An Axial and Torsional Percussion Hammer with Considerable Potential to Increase the Drilling Speed of High-Temperature Geothermal Wells

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Abstract. Geothermal energy is a kind of green and sustainable energy and an essential alternative energy in the future. Improving the drilling speed of geothermal wells is helpful for the efficient exploitation of geothermal resources. Axial & Torsional Percussion Hammer (ATPH) was proposed in this paper for drilling enhancement. ATPH can convert the kinetic energy of the drilling fluid to percussion load, and improve the rock-breaking efficiency of the bit. Because of its mechanical seal design, it can operate efficiently at temperatures over 200 °C, which proves that it can be used in geothermal wells. The large eddy simulation (LES) method is chosen to calculate the percussion load characteristics of the ATPH oscillator, including its main frequency and amplitude. In the field drilling experiments of two high-temperature wells, ATPH showed better ROP enhancement ability and longer working life than PDM. In the well interval drilled by ATPH, the maximum temperature at the well bottom reached 202.54 °C.

1. Introduction

In recent years, with the massive consumption of traditional resources such as oil, gas and coal and the requirement of environmental protection, the efficient development and utilization of new green energy have been paid attention to all over the world [1]. The geothermal resource is a kind of renewable resource with considerable reserves, wide distribution, green and clean, and has a broad energy recovery prospect [2]. In the process of geothermal development, the drilling rate of penetration (ROP) enhancement technology can decrease the construction period and improve development efficiency. Different from conventional oil and gas well drilling, due to the sizeable geothermal gradient and high bottom-hole temperature in geothermal wells, it is easy to accelerate the erosion and wear of bottom drilling tools and seal failure, which seriously affects the life of tools. Therefore, geothermal drilling puts forward higher requirements for the high-temperature resistance performance of well bottom ROP enhancement drilling tools [3, 4].

Percussion hammer is one of the most widely used in well drilling ROP enhancement [5]. It can convert part of the kinetic energy of the drilling fluid into impact load, which can be transferred to the bit to improve rock breaking efficiency and ROP. German W. Bush first obtained the patent of percussion drilling technology in 1887. With the vigorous development of the modern oil drilling industry, relevant scholars proposed a variety of percussion hammers for well drilling ROP...
enhancement. For example, Tork-Buster, developed by Ulterra of Canada, achieved excellent performance while drilling hard formation in Yuanba gas field of Sichuan province and other oil blocks in Xinjiang province [6, 7]. Although the percussion hammers have made noteworthy ROP improvement in the conventional oil and gas drilling, there is a lack of research on the development and application of percussion hammers for high-temperature geothermal drilling. In this paper, from the perspective of geothermal well drilling ROP enhancement, a new type of percussion hammer with high-temperature stability is proposed. This hammer has a reliable and straightforward structure. It can generate high-frequency impact loads in both axial and torsional directions, thereby improving rock breaking efficiency and reducing bit stick-slip and wear. Field tests show that the tool can typically work under the conditions of a geothermal gradient of 2.91°C/100m and bottom-hole temperature of 204.14 °C, and the ROP improved obviously.

2. Working Mechanism for Axial & Torsional Percussion Hammer

As shown in figure 1, ATPH is composed of a nozzle, oscillator, rotary valve, shell, anvil, and driving joint. ATPH adopts the mechanical seal, which can resist high temperature and avoid sealing failure caused by rubber aging under high temperature well bottom. Therefore, ATPH can be used for high-temperature geothermal well drilling. The adapter sub is connected to drilling string or positive displacement motor (PDM), and the bottom driving-joint is connected to bit. Firstly, the drilling fluid flows into ATPH from the drill pipe. After passing through the nozzle, the velocity of the drilling fluid increases dramatically and injects into the oscillator, thus generating a strong fluid self-oscillation [8].

Figure 1. ATPH structure schematic drawing.

ATPH is designed with a two-stage oscillator, which helps enhance the self-oscillation of the drilling fluid and generate violent pressure fluctuations within the oscillator. When the fluctuating pressure passes through the rotary valve, it is converted into a high-frequency percussion load both in axial and torsional directions, and the axial and torsional percussion load is then transferred to the bit through the bottom driving joint. In this way, the bit can break rocks stably and efficiently with the aid of high-frequency percussive loads [9].

3. Numerical Simulation of Two-Stage Oscillator

The fluid in ATPH oscillator is typical turbulence flow, which needs to be calculated by turbulence model. Among the main turbulence models, LES method can not only obtain the mesoscopic structure and image of turbulence, but also save more computational resources. Therefore, the LES model is adopted in this paper to study the characteristics of the ATPH percussion load. ATPH fluid domain and meshing results are shown in figure 2. The velocity boundary is applied to the inlet, the drilling fluid flow is 20 L/s, and the density is 1.2 g/cm³ [10].

Figure 3 shows the resultant percussion load generated by the self-excited oscillator, whose mean value can be calculated as 8.71 kN. The Fourier transform of the resultant percussion load yields the amplitude-frequency figure shown in figure 4 after 0.1 s in the plot section of stable oscillation of the flow field. The dominant frequency of the resultant percussion load of the ATPH oscillator is 801Hz, and the corresponding amplitude is 25.67 kN. The rotary valve decompositions the resultant percussion load into axial percussion load and torsional percussion load, which are applied to the bit simultaneously through the bottom driving joint. The structure angle of the rotary valve is 50°, which ensures that the ratio of axial percussion load and torsional percussion load equals tan(50°). When the
resultant percussion load is distributed according to this ratio, the maximum volume of rock failure and the highest rate of unit failure occur [11].

Figure 2. The fluid domain and meshing result of ATPH.

Figure 3. Simulation result of oscillator percussion load.

Figure 4. Amplitude-frequency figure of oscillator percussion load.

4. Field Test
ATPH ROP enhancement filed tests have been successfully carried out in two high-temperature wells drilling. The test wells are located in Langfang, Hebei Province, China. Before ATPH tests, PDM was used in both wells. The rubber seal inside the PDM resulted in a short downhole life of PDM. There is a lack of high-temperature well drilling ROP enhancement methods in this block. ATPH was tested at the interval of 6307-6455 m in well AT4, and 4831-5090 m section in well AT5. During the experiment, the surface temperature was 14.7℃, and the geothermal gradient of the test block was 2.91℃/100m. Therefore, the bottom-hole temperature was over 200℃ during ATPH working. The results entirely presented the broad application prospect of ATPH in high-temperature geothermal well drilling ROP improvement.

(1) Test well AT4
Detailed parameters of the ATPH test in well AT4 are illustrated in table 1. The drilling footage of ATPH reached 184 m in one trip, and drilled formations include group Xuzhuang, Mantou and Maozhuang with a maximum temperature of 202.54 ℃ and an average ROP of 3.38 m/h. Due to the downhole high temperature, the sealing rubber fell off only 14.5 hours after PDM tripped in the well, and then tripped PDM out of the well. ROP comparison between PDM and ATPH drilling well sections is shown in figure 5. Although the ROP of PDM drilling is not significantly different from
that of ATPH drilling, compared with PDM, ATPH increased the single trip footage by 236%, as shown in figure 6.

Table 1. ROP for different lithology of well AT 4.

| Formation        | Well interval (m) | Footage (m) | WOB (kN) | RPM (r·min⁻¹) | Drilling time (h) | ROP (m·h⁻¹) |
|------------------|-------------------|-------------|----------|---------------|------------------|-------------|
| Group XZ         | 6307~6325         | 18          | 50~80    | 35~50         | 5.26             | 3.42        |
| Group MT–MZ      | 6325~6455         | 130         | 80       | 50            | 38.52            | 3.37        |

Figure 5. Average ROP of ATPH drilling section and PDM drilling section in well AT4.

Figure 6. Drilling footage in one trip of PDM drilling and ATPH drilling well interval.

(2) Test well AT5
In the ATPH drilling section, the maximum temperature in the well bottom is 162.82 °C. Based on the experiment results of well AT4, the drilling parameters for well AT5 were optimized and adjusted, as shown in table 2, aiming at improving the ROP of ATPH further. The main measures included improving the weight on bit (WOB) and increasing rotate speed. Average ROP of ATPH drilling section and PDM drilling section in well AT5 is shown in figure 7. The ROP of the ATPH drilling section was 4.35 m/h in single trip footage of 259 m, which increased by 102.5% and 61.9% compared with that of the previous PDM drilling section, respectively. Besides, the ROP of three other wells in the same block is listed in table 3. The results show that ATPH has a better ROP enhancement effect than PDM in high-temperature well drilling.

Table 2. ROP for different lithology of well AT5.

| Formation           | Well interval (m) | Footage (m) | WOB (kN) | RPM (r·min⁻¹) | Drilling time (h) | ROP (m·h⁻¹) |
|---------------------|-------------------|-------------|----------|---------------|------------------|-------------|
| Group Kongdian      | 4831~4841         | 10          | 80~120   | 60~80         | 2.97             | 3.37        |
| Carboniferous and   | 4841~5090         | 249         | 80~140   | 80            | 56.55            | 4.40        |
| Permian             |                   |             |          |               |                  |             |
Figure 7. Average ROP of ATPH drilling section and PDM drilling section in well AT5.

Table 3. ROP comparison of test well AT5 with offset wells in the same block.

| Well No. | Bit          | Tools | Well interval (m) | Footage (m) | ROP (m·h⁻¹) | ROP improved (%) | Footage improved (%) |
|----------|--------------|-------|-------------------|-------------|-------------|------------------|---------------------|
| AT 5     | T1655AUG     | ATPH  | 4831~5090         | 259         | 4.35        |                  |                     |
|          | T1665DG      | PDM   | 4196~4433         | 237         | 1.70        | 155.8            | 9.3                 |
| AT 2     | T1665DG      | PDM   | 4433~4474         | 41          | 1.42        | 206.0            | 531.7               |
|          | T1665DG      | PDM   | 4483~4651         | 168         | 3.33        | 30.8             | 54.2                |
|          | T1665DG      | PDM   | 4651~4874         | 223         | 1.68        | 158.8            | 16.1                |
| AT 3     | M1655DG      | PDM   | 4313~4791         | 478         | 4.93        | -11.7            | -45.8               |
| AT 4     | T1665B       | PDM   | 4480~4635         | 155         | 1.81        | 140.4            | 67.1                |
|          | T1655AUG     | PDM   | 4635~4813         | 178         | 4.92        | -11.6            | 45.5                |
| Average improved | |       |                   |             |             | 57.5             | 48.2                |

5. Conclusion
ATPH for high-temperature geothermal well drilling is proposed. The tool is mechanically sealed, and it can work stably at high temperatures well bottom. Based on the principle of fluid self-excited oscillation, the rotary valve is designed to convert the pressure fluctuation of the fluid into axial and torsional percussion load, which can improve the rock-breaking efficiency of the bit. The percussion load generated by the two-stage oscillator is simulated and calculated by LES mode. Then the amplitude-frequency characteristics of the output percussion load of the oscillator are analyzed. Finally, filed tests were carried out in two high-temperature wells AT4 and AT5. Experiments have shown that ATPH can operate well at more than 200°C and can significantly improve ROP and single-trip footage. Therefore, ATPH has considerable application prospects in high-temperature geothermal well drilling ROP enhancement.

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