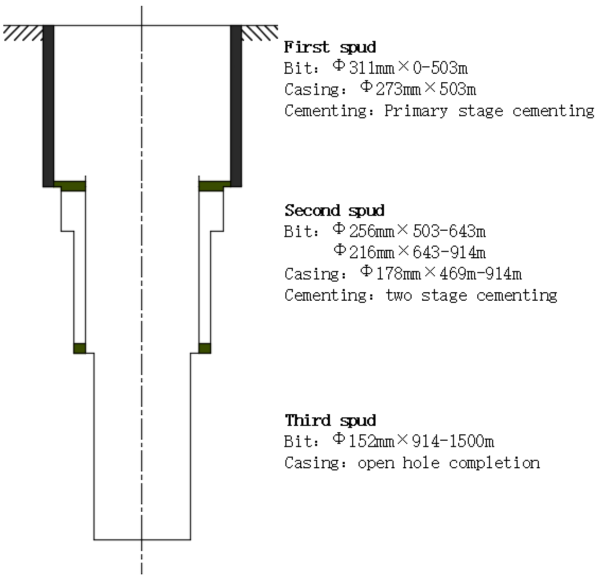

Figure 1: Wellbore structure.

4.2 Application of Multi-Technology of Air Underbalanced Drilling with Very Large Water Surges

4.2.1 Air DTH Hammer Technology

Drilling process: The drill bit diameter φ311mm was used in the 0-503m section. As the well depth increased, the water influx in the formation increased, and the difficulty of drilling with the air DTH hammer increased. After the water isolation, the drilling was continued by air DTH hammer with φ254mm bit diameter to 543m, when the new water-bearing formation was encountered and continued to drill for 3m to 547m, the formation water influx reached 68m³/h. A supercharger which a rated discharge pressure of 12MPa was called and three air compressors were connected in series for gas supply, and the gas injection volume was 90Nm³/min. At a well depth of 641.89m, the supercharger was faulty and drilling was stopped. Later, two superchargers unit which rated discharge pressure of 7 MPa were called to supply air in parallel, but under the large water influx condition, several attempts to drill with the air DTH hammer encountered the problem that the supercharger discharge pressure was too high and stopped working. It was decided to stop drilling with air DTH hammer technology.

Drilling parameters: A reasonable choice of air volume, revolution per minute, weight on bit, torque, and other drilling parameters can effectively improve the rate of penetration, Table 2 describes the drilling parameters and rate of penetration at different water surges.

Table 2. Air submersible hammer drilling parameters

Well depth (m)	weight on bit (t)	revolution per minute (rpm)	Torque (kN·m)	Air volume (Nm³/min)	Discharge pressure (MPa)		Water temperature (℃)	Formation water inflow (m³/h)	Rate of penetration (m/h)
					Low	High			
547.27-572.35	1.5	40	8-9	90	5.0	7.0	21	68.8	15.84
572.35-584.17	1.5	40	8-9	90	5.1	7.5	21	80.9	19.16
584.17-601.91	1.5	40	8-9	90	5.2	7.7	23	91.1	23.64
601.91-619.37	1.5	40	8-9	90	5.5	7.7	23	100.4	18.70
619.37-631.53	1.5	40	8-9	90	5.5	7.7	23	110.2	12.57
631.53-641.89	1.5	40	8-9	90	5.7	7.8	24	119.9	10.53

Rate of penetration analysis: 547.27m-641.89m well section, total footage of 94.62m, reciprocating time of 5.5h, average rate of penetration of 17.20m/h, maximum rate of penetration of 23.64m/h, responding to a maximum surge of 120m³/h.

4.2.2 Air-cone Technology

Due to the large amount of water in the formation, the rated discharge pressure of the supercharger was low, and the air DTH hammer could not reach the normal working back pressure, so the air DTH drilling was used instead, with air and formation water as the circulating medium, and the diameter of the tooth wheel bit was φ216mm.

Table 3. Air-cone drilling parameters

Well depth (m)	weight on bit (t)	revolution per minute (rpm)	Torque (kN·m)	Air volume (Nm³/min)	Discharge pressure (MPa)		Water temperature (℃)	Formation water inflow (m³/h)	Rate of penetration (m/h)
					Low	High			
547.27-572.35	1.5	40	8-9	90	5.0	7.0	21	68.8	15.84
572.35-584.17	1.5	40	8-9	90	5.1	7.5	21	80.9	19.16
584.17-601.91	1.5	40	8-9	90	5.2	7.7	23	91.1	23.64
601.91-619.37	1.5	40	8-9	90	5.5	7.7	23	100.4	18.70

Rate of penetration analysis: 643.39-914.07m well section, total footage 270.68m, reciprocating time 64.0h, average rate of penetration 4.22m/h, maximum rate of penetration 8.33m/h, responding to maximum water surge 204m³/h.

4.2.3 Air-filled liquid technology

Due to the great amount of water surging from the formation and the static water level being only 9m below ground, the pressure at the bottom of the well will exceed the rated working pressure of the supercharge in a short time after lifting water and stopping gas, and each time trip faces the problem of long operating time and high cost, and the water surging tends to increase further, and the permitted pick-up time of making up a joint is getting shorter and shorter. If the supercharge with higher-rated discharge pressure is replaced, the cost will rise rapidly. Therefore, the construction of air-cone drilling technology ended at the well depth of 914.07m, and φ178mm petroleum casing pipe was run, and the construction was carried out by air-filled fluid technology after shoe and cap cementing, with a cone bit diameter of φ152mm.

Drilling process: The pumping volume of the mud pump was about 60m³/h, and the gas injection volume was 5 Nm³/min. The gas injection volume was small, the gas-water two-phase flow injected at the wellhead was denser, and the pressure at the bottom of the well was higher than the pore pressure of the formation, so the water returned was only about 27m³/h. The cuttings were fine, with a maximum diameter of 2.5mm, and there was no sinking sand at the bottom. With the increase of well depth, the leakage was gradually reduced, and when the wellhead was drilled to 1271m, the amount of water returned to the wellhead was about 51m³/h, and it was presumed that many cuttings had entered the formation.

Rate of penetration analysis: 914.07m-1279.49m well section, 365.42m of total footage, 175.9h of reciprocating time, 2.08m/h of average rate of penetration and 5.72m/h of maximum rate of penetration.

4.2.4 Fresh water blind drilling

In order to further reduce costs, when drilling to 1279.49m, the mud pump with a pumping capacity of about 88m³/h was replaced and fresh water blind drilling was adopted. The fresh water blind drilling had a greater impact on the formation water output, and the wellhead return water gradually increased from 28m³/h to about 60m³/h.

Rate of penetration analysis: 1279.49m-1500.00m well section, total footage 220.51m, reciprocating time 140.0h, average rate of penetration of 1.57m/h, maximum rate of penetration 2.29m/h.

4.3 Effectiveness of applying multi-technology of air underbalanced drilling

Through the construction of the Yichun geothermal well, the economic benefits achieved by the multi-process air underbalanced drilling technology are obvious, with obvious advantages in protecting the reservoir and coping with the oversized formation water surge, and handling the complex situation downhole. It is outstanding in the following aspects.

- The application of multi-technology of air underbalanced drilling reduces wellbore pressure and reduces or even eliminates damage to the reservoir during drilling.
- The air injection reduces the confining pressure on the cutting surface of the bit, which is conducive to breaking the rock and improving the drilling efficiency.
- Through the rational selection of different types of air drilling technologies, a breakthrough was achieved in the drilling of geothermal wells with large water surges, and geothermal reservoirs with water surges of up to 204m³/hour were successfully drilled.
- It is highly adaptable and can cope with a variety of working conditions, which greatly improves drilling efficiency and drilling benefits.

5. CONCLUSION

Geothermal wells are generally drilled in bedrock formations, where formation leakage mostly occurs. By using multi-technology of air underbalanced drilling to reduce wellbore pressure, the damage to geothermal reservoirs can be reduced or even eliminated, and the reasonable selection of different types of air drilling technology can improve the rate of penetration, effectively respond to various complex formations, and reduce the incidence of downhole accidents.

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